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Possibilities of IRNDT inspection of laser marked stainless steel surfaces

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Abstract

Laser marking is an advanced technology of surface optical properties modification. A laser beam interaction with the treated surface causes a change of its optical properties and it can also affect corrosion resistance in the case of a stainless steel. The fundamental parameters of the marking process and their influence on the stainless steel corrosion properties are introduced. Possibilities of the laser treated surfaces inspection by infrared non-destructive testing are discussed. Results examples of flash-pulse and LED Lock-In thermographic analyses are presented.

1. Introduction

Laser colour marking is an advanced method for material surface laser treatment, which overview and application examples can be found for example in [1]. Laser marking is based on an interaction of a laser beam with the treated surface, which causes a change of the surface optical properties. The marking can be produced by different ways in dependence on marked material properties or other requirements including production costs, required wear resistance, acids resistance, production speed etc. The used laser marking approaches are scanning marking or mask marking, which principles, advantages, disadvantages and practical applications are described in [1]. The mask marking is applied mostly in mass production lines. The scanning marking is more flexible and actually also more popular technology. Its application brings a lot of advantages compared to other techniques such as dot peen marking, self-adhesive labels, printing, anodization or emulsion coating. It is relatively un-expensive, operating costs are low and it is usable for a wide range of applications. It can be used for very different materials, for example metals, plastics, ceramics or leather. It can be applied for decorative or informative purposes in a form of coloured texts, pictures, barcodes or data-matrix codes.

The laser marking is often used also for stainless steel, which is one of the most used technical materials. This contribution deals with AISI 304 type steel laser marking. This material belongs to the austenitic steels group, which is one of the most used steels because of their good corrosion and processing properties. These steels are used in food and chemical industry, in medicine and in many other applications, where the also an informative or decorative marking takes place. In this case, an issue of treated surface corrosion resistance maintaining has to be solved in addition to other common requirements (visibility, contrast, surface quality etc.).

2. Stainless steel laser marking

Stainless steel is high-alloyed steel with an enhanced corrosion resistance, which has a minimum of 10.5 % chromium content by mass. Stainless steels can be sorted in four groups depending on a chemical composition and structure:

- Martensitic stainless steels - consist of iron, chromium and carbon.
- Ferritic stainless steels - consist of iron and chromium, contain very little carbon and are essentially nickel free.
- Austenitic stainless steels - consist of iron, chromium, nickel and have generally low carbon content. Their corrosion properties can be improved by other alloying elements (e.g. molybdenum).
- Duplex stainless steels (austenitic-ferritic) - consist of iron, chromium, nickel, molybdenum and copper. The structure, which is a mix of austenite and ferrite, gives to the duplex steels the corrosion resistance of austenitic steels and greater strength.

More details about composition, organization to "grades", corrosion behavior, structure, physical properties or fabrication methods of the individual stainless steels can be found for example in [2].

The corrosion resistance of stainless steels is given due to a passive chromium-rich oxide film on their surface. The chromium reacts with oxygen and moisture and forms the oxide film, which is also known as the passive layer. The layer is a few nanometres thick and envelopes and protects the steel surface against corrosion. As described Crookes [3], the passivation layer can form naturally in suitable conditions (auto passivation) or the layer forming can be stimulated by staining and passivation procedures. The layer is self-regenerating when it is damaged. The corrosion resistance of the steel is mostly given by chromium content - increasing of the chromium content causes greater corrosion resistance. However, other alloying agents and surface state parameters like roughness, residual stress, crystalline defects, cracks occurrence etc. can affect the corrosion properties of the steel as well.

Interaction of a laser beam with a treated material surface can lead to different processes: heating, oxidation, melting, vaporization, ionization, sublimation and direct dissociation. The processes can be controlled by a suitable combination of laser processing parameters: laser power, pulse frequency, pulse length, scanning speed, spot size and line spacing. Set-up of these parameters defines a used marking strategy. Different laser marking strategies can be used based on used laser, treated material properties and final product requirements (for example oxidation, ablation, single line overlapping, multiple line overlapping or grating surface). The overview of the laser processes used for material treatments, physics and principles of stainless steel laser color marking are described in [4]. Results of various strategies of the stainless steel laser marking with a pulsed fiber laser are presented in [5], where an influence of laser parameters on marking contrast properties, treated surface roughness, phase composition or corrosion resistance of the treated surfaces are showed.

Strategies based on a thermal oxidation with low thermal affection of an original material are often used for stainless steel laser marking. Marked surfaces of different contrast and colour can be created by a suitable laser parameters combination. An example of different laser marked surfaces on a stainless steel plate type AISI 304 is shown in **Fig. 1**. Even if the thermal affecting is small, the marked surface structure, morphology or chemical composition can be influenced. These changes can be accompanied by an undesired surface corrosion resistance reduction, as it is referenced in [6] or [7]. The stainless steel laser marking processing parameters should be therefore optimized by such a way, that the marking contrast meets the specified requirements, but the corrosion resistance of the material is not reduced by the marking procedure.

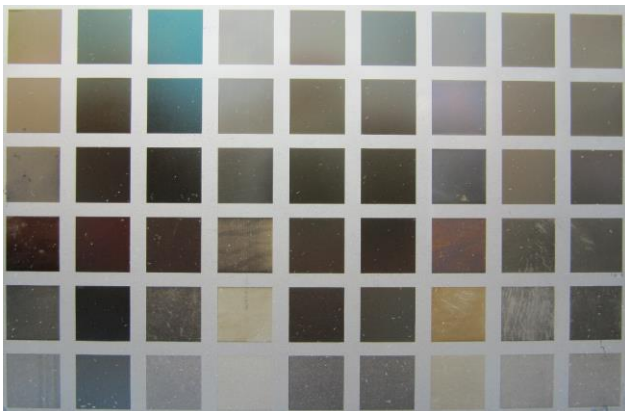

Fig. 1: *Example of laser marked surfaces made by different laser processing parameters on a stainless steel plate type AISI 304.*

For these reasons, a corrosion testing should be a part of a laser marking processing parameters optimization procedure. The most reliable test of corrosion resistance of the marked surface is a standard corrosion test, for example by an exposure in a saline mist. However, evaluation of possible influence of the laser marking process on the corrosion resistance by standard methods is quite expensive and time consuming. It is therefore not suitable for a optimization procedure. Thus, possible relationships between the material corrosion resistance and analyzed material properties change due to the laser marking were investigated [5], [8].

The laser processing based on an oxide layer growth, can be accompanied by other processes, which are related with process parameters and the final marked surface properties. It brings a possibility of using other analytics techniques for the marked surfaces corrosion resistance estimation. The very promising method seems to by the grazing incidence X-ray diffraction [4], which can analyze the austenite, ferrite and oxides occurrence in the surface layer after the laser marking. The differences in structural phases, which were also confirmed by a ferrite content measurement, are in relation to corrosion properties of the stainless steel and have also different thermal and thermal radiative properties. The experiments performed showed that these changes could be detected by the infrared non-destructive testing (IRNDT) methods and could be used for corrosion properties estimation of the marked surfaces. Example of results of Lock-In and Pulse-Phase active thermography using periodical LED and flash-pulse excitation sources respectively are presented in this paper.

3. Infrared non-destructive testing

Infrared thermography [9] is an analytical technique for non-contact measurement of temperature fields. It can be used for measurement of spatial and time distribution of surface temperature of a measured object. It is based on a detection of surface radiation in the infrared range, which is mostly dependent on a temperature and thermo-optical properties of the surface [10]. The main advantages of the infrared thermography are that it is non-contact, it does not influence the measured object, it records temperature fields, it is able to measure rotating or moving objects, it able to measure very fast processes and it is able to measure very high temperatures. The main disadvantages are that it is influenced by the measured surface thermo-optical properties, ambient temperature or surrounding atmosphere properties.

The thermography can be classified as qualitative or quantitative and passive or active. In the case of passive thermography, temperature contrast or the temperature changes are of natural origin. The qualitative thermography

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evaluates infrared radiation contrasts between individual positions of different temperature or thermo-optical properties. It has many important applications, for example heat leaks diagnostics, electrical components inspections, surveillance of people, medical applications etc. Quantitative thermography evaluates exact numerical values of measured objects temperature. Thermo-optical properties of the measured objects and surroundings properties should be known in this case. Quantitative thermography is used for example in heat treatment applications [11] or in monitoring of technological processes [12]. Passive thermography uses a natural radiation of the measured object. Active thermography [13] uses a thermal excitation of the analyzed objects. The excitation causes a measured object response resulting in temperature contrast, which is connected with defects, thermal properties local differences, thermo-optical properties differences or local heat sources concentration. The response can be detected directly or by using advanced evaluation techniques. The active thermography is the basic technique infrared non-destructive testing (IRNDT), which is widely described for example in [14]. Reviews of thermography temperature measurement methods and infrared non-destructive testing procedures are in [15] or [16].

The excitation of an inspected sample can be external (by an external heat source) or internal (using thermo-physical processes in a measured material: ultrasound or mechanical excitation for example). The sample can be excited by continuous, periodical or pulsed loading and the response can be detected as a simple temperature difference or by advanced evaluation methods: lock-In thermography, pulsed thermography or transient (step) thermography. Halogen lamps or lasers with amplitude and frequency adjustable light power are used for lock-in thermography (see [17] or [18] for example). The lock-in thermography is based on a modulated periodical excitation of the analysed object and subsequent amplitude and phase analyses of a response signal. Lasers or flash lamps are used for flash-pulse thermography (see [19] or [20] for example). The flash-pulse thermography is based on the inspected object excitation by a very short light/thermal pulse produced by a flash lamp or laser. The pulse length is normally a few milliseconds and the material response should be detected by a high-speed high-sensitivity cooled-type infrared cameras. However, the flash-pulse thermographic methods allow to inspect very different materials in depths from the surface up to several millimeters under the surface [21]. Thus, the flash-pulse inspection method is suitable also for thin surface layers inspection. The transient thermography is in principle similar to the pulsed thermography. However, the pulse length is longer (in order of seconds or tens of seconds) and the pulse can be of various shapes. Application of transient thermography for aircraft components testing is presented for example in [22]. Infrared cameras are used for a detection of the response. A standard bolometric infrared cameras or high-speed high-sensitivity cooled infrared cameras can be used. A suitable combination of an excitation source, infrared camera and evaluation method should be chosen based on application requirements. An overview, state-of-the-art and trends of IRNDT are extensively described in [23].

4. Experimental procedure

A laser marked sample made from a AISI 304 type stainless steel plate was the investigated object. A pulsed fiber laser of average output powers 20 W with scanning head with 160 mm f-theta lens was used for laser marking experiments. Laser marked areas were prepared the sample using different process parameters. The areas with reduced corrosion resistance were marked using the heat input 3 J.mm^{-2}, pulse repetition frequency 250 kHz, pulse length 15 ns and scanning speed 800 mm.s^{-1}. The areas with good corrosion resistance were marked using the heat input 1.4 J.mm^{-2}, pulse repetition frequency 400 kHz, pulse length 200 ns and scanning speed 800 mm.s^{-1}. The laser marking parameters influence on a corrosion resistance of the AISI 304 steel was verified by a corrosion test according to the ČSN EN ISO 9227 standard (exposure in a saline mist with 5% NaCl solution).

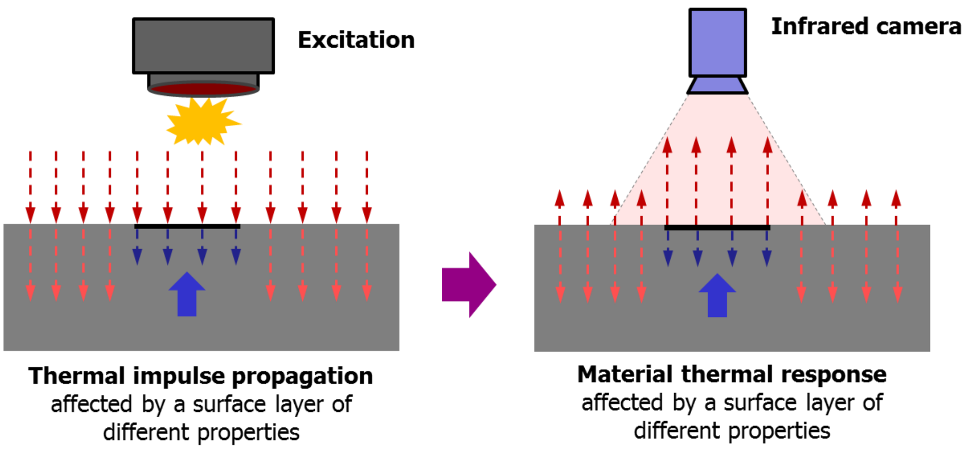

***Fig. 2**: Schematic illustration of the IRNDT measurement principle: the inspected sample is excited by a light source and the response is detected by an infrared camera.*

The thermographic inspection was performed by flash-pulse and lock-in thermography using a flash lamp and LED light source respectively. The measurement procedure is schematically shown in **Fig. 2**. The sample surface with

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marked areas was illuminated, i.e. excited, by the excitation source. The excitation source had a pulsed or periodical character in dependence whether used the flash-lamp or the LED-lamp respectively. The flash lamp excited (illuminated) the sample for a few milliseconds and the object cooling progress was analysed using different flash-pulse evaluation methods. A flash lamp of the power about 6 kJ was used as the excitation source. The IR camera framerate was from 300 to 500 fps. A modulated periodical excitation was used by the LED-lamp. Amplitude and phase of the response signal were analyzed by different lock-in evaluation methods. The LED lamp consisted of 196 LED diodes of different wavelengths and its overall power was 1.2 W. One loading period length was about 20 s and the overall excitation (measurement) time was several minutes. The IR camera framerate was 50 fps for the lock-in LED-lamp excitation measurement. The measurement configuration using the LED-lamp is shown in **Fig. 3**.

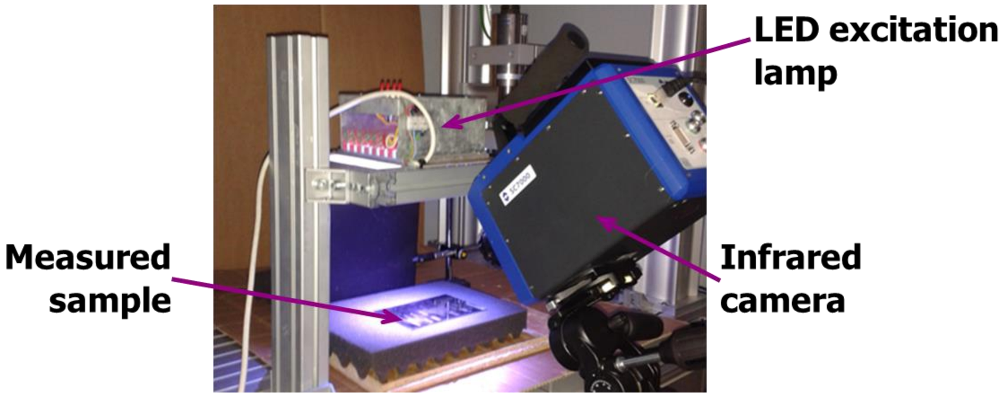

***Fig. 3**: IRNDT lock-in inspection of the laser marked stainless steel sample using the LED-lamp excitation.*

The previous experiments published in [7] or [8] showed that laser marking parameters set-up affected the treated surface. The influence of the laser marking on the treated surface concerns contrast properties, but also a corrosion resistance properties and material structure changes. It was also presented that these properties changes are connected. The structural or chemical changes of the treated material (AISI 304 stainless steel) can influence also its thermo-optical or thermal properties. It is therefore expected, that a response to the used excitation of areas affected by the laser marking can reflect possible structural or chemical changes and thereby corrosion resistance changes of the treated surface due to the laser marking processing.

5. IRNDT inspection results

The inspected sample with the laser marked areas and examples of results of the flash-pulse and LED lock-in inspections are in **Fig. 4**. The example of a laser marked areas with good and reduced corrosion resistance are designated A and B respectively. Examples of the IRNDT inspection results by the flash-pulse (A1, B1) and LED lock-in (A2, B2) methods are presented.

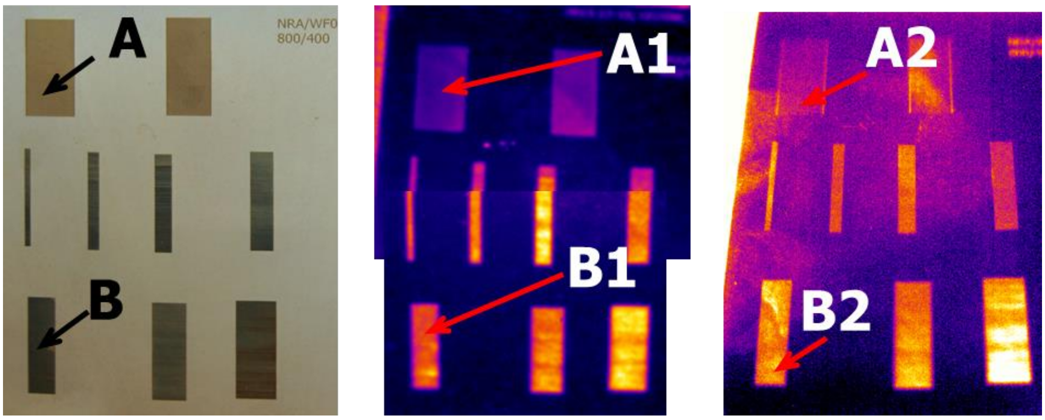

***Fig. 4**: Stainless steel sample with the laser marked areas. Areas A and B with good and reduced corrosion resistance respectively are indicated on the sample, on the flash-pulse evaluation results (A1, B1) and on the LED Lock-In evaluation results (A2, B2).*

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The presented IRNDT inspection results show differences between the areas with expected good and reduced corrosion resistance. The laser marked areas with expected good corrosion resistance (A) are less distinct compared to areas, which were not affected by the laser treatment. On the other hand, the laser marked areas with expected reduced corrosion resistance (B) are more clearly indicated on the IRNDT inspection results. This can be observed for the both IRNDT methods used: flash-pulse inspection using the flash-lamp pulse excitation (A1/B1) and lock-in inspection using the LED-lamp periodical excitation (A2/B2).

The results published in [7] or [8] and other related experiments performed indicated connections between the corrosion resistance reduction of laser marked stainless steel areas and their structural changes. These experiments included namely standard corrosion tests, grazing incidence X-ray diffraction analyses and ferrite-scope analyses. Corrosion resistance reduction of laser marked surfaces was accompanied by an increase of a content of ferrite phase and by differences in an oxide layer and chemical composition near the surface. These changes could also affect thermal (thermal conductivity) and thermo-optical (emissivity, transmissivity) properties of the laser treated surfaces. As it is shown in this contribution, it could allow an inspection of the laser marked stainless steel corrosion properties after the laser marking by the presented IRNDT methods.

6. Conclusions

The laser marking procedure of the AISI 304 stainless steel and related problem of its possible corrosion resistance reduction were introduced in the contribution. Infrared non-destructive testing methods were introduced and their possible application for the stainless steel laser marking surface inspection was suggested. The flash-pulse and lock-in IRNDT methods using the flash-lamp and LED-lamp respectively were introduced. The advantages of the flash-pulse method is a high speed of the measurement, the disadvantage is necessity to use a high power flash generator and a high-speed cooled infrared camera. On the other hand, the LED Lock-In measurement takes much longer time (several minutes with the used equipment), but a low-power LED lamp with a standard IR camera are usable for the inspection. However, the both IRNDT methods brought similar results.

The presented results showed, that the both methods had a potential for identifying the laser marked areas with reduced corrosion resistance. The used IRNDT methods brought interesting results for the tested AISI 304 type stainless steel sample. On the other hand, some level of uncertainty of the inspection was shown, which could be caused by a configuration of an experiment and by a surface affection ratio. The current state of the research also does not allow quantitative evaluation of the results. However, the presented IRNDT testing procedures are very fast and can be performed at low cost compared to a standard corrosion testing. So, even if the most reliable information about a corrosion resistance can give the standard corrosion testing only, the proposed IRNDT methods could be a helpful tool for a preliminary testing during an optimization of laser marking processing parameters.

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