Sensitivity analysis of nondestructive magnetic techniques for the restoration of stamped marks on low carbon steel

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1. Introduction

Stamped serial codes are commonly impressed onto the metal surface for the identification of several items, such as vehicle chassis and engines. However, criminal organizations, during robberies or illegal transactions, remove or alter these identification marks to conceal the identity of the vehicle \cite{1,2}. These serial codes are normally impressed on the metal substrate by die stamping, although engraving, roll pressing, and embossing are also used in some cases. After the obliteration produced by the criminals, the recovery of the original identification marks is critical to criminal investigators \cite{3,4}.

The science behind the restoration of stamped marks previously removed or altered is based on the detection of the plastic deformation zone created during the stamping process. The plastic deformation zone extends from the end of the cavity created by the die to the metal interior, and its depth depends on the microstructural and mechanical properties of the metal. According to previous studies, the plastic deformation zone carries information regarding the stamped mark; however, this zone tends to be more diffuse with increasing depth \cite{5-7}.

Thus, if a metal plate previously identified suffers a great thickness loss during the obliteration process or if a new code is stamped on the metal surface, the detection of the plastic deformed zone and, therefore, the restoration of the original
serial code becomes challenging. Hence, the restoration of the identification codes will be possible only if the material onto which the original codes were stamped, still contains the plastic deformation zone produced by the original stamping, and if the restoration technique applied is sensible enough to detect this permanently deformed area.

In the literature, there are several methods capable of restoring stamped identification codes: (i) Destructive Methods: chemical etching, heat treatment, ultrasonic cavitation, and relief polishing; (ii) Nondestructive methods: Magnetic particle, eddy current, magneto-optic imaging, active thermography, electron backscatter diffraction, and x-ray imaging [2,8–10].

With regard to destructive methods, chemical etching is the most commonly used due to its higher sensitivity, lower cost, and versatility [11]. As presented by previous works, Fry’s reagent was found to be ideal for revelations on steel surfaces. However, the aging of Fry’s reagent increases the etching time from 95 to 115 min for restoration of the obliterated stamped code in mild steel. Thus, Fry’s reagent is known to be toxic, highly corrosive, and also to produce nitrous gases when in contact with steel [4,12]. On other hand, chemical etching also has the disadvantage of not preserving the material surface and, in addition, the reagents used are dependent on the composition of the metal being distinct acids solutions, which is necessary for different alloys [5,12–14].

Hence, to maintain the material integrity considering the constant development of new alloy components in the automobile industry, the evaluation of the feasibility of nondestructive techniques, which are only dependent on metal magnetic characteristic, has been growing over the years [9,15–17].

Some nondestructive methods, like active thermography and electron backscatter diffraction, show a good performance in recovering identification marks. Nevertheless, most of the proposed techniques are intended for laboratory use [9,10]. Therefore, the complex equipment apparatus makes field application difficult. Due to this reason, magnetic particles and magneto-optic imaging seem to be more suitable to be employed by criminal investigators in vehicle forensics [6,15–17].

However, despite the advantages of magnetic particle in restoring new stamp marks in comparison with chemical etching, this technique is not frequently used by criminal investigators due to the unhandy electromagnets and contamination of the surface with oil during the testing [6,15].

In addition, recent studies on the development and application of a new nondestructive technique based on magneto-optical imaging also presented the capability of this method to restore obliterated stamped codes. Magneto-optical imaging was not only capable of detecting plastic deformation zones but also of restoring the stamp marks responsible for these permanently deformed areas [15,17].

Thus, based on the performance of both nondestructive techniques pointed in previous works, this study aims to evaluate the sensibility, according to depth restoration limit and feasibility of restoration after plastic deformation zone overlap, of magnetic particle restoration and magneto-optic imaging. Also, it aims to evaluate both methods according to imaging capacity, workers’ safety, versatility, and mobility (Ability of the technology to be used in field application). In addition, considering the importance of the material microstructural, mechanical, and magnetic properties in the recovery process and in the relationship between the stamp mark depth and restoration depth, the sample material was characterized by optical, magnetic, and mechanical techniques prior to the restoration of the stamp marks study.

2. Materials and methods

2.1. Material characterization

A representative sample of low carbon steel with approximate dimensions of 300 mm × 220 mm × 1.55 mm was obtained to evaluate the microstructural, mechanical, and magnetic characteristics of the sample material. The chemical composition of the sample is shown in Table 1.

The sample was then cut in four plates of 10 mm × 10 mm × 1 mm for the microstructural and mechanic analysis and in one quadrangular prism of 3 mm × 1 mm × 6 mm for the magnetic examination.

Thus, in order to contribute to the knowledge about the microstructural phases present in the bulk of the metal, a plate was characterized by scanning electron microscopy (SEM) using the VEGA 3LMU TESCAN in the secondary electron mode (SE) with Energy Dispersive X-Ray Spectroscopy (EDS) for the semi-quantitative elemental mapping results about specific locations of the sample microstructure. Additionally, the magnetic behavior of the metal sample was also determined, using a vibrating sample magnetometer (VSM, LakeShore), with a cycle of 0 to 10,000 Gauss.

Lastly, in order to determine the hardness of the metal sample, Vickers microhardness was applied. In this analysis the material hardness was determined, and the plastic deformation depth created after stamping by a cross-sectional Vickers microhardness in the plastic deformed area below the cavity created by a stamp mark was also calculated. Since the plastic deformation increases the material hardness locally [18], the zone under the cavity was considered plastically deformed when the Vickers hardness measurement was higher than the hardness of the metal sample without deformation.

2.2. Restoration of stamp marks

2.2.1. Samples

After the characterization, six samples were cut for the restoration of stamp marks. From these, two representative samples were chosen for the results. The samples were named B1 and B2, with dimensions: 55 mm × 30 mm × 1.51 mm and 55 mm × 30 mm × 1.54 mm, respectively.

Each plate was identified with an alphabetic code “END” printed by die stamping, with a cavity depth of 245 μm and 230 μm, respectively, measured by a profilometer. After the identification, the plates were separated for different studies. Plate B1 was chosen for the recovery of stamped marks obliterated by overstamping and plate B2 was chosen for the sensitivity test.

In the obliteration process, the stamp mark of plate B1 was totally removed by abrasion with sandpaper followed by the
stamping of a new identification code “BAP”. For plate B2, the original identification code was also totally removed by abrasion. After that, the plate B2 was then abraded down to an approximately 200 μm step for the sensitivity test.

For the restoration, the samples were sanded after the obliteration. No polishing or etching of the sample surface were applied since they do not affect the sensitivity of the magnetic nondestructive techniques used in this study [6,19].

2.2.2. Restoration techniques

2.2.2.1. Magnetic particle. As unhandy electromagnets and oil do not make the magnetic particle use preferable by criminals, investigators, in this work we explored the possibility of using permanent magnets and a solution of iron particles and water for the adaptability of this method to vehicle forensics [15].

Therefore, in magnetic particle restoration, the plates were colored with a white contrast ink, produced by Metal-Chek to enable the observation of the magnetic particle agglomeration on the plastically deformed regions. The plates were then placed between the two poles of a permanent magnet of 300 mT so that the area onto which the stamp marks were previously printed became centered between the poles. Additionally, a Metal-Chek solution composed of iron oxide and water was pulverized on the surface of the plates. Finally, the restoration images were acquired by a photographic camera.

2.2.2.2. Magneto-optical imaging. In magneto-optical imaging, the plates were analyzed with an eddy-current magnetograph device, Regula 7515 M, and a Magneto-optical device, Regula 7505 M. Both produced by Regula Forensics®.

For this examination, the procedure was implemented according to Agalidi et al. work [17]. Initially, the magnetic tape was demagnetized to remove all previously recorded data attaching the tape onto the plates with adhesive tapes. Afterwards, both plate and magnetic tape were scanned by an eddy current magnetograph device. The magnetic tape, with the recording of the magnetic leakage fields induced by eddy current, was then scanned by a magneto-optical device which converts the magnetic information in spatial distribution of brightness, forming a magneto-optic image of the defects detected. Moreover, the formation of the magneto-optical image and capture was carried out by a NUCA® software.

In the magnetic analysis, the hysteresis curve obtained by the VSM showed a ferromagnetic behavior. When H is at 10,000 G, the material presented a magnetization of approximately 250 emu/g. Such behavior will enable the use of a magnetic particle technique for the restoration study of the steel samples.

Lastly, in the Vickers microhardness analysis a longitudinal sample, free of deformation, presented a medium hardness of 66.34 HV. Furthermore, in a transversal sample, previously deformed by stamping, the plastic deformation zone depth caused by a stamp mark cavity of 288.5 μm was approximately 571.89 μm, almost two-fold the stamp marks depth.

Based on the characterization results, the sample analyzed in this work is composed of low carbon steel, with a ferrite matrix and Fe3C carbides, which is commonly used for automobile components, especially in vehicle frames.

3.2. Restoration of stamped marks obliterated by overstamping

In order to determine the effectiveness of the magnetic nondestructive techniques in the recovery of identification codes obliterated by overstamping, the original code “END” was totally removed and a new false code “BAP” was printed over the sample surface (Fig. 2a and b). After the obliteration, the samples were examined with the magneto-optic imaging and magnetic particle restoration techniques, as shown in Fig. 2(c) and (d). The restoration time was approximately 10 and 7 min for magnetic particle restoration and magneto-optical imaging, respectively.

In this experiment, the negative influence of the previous and new plastic deformation zone overlap on the restoration process of the sample was observed. This overlap is responsible for the obliteration by overstamping being one of the most challenging cases of stamp mark recovery [1,7].

However, besides the critical case of plastic deformation zone overlap, both nondestructive techniques were able to partially reveal the original code as presented by sample B1 restoration where the letters “N” and “D” could be identified, Fig. 2(c) and (d).

3.3. Sensitivity test

For the evaluation of the restoration depth limit of both magnetic nondestructive techniques, a representative letter “N” was chosen from the identification code “END” of sample B2. In this test, firstly the initial code was totally removed from the plate surface by sanding. The thickness of the plate was measured resulting in an initial restoration depth of 90 μm. The plate was then abraded down to approximately 200 μm steps.

The magneto-optical imaging technique was able to restore the letter “N” with good contrast and definition until a restoration depth of 260 μm. For higher depths, the letter could not

| Table 1 – Chemical composition of the sample metal (wt%). |
|----------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Fe  | C  | Cr  | Al  | Cu  | Ni  | Ti  | Mn  |
| 99.5% | 0.05% | 0.021% | 0.046% | 0.005% | 0.016% | 0.001% | 0.320% |

3. Results and discussion

3.1. Material characterization

Fig. 1(a) shows the SEM micrograph obtained. From the micrograph, it is possible to notice that the microstructure of the sample steel is composed of a fully ferrite matrix and carbides. Based on the spectrum obtained in the EDS analysis, Fig. 1(b), and considering the carbon content, Table 1, the colonies of carbides observed in the ferrite matrix are iron carbides, also known as cementite (Fe3C).
be visualized probably due to the low lateral resolution of the magneto-optical imaging by Faraday effect as a result of the domain structure of the garnet in the magnetic tape [19]. In order to increase the sensitivity, the magneto-optical Kerr effect (MOKE) and magneto-optical indicator film (MOIF) technology [20] have shown good results in laboratory testing. However, for these technologies a finer surface finishing is required.

In the magnetic particle restoration, the stamped mark was perfectly restored until a restoration depth of 470 μm. For a 670 μm depth, below the cavity, the contrast was negatively affected by the diffusion of the plastic deformation due to the high depth [3,6]. This resulted in a low contrast and definition; however, the letter “N” was still detected. The results of this experiment are summarized in Table 2.

Based on the results of this test, the magnetic particle restoration presented a higher restoration depth limit. This technique could restore the stamp mark “N” in 670 μm depth below the cavity in a low carbon steel plate with a 230 μm stamp mark depth as the magneto-optical imaging was able to restore the stamp mark until 260 μm below the cavity in the same plate.

3.4. Magneto-optical imaging and magnetic particle restoration evaluation

After experimental tests, the techniques presented in this study were compared according to imaging capacity, workers’ safety, sensitivity, versatility, and mobility (Ability of the technology to be used in field application). This discussion is summarized in Table 3.

In regard to imaging, versatility, and mobility, the magneto-optical imaging presented a better performance once the digital recording was made directly from the computer attached to the equipment, since in magnetic particle restoration the restoration results are indirectly acquired by a photographic camera. Thus, the magneto-optical imaging equipment showed an improved mobility and adaptability.
The capacity restoration techniques for plate B2.}

<table>
<thead>
<tr>
<th>Restoration depth</th>
<th>Magneto-optical imaging</th>
<th>Magnetic particle restoration</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 µm</td>
<td>Visible (Clear)</td>
<td>Visible (Clear)</td>
<td>In both techniques the restoration presented an excellent contrast and definition.</td>
</tr>
<tr>
<td>260 µm</td>
<td>Visible (Clear)</td>
<td>Visible (Clear)</td>
<td>In both techniques the restoration presented a good contrast and definition.</td>
</tr>
<tr>
<td>470 µm</td>
<td>Invisible</td>
<td>Visible (Clear)</td>
<td>For magneto-optical imaging, the recovery was not possible. However, for magnetic particle the code was still detectable.</td>
</tr>
<tr>
<td>670 µm</td>
<td>Invisible</td>
<td>Visible (Not Clear)</td>
<td>The code was still detected by magnetic particle restoration, but with low definition. In magneto-optical imaging the code remains undetected.</td>
</tr>
</tbody>
</table>

### Table 3 - Performance of magnetic nondestructive techniques

<table>
<thead>
<tr>
<th></th>
<th>Magneto-optical imaging</th>
<th>Magnetic particle restoration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imaging</td>
<td>++</td>
<td>+++</td>
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<tr>
<td>Workers’ Safety</td>
<td>+++</td>
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<tr>
<td>Sensitivity</td>
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<tr>
<td>Versatility</td>
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<tr>
<td>Mobility</td>
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(+) Good; (++), Moderate; (+++), Excellent.

to vehicle inspection. The permanent magnets also demonstrated to be unhandy and not easily adapted in certain areas of the vehicle. In addition, according to the literature, magneto-optical imaging technique is able to analyze both ferromagnetic and paramagnetic materials as the magnetic particle is restricted to ferromagnetic [15,17].

Finally, in the sensitivity test, a greater restoration depth was observed in the magnetic particle restoration, being the most sensible technique. In terms of workers’ safety, both methods present no harm to the forensic inspector or the environment.

### 4. Conclusion

According to the results obtained in the restoration of stamped marks obliterated by overstamping, nondestructive techniques of magnetic particle restoration and magneto-optical imaging were able to partially restore the original stamp marks of the plate, despite the plastic deformation zone overlap. In addition, the result of the sensitivity test also showed that both techniques were able to detect and restore the original stamp mark, with good contrast and definition, as far as a restoration depth of 260 µm. Although the magnetic particle restoration presented a higher detection sensitivity with a restoration depth limit of 670 µm, the magneto-optical imaging presented an improved mobility, versatility, and imaging capacity in comparison with magnetic particle imaging.

### Declaration of interests

The authors declare that they have no conflict of interest.

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### References


