Noncontact temperature measurements in laser machining

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Abstract

Absence of on-line control in laser machining is one of the main obstacles on the way of its further industrial implementation. The method of non-contact temperature measurements by a pyrometer in laser machining provides a number of potential advantages for a detailed analysis of surface temperature evolution versus laser operation parameters and materials properties. However the proper application of pyrometry in laser machining requires the solution of a number of methodological difficulties. The two basic problems are: (a) correct measurements of brightness temperature (that is to avoid superposition of proper thermal radiation to be measured with different types of “noise”) and (b) correct determination of true temperature.

The originally developed pyrometers, as well as infra-red camera and high speed CCD camera were applied for comprehensive optical monitoring in pulsed laser action, lap laser welding and laser cladding.

Keywords: Optical sensing, pyrometry, temperature, laser machining

1. Introduction

Application of comprehensive optical diagnostics for analysis and optimisation of laser technologies is the promising and well-known approach. For example, to control the quality of laser welding the following methods are used: Recording of signals from plasma plume, thermal radiation from molten pool, intensity of back reflected laser radiation, treatment of images from CCD and infra-red cameras, tracking of welding seam geometry [1-4]. One may note that often interpretation of the recorded signals is not evident, in particular when they represent a superposition of diverse physical phenomena.

The physical phenomena in pulsed Nd:YAG laser irradiation with millisecond pulse duration were intensively studied in the early 1970-1990. This is one of the relatively simple and probably one of the most studied fields of laser applications [5, 6]. Actually laser pulses of millisecond duration are applied in laser welding of thin plates (for example, hermetically sealed Kovar boxes for micro-electronics), laser cladding (for example, moulds repairing), remelting of upper layers of thermal sprayed coatings and other applications where laser radiation is used to melt a thin layer and to avoid creating a large heat affected zone (HAZ).

The problem of laser lap welding of zinc coated steels is of great interest to the automotive industry. The objective of the present study is to use pyrometers for: (a) process optimisation and (b) on-line process control in Nd:YAG laser lap welding. To reach these goals the following technical tasks must be completed: (1) to confirm stability and reproducibility of pyrometer measurements; (2) to define the value of the mean temperature and its acceptable deviations; (3) to apply Fourier analysis to define characteristic frequencies and to eliminate noise; (4) to correlate variations of the surface temperature with the typical welding defects.

Actually laser cladding represents the most rapidly growing field of industrial laser surface treatment [1]. Cladding of Stellite is a common service proposed by laser job shops. When using multi-component powder blends, for example metal matrix composite with
ceramic reinforcement, one need to control temperature of the melt to avoid thermal decomposition of certain compounds (as WC) and to assure melting of the base metal (as Co). Even for Stellite cladding temperature control may be applied to assure stability of the process and the coating quality: on the one hand to avoid useless overheating and on the other hand to prevent formation of residual porosity.

2. Experimental set-up

A pulsed-periodic Nd:YAG laser source HAAS HL62P (maximal average output power 60W, maximum peak power 3000 W, pulse duration up to 20 ms) was applied and laser radiation was focalised in a spot of 2.1 mm diameter on stainless steel (INOX 304L) substrates. To minimise the influence of surface thermo-chemistry on emissivity variations, a flux (5 l/min) of Ar was applied.

Nd:YAG laser HAAS 2006D in continuous wave (CW) mode (maximal output power is 2kW) was used, laser radiation was delivered by optical fibre. The laser optical head has a focal distance 200 mm and provides focal spot diameter of 600 µm. Lap welding was performed at laser power 2 kW and welding velocity 2500 mm/min. The materials used are Zn-coated steel sheets with various thicknesses: from 0.7 mm up to 1.25 mm. The size of the gap was varied in the range of 0 – 0.5 mm.

The following two non-commercial pyrometers developed by DIPI Laboratory were used: (1) 12-wavelength (in the range of 1.001 – 1.573 µm) one-spot (diameter of the temperature measurement zone is 800 µm) instrument with the sampling time of 50 µs; (2) monochromatic 2D pyrometer (the frame of 100 photodiodes) for measurement in a zone 3 by 3 mm with the sampling time of 17 µs per one photodiode.

Visualisation of the welding process was carried out by an infra-red camera FLIR Phoenix RDAS™ with InSb sensor: 3 to 5 µm band pass arranged on 320x256 pixels array. Acquisition time varied from 9µs to 16.5 ms, frequency of the measurements went up to 38 kHz.

Optical monitoring in the visible spectral range was carried out by commercial camera Phantom V7.1 with SR-CMOS monochrome sensor, 12 bits in the visible range, 105 frames per second for 64x88 pixels array, 60° angle relatively surface normal, protection by “notch” filters.

3. Results and discussion

3.1. Comprehensive optical diagnostics in pulsed laser action

The results of pyrometer measurements are compared with the visualisation of zone of laser impact by high speed CCD-camera (Fig. 1a, b) and infra-red camera (Fig. 1b). Note that CCD-camera was fixed at about 60° relatively laser beam.

It is found that with the low surface roughness and Ar protection, the evaporation products are absent and the maximum surface temperature is the smallest (compare Fig. 1a with Figs. 1b). The bright zone on CCD-camera image is associated with the melted zone providing high reflection of laser radiation. The dark spot in the middle of the bright zone Fig. 1a probably is the result of Ar flux, as it is absent in the records without Ar protection.

The spatial distribution of laser beam was measured and found close to the Gaussian one with maximum in the middle. Therefore temperature maximum can not be found at the beam periphery.

The visualisation of vapour plume in case of Ar flux absence indicates that even at relatively low energy density flux \((q = 8.6 \times 10^4 \text{ W/cm}^2)\) when surface temperature is higher than 2300°C the evaporation takes place. The vapour plume is visible because of its illumination by incident laser radiation, it is not seen in infrared camera records (Fig. 1b).
Fig. 1. Optical diagnostics applied to irradiation of INOX 304L by rectangular Nd:YAG laser pulse with 30 J energy and 10 ms pulse duration (surface roughness is \( R_a = 0.04 \) \( \mu \)m) : (a) application of Ar as protective gas with 10 l/min flow rate; (b) without protective gas.

3.2. Overlap laser welding of Zn-coated steel sheets

Geometry and mechanical properties of the welding seam are strongly influenced by the gap between the sheets. Good welding quality may be achieved by the optimisation of the gap size [1, 2]. In case of an insufficient gap between sheets, vapour cannot be evacuated freely thus leading to instability of the molten pool and defects of the welding seam.

The zero gap results in appearance of welding defects and in strong variations in the depth of the welding seam and leads to intense ejection of the melted matter in the form of drops of various size. With zero gap during welding, the brightness temperature is below the average temperature (1980 °C) for the reference conditions (gap 0.2 mm).

Various low-amplitude frequencies of temperature are observed, but a characteristic frequency cannot be determined. These frequencies are related to oscillations of the free surface of the molten pool that are induced by zinc vapour which escapes mainly through the irradiated surface.

Fig. 2. Lap welding of zinc coated steel sheets by continuous Nd :YAG laser. Parameters: welding speed is 2500 mm/min, laser power is 2kW, sheets of 0.7+1.25 mm, gap 0.2 mm. (a) pyrometer records and photos of the welding seam cross sections; (b) frequency analysis by fast Fourier transform.

The results are different for the gap of 0.1 mm which provides a better appearance of the seam and a smaller depth of the crater. Mean temperature during welding approaches the reference values obtained for the gap of 0.2 mm.

Using the reference conditions (gap 0.2 mm), the through-weld is obtained (Fig. 2a), the seam on the side of the irradiated surface is concave (photographs of the cross sections A and B of the welding seams).
The brightness temperature fall at the instant B can be explained by the formation of a cavity in the molten mass. Analysis by fast Fourier transform shows the presence of low-frequency components of the signal (Fig. 2b), which correspond to the modes of oscillation of the molten pool, i.e. regular oscillations (~ 33 Hz) appear during the through-welding of two sheets which correspond apparently to the modes of oscillation of the entire molten pool.

If the size of the gap exceeds the reference value either the weld fails (Fig. 3a, cross section A) or it occurs only on one side of the sheet (Fig. 3a, cross section B). During welding the brightness temperature is below its average value for the reference conditions (gap 0.2 mm). The signal is characterized by low-amplitude frequencies related to motion of the entire melt pool.

![Fig. 3. Lap welding of zinc coated steel sheets by continuous Nd :YAG laser. Parameters: welding speed is 2500 mm/min, laser power is 2kW, sheets of 0.7+1.25 mm, gap 0.5 mm. (a) pyrometer records and photos of the welding seam cross sections; (b) frequency analysis by fast Fourier transform.](image)

During welding (laser power is 2 kW, welding speed is 2500 mm/min) with the given gap size of 0.2 mm, the surface temperature is stable: for the lap welding of a sheet of 0.7 mm on a sheet of 1.25 mm, the mean temperature is 1980°C with signal deviations of ± 78 °C (4%); for the lap welding of a sheet of 0.7 mm on a sheet of 1 mm, the mean temperature is 1917°C with signal deviations of ± 37 °C (2%).

### 3.3. Laser cladding

Laser cladding (LC) is flexible and efficient method for elaboration of diverse protective coatings including functionally graded, multilayered, etc. It is possible to mix different powders while injecting them into cladding zone and produce coatings with desired content in situ, to create engineered internal structures [1, 2]. In the so-called coaxial LC the desired composition of powders is delivered to the substrate coaxially with the laser beam. Temperature profiles in LC of thick protective coatings are measured with the help of infrared camera FLIR. The camera was calibrated with the help of a black body MIKRON to measure brightness temperature. Non-monotone temperature profiles indicate the position of powder injection zone that is characterised by lower temperature values.
Fig. 4. Coaxial laser cladding of Ti6Al4V powder on steel substrate: (a) surface temperature profiles (axis perpendicular to the cladding line); (b) two-dimensional temperature field. Brightness temperature was measured by infra-red camera FLIR Phoenix. Cladding parameters: laser power is 4kW, cladding velocity is 700 mm/min, powder flow rate is 52 g/min.

4. Conclusion

The originally developed pyrometers are the appropriate instruments to control surface temperature evolution in laser welding, cladding, and surface treatment. The absolute majority of commercial pyrometers that operates in the near-infrared spectral band can not be applied in the Nd-YAG and fibre laser machining because of the low protection from reflected laser radiation, too large zone of temperature measurements, low sampling rate, etc. To reach the goal the pyrometers specially adjusted for laser machining should be developed.

References