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Application specific intensity distributions for laser materials processing: Tailoring the induced temperature profile

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ABSTRACT

In laser materials processing the intensity distribution of the laser beam strongly influences the spatial and temporal temperature profile that is induced within the treated material and therefore the shape of the heat influenced zone. As a consequence, the processing quality and efficiency can be increased by using adapted intensity distributions that explicitly tailor the generated temperature profile. In this work, an efficient numerical method to calculate application specific intensity distributions is presented that induce prescribed spatial and temporal temperature profiles in the material. To this end, this task is described as an inverse heat conduction problem which is solved with the conjugate gradient method with adjoint problem. As temperature-dependent thermo-physical material properties, volumetric beam absorption and quasi-stationary distributions can be accounted for, this approach proves to be very general. The performance of the algorithm is then shown by presenting two different test cases. While the first one is taken from the application of laser softening, the second one simulates a time-dependent intensity distribution for laser transmission welding. Furthermore, ideas how to implement the obtained intensity distributions, which are very inhomogeneous, are provided using specialized beam shaping techniques. The results for both test cases are validated using commercial FEM solvers.

1. Introduction

Among others, the main advantages of laser-based materials processing techniques are their local applicability, their efficiency and their cleanness [1]. These characteristics make them convincing alternatives to more established processes which is why they are increasingly introduced in industrial applications. With this work, we intend to further increase the process efficiency and the machining quality of laser-based heat treatments such as laser hardening, laser softening, or laser functionalization, as well as laser transmission welding.

In a laser heat treatment applications or in laser transmission welding, the laser beam is moved over the surface of a workpiece at a certain feed speed which results in a heating of the treated material. Depending on the process, different material modifications are obtained to harden, soften, weld, or otherwise change the material's physical properties [2]. It has been known for some time, that the beam's intensity distribution influences the induced temporal and spatial temperature profile and therefore determines the shape of the heat influenced zone [3]. This can be illustrated considering a beam with a Gaussian intensity distribution which has a high peak in the center and decreases towards its edges. If a laser heat treatment is performed using this intensity distribution the material in the center part of the processed line is heated to a higher temperature than the material towards the edges. In a plane perpendicular to the feed speed direction, the geometry of the isotherms is formed in a lens-like or nearly elliptic shape. Accordingly, the material modifications also have a lens-like shape which usually yields suboptimal processing results. If for example the complete surface of a workpiece shall be treated by placing several lines next to each other, lens-like shapes result in an inhomogeneous depth of the modifications [4]. It might therefore become necessary to overlap neighboring lines which additionally results in a decrease of the process efficiency. Although the process results become somewhat better, similar considerations still hold for modified laser beam intensity distributions such as tophat profiles [5].

There are only a few publications known in which the intensity distribution is formed intentionally to shape the induced temperature profile and thereby optimize the obtained material modifications [6,7]. In these works, the authors provide a temperature profile that yields optimal material modifications and derive the necessary intensity distributions from this. However, none of the

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presented methods to obtain such application specific intensity distributions is rigorous in such a way that complexities such as arbitrary 3D geometries, temperature-dependent thermo-physical properties, time-dependence, quasi-stationary distributions and volume absorption can be taken into account. Additionally, in these publications, the temperature profile is prescribed on the material's surface and they are focused on laser hardening.

The problem stated above – finding the intensity distribution that induces a prescribed spatial and temporal temperature profile – is an inverse heat conduction problem which is known to be ill-posed [8]. This means that if the input data – e.g. the prescribed temperature profile, the material properties, or the process parameter – are perturbed even only slightly the changes in the resulting intensity distribution can become very large. Therefore, to derive a stable solution for the inverse heat conduction problem, special regularization strategies become necessary [8].

Subsequently, in this work, a robust and efficient method to compute application specific intensity distributions for various laser-based material processing techniques is presented. The resulting intensity distributions are calculated in such a way that a previously defined optimal temporal and spatial temperature profile is induced within or on the surface of the treated material. To this end, the conjugate gradient method with adjoint problem [9] is implemented to solve the inverse heat conduction problem. This approach is applicable to time-dependent as well as quasi-stationary distributions, and volume absorption, arbitrary 3D geometries, and temperature-dependent thermo-physical properties can be taken into account. We will describe this method in Section 2.

In Section 3, two simulation results are presented as test cases. The first one is an example for laser softening where the processing of a thin steel sheet is considered. In this test case, the distributions are quasi-stationary as the spot moves at constant feed speed and the prescribed temperature profile stays constant within a prescribed time interval. The second test case which is taken from the process of laser transmission welding is a time-dependent distribution where the laser beam moves in a start-stop process. Here, polycarbonate is chosen as material which has completely different thermo-physical and optical material properties than the steel of the first example.

The intensity distributions that are obtained by solving the inverse heat conduction problem are very inhomogeneous. Therefore, sophisticated beam shaping methods need to be implemented to realize these intensity distributions in a real experimental setup. It has been suggested to use freeform optics [10] for quasi-stationary distributions and VCSEL-arrays [11] for time-dependent beam profiles. For the first test case, it will be shown that it is possible to design freeform optics in such a way that the obtained intensity distribution can be realized at least approximately.

Finally, the work is concluded in Section 4 by giving a short summary and providing an outlook on future work.

2. Problem statement & simulation method

The temporal and spatial temperature profile $T = T(x, y, z, t)$ that is induced in the material by a laser beam moving at feed speed $\vec{v}$ is best calculated in the coordinate system of the laser beam. To this end, the following heat conduction equation needs to be solved [12]

$$\rho(T)c(T)\frac{\partial T}{\partial t} - \nabla(k(T)\nabla T) = p - \vec{v}\,\nabla(\rho(T)c(T)T) \tag{1}$$

with the material's density $\rho(T)$, specific heat $c(T)$ and thermal conductivity $k(T)$. p refers to a source term which represents the absorbed laser beam power per volume. Usually, this absorbed energy can be calculated from the Beer-Lambert law [13] yielding

$$p(z) = A\frac{\partial}{\partial z}\left(I \cdot \exp\left(-\frac{z}{\delta_p}\right)\right) = \frac{AI}{\delta_p}\exp\left(-\frac{z}{\delta_p}\right) \tag{2}$$

where $I = I(x, y, t)$ is the beam's intensity distribution, A the absorptivity and δ_p the penetration depth of the radiation within the material. To solve Eq. (1), it is necessary to define boundary conditions. Here, the Neumann boundary condition which prescribes a boundary flux or the Dirichlet boundary which prescribes a boundary temperature are the mainly used ones [12]. A special form of the Neumann boundary condition is the adiabatic boundary condition which implies isolation, i.e. the flux at the boundary vanishes.

In the special case where the penetration depth of the laser beam within the material is very small, it is possible to simulate the laser beam absorption via a Neumann boundary condition

$$-k(T) \cdot \vec{n} \cdot \nabla T = A \cdot I \tag{3}$$

Here, $\vec{n}$ refers to the boundary normal. In this case, p in Eq. (1) is set to zero.

When a laser beam with a constant intensity distribution is moved at a constant feed speed over the surface of a workpiece that is much larger than the spot size and the temperature profile reaches a steady state, it is possible to neglect the time dependency in Eq. (1). Therefore, the coordinate system of the laser beam is very advantageous as reference frame because in this formulation the heat conduction problem can be solved very efficiently. In this case, the distribution is called quasi-stationary.

As stated in the introduction, the aim of this work is to calculate the intensity distribution that induces a prescribed temperature within the heat-treated material. Here, the conjugate gradient method with adjoint problem is implemented to solve this inverse heat conduction problem numerically. This method has been developed by Alifanov [14] and further adapted by Özisik [9]. Furthermore, previous work on this subject [15] will be extended.

It is assumed that the temperature profile is prescribed on a certain set of M points with coordinates $(\vec{r}_m, t_m)$, which will in the following be noted as Y_m. The conjugate gradient method with adjoint problem is then based on the least-squares sum as a deviation measure

$$S(I) = \sum_{m=1}^{M}\left(Y_m - T\left(\vec{r}_m, t_m; I\right)\right)^2 \tag{4}$$

This quantity is iteratively minimized where the discretized intensity distribution is updated in iteration $n+1$ according to

$$I^{n+1} = I^n - \beta^n d^n \tag{5}$$

here, d^n is a conjugation of the previous update direction and the steepest descent direction which is given by the gradient of S with respect to I, i.e. ∇S_I.

$$d^n = \nabla S_I^n + \gamma^n d^{n-1} \tag{6}$$

The calculation of the step size β^n and the conjugation coefficient γ^n will be provided below in Eqs. (16) and (18).

In standard optimization techniques, it is necessary to approximate derivatives by finite differences to obtain ∇S_I For the given case, this implies that for each entry in ∇S_I at least one direct problem as in Eq. (1) must be solved which is discouragingly inefficient. Subsequently, in the conjugate gradient method with adjoint problem, a special approach is used to compute this quantity efficiently. In the following, the derivation as presented by Plessix [16] is followed which leads to the same equation as the approach by Özisik [9].