Tamper-proof markings for the identification and traceability of high-value metal goods
Wlodarczyk, Krystian Lukasz; Ardron, Marcus; Waddie, Andrew John; Taghizadeh, Mohammad Reza; Weston, Nicholas J.; Hand, Duncan Paul

Published in:
Optics Express

DOI:
10.1364/OE.25.015216

Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

Link to publication in Heriot-Watt University Research Portal

Citation for published version (APA):
Tamper-proof markings for the identification and traceability of high-value metal goods

KRYSAN L. WLODARCZYK,1,* MARCUS ARDRON,2 ANDREW J. WADDIE,1 MOHAMMAR R. TAGHIZADEH,1 NICHOLAS J. WESTON,2 AND DUNCAN P. HAND1

1Institute of Photonics and Quantum Sciences, School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, EH14 4AS, UK
2Renishaw plc, Research Park North, Riccarton, Edinburgh, EH14 4AP, UK
*K.L.Wlodarczyk@hw.ac.uk

Abstract: A customized UV nanosecond pulsed laser system has been developed for the fast generation of tamper-proof security markings on the surface of metals, such as stainless steel, nickel, brass, and nickel-chromium (Inconel) alloys. The markings in the form of reflective phase holographic structures are generated using a laser microsculpting process that involves laser-induced local melting and vaporization of the metal surface. The holographic structures are formed from an array of optically-smooth craters whose depth can be controlled with ±25nm accuracy. In contrast to conventional security markings, e.g., engraved serial numbers, etched part numbers and embossed polymer holographic stickers, which are only attached to the metal products as an adhesive tape, the phase holographic structures are robust to local damage (e.g. scratches) and resistant to tampering because they are generated directly on the metal surface. This paper describes a novel laser-based process for security marking of high-value metal goods, investigates the optical performance of the holographic structures, and demonstrates their application to watches.

Published by The Optical Society under the terms of the Creative Commons Attribution 4.0 License. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI.

OCIS codes: (140.3390) Laser materials processing; (220.4000) Microstructure fabrication; (090.1970) Diffractive optics; (090.2890) Holographic optical elements; (240.0240) Optics at surfaces; (160.3900) Metals.

References and links
1. Introduction

Trade of counterfeit goods causes serious harm to the global economy and society, affecting both customers and companies [1]. The lower demand for legitimate products resulting from illicit trade reduces revenues of companies and creates an unfair advantage for those enterprises that exploit the development costs of intellectual property rights owners. The production and sale of fake items may damage well-established reputations of trademarks and brands if those goods are poor quality, defective or harmful. Customers can be the victims when they are unaware of buying a fake product whose quality is often very low. These products may be unusable, ineffective or even dangerous. Therefore, the full identification and traceability of the items leaving the manufacturing process must be ensured in order to reduce the trade of counterfeit goods. This is very important in many industry sectors, such as aerospace, aviation, automotive and medicine, in which the products must meet specific requirements, standards, and be the highest quality to ensure safety and reliable performance.

Many techniques have been developed for marking metal products [2–6]. The most common include mechanical processes (e.g. indentation, stamping, dot peening), electro-chemical processes (e.g. chemical etching), printing techniques (e.g. ink-jet printing), as well as laser-based processes (e.g. annealing marking, engraving). All these techniques enable the generation of different markings that can be in the form of alphanumeric characters (showing a part number or a serial number), bar codes, data matrices, QR codes as well as company logos and trademarks. These ‘standard’ markings, however, can be readily forged, i.e., copied onto a fake item. Moreover, the markings containing alphanumeric characters are vulnerable to tampering because removal or damage of a single character in the serial number typically leads to the loss of the product traceability.

More sophisticated markings are ‘tamper evident’ polymer holographic stickers [7,8]. Such holograms are used in the industry as anti-counterfeit labels for the identification of genuine products. Although these labels are attached to the product surface as an adhesive tape, they cannot be removed from its surface and transferred onto another product without showing any evidence of tampering as they get damaged. If required they can be supplied on films that leave behind a specific pattern, e.g. ‘void’ or a checkerboard.

Recently, it has been demonstrated that lasers can be used for the generation of ‘hard-to-replicate’ security markings on metal surfaces [9–11]. Dusser et al. [9] reported on the use of a femtosecond laser for the generation of nanostructures containing periodic ripples with a controllable orientation (via polarization rotation) that can generate specific color patterns. In
our earlier work [10], we used a picosecond laser and a liquid-crystal-based spatial light modulator (LC-SLM) for the generation of speckle-free miniature data-matrices with overall dimensions of approximately 300\(\mu\)m by 300\(\mu\)m. Murphy et al. [11] in turn demonstrated that a low-cost fiber laser can be used for producing permanent (black) markings on various grades of stainless steel, without ablating the material.

This paper reports on the further development of a laser-based process for the generation of ‘tamper-proof’ holographic structures on the surface of metals [12]. This process relies on the generation of optically-smooth craters (dimples) arranged in a specific pattern by laser-induced melting and gentle vaporization of the metal surface. To date it has been demonstrated that the process can be successfully used for producing sinusoidal gratings (scales) for high accuracy positioning encoders [13] as well as for generating phase holographic structures, but at very low processing speeds [12]. This time we demonstrate a laser processing system that enables the same holograms to be generated in less than a minute. In comparison to the previous paper, we investigate the laser-induced surface deformations on three additional metals (brass, silver and Inconel®X750), study the impact of the metal surface quality on the optical performance of the holographic structures, and demonstrate the use of the process on real parts of high-value products.

2. Experimental setups

2.1 Laser marking system

The marking system is based around a diode-pumped Q-switched 10W laser that provides horizontally polarized 35ns long pulses (FWHM) of wavelength 355nm. The beam from this laser is delivered to the work piece via a 2-axis galvo-scanning system that enables fast generation of the holographic structures. The galvo scan head was equipped with an F-Theta lens, in order to focus the laser beam to an 11 ± 2.2\(\mu\)m diameter spot (measured at 1/e\(^2\) of its maximum intensity using an Ophir-Spiricon CCD camera), and combined with the laser such that pulses are delivered on demand to a defined location on the work piece. This laser system enables accurate mapping of the hologram designs onto the work piece surface with a positioning accuracy of < ± 1.5\(\mu\)m, as measured for individual hologram pixels.

2.2 Optical setup for reading the holograms

Although the holographic structures may be read using a low-cost handheld laser pointer, in order to properly evaluate their optical performance the optical setup shown in Fig. 1 was employed.

![Fig. 1. Setup used for reading the laser-generated holographic structures and measuring their optical performance.](image)

In this setup, a He-Ne laser beam (\(\lambda = 632.8\)nm) was expanded to a 1.8mm diameter spot (measured at 1/e\(^2\) of its maximum intensity) using a beam expander (BEX) that consisted of two (plano-concave and plano-convex) lenses of focal lengths -30mm and 75mm. This beam was ‘cleaned’ using an adjustable aperture and used to illuminate the holographic structures
that were placed approximately 0.7m from the second lens of the BEX. The laser beam was incident at an angle of 3.5° to the hologram surface. The diffractive images generated by the holographic structures were projected onto a paper screen that was located 1.7m from the hologram surface. The optical power delivered to the holograms (PINC) was measured to be 4.6mW using an OPHIR power meter (PM).

The optical performance was assessed as shown in Fig. 1, using masks to collect the optical power from selected areas of a diffraction image, (i) the area containing the target image (PT), (ii) the twin image (PTWIN) and (iii) the undiffracted 0th order beam (P0th), as indicated in Fig. 2. These were compared with PINC and the total power reflected from the holographic structure (PREF).

3. Interaction of UV nanosecond laser pulses with different metals

3.1 Experimental procedure

Seven different metals: stainless steel (grade ST304LD), 99% pure nickel, silver, brass, and three nickel-chromium Inconel® alloys (grade 625, 718 and X750), were treated with single laser pulses of different energy to determine a range of pulse energies that can generate optically-smooth craters on these metals. Prior to the laser treatment, one surface of the metal samples was lapped and polished in order to reduce a relatively high initial surface roughness (rms from ~100nm to < 10nm, as measured for the area of 0.35mm by 0.26mm).

Figure 3 shows an example of the calibration maps that were generated on the metal samples. This map contains an array of the laser-processed areas; each having an array of the laser-induced surface deformations (LISDs) that were generated by single laser pulses of the same energy being a fraction of the pre-defined energy.

An investigation of the calibration maps was performed using an optical microscope (Leica), a non-contact 3D surface profilometer (Zygo) and an atomic force microscope (Digital Instruments Veeco). The last two instruments (Zygo and AFM) enabled accurate measurement of the shape and dimension (depth and diameter) of the LISDs, with a lateral (spatial) resolution of < 0.2µm and a vertical resolution of ≤ 1nm.
The LISDs generated on the metal samples were observed in the form of either micron-scale protrusions [see Fig. 4(a)] or craters [see Fig. 4(b)], dependent on the metal and the pulse energy used.

For the purpose of our work, we measured the following characteristic features of the LISDs: a) Height (H) or Depth (D) defined as a difference between the untreated surface level and the centre of the LISD, b) Diameter (\(\Phi\)) defined as a maximum diameter of the LISDs (measured from ‘edge’ to ‘edge’), c) Peak-to-valley (PV) defined as a difference between the highest and the lowest point of the LISD, and d) Effective diameter (\(\Phi_{\text{EFF}}\)) defined as a diameter of a rim within the LISD. PV and \(\Phi_{\text{EFF}}\) were measured because these parameters are more appropriate when considering the generation of phase holographic structures. For instance, it is important to know the effective diameter of the LISDs (\(\Phi_{\text{EFF}}\)) in order to select the optimum separation distance between adjacent craters within the hologram structures, because this parameter was found to have an impact on their optical performance (details in Section 4.3).

3.2 Results

Due to the intended application of the holographic structures for anti-counterfeiting security marking, the pulse energies used for the generation of optically-smooth deformations on the surface of the studied metals cannot be provided in detail. Nevertheless, it can be revealed that the deformations started to appear on the metal samples at similar but different pulse energies (\(E_{\text{TH}}\)). In the case of the stainless steel, brass, Inconel®X750 and Inconel®718, these
deformations were detected by the AFM to be in the form of shallow dimples with \( D < 100\,\text{nm} \), as can be seen in Figs. 5–8 respectively, whereas the LISDs on the Inconel®625 and nickel were observed as low bumps with \( H < 50\,\text{nm} \), as shown in Figs. 9 and 10. Interestingly, these bumps were growing in size with increasing pulse energy up to the point at which they began to be transformed into optically-smooth craters. Laser pulses of too high energy (\( E > 4 \times E_{\text{TH}} \) for the stainless steel and Inconel®625, \( E > 3.5 \times E_{\text{TH}} \) for Inconel®718, \( E > 3.0 \times E_{\text{TH}} \) for nickel, \( E > 2.6 E_{\text{TH}} \) for Inconel®X750, and \( E > 2 E_{\text{TH}} \) for brass) generated a keyhole within the crater, rapidly increasing their depth (\( D \)) above 500nm, together with the appearance of re-solidified splashes of molten metal around the LISDs.

In general, the LISDs of a specific size and shape can be repeatedly generated (with typically \( \pm 25\,\text{nm} \) depth accuracy) by using the same value of pulse energy, with stainless steel, nickel, brass and the three Inconel® alloys. This was not however possible with silver due to its high reflectance (\( R > 65\% \)) at the wavelength of 355nm [14,15] and the resulting highly nonlinear absorption with pulse energy (due to thermal effects).

Fig. 5. Example of the LISDs generated on stainless steel. The deformations were generated by single laser pulses with: a) \( E_p = 1.4 \times E_{\text{TH}} \), b) \( E_p = 3.6 \times E_{\text{TH}} \), c) \( E_p = 4.3 \times E_{\text{TH}} \), d) \( E_p = 6.6 \times E_{\text{TH}} \).

Fig. 6. Example of the LISDs generated on brass. The deformations were generated by single laser pulses with: a) \( E_p = 1.05 \times E_{\text{TH}} \), b) \( E_p = 1.2 \times E_{\text{TH}} \), c) \( E_p = 1.6 \times E_{\text{TH}} \), d) \( E_p = 1.9 \times E_{\text{TH}} \).
Fig. 7. Example of the LISDs generated on Inconel®X750. The deformations were generated by single laser pulses with: a) \( E_p = 1.1 \times E_{111} \), b) \( E_p = 1.5 \times E_{111} \), c) \( E_p = 2.3 \times E_{111} \), d) \( E_p = 3.4 \times E_{111} \).

Fig. 8. Example of the LISDs generated on Inconel®718. The deformations were generated by single laser pulses with: a) \( E_p = 1.1 \times E_{111} \), b) \( E_p = 2.9 \times E_{111} \), c) \( E_p = 3.4 \times E_{111} \), d) \( E_p = 3.8 \times E_{111} \).

Fig. 9. Example of the LISDs generated on Inconel®625. The deformations were generated by single laser pulses with: a) \( E_p = 1.2 \times E_{111} \), b) \( E_p = 2.0 \times E_{111} \), c) \( E_p = 3.6 \times E_{111} \), d) \( E_p = 4.1 \times E_{111} \).
3.3 Discussion

The optically-smooth surface deformations on the studied metals were generated by either laser-induced local melting or the combination of melting and evaporation, depending on the pulse energy used. Using the formulae given in [12], it was calculated that a 35ns duration laser pulse must have an energy somewhere between 3.2μJ and 6.4μJ in order to initiate the vaporisation of stainless steel (estimated for a laser spot diameter of 11 ± 2.2μm). This range of pulse energies was found to be in good agreement with our experimental results. Above this range of pulse energy, the depth of the LISDs generated on ST304LD rapidly increased.

The melt-only process is possible as a result of the combination of the laser wavelength (providing a relatively high linear absorption at λ = 355nm) and pulse length (being relatively long at 35ns). Laser pulses of longer wavelengths (e.g. λ = 532nm or 1064nm) result in less controlled material vaporisation due to an increase of the metal reflectivity [15,16], whereas shorter (e.g. picosecond) laser pulses lead to significant reduction of the molten area and the formation of rough laser-ablated surfaces [12,17].

As shown in Figs. 5–10, the LISDs generated at low pulse energies (E < 1.5 × Eth) are either shallow optically-smooth dimples or low optically-smooth bumps, dependent on the metal. As explained by Wissenbach et al. [18], the shape of the LISDs depends on the temperature and temperature gradients generated by the laser beam as well as the physical and chemical properties of the metal. A laser spot with a Gaussian intensity profile generates a radial temperature gradient, leading to the formation of a melt pool on the material surface when the temperature exceeds the melting point. This molten pool can flow under surface tension forces, resulting in topological changes within the laser-irradiated area.

The flow direction of the molten material depends on the temperature coefficient of the surface tension (dϒdT). For most pure metals, including iron and steel with low content of oxygen and sulphur, the dϒdT has a negative sign [19,20]. This results in melt flow from the ‘hot’ centre towards the ‘cooler’ edges of the pool. Because shear stresses cause a flow of the melt along the solid-liquid interface towards the centre, drawing the molten material on the bottom of the pool back towards the surface, this leads to the formation of a protrusion (bump) within the laser-irradiated area, such as that observed in the nickel sample. The appearance of bumps on metals may also result from rapid heating that leads to the material expansion.

According to the Heiple-Roper theory [21], the surface tension of iron and other elements can be modified due to change in the concentration of surface-active elements, such as sulphur and oxygen. This may change the sign of dϒdT (from negative to positive), leading...
to the change in the flow direction of the melt pool. Then, the molten metal flows radially inwards, transferring hot metal from the centre to the bottom of the pool and forming a dimple (crater) within the laser-irradiated area, like those observed in the stainless steel, brass and Inconel®X750 samples.

The LISDs on the Inconel®625 and 718 alloys, generated by laser pulses of the energy $E < 2.5 \times E_{TH}$ (for Inconel®625) and $E < 3.5 \times E_{TH}$ (for Inconel®718), were found to have a more complex shape. The cross-section of these surface deformations was similar to the letter “W”. The “W-shaped” surface deformations can be explained using the theory provided by Keene et al. [22] who pointed out that a system that exhibits a positive surface tension gradient with temperature must eventually go through a maximum at some temperature above which the $\frac{d\gamma}{dT}$ value becomes negative. Since the Inconel® alloys contain a small amount of sulphur ($< 0.015\%$) and were processed in air, it seems likely that the $\frac{d\gamma}{dT}$ value could change sign at some pulse energy (temperature), thereby leading to a complex flow of the melt and the formation of protrusions in the centre and around the edge of the melt pool.

4. Holographic structures

The procedure for designing the phase holographic structures has been described in our previous works [12,23]. These structures are in the form of phase Computer Generated Holograms (CGHs); designed using the Iterative Fourier Transform Algorithm (IFTA). This algorithm enables the design of both binary and multi-level phase CGHs for the generation of diffractive images in the far field.

The fabrication of the holographic structures was performed using the laser system described in Section 2.1. The system enabled the hologram designs to be mapped onto the metal surface, with a processing speed of 1000 hologram pixels (craters) per second and positioning accuracy of $< \pm 1.5\mu m$. The system was capable of generating repeatedly optically-smooth and almost identical craters with the depth variation of $< \pm 25nm$.

4.1 Metal surface requirements

The holographic structures must be generated on flat and relatively smooth metal surfaces. Curved or wavy surfaces are not appropriate because they distort the diffractive image generated by the hologram, since they act as curved mirrors, making the image blurred and unreadable in the far field. To obtain high quality diffractive images, the holographic structures should be generated on the metal surface with low roughness. This is because the individual hologram pixels are either dimples or areas of the unprocessed surface, and both of these must be smooth to generate a sharp and bright diffractive image. For example, holographic structures produced on a grained or rough metal surface (with the values of $Ra > 30nm$, $rms > 40nm$, and $PV > 250nm$, as measured for a $0.35mm$ by $0.25mm$ area) were unable to generate sharp and bright images due to the strong scattering. Readable but scattered diffractive images, as shown in Fig. 11(a), were possible on moderately-polished metal surfaces ($Ra = 10-30nm$, $rms = 10-40nm$, and $PV < 250nm$, as measured for a $0.35nm$ by $0.25mm$ area). Such surfaces can be easily prepared by lapping and polishing, using abrasive papers of different grit sizes (starting with P800 and finishing with P2500). With a highly-polished metal surface ($Ra < 10nm$, $rms < 10nm$, and $PV < 50nm$, as measured for a $0.35nm$ by $0.25mm$ area), very sharp diffractive images can be obtained, as shown in Fig. 11(b). To achieve such a highly-polished surface, the metal was initially polished using the abrasive papers of different grit sizes and subsequently using 3 micron and 1 micron diamond suspension liquid. The polishing process was carried out using a Struers grinding/polishing machine. The total polishing time to obtain a highly-polished surface with this machine was approximately half an hour for stainless steel. However, this time is of course dependent on the initial metal surface roughness as well as the metal type.
4.2 Optical performance of the binary holographic structures

The optical performance of the laser-generated holographic structures was measured using the optical setup described in Section 2.2. This setup enables measurement of optical powers in different areas of the diffractive image, i.e. the target image ($P_T$), the twin image ($P_{TWIN}$) and the undiffracted 0th order beam ($P_{0th}$).

A large number of binary holographic structures was generated on the highly-polished surface of stainless steel (ST304LD) using different values of pulse energy. Each hologram had an identical pattern but was formed of craters of different depths and diameters. The distance between the adjacent craters ($d$) was fixed at 10.5\,\mu m for all holograms.

The reflectivity of the highly-polished stainless steel surface was measured to be approximately 60\% at the wavelength of 632.8\,nm. In the case of the holographic structures, the reflectivity ($R$) that was defined as a ratio between the total reflected power ($P_T + P_{TWIN} + P_{0th}$) and the incident power ($P_{INC} = 4.6\,mW$) was found to be dependent on the size of the hologram individual elements (craters). The holograms formed from very shallow craters ($D < 100\,nm$ and $PV < 200\,nm$) were measured to have reflectivities between 60\% and 30\%, as shown in Fig. 12, and diffraction efficiencies ($P_T/P_{INC}$) of $< 1.5\%$, as can be seen in Fig. 13. The high reflectivity (even comparable to the $R$ value of the highly-polished stainless steel) resulted from the fact that these structures contained areas of the highly-polished surface between adjacent craters [see Fig. 14(a)] because the diameter of these craters was smaller than the separation distance between them. In general, these holograms did not generate bright and sharp diffractive images mainly due a strong undiffracted 0th order beam, as can be concluded from the $P_{0th}/P_{INC}$ data in Fig. 13.
The diffraction efficiency of the holographic structures containing craters with depths between 0.1 μm and 0.7 μm (PV = 0.2μm – 1.0μm) was measured to be approximately 3.5 ± 0.5%, as shown in Fig. 13. The same amount of diffracted power was collected in both the target image and the twin image, as expected and explained in [12]. The reflectivity of these holograms was between 25 and 30%. The structures generated bright and sharp diffractive images even though approximately 20% of the incident power was collected within the undiffracted 0th order beam.

Distorted and slightly blurred diffractive images were generated by the holograms that contained craters deeper than 0.7 μm. The diffraction efficiency of these structures was less than 3.5% and decreased with increasing depth of the craters, as can be seen in Fig. 13. Also the reflectivity of these structures decreased with crater depth, as shown in Fig. 12. The lower optical performance of these holograms resulted from the fact that these structures contained craters that partially overlapped each other and were surrounded by re-solidified splashes that scattered the laser light.

4.3 Importance of the separation distance between the hologram pixels

Not only the size of the craters, but also the separation distance between them (d) was found to play an important role in the generation of diffractive images by the holographic structures. In general, the holograms that contained craters with a separation distance (d) greater than their effective diameter (Φ_{EFF}) generated slightly distorted images. This distortion was caused by the dimples which in this case form between the adjacent craters, as illustrated in Fig. 14(a). When the separation distance was well matched (d = Φ_{EFF}), as shown in Fig. 14(b), the holographic structures generated sharp and bright diffractive images.

The binary holographic structures containing more closely-spaced craters (d = 7.1μm and 7.9μm) were measured to have lower reflectivity, as shown in Fig. 15. Moreover, the P_{0th}/P_{INC}
and $P_T/P_{INC}$ ratios measured for these holograms were found to significantly vary with the depth of the craters, as can be seen in Figs. 16 and 17. A good match between the spacing ($d$) and the effective diameter ($\Phi_{EFF}$) as well as an appropriate depth of the craters led to an increased diffraction efficiency. This was clearly seen for the holograms that contained craters of depth ($D$) between 0.16 and 0.22 $\mu$m, where the spacing between the craters ($d$) was almost the same as their effective diameter ($\Phi_{EFF} \approx 8 \mu$m). These structures generated bright target and twin images ($P_T/P_{INC} = P_{TWIN}/P_{INC} > 6\%$) and less intense undiffracted 0th order beam ($P_{0th}/P_{INC} < 12.5\%$).

![Fig. 15. Reflectivity of the binary holographic structures vs. a) depth and b) PV of the craters. Results are presented for different separation distances between the craters ($d = 7.1 \mu$m, 7.9 $\mu$m, and 9.5 $\mu$m).](image)

![Fig. 16. The fraction of the incident power within the undiffracted 0th order beam measured for the binary holographic structures with different separation distances between the craters ($d = 7.1 \mu$m, 7.9 $\mu$m, and 9.5 $\mu$m).](image)
Fig. 17. Diffraction efficiency of the binary holographic structures vs. a) depth and b) PV of the craters. Results are presented for different separation distances between the craters (d = 7.1μm, 7.9μm, and 9.5μm).

4.4 Multi-level holographic structures

As shown in Section 3.2, UV nanosecond laser pulses are able to produce optically-smooth surface deformations on different metals and the dimension of these deformations can be controlled by the amount of pulse energy delivered to the work piece. This enables the generation of both two-level (binary) and multi-level phase holographic structures, as reported in our previous work [12]. The multi-level holograms are particularly interesting as security markings because they cannot be generated via laser ablation.

The diffractive images generated by the binary holographic structures contain the target image and the twin image [see Fig. 18(a)], that are rotated by 180° with respect to each other, as a consequence of the structure to have only 2 phase levels [12]. These two images have almost identical intensities, as shown in Fig. 13.

Fig. 18. Diffractive image generated by: a) two-level (binary) and b) three-level holographic structure.

Our experiments have shown that an additional phase level added to the holographic structure can successfully break the intensity symmetry between the target and twin image, as shown in Fig. 18(b). The three-level holograms that contained craters of two different specific depths were able to generate diffractive images in which the power in the target image was at least 2 times greater than that of the twin image.
5. Demonstration of the security markings on real metal products

Binary holographic structures have been generated on the surface of stainless steel watch back covers in order to demonstrate the feasibility of the developed laser technique for marking commercial products.

5.1 Brand new watch back covers

Figure 19 shows a binary holographic structure that was generated on the flat and smooth surface of a brand new watch back cover. This structure contained four different holograms which were placed next to each other in a $2 \times 2$ array. Each hologram generated a different diffractive image, as shown in Fig. 19(b). These images were very sharp and readable. The whole structure contained approximately 320,000 optically-smooth craters and was generated in 5 minutes and 40 seconds.

![Fig. 19. a) Watch back cover with the embedded structure containing four different binary holograms (placed next to each other in a $2 \times 2$ array); b) diffractive images generated by these holograms.](image)

The holographic structure that can generate a ‘9-character long’ serial number of the watch back cover is shown in Fig. 20. This hologram contained approximately 370,000 optically smooth craters and was generated in 6 minutes and 40 seconds.

![Fig. 20. Watch back cover with the embedded holographic structure that displays the serial number.](image)
5.2 Impact of scratches on the performance of the holographic structures

It is important to evaluate the robustness of the laser-generated holographic structures to subsequent surface abrasion, due to handling and wear. Severe scratches that can be seen in Fig. 21(a) were created by hand using an abrasive paper (grit P120); on the same watch back cover that was shown in Fig. 19. Then, the holographic structure was tested using the optical setup described in Section 2.2.

Figure 21(b) shows clearly that the holograms can still generate readable diffractive images even though the metal surface was significantly scratched, demonstrating that they are robust to local damage and hence are suitable as anti-counterfeiting (tamper-proof) security markings on many commercially-available metal components.

6. Conclusions

The UV nanosecond laser marking approach described in this paper may be used to generate phase holographic structures directly on the surface of metals, such as stainless steel, nickel, brass and nickel-chromium Inconel® alloys. The process is sufficiently well-controlled to enable the generation of multi-level phase holographic structures; these holograms are more difficult to replicate and provide a feature obvious to the naked eye in that the twin image is suppressed when the correct levels are chosen. Although it is necessary to have a polished surface before writing the hologram, the level of polish required is only moderate and hence easy to achieve. Example holograms were demonstrated on commercial watch back covers and these were shown to be robust to subsequent mechanical abrasion.

Funding

Engineering and Physical Sciences Research Council (EPSRC, Grant No.: EP/K030884/1).

Acknowledgments

The authors would like to thank SISMA Spa (Italy) for provision of silver samples. The data underlying this work are commercially confidential.