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Laser-induced colour marking—Sensitivity scaling for a stainless steel

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42.62.Cf
42.55.Wd
07.60.Dq

ABSTRACT

This paper presents the results of measurements and analysis of the influence of laser marking process parameters on the colour obtained. The study was conducted for AISI 304 multipurpose stainless steel using a commercially available industrial fibre laser. It was determined how various process parameters, such as laser power, pulse repetition rate, scan speed of the material, spacing between successive lines, thickness and temperature of the material, location of the sample relative to the focal plane, size of marked fields and position in the workpiece, affect the repeatability of the colours obtained. For objective assessment of colour changes, an optical spectrometer and the CIE colour difference parameter $\Delta E_{ab}{}^*$ were used. Additionally, in order to determine the susceptibility of laser colour marking to the ageing process, two types of tests – UV radiation and a salt spray test – were performed. Based on this analysis, necessary modifications to the laser systems commonly used for monochrome marking are proposed in order to achieve greater repeatability in colour marking.

1. Introduction

Colour marking on metal surfaces is typically performed by printing, emulsion coating or electrolytic oxidation (anodizing) techniques. Scratch properties, poor wear resistance, the complexity of the process and colour fading over time are typical drawbacks of printing methods. Anodizing, in turn, does not make it possible to obtain either selective marking or more than one colour at a time.

Laser colour marking as a process has been known for 15 years [1], but it has not been used widely in the industry, because it is regarded as difficult, time-consuming, and above all not repeatable. Two main methods of laser colouring of metals have been reported in the literature. The first utilizes a laser as a heat source, which allows the formation of a transparent or semi-transparent oxide film on the metal surface [2,3]. White light illuminating the sample surface is reflected from the surface of both oxide and metal. As a result of interference of the reflected beams a colour effect can be obtained. The thickness of the oxide layer, the order of interference [4] and its refractive index determine the colour spectrum. Secondly, colour can be obtained on the surface of various metals by laser-induced formation of periodic surface structures (LIPSS), so-called “laser-induced ripples”, on the surface using femto- or picosecond lasers [5,6].

In most applications laser marking is the fastest and the cheapest method. There is strong demand to extend the capabilities of these systems as regards the possibility of colour marking. The main problems are the reproducibility and stability of the process. Often, experimentally determined parameters to obtain a specific colour on one system does not give a positive result for other systems, even if very similar (the same model). Several descriptions of laser colour formation on a metal surface can be found in the literature, but there is still a lack of information about which of the process parameters have an impact, and to what extent, on the reproducibility of the colours obtained.

2. Experimental details

The study was performed for the commonly used MOPA configuration Yb:glass fibre laser (1062 nm) with output power 20 W, beam quality factor $M^2 = 1.5$, pulse duration 100 ns and pulse repetition rate 20–100 kHz (IPG type YLP-C-1-100-20-20). The system was equipped with galvanometric scan mirrors that allow the beam

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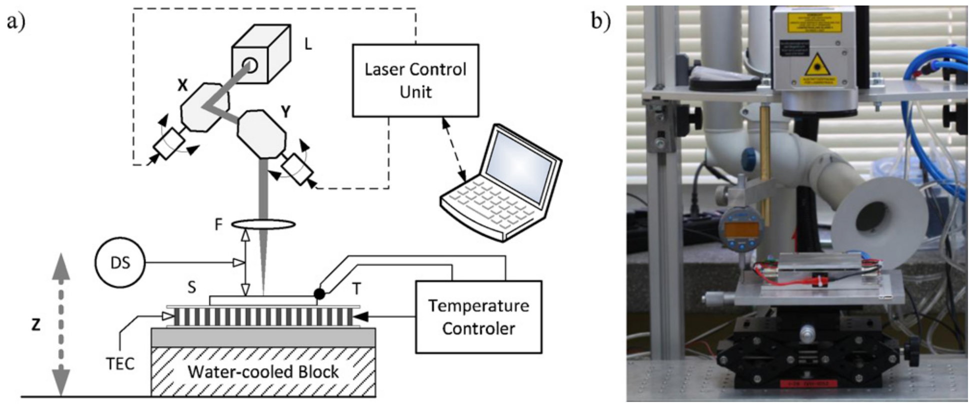

Fig. 1. System used for investigation of laser-induced colouring: (a) block diagram of the system, where: L – laser; F – F-Theta lens; DS – distance sensor; T – temperature sensor; TEC – thermo-electric cooler; S – tested sample of stainless steel; *X*, *Y*, *Z* – axes of the system and (b) photograph of the setup.

to be deflected. The laser beam was focused on the target through a 160 mm focal length F-Theta lens (LINOS type 4401-305-000-21). The beam diameter at the focal point was approximately 40 μm. Samples of materials used for marking were placed on an adjustable *Z*-axis table. A block diagram of the diagnostic system is shown in Fig. 1.

The external distance sensor allowed the displacement of the sample in the *Z*-axis to be measured with an accuracy of 0.01 mm. For temperature changes of the marked plates with resolution 0.1 °C, a thermo-electric cooler TEC and a temperature controller (ILX Lightwave type LDT-5525) were used.

Tests were carried out for plates of multipurpose stainless steel of grade AISI 304 (0H18N9, chemical composition Cr = 19%, Ni = 9.5%, Mn = $2\%_{\max}$, C = $0.08\%_{\max}$) with dimensions of 100 nm × 100 mm and thicknesses of 0.6, 0.8 and 1.0 mm. The plates were pre-coated with a protective film, which was removed just before the experiment. The samples were marked in an atmospheric air.

For an objective evaluation of colour changes due to changes in the process parameters, an optical spectrometer (Ocean Optics type USB4000) was used. The light source was a GrafiLite lamp of True Colour type (colour rendering index *CRI* = 82, colour temperature $T_C = 5600$ K). The lamp was also used to take pictures of the samples. The configuration of the colour measuring system is shown in Fig. 2a.

The software used to control the spectrometer (Spectra Suite) allows operation on several colour spaces. For colorimetric identification, the useful CIE $L^*a^*b^*$ colour space was used. It allows easy evaluation of colour difference. The CIE $L^*a^*b^*$ colour space is organized in cube form (Fig. 2b) and is almost uniform. The unit vector in the CIE $L^*a^*b^*$ colour space is approximately equivalent to the colour resolution of the human eye.

As the perceived colour depends on the angle of observation [4], many measurements were performed in order to find the optimal angle. The similarity of the perceived colour on the metal plate and the colour generated on the basis of measured $L^*a^*b^*$ data was adopted as a criterion for the optimal angle. On this basis, an angle of about $\alpha = 60°$ was chosen, and this was kept constant for all measurements. The measuring fibre was completed with a collimating lens (Ocean Optics type 74-VIS; 0.35–2 μm). The collimator's distance to the surface of the plate was fixed at 10 mm (the focal length of the collimator). In the CIE $L^*a^*b^*$ colour space, the difference between two measured colours can be expressed by the CIE colour difference formula [7]:

$$\Delta E^*_{ab} = \sqrt{(\Delta L*)^2 + (\Delta a*)^2 + (\Delta b*)^2} \qquad (1)$$

where $\Delta E_{ab}{}^*$ (total colour difference) is the Euclidean distance between two points in three dimensional colour space, and ΔL^*, Δa^* and Δb^* indicate how much a standard and a sample differ from one another in L^*, a^* and b^*. The idea is that a value of $\Delta E_{ab}{}^* = 1.0$ corresponds to the smallest colour difference that a statistical human eye can recognize. In practice $\Delta E_{ab}{}^*$ values corresponding to 4 and over are normally recognized by an average person, while those of 2 and over may be visible by an experienced observer. Statistical studies indicate that a colour difference of 6–7 $\Delta E_{ab}{}^*$ is often considered as "acceptable" to buyers of print materials [8]. After analysing the results of laser colour marking, it was decided to apply the same scale to assess the similarity of the colour obtained. To determine the reproducibility and the measurement error of the $\Delta E_{ab}{}^*$ parameter, statistical measurements of selected samples were performed. By measuring the same sample 25 times the average value of the $\Delta E_{ab}{}^*$ parameter was determined as 1.14. The variance of the measurement error value was 0.12. In the tests we used a rolled-type metal sheet which flatness (measured by atomic force microscope) was estimated at about ±400 nm (mostly grooves arranged in one direction). During determining the repeatability of the measurement, we measured the same sample by placing it on the test bench at random, with no preferential direction. In addition, as a light source, no stabilized lamp was used (the manufacturer does not specify this parameter). Both of these factors could be sources of repeatability errors. Assuming that the

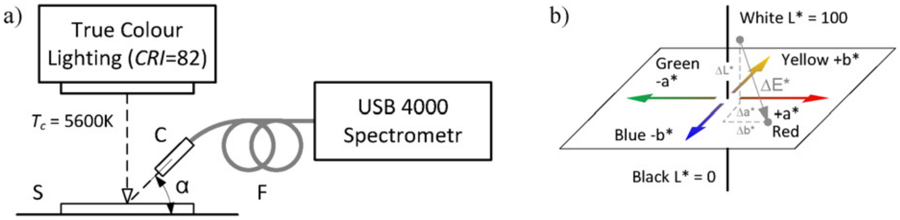

Fig. 2. System for measuring laser-marked colours, (a) block diagram, where S – measured sample; α – angle at which colour was measured; C –collimating lens; F – fibre and (b) diagram representing the CIE $L^*a^*b^*$ colour space with interpretation of the parameter $\Delta E_{ab}{}^*$.