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Dynamic method for determination of coupling efficiencies in laser material processing

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Abstract

The knowledge about the amount of power transferred to a workpiece in relation to the applied total power of a particular heat source is crucial for every kind of thermal material processing. It allows the evaluation of process efficiencies for competing technologies and enables predictions of the thermal load of a workpiece. In case of laser material processing, in which the workpiece is heated up by laser radiation, the coupling efficiency is often strongly affected by or even corresponds to the absorptivity of the material being processed. However, documented values in literature are only valid for perfect and smooth surfaces, mostly incomplete in terms of different laser wavelengths, inconsistent or not available for relevant technical alloys. Therefore, a new method for determining absorptivity values and energy coupling efficiencies for almost arbitrary materials and processing conditions was developed. This technique relies on an adjustment of data achieved by experimental thermographic imaging and numerically computed temperature fields and provides as a result the energy coupling efficiency of the considered process. The potential of the proposed method was evaluated by performing experiments on standard type 304 stainless steel with the purpose to determine its absorptivity for solid-state laser radiation with a wavelength of 1.07 µm. The results show the absorptivity as a function of both the angle of incidence and the polarization state of the laser light.

Keywords: Absorptivity; Thermography; Simulation

1. Introduction

Material processing with lasers has become a pervasive technique in a wide range of industries, but there are still a lot of unresolved topics wherefore it continues to be a major research focus. All these processes like cutting, welding, hardening and so forth are based on the same physical mechanism, the interaction of light with matter. During the process of absorption, the energy of the laser light is converted into heat inside the material and leads to a temperature rise of this. But not the entire incident light is absorbed, a part of it is reflected and, depending on the material and wavelength, also transmitted. The ratio of the total incident light energy and the amount, which is absorbed in the material, is called *absorptivity A*. The knowledge of *A* is essential for every mathematical consideration of the process and it determines whether the process is

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successful for the used material-process parameter combination or not. The absorptivity also affects strongly the energy coupling efficiency, since the coupling efficiency is defined as the sum of several absorption processes through multiple reflections on the surface. In the case of only one reflection on the workpiece surface the coupling efficiency is therefore equal to the absorptivity.

Documented values for *A* mostly originate from the literature about solid state physics or chemistry, are only valid for perfect flat and smooth surfaces (Bergström, Powell, & Kaplan, 2007a) and for environments which differ considerably from normal process conditions (Silva, Monteiro, Rossi, & Lima, 2000). Further there is a vast difference between the values derived from various sources. *Fig.* 1 shows the absorptivity of pure iron as a function of the angle of incidence calculated using Fresnel´s Formula (for details see Prokhorov, Konov, Ursu, & Mihailescu, 1990, pp. 15–18) and the values for the refractive index *n* and the extinction coefficient *k* from different publications. One can see, that for perpendicular incidence of the radiaton the absorptivity values differ more than 0,08 which equals to 28 % in variance.

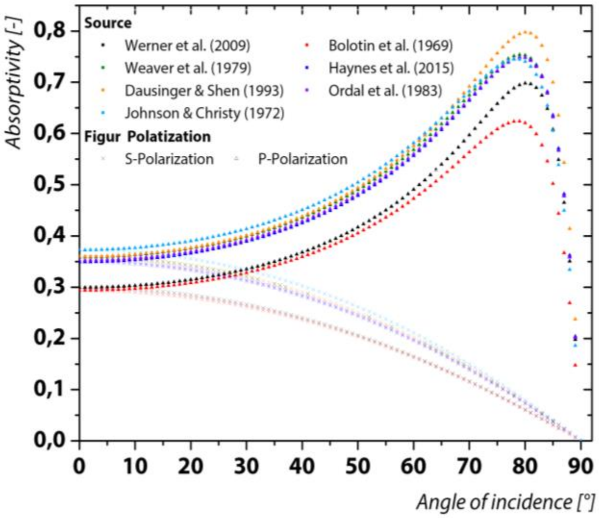

Fig. 1. Theoretically calculated absorptivity using Fresnel formula and values for n and k from different literature sources

Furthermore the absorptivity heavily depends on the process parameters like intensity (Beyer, 1995), polarization and wavelength of the laser radiation (Dausinger & Shen, 1993; Hügel & Graf, 2009), temperature of the material and surface roughness (Konov & Tokarev, 1983). This leads to the conclusion that in most cases the values depicted from literature are not applicable in practice and an experimental determination is inevitable.

Several methods for the estimation of the absorptivity or the coupling efficiency were purposed in literature, the first one from Daunt, Keeley and Mendelssohn in 1932 long before the invention of the laser. They used a black body at room temperature as the radiation source, while the probe out of lead was mounted in a vacuum chamber surrounded by liquid helium. The temperature increase through the absorption of irradiation on the probe led to the evaporation of the liquid helium, which they measured in an evaporation calorimeter. Through the experiments Daunt et al. (1932) tried to find evidence for the theory of Drude about the relationship between the electrical conductivity and the optical constants of materials. However, at the temperature of the experiments (4,2 K) there was no change in absorptivity observable at the transition of lead to superconducting state[†]. This method was later used by various authors for determining *n* and *k* of materials (e.g. Bos & Lynch, 1970; Ramanathan, 1952; Weaver, Colavita, Lynch, & Rosei, 1979). The advantage of this method lies in the low measurement error, which is according to Bos and Lynch (1970) below 2%. This high measuring accuracy can only be obtained at very low temperatures, which is the

[†] Since the theory of Drude connects the optical behavior of metals with their electrical conductivity, the absorptivity should become zero in the case of superconductivity where there is no electrical conductivity.

disadvantage of this method. Studies at room or even process temperatures are not feasible.
A method for the direct measurement of the coupled energy at room temperature was described by Stegman, Schriempf and Hettche (1973). They used thermocouples on the rear surface of the probe for determining the maximum temperature increase through irradiation. In a later article they used this increase in an analytical model to estimate the energy coupling efficiency (Hettche, Tucker, Schriempf, Stegman, & Metz, 1976). The results were indicative of a correlation between the coupling efficiency and the wavelength as well as the power density of the radiation. Dausinger and Shen (1993) used this method for the evaluation of the absorptivity of mild steel and experimentally found a correlation between the wavelength, the polarization state and the absorptivity. Kim, Albright and Chiang (1990) used the same analytical model, but measured the maximum temperature increase on the side surfaces of a thermally isolated steel probe. This resulted in the finding of a nonlinear dependence of the coupling efficiency on the feed rate. The direct measurement of the coupled energy and the fast determination at different temperatures is an advantage of this technique. Despite the high accuracy of thermocouples this method has a high measuring error since the position of the heat measurement and the heat distribution inside the material are not considered in the analytical model. However, the consideration of the position of the thermocouples is crucial for high accuracy measurements (Gonzalez, Freton, & Masquère, 2007).
Miyamoto, Maruo and Arata (1986) used therefore a calorimeter, which measures the transferred heat independent of the heat distribution inside of the material. The welds were conducted and the probe was subsequently transferred in a water calorimeter. Through the evaporation of the water the coupled energy could be estimated. They found a correlation between the absorptivity and the feed rate of the process. A potential source of measuring error for this method is the heat loss during the process and the transfer of the probe which equals according to Pépe et al. (2011) to around 5%. For this reason Fuerschbach (1996) conducted his experiments inside a commercially available Seebeck-Envelope Calorimeter which reduces the named error to 2 % (Pépe et al., 2011). Fuerschbach (1996) found a nonlinear correlation between the coupling efficiency and the power density of the laser. In further studies using a Seebeck-Envelope Calorimeter the nonlinear correlation of the melting efficiency and the feed rate for a laser welding process was found (Fuerschbach & Eisler, 1999) and there was no proof for a dependence of the coupling efficiency on the power density as well as the pulse width for a pulsed laser beam welding process (Fuerschbach & Eisler, 2002). A drawback for practical application of a Seebeck-Envelope Calorimeter is the long measuring time, which can be as high as 10 hours for reaching equilibrium state (Hu, 2002). Also experiments at higher temperatures are complicated and the process realization inside the calorimeter can lead to a heat input through scattered irradiation and thus an increased measuring error.
Since for metals the absorptivity is connected to the reflectivity through the relation $A=1-R$, A can be measured indirectly through an integrated sphere, which is capable of determining the spectral reflectivity. Bergström, Powell and Kaplan (2007b) estimated with this method the absorptivity of standard type 304 stainless steel and other steel alloys. They found a positive correlation between the surface roughness of stainless steel and the absorptivity for values above R_a=1,5 µm. In a further study they used this method for the determination of the absorptivity for aluminum alloys, copper and zinc coated probes (Bergström et al., 2007a). According to Clarke and Compton (1986) the possible measuring errors for this methods are loss of radiation through the ports of the sphere, the unequal illumination of the probe and the directional dependence of light scattering from the sample and the sphere walls. In sum the error can be as high as 5-6 % of the measured reflectivity. Another disadvantage of this method is that it is not applicable at typical process conditions and higher temperatures.
In summary, all methods accompany several weaknesses regarding the accuracy, the potential errors or the needed environmental conditions. Therefore a new dynamic method for the determination of the coupling efficiency is presented. It uses a numerical model which is adjusted to thermogaphic process observations for the calculation of temperature fields. Therefore it accounts for the heat distribution inside the material and also includes the measurement positions of the temperature curves. The measurement can be conducted at process conditions without further precautions needed. In the next chapter the method is presented, followed by the experimental results for the determination of the absorptivity on standard type 304 stainless steel. It concludes with the evaluation of the method and a short outlook.

2. Description of the method

The purposed technique to estimate the energy coupling efficiency consists of two parts:

1. During process or experiment the temperature of the probe is recorded for the time of the light-matter interaction and the subsequent 300 seconds.
2. The temperature-time curve is used to adjust a numerical simulation to the measured values and to calculate the energy coupling efficiency.

2.1. Test execution

A picture of the experimental arrangement is shown in *Fig.* 2. The probe is mounted on a plate out of glass fiber reinforced epoxy and is clamped on four points using the same material. The heat conductivity of the glass fiber reinforced epoxy plate is 0,20 $W*m^{-1}*K^{-1}$, wherefore the probe is considered to be thermally isolated. The probe is moved under the heat source (i.e. the laser beam) while a thermographic camera is fixed above the workpiece. During the conduction of the experiment and for the subsequent 300 seconds the temperature distribution of the probe is recorded. Four different measuring areas A1-A4 are defined on the probe and coated with graphite to ensure a uniform surface with a known emission coefficient. One measuring area has the size of 10x10 mm^2 and the temperature in the area is averaged to receive the time-temperature curve for the heating and cooling during and after process.

There can be two possible sources for measuring errors identified. First, the accuracy of the thermographic camera has to be taken into account. Modern systems have a temperature resolution of less than 0,025 K with an accuracy of +/- 1 %. Second, the error of the determination of the emission coefficient is another factor influencing the accuracy of the method. In our determination the standard deviation of the values for the emission coefficient accounts to 0,9 %. In conclusion the accuracy of the temperature estimation is better than +/- 2 %.

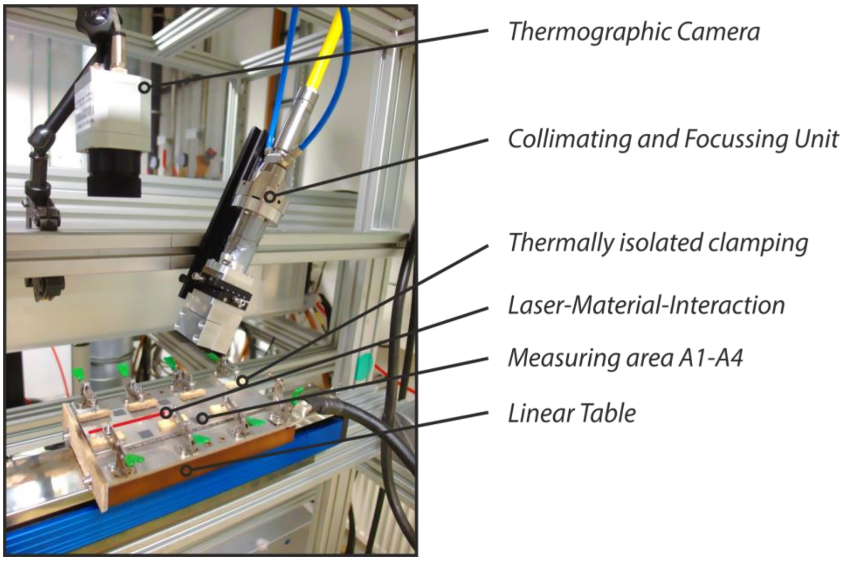

Fig. 2. Schematic drawing of the experimental procedure

2.2. Numerical Model

The applied numerical model computes the temperature field in the tested probes in two stages. First, the steady-state temperature distribution at the end position of the laser beam (moved at constant speed along a straight path) is determined. This approach is much less time-consuming than a fully transient computation and the error regarding the temperature profiles in the measuring areas was verified to be small. Second, the cooling down regime of the probe was computed as a function of time within the experimentally considered time interval [0,300 s]. For this period, the average temperatures over the measuring areas were calculated. An agreement between experimental and numerical values is only achievable when the considered absorptivity of the model equals the real one. Other factors of influence were adapted to experimental conditions (ambient temperature, heat transfer coefficient, emissivity, heat source characteristics) or do not play a crucial role for the evaluated results. With regard to the small thickness of the probes, a two-dimensional modelling was adequate to fit the experimental temperature profiles.

3. Experiment

Experiments on X5CrNi1810 (AISI 304) stainless steel plates with a thickness of 1 mm were conducted. The plates had the dimensions of 60 x 200 mm² and were partially coated with graphite on the four measuring areas, each 10 x 10 mm² in size. The location of the graphite coated areas can be seen in *Fig.* 2. A single-mode (SM) fiber laser with a maximum output power of P_L= 400 W and an emission wavelength of λ= 1,07 µm was used as heat source. The focus radius amounted to ω_0= 1,5 mm with a Gaussian intensity distribution while the power for the runs was chosen to be P_L= 200 W to avoid melting of the material. For the evaluation of the influence of the polarization state – parallel and perpendicular to the plane of incidence – on the absorptivity, the incidence angle α was varied from 0 until 80 degree in 10 degree steps. The feed rate was set to v_0= 0,8 m/min and the path length of the irradiation stage was 150 mm.
The used thermographic camera measures in the infrared spectral range of 7,5 until 13 µm, wherefore no special care about scattered radiation of the laser is needed. The camera records with a frequency of 80 Hz and has a thermal resolution of 0.08 K at room temperature with a 2 % accuracy. The emission coefficient of the graphite coated surface was determined for the used wavelength in preliminary tests and amounts to 0,77, which is in agreement with the calculated value of 0,83 for the spectral emissivity at 10 µm using data from Nemanich, Lucovsky and Solin (1977). The measurement started simultaneously with the process and ended 300 seconds later to capture the cooling rate of the material. The temperature inside the measurement areas was averaged to receive the time-temperature curves.

4. Results

In *Figure 3* the temperature profiles of two experimental runs are presented. As can be seen in both graphs, the curves of the different measuring areas are in good agreement with each other in terms of maximum temperature and cooling behavior. The small difference between the measuring areas points at the precise located fields and at the symmetrical heat distribution inside the material. Therefore a numerical simulation with the assumption of symmetry seems justified.

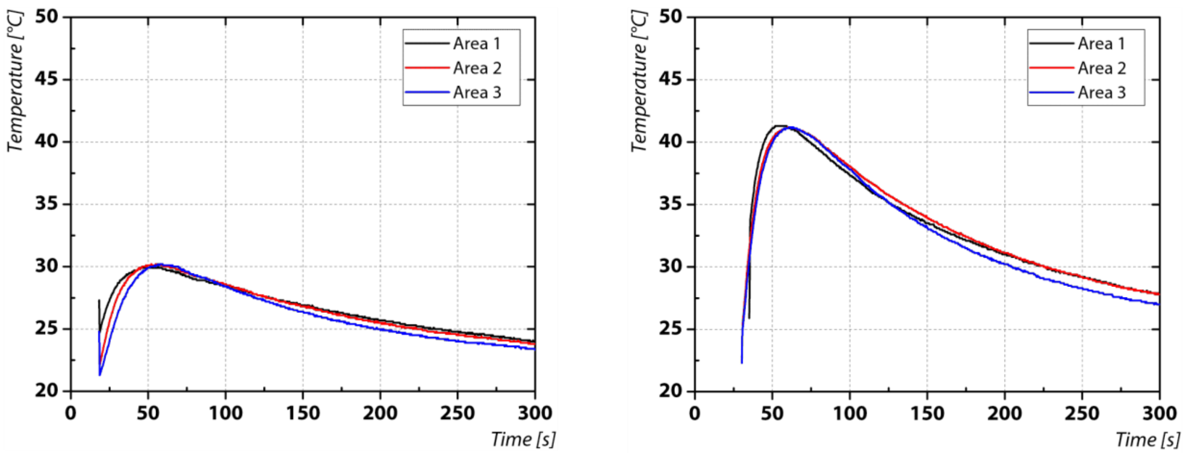

Fig. 3. Temperature curves: P_L= 200W, s-polarization, α=30° (left); P_L=200W, p-polarization, α=80° (right)

The maximum temperature increase at the location of the measuring areas ranges for the evaluated parameter field between 4 and 22 °C. Therefore the signal-to-noise ratio (SNR) is higher than 10 and all observation are considered to be based on effects rather than measuring deviation.
As described above, the simulation is structured in two parts. First a steady-state temperature distribution is computed for the process of heat input followed by the transient calculation of the cooling regime. The temperature field of the steady-state solution of one experimental run can be seen in *Figure 4*. Because of the small heat conduction of 304 stainless steel, the temperature rise at the position of the measuring areas takes place after the heat input of the laser. For this reason the temperature increase in *Figure 3* does not coincide with the start of the process at t=0 s. The maximum temperature in the direct interaction zone between the laser and the material does not exceed 250 °C in this run. Consequently no change of the state of the material takes place during the process and it can be assumed that the energy coupling efficiency equals the absorptivity in this case accordingly.

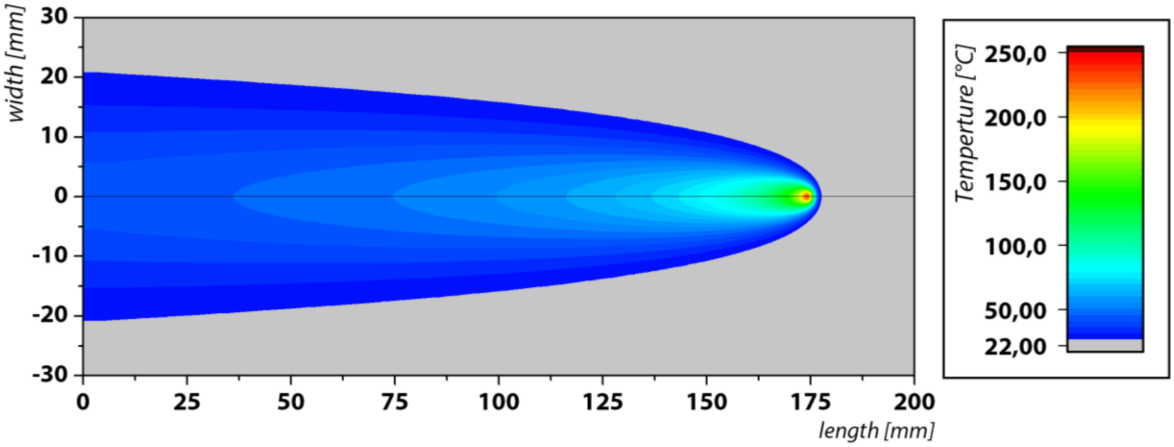

Fig. 4. Steady-state solution: Temperature field for P_L= 200W, s-polarization, α=30°

The solution of the transient computation can be seen in *Figure 5*. For the majority of runs the match between the experimental and theoretical calculated temperature curves is almost perfect, as can be seen exemplary in the left part of *Figure 5*. The cooling behavior is described with the evolved numerical model in these cases. However, for some runs the heating and cooling regime exhibits a lack between the experiment and the numerical simulation (see *Figure 5* on the right). Thus the Simulation underestimates the temperature increase as well as the cooling rate. One reason for that may be found in the two-dimensional calculation approach. It is possible that for the description of the temperature curves a three dimensional approach is needed. Another possible reason for the deviation is the steady-state approach to calculate the heat input. Since the measured curves are always inside the calculated maximum and minimum temperature boundaries, the deviation can also be ascribed to a minimal dislocation of the measurement area of the thermographic camera. As Gonzalez et al. (2007) indicated, the position of the measurement location is crucial for a perfect fit between calculation and experiment. Despite all these possible errors, the deviation between experimentally and numerically derived temperature curves is less than 1 °C or 2 %, respectively. The influence of this deviation on the calculated coupling efficiency value is therefore seen to be negligible.

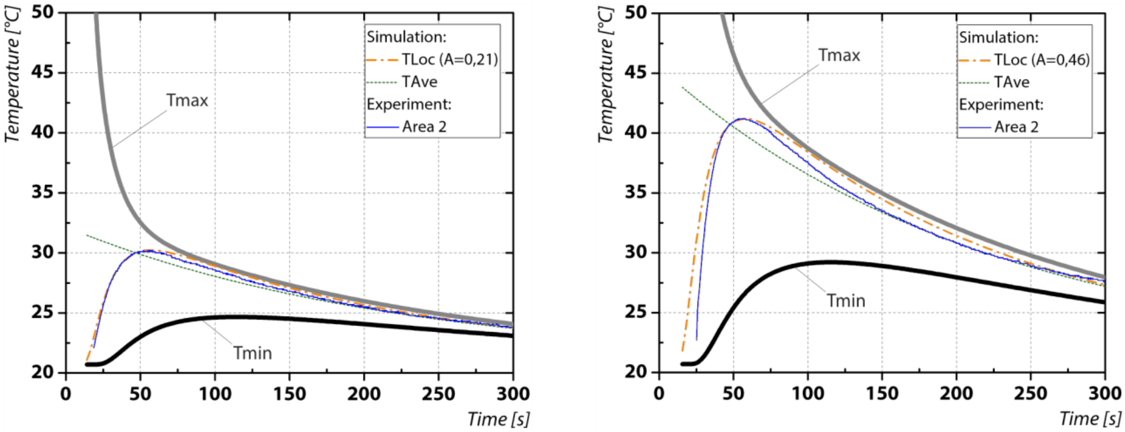

Fig. 5. Simulated temperature curves: P_L= 200W, s-polarization, α=30° (left); P_L=200W, p-polarization, α=80° (right)

A summary of the determined absorptivity values for all runs is presented in *Figure 6*. The relationship between the polarization state, the angle of incidence and the absorptivity can be seen. The measured absorptivity of the s-polarization state decreases with higher angles of incidence and tends to zero at 90 degrees. For the p-polarization state of the incident laser light the absorptivity first increases until a maximum around 80° of inclination is reached. After this maximum at the so-called Brewster angle the absorptivity decreases rapidly and tends also to zero at 90 degrees. The absorptivity values for perpendicular incidence of the laser beam amounts to A= 27 % for both polarization states and at the Brewster angle a maximum value of A= 46% for the p-polarization state is measured.

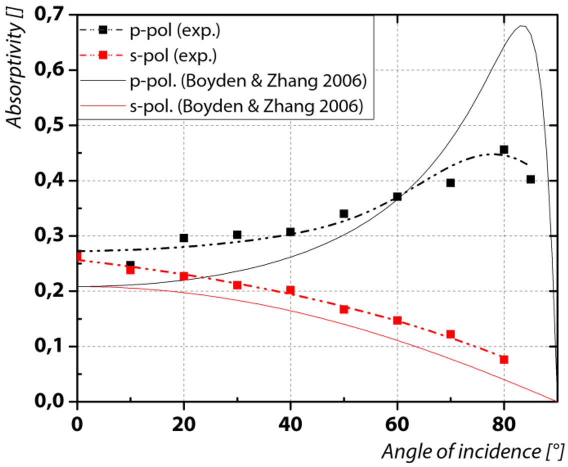

Fig. 6. Experimental determined and theoretical calculated values for absorptivity in dependence of angle of incidence

For comparison and evaluation of these results, the calculated absorptivity using the diffractive index for 304 stainless steel from Boyden and Zhang (2006), which they derived from the Drude model, are drawn in *Figure 6*. At normal incidence the measured values exceed the theoretical ones. A possible explanation for this deviation is the surface roughness of the used probes. The model by Drude is only valid for perfect and smooth surfaces, while the probes in the experiments were used as received with a surface roughness exceeding this condition by more than one magnitude. The experiments of Bergström et al. (2007b) and Stern (1990) showed the positive correlation between the surface roughness and the absorptivity leading to a higher absorptivity at greater surface roughness. Therefore the higher absorptivity values at normal incidence and for the s-polarization state can be explained using this thesis.

The deviation of the absorptivity values of the p-polarization state at higher inclinations can also be ascribed to the difference in surface roughness. The experiments of Matsuyama, Sakamoto and Shibata (1993) showed, that at higher angles of incidence the above described relation between the surface roughness and the absorptivity reverses for the p-polarization state. Therefore the calculated absorptivity values using

Drude´s theory overestimates the experimental values for higher surface roughness paired with higher inclination angles. Another effect which one should consider in this context is the decrease in the power density of the irradiation. Prokhorov et al. (1990) stated, that for fixed parameters of the radiation incident on a probe, the intensity of the irradiation spot decreases by a factor 1/cos(α). Applied to the intensity of the irradiation used in the presented experiments, the decrease amounts to 92% from 0 until 80 degree inclination angle. The intensity at an angle of incidence of 80° is only 8 % of the intensity at normal incidence, accordingly. However, the relationship between the absorptivity and the intensity is assumed to be nonlinear (Fuerschbach, 1996), wherefore the effect of this irradiation drop can't be estimated.

5. Conclusion

A dynamic method for the determination of absorptivity and energy coupling efficiencies under process conditions and for almost arbitrary materials is presented. Using thermographic imaging technique, temperature curves of the process and the subsequent 300 s of cooling phase were recorded for measuring areas apart from the processing zone. With a two-dimensional heat conduction model, which was adjusted to the temperature curves of the process, the energy coupling efficiency could be determined. The total measurement accuracy of the model is assumed to be better than 2 %. The method was used to estimate the absorptivity of standard type 304 stainless steel under different angles of incidence and polarization states. At normal incidence the absorptivity amounts to A= 27 % for both states of polarization. The value is higher than the theoretically calculated, which was attributed to the not ideal surface condition of the probes used in the experiments. For higher angles of incidence the absorptivity of the s-polarization state tends to zero while that of the p-polarization state first increases until reaching a maximum at the Brewster angle around 80 ° and then also tends to zero. The maximum absorptivity value of the p-polarization state evaluates to 42 %, which is less than the calculated one using Drude´s theory. This leads to the conclusion that under processing condition a higher absorptivity can be obtained by inclining the irradiation source, however, the increase is not as much as expected from theory.
For the deviation between experiment and theoretically calculated values two possible effects have to be considered. On the one hand the surface roughness of the probes is much higher than the scope of Drude´s theory and on the other hand the intensity decreases with higher inclination angle. In future the authors intend to conduct further experiments to try to explain whether the decreasing intensity or the surface roughness accounts for the lower absorptivity values. Therefore the material surface roughness will be systematically varied to obtain the influence on the absorptivity. In addition the numerical calculation model will be extended to a three-dimensional heat conduction case to further increase the accuracy of the method.

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