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A novel thermal sensor applied for laser materials processing

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Abstract

In materials processing heat input into parts is a major issue. To reduce heat impact, temperatures can be evaluated to optimize processes i.e. for low distortion, low dilution or small heat affected zones. For the first time a new sensor which combines ratio pyrometry with 2D-resolved measurement is applied for laser processing. The advantages of independence of emissivity and attenuation of the thermal radiation together with 2D-temperature information are demonstrated on laser cladding. The temperature distribution at the parts’ surfaces becomes available with quantitatively high precision. This information was successfully applied to validate FEM-based temperature field simulations.

Keywords: laser surface processing; sensing and control; FEM simulation

1. Introduction

Reproducibility, reliability and low costs are driving criteria in industrial applications for the choice of processes. Heat conduction processes need to be well controllable to supply workpieces with adapted heat input to maintain homogeneous temperature profiles like shown for soldering by Conway et al. [Con99]. To increase the spatial resolution and reduce heat coupled into a workpiece, which can induce distortion and an altering of material properties, the laser has established for surface treatment in industry over the past decades as already summarized by Heuvelmann et al. in 1992 [Heu92].

Laser cladding has merged to a key technology in industry as for example published by Walz and Nägeler [Wal08]. Especially the marine engineering industry can benefit as described by Wagner et al. [Wag08].

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Monitoring temperatures is an essential key to further reduce the heat input. At present a variety of non-contact methods are applied which often are lacking accuracy if gas, dust or particles are attenuating the temperature signal in the optical path. Detectors applying the rationing method are capable to shorten out these factors as presented by Doubenskaia et al. in [Doub06]. Yet, the market only supplied point or line detectors. Recently a novel 2D-detector has been developed and was introduced by Hutter et al. in [Hut08] and [Hut09] which is able to detect temperatures in a range of 600 °C to 1900 °C on a ratio pyrometric basis. Within this work this detector type is applied for laser processing for the first time.

2. Experimental

A system for laser surface treatment has been applied. This included the lamp pumped Nd:YAG laser Trumpf HL 4006D as heat source. The laser radiation was collimated and focused to the working plane by the process head Precitec YC50. For laser cladding additional material was delivered to the process head by the powder feeder GTV MF-PF-2/2. The coaxial powder jet was directed to the surface of the work piece below the nozzle. A rotational axis together with a 3-axis-CNC was used for the specimen manipulation.

The process was carried out with closed-loop control on the basis of temperature measurements executed by the ratio pyrometer Impac IGAR 12 LO. Its beam path was guided through the applied process head. By a dichroitic mirror the temperature signal was coupled out of the head. The pyrometer measured at two wavelength, 1.28 μm and 1.65 μm. As the dichroitic mirror attenuated these wavelengths by different magnitudes the internal compensation factor K was applied to correct the temperature evaluation. By preliminary calibrations on a tungsten filament the K factor could be determined to 0.571. Detectable temperatures range from 500 °C to 2200 °C at a measurement frequency of 0.5 kHz. By on-line evaluation of the melt pool peak temperature, laser power was adapted in a way that this temperature was kept constant along the cladded track.

The transient temperature field was recorded by the ratio pyrometric, CMOS-based camera Pyrocam from IMS Chips, Stuttgart. Detectable temperatures of the applied calibration were in the range from 650 °C to 1900 °C. The camera was positioned in off-axis configuration with an angle of 34° and a distance of 71.4 cm from camera housing to the specimen surface. A program was developed at BIAS to record the data stream from the camera and to evaluate the resulting melt pool width. The system was capable of recording at a frame rate of about 8 Hz at the full resolution of 640x480 pixels. For this article melt isothermes have been evaluated on basis of single images recorded during processing.

Round four-point bending test specimens out of the base materials steel X5CrNi18-10 and steel 42CrMo4 were laser cladded with the cobalt-based alloy Deloro Stellite 21. The specimen geometry is shown in figure 1. The length of the waisted section was 40 mm. The initial diameter d₁ in the specimen center accounted for 10.3 mm. The waisted section was laser cladded circumferentially to a diameter d₂ in the center exceeding 12.2 mm. Parameters shown in table 1 were applied for laser cladding of the geometries shown in figure 1. Argon was used as shielding and carrier gas.
The recorded temperature field during laser cladding of the high alloy steel X5CrNi18-10 at a feed velocity of 1 m/min was utilized to validate a finite element method model for the prediction of temperature fields and resulting residual stresses. The simulation model itself was set up in Sysweld 2010 on basis of investigations of laser cladding of respective material combinations as well as investigations of thermo-physical material properties. The ability of the software to consider phase transitions was utilized to simulate the addition of the cladding material. This phase was activated after respective elements were touched by the heat source, thus locally exceeding a threshold temperature of 1300 °C. Parameters applied in the experimental investigations like laser power, track offset and feed velocity were input for the model. A value of 50 % was assumed for the coupling efficiency of laser power into the work piece. The laser radiation was defined as double ellipsoid volume heat source according to Goldak [Gol84]. Details on the applied simulation model as well as experimental results at low speeds were previously published in [Koe12].

3. Results

Representative two dimensional temperature distributions recorded with the Pyrocam during experimental and simulative laser cladding of steel X5CrNi18-10 at a feed velocity of 1 m/min are shown in figure 2. Figure 2a shows the round specimen clamped to the rotational axis and positioned below the powder nozzle. The image was recorded close to the specimen’s center position. The laser beam heats the surface of the specimen above 1900 °C. A melt pool is formed as the melting temperature of the steel of about 1400 °C is exceeded. Powder fed to the melt pool is heated above its melt temperature of about 1350 °C and generates a cladding on top of the base material. In the background of the specimen hot powder particles which are flying away from the processing zone can be identified. Their temperature is determined to be above 1250 °C. In the upper part of the image the powder nozzle can be seen. On its lower edge thermal radiation is reflected. The powder is heated, thus giving a certain amount of thermal radiation to the detector. Moreover, it is scattering and reflecting radiation from the surrounding thus giving artefacts to the thermal image. Likewise, the false colors on the specimen surface are to be interpreted. The complete image shows temperatures higher than
600 °C. Yet, melt pool and trail can very well be distinguished from ambient artefacts. Qualitatively the simulated temperature distribution in figure 2b is in good agreement with the Pyrocam measurement in figure 2a. Compared to the experiment a flatter temperature gradient left and right of the melt pool can be evaluated from the simulated temperature distribution. The peak temperatures account for > 1900 °C.

The transient laser power and the resulting peak temperature in melt pool center over the cladding track length for different feed velocities and material combinations is shown in figure 3a. For all velocities and material combinations processed it can be evaluated that laser power was adapted significantly along the cladding to achieve the desired temperature. In all cases the temperature was set with low deviations. For laser cladding of steel X5CrNi18-10 it can be evaluated that an increase of feed velocity by a factor of 4 leads to an increase of laser power by a factor of 2. Comparing the power profile of steel X5CrNi18-10 and steel 42CrMo4 at 4 m/min feed velocity it can be observed that the latter requires slightly more laser power to achieve identical temperature within the first half of the cladding track. Power and temperature characteristics can be described as qualitatively identical for both steels.

Representative Pyrocam images recorded at the position of 1.2 m in all processed combinations are shown in figure 3b. At elevated speed the melt pool width can clearly be identified as smaller compared to lower speed. Temperature fields induced in both steels at a feed velocity of 4 m/min can be described as identical. In case of a low feed velocity the surrounding temperature is not interfering with the melt pool nor with the specimen surface temperature. In contrast, at elevated feed velocity higher temperatures in the surrounding of the melt pool can be found. High temperatures ranging up to the magnitude determined in the melt pool center can be observed at both base materials, whereas in case of steel 42CrMo4 these appear to be higher than in case of steel X5CrNi18-10. These temperature signals are however interfering with parts of the melt pool, which makes interpretation of the image difficult in the melt pool region.
In figure 3c the evaluated transient temperature fields recorded by the Pyrocam are shown. In all results it can be seen that melt pool size is very low close to the starting point, is increasing to its maximum shortly after and from there on drops towards the end point. The characteristics of the melt pool width during cladding of steel X5CrNi18-10 and steel 42CrMo4 at 4 m/min are very similar. The latter shows a slightly higher melt pool width up to the specimen center. This corresponds to the higher laser power set to achieve identical melt pool peak temperature as it can be seen in figure 3a. On the example of steel X5CrNi18-10 it can be evaluated that an increase of feed velocity by a factor of 4 leads to a reduced mean width by about 30%.

Steel X5CrNi18-10 + Stellite 21
1 m/min

Steel 42CrMo4 + Stellite 21
4 m/min

b) Pyrocam image at a track length of 1.2 m

Fig. 3. a) Laser power and peak temperature, b) melt pool size and c) Pyrocam image recorded during controlled laser cladding of steels with Stellite 21
4. Discussion

The Pyrocam evaluation shows elevated temperatures on the specimen, in its surrounding as well as close to the melt pool which are in the order of the melt pool peak temperature. This can be traced back to scattering and reflection of the melt pool radiation on the powder particles, the powder nozzle and on the specimen surface. For low feed velocities the reflections are not interfering with the radiation of the melt pool nor of the specimen surface around, thus can be neglected for the evaluation. At high feed velocity, the thermal radiation scattered on powder particles is much stronger, thus impeding temperature field evaluation of melt pool and surrounding. Generally, no position in the measurement shows temperatures below about 800 °C. It is anticipated that this is a result of scattered thermal radiation. As the specifications of the camera allow a calibration for temperatures of up to 3000 °C [Hut09], in future steps the calibration is planned to exceed 1900 °C. This might increase contrast in high temperature range and improve distinguishing of reflections and actual temperature signal.

Pyrocam results correlate very well with temperature fields simulated by the FEM model. The measurement of peak temperatures by pyrometer during the cladding process gives values at least 200 °C lower than evaluated by the Pyrocam. It is assumed that the pyrometer signal was influenced by the dichroitic mirror in a way that this systematic deviation resulted. Nevertheless, the pyrometric temperature measurement is qualified well as a basis of closed-loop control. The temperature values on the other hand appear to be only qualitatively valid. To more accurately determine absolute temperatures an adapted dichroitic mirror could be applied to less influence the pyrometer’s measuring wavelengths. The Pyrocam was oriented in an angle of 34° towards the specimen and the specimen surface itself was also curved. It has yet to be investigated in how far this influenced the temperature values.

5. Conclusions

For the evaluation of temperature distributions induced by laser cladding in the steels X5CrNi18-10 and 42CrMo4 with Stellite 21 the Pyrocam successfully qualified. Temperature field information could be streamed and be evaluated in-situ as well as post processed. Thermal information recorded with the Pyrocam during laser cladding showed no signs of falsification due to powder, gas or smoke, neither due to varying emissivity in the measured area. At low feed velocity and low laser power a good contrast of actual temperature over background signals due to low amount of scattered and reflected thermal radiation could be observed. Within the temperature range of 800 °C to 1900 °C the melt pool edges as well as the melt trail could be resolved clearly. At elevated feed velocity the amount of scattered and reflected thermal radiation leads to a reduced contrast to evaluate the melt pool geometry. Background radiation affected the evaluation of temperatures lower than 800 °C in all measurements.

The Pyrocam images corresponded very well to actual results of FEM simulations of temperature fields. It can be estimated that after further validation steps the 2D emissivity compensated thermal field detection can contribute to improve the precision of temperature field simulation.

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