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Time-resolved temperature measurement during laser marking of stainless steel

M. Kučera *, J. Martan, A. Franc

New Technologies Research Centre (NTC), University of West Bohemia, Univerzitni 8, 306 14 Pilsen, Czech Republic

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ABSTRACT

A new measurement system was developed for time-resolved surface temperature measurement in nanosecond time scale. A study of surface temperatures reached by different parameters of laser marking and their correlation with resulting microstructure, phase composition and corrosion tests performed on marked samples is presented. The marking was done using a nanosecond pulsed fibre laser with variable pulse duration (from 9 to 200 ns), repetition frequency and pulse energy. Different phase composition and corrosion resistance were observed for visually similar marking results obtained by different laser parameters. This correlates well with maximum temperatures reached in the laser spot, which varied from less than 1100 °C for longer pulses to more than 1800 °C for shorter pulses. Melting of the surface with up to 4 μm thickness was observed for marking processes inducing high temperatures. The maximum temperatures in the pulse depend not only on pulse duration but also on previous pulses due to the heat accumulation effect. A temperature difference of up to 500 K was observed due to heat accumulation. From the results it can be concluded that combinations of longer pulse duration and higher repetition rate are the most suitable parameters for preserving corrosion resistance of stainless steel after laser marking.

1. Introduction

Knowledge of the temperatures of a material surface during laser irradiation is important for understanding the processes during laser processing of the material. For the temperature measurement during the pulsed laser heating of the material surface, different experimental methods are used, based on different physical principles. Frequently, procedures are used which combine several methods together to compare and verify the results. For example, for the investigation of the melting dynamics and resolidification of an a-Si thin film [1], the reflectivity, transmissivity, emission and electrical conductance are measured.

The methods for surface temperature measurement can be classified according to the following criteria: the principle of the method, the detector used, the response time, the temperature range and the output of the method. There are methods based on the electrical conductance measurement [2], on the reflectivity or transmissivity of the measuring laser [3,4], on the VIS, NIR and IR radiation measurement of the sample surface [5,6], on the detection of the Raman scattering induced by the measuring laser [7] or on XRD diffraction [8]. The time-resolved reflectivity measurement is used more often than the emission measurement using pyrometry or other radiometric methods [9]. To achieve the time resolution in microseconds and space resolution in μm, the contact methods [10] fail, and the standard pyrometers and IR techniques also do not work due to the lack of the space resolution or an unknown emissivity value [11].

For calibration of IR radiometry system, phase change (e.g. solidification) can be used. For the IR radiometry in the case of only heating a smooth surface temperature evolution is obtained. In the case of melting, during the cooling phase a plateau of almost stable temperature (or inflection point) forms at the end of the solidification of the liquid phase. The temperature level of the plateau is close to the equilibrium melting temperature. The TRR evolution shows a rapid change during melting of the material surface [9].

Laser marking of stainless steel surfaces can improve or worsen their corrosion resistance depending on the laser type, process parameters, material properties and laser marking-related material processes. Laakso et al. [12] presented measurement of critical pitting temperatures for laser marked AISI 304 steel samples. It was shown that the critical pitting temperature depends on the heat input and scanning velocity. In [13], the relation between laser marking parameters and corrosion resistance is discussed. The higher heat inputs reduce the material corrosion resistance. The

* Corresponding author.
E-mail address: kucera82@ntc.zcu.cz (M. Kučera).

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longer pulse duration and higher frequency are more advantageous for preserving corrosion resistance.

The influence of nanosecond laser marking on the pitting corrosion resistance is discussed in [12,14,15]. The lower content of the ferritic/martensitic phase in the treated surface [14] leads to higher pitting corrosion resistance. For the higher overlap of laser pulses over 90%, it GIXRD measurement detected an increase in the ferritic/martensitic phase (delta-ferrite), which is induced due to the fast solidification after the end of the laser pulse.

Up to now, time-resolved temperature measurement was not applied to the laser marking process. This article presents a new measurement system for time-resolved surface temperature measurement in the nanosecond time scale and its application to the laser marking of stainless steel. The measured results enable deeper understanding of the thermal processes during laser interaction with material and also the reasons for resulting material microstructure, phase composition and corrosion resistance.

2. Experimental

2.1. Laser marking system

For laser marking experiments, the pulsed fibre laser SPI G3-HS having a maximum average output power of 20 W, with a SCANLAB SCANcube 10 scanning head with a 160 mm f-theta lens, was used. The duration of the laser pulse is in the range of 9–200 ns and pulse repetition frequency can be adjusted in the range of 1 to 500 kHz. The pulse energy was in the range from 0.04 to 0.78 mJ. The laser spot diameter $1/e^2$ was 65 μm.

2.2. Temperature measurement system

The sample irradiated (heated) by a pulsed fibre laser at 1064 nm emits infrared radiation from its surface, see Fig. 1. The emitted radiation from the surface is then focused by a lens with the focal length of 50 mm, and transmitted through the shortpass filter Thorlabs FES1000, which eliminates the reflected laser radiation at 1064 nm. The filter FES1000 transmissivity for wavelengths from 700 to 1000 nm is higher than 90% and the optical density for laser wavelength 1064 nm is higher than 5. The radiation is focused by the lens to a silicon PIN photodiode 1 (Hamamatsu S5052). The PIN photodiode operates with a reverse voltage applied and has a high-speed response of 500 MHz. Its spectral sensitivity is in the range of 300–1100 nm. The obtained signals are then recorded by a digital oscilloscope (500 MHz).

The time-resolved reflectivity (TRR) method [9] is used for phase changes detection. The He–Ne CW probe laser is directed onto the heated zone of the sample and is reflected to the same photodiode as IR radiation (photodiode 1). When the probe laser is switched on, the photodiode measures both reflection and emission signals. In most cases the probe laser was switched off and only emission signals were measured. The reflectivity of the probe laser depends on the temperature, phase variation and roughness of the sample's surface. The TRR signal is analysed for changes from the initial signal before the laser pulse (difference mode).

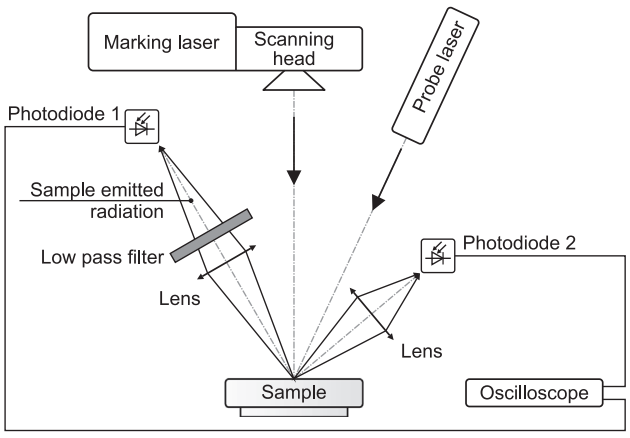

Fig. 1. Schematic representation of the experimental system.

The diffusely reflected light from the marking laser (fibre laser) is focused by the lens, focal length 25.4 mm, onto the silicon PIN photodiode 2 (Hamamatsu S5972). This photodiode is used mainly for triggering the measurement, but also changes of reflectivity of the marking laser pulse can be observed during its duration.

The laser marking experiments are done on square area of 1 mm × 1 mm size. The laser is scanned on parallel lines with certain line overlap. Laser pulses are overlapped in each line (pulse overlap) depending on scanning speed and pulse repetition frequency. The temperature measurement system (photodiode 1) measures radiation from circular sensed area of diameter of 0.9 mm. It measures radiation emitted by each laser pulse in the senses area (laser spot size of 65 μm is much smaller than sensed area). For the further analyses measurement from one laser pulse is selected. Preferably laser pulse in the centre of the sensed area is selected. First line and beginning of lines are excluded from selection due to possible differences of signals from unaffected material. The intension of this work is to investigate fully developed marking process including pulse overlap.

2.2.1. Calibration

The size of measured area on the sample surface is 0.8 mm^2 for the temperature measurement system. This means that the system measures radiation from many pulses consecutively during the processing of the marking lines. This is advantageous for the possibility of monitoring process development from the start of the line and stability during the line, but there is a disadvantage in that there is no possibility of classic calibration in the case of a constant temperature plate or a black body. The laser spot is very small compared to the measurement area and if classic calibration is used, much higher signals will be obtained compared to the measurement of the process.

In order to obtain the absolute surface temperature, the PIN photodiode 1 output was calibrated by using phase transition of the measured material. The calibration procedure is as follows: (1) Theoretical calibration curve is calculated for a given detector and filter, (2) multiplication factor is determined for a measured material and used optics and measurement geometry by measuring voltage signal at a known temperature (solidification), (3) corrected calibration curve is calculated from the theoretical calibration curve and the multiplication factor, (4) inverse calibration curve is calculated by numerical inversion of the corrected calibration curve; this equation is then used for the temperature calculation from the voltage signal during and after the laser pulse.

The spectral sensitivity of the detector (PIN diode S5052) with the filter FES1000 is obtained by multiplication of the sensitivity of the diode S5052 and the transmissivity of the filter FES1000 for the wavelengths in the range of 300–1100 nm. The voltage sensitivity of the detector $y_V(\lambda)$ [V/W] was obtained by interpolating the spectral sensitivity of the detector S5052 with the filter FES1000 with the steps of 1 nm in the range of 300–1100 nm and multiplication with the gain of the detector system.

The theoretical calibration curve $U_0(T)$, see Eq. (1), was obtained by numerical integration of the spectral power density given by Planck's law, multiplied by the voltage sensitivity of the detector $y_V(\lambda)$ and the detector sensitive area S, across wavelengths of detector sensitivity.