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Chromatic modulation technique for in-line surface monitoring and diagnostic

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Abstract – A fast and reliable surface monitoring and diagnostic technique is essential to develop a real-time automatic control system for laser cleaning of artworks. In this paper, an in-line surface monitoring and diagnostic system based on chromatic modulation using tristimulus detectors and fibre optics is presented. The system produces measurements that are dependent on the spectral signature of the incident light but are independent of intensity. In order to demonstrate its usefulness and versatility, the technique was applied to surface monitoring in the laser cleaning of metal and stone. Results show that the spectral parameters derived from chromatic detection not only provide a clear indication of the surface cleanliness and surface damage but also much surface chromatic information from its versatility. It is also shown in this paper how a chromatic modulation technique may be utilised as a robust method for monitoring and diagnosing the surface during laser cleaning. © 2000 Éditions scientifiques et médicales Elsevier SAS

Keywords: chromatic modulation / surface monitoring and diagnostic / laser cleaning / tristimulus detectors / fibre optics

1. Introduction

On-line monitoring and diagnostic techniques measure physical quantities during the laser cleaning process. They provide information about the threshold energy density for ablation, the ablation rate per laser pulse, the evolution of the laser-generated shock waves and the nature of the removed layer, etc.

The conventional in-line optical monitoring systems in laser material processing use single or multiple photodiodes having certain wavelength bandwidths of interest (ultraviolet, visible or infrared region) to produce the simple specific output that is investigated during the process and then the value is utilised as an indicator for monitoring the process [1–4]. All these methods are based on light intensity modulation, which offers the advantage of inherent simplicity. However, these basic intensity modulation systems tend to be sensitive to spurious changes in intensity resulting from variations in the electrical components or light source within the system and the noise from the industrial environments. It is also difficult to remove these spurious effects owing to their intrinsic nature, which leads to complicated and expensive systems such as spectrometers.

As a more advanced monitoring technique, spectrometers and CCD cameras have been widely used in the laser cleaning process and have shown successful results on various materials [5–8]. However, these methods have certain limitations for practical applications in real-time. For example, they are basically complicated and expensive systems and take a long time to process the signals, which are also difficult to analyse.

In this paper, a new type of optical monitoring technique based on chromatic modulation using tristimulus detectors and fibre optics is investigated for the application of surface monitoring in the laser cleaning process. The monitoring system offers

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many advantages such as accuracy, reliability, speed of response and cost over the conventional optical monitoring systems using a simple photodiode or spectrometer. As a background, the chromatic monitoring technique is described in the following section. It is also shown how the chromatic modulation technique is utilised for monitoring the surface during laser cleaning. The results from applying the chromatic technique to surface monitoring in the laser cleaning of various materials such as copper and marble are also presented in this paper.

2. Chromatic modulation technique

Chromatic modulation is principally a technique for measuring changes in the spectral parameters of polychromatic light using carefully configured combinations of broadband detectors [9]. As every colour in colorimetry can be described by three spectral parameters, hue, lightness and saturation (HLS colour model) [10], the process that produces polychromatic light can in principle be specified and identified by these three parameters obtained by chromatic modulation.

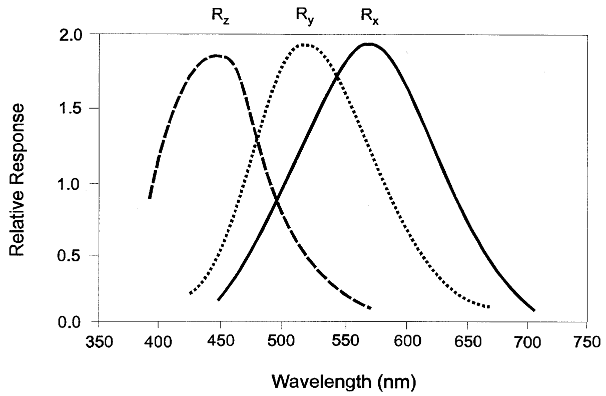

Figure 1. Relative spectral responses of three photodetectors.

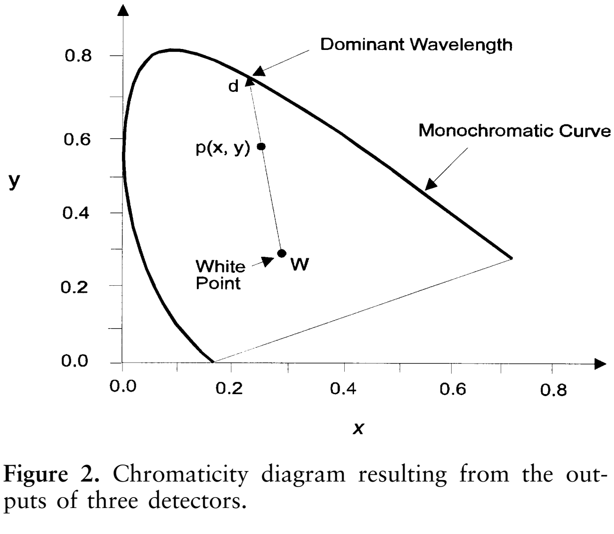

Figure 2. Chromaticity diagram resulting from the outputs of three detectors.

Chromatic modulation is principally a technique for the introduction of spectral changes into a polychromatic signal. A chromatic modulation system consists of polychromatic light for sensing changes during the progress of a physical process and an array of photodetectors with overlapping wavelength-dependent responses $R(\lambda)$ for chromatic detection.

An example of the form of response from three photodetectors is shown in *figure 1*. When the detectors are used to monitor an optical signal having a spectral power distribution $P(\lambda)$ the output from each detector will be:

$$V = \int_{\lambda} P(\lambda)R(\lambda)\mathrm{d}\lambda \tag{1}$$

In general, three detectors provide an optimum arrangement for most applications. If we let the responses of the detectors be $R_x(\lambda)$, $R_y(\lambda)$ and $R_z(\lambda)$, respectively, each detector gives the output as follows:

$$\begin{aligned} V_x &= \int_{\lambda} P(\lambda)R_x(\lambda)\mathrm{d}\lambda \\ V_y &= \int_{\lambda} P(\lambda)R_y(\lambda)\mathrm{d}\lambda \\ V_z &= \int_{\lambda} P(\lambda)R_z(\lambda)\mathrm{d}\lambda \end{aligned} \tag{2}$$

To specify the chromatic information obtained from tristimulus detection onto a two-dimensional plane, each of these responses can be divided by the sum of the three:

$$x = \frac{V_x}{V_x + V_y + V_z} \quad y = \frac{V_y}{V_x + V_y + V_z} \quad z = \frac{Vz}{V_x + V_y + V_z} \tag{3}$$

These parameters, x, y and z, are named trichromatic coefficients or chromaticity co-ordinates and they quantify the spectral signatures $P(\lambda)$. The resultant chromaticity diagram by x–y plotting is shown in *figure 2*. In this diagram the spectral parameters, such as dominant wavelength (or hue) and excitation purity (or saturation) of the coloured source, can be determined. Let the point W(0.3, 0.3) represent the chromaticity of a white illuminant and the

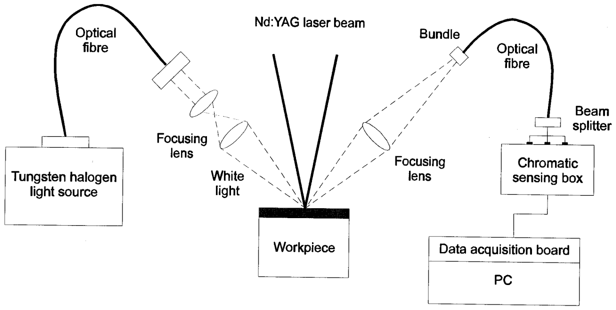

Figure 3. Schematic diagram of the chromatic optical monitoring system for surface monitoring and diagnostic of the laser cleaning process.

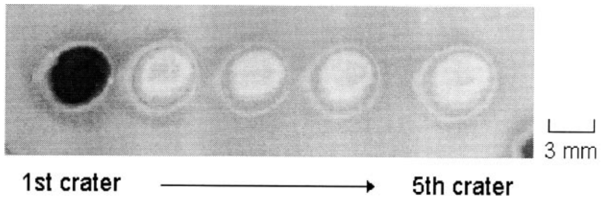

Figure 4. Laser craters on an oxidised copper surface with the sequence of the number of laser pulses with a fluence of 3.5 J/cm^2.

chromaticity of a coloured source have co-ordinates p(x, y) in *figure 2*. The dominant wavelength, which is represented as a point 'd', is achieved by connecting the point W and p and extending the line until it intersects the locus of the spectrum. The excitation purity of the source is calculated form the ratio of the distance pW/dW. If p were coincident with d the excitation purity would be 1.0 or 100 %.

If the detector responses $R_x(\lambda)$, $R_y(\lambda)$ and $R_z(\lambda)$ were made to correspond to the detectors in a standard human observer, as laid down by the International Commission on Illumination (CIE) then the resulting x–y plot would be the CIE chromaticity diagram, which is well-known in the field of colorimetry [11, 12].

The chromaticity diagram, which can be used to determine spectral parameters such as dominant wavelength and excitation purity, is important for optical sensing and monitoring because even complicated spectral signatures can be quantified in terms of only two parameters, x and y. In addition, these spectral parameters are independent of the intensity. Therefore, changes in the spectral signature during the process can be monitored by measuring the chromaticity x, y and clearly quantified on the chromaticity diagram.

This technique has the advantages of being fast, simple, sensitive and cost effective. Successful applications for plasma monitoring in the thin film process, electric circuit monitoring in circuit breakers and LPG quality control have been reported [9, 13, 14].

3. System and experimental description

Figure 3 shows the schematic diagram of the overall chromatic monitoring system designed for surface monitoring and diagnostic of the laser cleaning process. A stabilised tungsten halogen light source passed through an optical fibre was used to irradiate white light on the surface. The reflected spectra were collected by a fibre bundle through a focussing optic and the captured light divided into three by a fibre optical beam splitter and then detected by same three photodetectors passed through three different glass filters.

The filters have their major transmission in red, green and blue wavelength regions, respectively. The photodetector, which is a silicon photodiode produced by Centronic (BPX65 series), has a response time of 3.5 ns and wide spectral sensitivity in the range 400–1 100 nm.

The responses of the photodiodes are recorded on the data acquisition system in the PC with a sampling rate of 10 kHz. The recorded data are analysed in the way of chromaticity co-ordinates.

4. Results and discussion

4.1. Copper cleaning

The removal of copper oxides from a copper surface was conducted using a Q-switched Nd:YAG laser irradiation with a wavelength of 1 064 nm. *Figure 4* shows the magnified laser craters on an oxidised copper surface with the sequence of the number of laser pulses with a fluence of 3.5 J/cm^2. The first spot at the left end is the crater by the first laser pulse and the number of laser pulses increases one by one towards the right up to the fifth crater. It is seen that a well-cleaned copper surface was achieved after the irradiation of the second laser pulse.

Figure 5 shows the output voltages as a function of the number of laser pulses irradiated on the same spot which was obtained from the three photodetectors through three optical filters of different responses, R_{red}, R_{green} and R_{blue}, covering the visible wavelength range 400–700 nm.

The resulting variation in chromaticities x, y and z is shown in *figure 6*. It is seen that clear changes in chromaticities, x and y, are apparent until the second laser pulse and then the value does not change with further laser pulses. This implies that the transition of the surface occurred during laser cleaning, i.e. the copper oxide was removed in the second laser pulse producing a well-cleaned copper surface. These results agree with those from the optical surface analysis shown in *figure 4*.

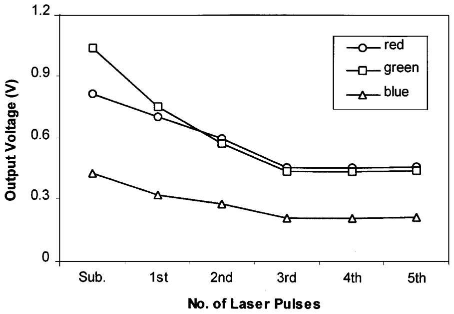

Figure 5. Output voltages from the three photodetectors as a function of the number of laser pulses.

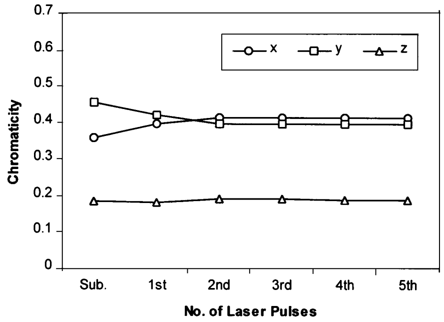

Figure 6. Chromaticity (x, y and z) variation as a function of the number of laser pulses.

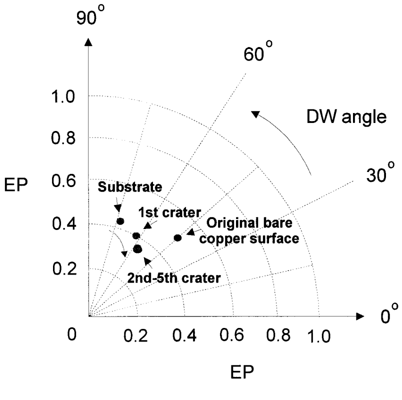

Figure 7. Spectral parameters change on DW–EP circular plane.

Figure 7 shows the DW–EP (dominant wavelength–excitation purity) circular plane where the change in spectral value was mapped in order to see clearly the changed patterns of the spectral signatures. It is shown that the DW value moves towards that of the original bare copper surface during cleaning. Meanwhile, the EP value of the cleaned surface is lower than that of the bare copper surface.

From these results, the chromatic monitoring technique provides not only simple and clear outputs but also much information on the surface in the laser cleaning of copper.

4.2. Marble cleaning

The removal of contaminants from the marble surface was carried out using a Q-switched Nd:YAG laser. It has a wavelength of 1 064 nm and a pulse length of around 10 ns. *Figure 8* shows the magnified laser craters on marble surface. A well-cleaned marble surface shown in *figure 8a* is obtained after the irradiation of the 7th laser pulse with a fluence of 0.8 J/cm^2. It is also shown in *figure 8b* that the damaged surface was induced after irradiation of the 15th laser pulse with a fluence of 2.0 J/cm^2. This implies that the overexposure to laser pulse with a slightly higher fluence can cause severe surface damage to the marble.

Figure 9 shows the DW–EP (dominant wavelength–excitation purity) circular plane where the chromatic spectra was mapped to see the spectral change with different surfaces, i.e. contaminated surface, clean surface and damaged surface. It is shown that both chromatic spectral parameters, DW and EP, clearly change towards higher values during the transition from the dirt surface to the clean surface while the damaged surface shows a lower value of EP compared to the clean surface.

In order to distinguish clearly the spectral difference between the different surfaces, the X–Y plot of the DW and EL (energy level or lightness) is shown in *figure 10*. It is seen that the DW value shows a large difference between the dirty surface and the clean one while a small difference is shown between the clean surface and the damaged surface. However, the EL value shows a clear difference between the clean surface and the damaged one.

From these results, the chromatic modulation technique monitors not only the surface cleanliness but also the substrate damage using the spectral parameters (DW, EL, EP) in the laser cleaning of marble.

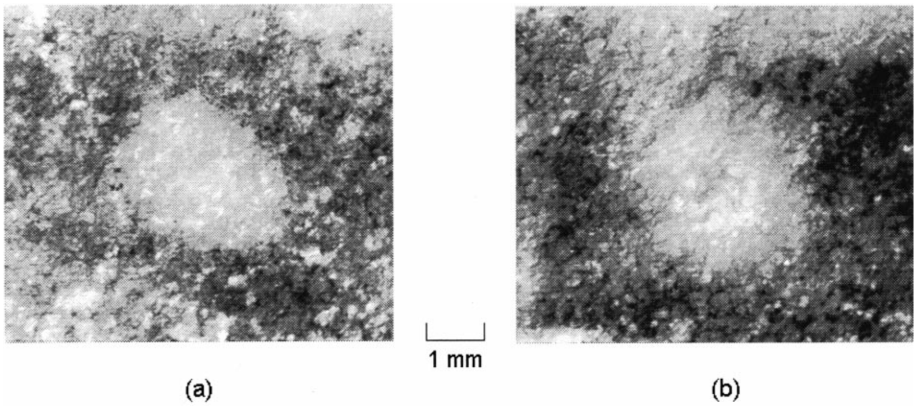

Figure 8. Magnified laser craters on contaminated marble surface: a) well-cleaned; b) damaged.

5. Conclusions

In this paper, a new type of optical monitoring system based on chromatic modulation was presented. The system was applied for in-line surface monitoring and diagnostic in laser cleaning of copper and marble. It was found that the spectral parameters derived from the detectors were able to track the change in surface condition during laser cleaning of copper and marble surfaces. In particular, the DW–EP (dominant wavelength–excitation purity) circular plane where the change in spectral value was mapped has shown graphically the changing patterns of the spectral signatures during the process. From the surface and the chromatic analysis, it was seen that the spectral parameters from the chromatic detection provide not only a clear indication of the surface cleanliness and substrate damage but also useful surface chromatic information from its versatility. As a result, the chromatic optical monitoring technique was successfully applied to monitor the surface in the laser cleaning of various materials such as copper and marble. In addition, the chromatic modulation technique has proved to be fast, simple, cost effective, sensitive and tolerant to fluctuation in external parameters as well as being an easy to use control system using simple chromatic output parameters.

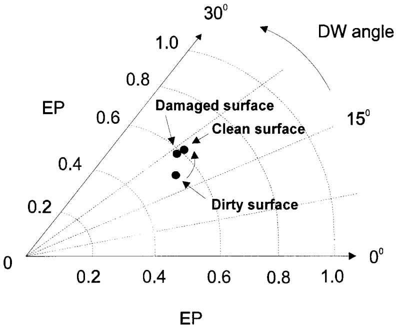

Figure 9. Spectral parameters change on DW–EP circular plane.

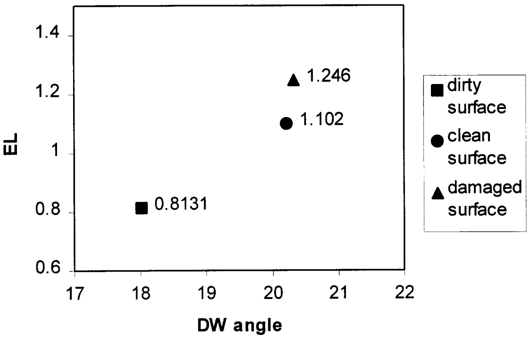

Figure 10. X–Y plot of the DW and EL.

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