Detection of micrometric surface defects in titanium using magnetic tunnel junction sensors

L. S. Rosado1,2, F. A. Cardoso3, F. Franco3, R. Ferreira4, E. Paz4, S. Cardoso3, P. M. Ramos2, P. P. Freitas3,4, M. Piedade1

1INESC-ID Instituto de Engenharia de Sistemas e Computadores - Investigação e Desenvolvimento, Lisbon, Portugal; Phone: +351 218417665; E-mail: luis.rosado@ist.utl.pt
2IT Instituto de Telecomunicações, Instituto Superior Técnico, IST, UL, Lisbon, Portugal
3INESC-MN and IN-Institute of Nanoscience and Nanotechnology, Lisbon, Portugal
4International Iberian Nanotechnology Laboratory (INL), Braga, Portugal

Abstract
Eddy current testing is applied in the detection of micrometric surface defects in Titanium parts. An advanced probe composed by a single excitation trace and magnetoresistive sensors (magnetic tunnel junctions) in a differential configuration is used for this purpose. Different samples of titanium alloy TA6Vα were tested using this probe and a previously developed eddy currents testing system. Surface notch defects with dimension as low as 40 µm in length, 30 µm width and 30 µm depth were successively detected when operating the probe at 10 MHz. The successful detection of such small defects is extremely dependent on sample surface condition.

Keywords: Eddy Current Testing, Surface Defects, Titanium, Magnetic Tunnel Junctions.

1. Introduction

Titanium alloys are widely used in military and commercial aerospace industries [1]. Titanium adds important advantages such as high strength/weight ratio, corrosion stability and resistance to high temperature operation. Lighter and more fuel efficient aircrafts are being produced with increasingly use of titanium components. Examples of these components are many of the aircraft fasteners, rivets, structural airframe components (for example the wings internal ribs) and landing gears. For these components, the use of titanium is justified by the good fatigue behavior and lightness. Titanium can also be found in aircrafts engines, in the blades, shafts and covers of the material for the front and rear entries. Here, titanium’s excellent mechanical behavior when subject to large thermal excursion is appreciated.

For the described components, Penetrant Testing (PT) methods [2] are usually done before deployment allowing the detection of small dimension surface cracks. Although they have small dimensions, these defects are prone to leading to a more serious and significant defects when the part is subject to fatigue loads. During maintenance, the use of PT methods may not be easy to implement since contaminants may be found in the component surface. Moreover, the post cleaning process of the defect free parts requires additional effort. Eddy Current Testing (ECT) is being considered as a replacement for the penetrant testing of titanium based components. Past experiments demonstrated that testing of titanium components can be accomplished using significantly high frequencies in the ECT range [3].

Magnetoresistive sensors are seen as a promising technology for ECT [4]. Field sensitivity is not dependent on the operation frequency (readout) in these sensors. They present then an advantage in the detection of deep buried defects at low frequencies (where the use of pickup coils fails). Beside this first advantage over pickup coils, magnetoresistive sensors can be designed to provide much better spatial resolution [5].

This paper reports the application of a previously proposed magneto-resistive based ECT probe [6] to samples of titanium TA6Vα with different surface defects and tooling conditions.
2. Probe architecture and ECT system

In the probe, the primary magnetic field generation is accomplished using a single conductive trace (a plated copper trace with 2 cm in length, 150 µm width and 35 µm thickness). This trace and the pads used for the magnetoresistive sensors connections are designed on a Printed Circuit Board (PCB) which is also the main structural element, Figure 1 a). The readout of the magnetic field is done with two magnetic tunnel junction sensors, mounted with their sensitivity axis perpendicular to the part surface, and therefore detecting the magnetic field coming out of this surface (in the direction Z of Figure 1 a) ). The two sensors were microfabricated at INL and INESC MN facilities in a similar process as described in [8]. Each individual sensor is composed by an 8x9 matrix of 72 Magnetic Tunnel Junctions (MTJ) connected in series in the geometry shown in Figure 1 b). Each of the sensors has 50 µm width by 50 µm depth, the entire matrix as 400 µm by 450 µm.

![Figure 1](image1.png)

**Figure 1** - a) Probe schematic representation. b) Sensors geometry.

Each sensor responds to the magnetic field following the transfer curve shown in Figure 2. The overall sensor nominal resistance (when no magnetic field is applied) is near 900 Ω and a sensibility of 0.18 V/mT per mA of biasing current.

![Figure 2](image2.png)

**Figure 2** - Probe schematic representation.

A differential configuration is applied in the measurement of the two sensors. The electric polarization of the sensors is accomplished with two resistances and a voltage source. The biasing current fed to each of the sensors is equal to 6.6 mA DC which leads to a final sensibility around 1.18 V/mT. An instrumentation electronic amplifier is used to amplify by 20 dB the difference between the signals on the two sensors. In the absence of defects, the two sensors are subject to essentially the same magnetic field (that results from surface roughness and materials inhomogeneity) and thus the difference signal will approach zero.
When a defect is near one of the sensors, the magnetic field on the two sensors becomes different leading to an amplitude increase of the observed difference signal. As described, the self-nulling behavior of the probe enables high amplification of the generated signal reducing the influence of the acquisition electronics quantification noise. Other advantages result from the proximity between the two sensors i.e., it is possible to improve the probe response immunity to slowly varying perturbations such as conductivity gradients and probe lift-off.

One problem found on ECT probes employing magnetoresistive sensors is the presence of inductive coupling between the excitation element and the sensors interconnection [6]. Its influence is best noted when using high frequencies (in example above 100 kHz) when this additional contribution may become higher than the sensor output itself. The proposed probe copes with this using MTJ sensors (which provide higher sensitivities and thus higher output signals for the same magnetic field) and an on probe amplifier circuit (which reduces the interconnections encircled area which is subject to coupling). Tests verified that the inductive coupling contribution at 5 MHz was more than 20 dB smaller than the signal produced by the sensors. The prototyped probe is shown in Figure 3.

Figure 3 - Probe prototype, on-probe electronics and protective casing.

The probe was operated using a custom ECT instrument whose design was previously reported in [8]. The instrument copes with the different ECT tasks such as the probe driving, signal amplification and demodulation and the control of scanning devices. Testing parameters definition and the results display is done in a graphical user interface in a computer. A XY scanning device was used to move the probe over the different samples.

Figure 4 - Employed ECT system.
3. Titanium Samples and Results

Several titanium TA6Vα (0.58MS/m conductivity) samples were available with overall dimensions of 10 cm length, 5 cm width and 1cm depth. Each sample has a specific surface defect machined by electrical discharge as represented in Figure 5. The defects dimensions and surface condition are summarized in Table 1. A profiler model Dektak 3030 ST Veeco was used to characterize the roughness condition of the different samples. The average roughness of the non-polished samples is almost twice the one observed in the polished ones.

![Figure 5 - Schematic representation for the defects on the TA6Vα samples.](image)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Length [mm]</th>
<th>Width [µm]</th>
<th>Depth [µm]</th>
<th>Surface Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>TA6Vα 1.1</td>
<td>1</td>
<td>30</td>
<td>30</td>
<td>Polished, rugosity aprox 35 µmRMS</td>
</tr>
<tr>
<td>TA6Vα 1.2</td>
<td>0.6</td>
<td>30</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>TA6Vα 1.3</td>
<td>0.4</td>
<td>30</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>TA6Vα 2.1</td>
<td>1</td>
<td>50</td>
<td>30</td>
<td>Surface marks, rugosity aprox 65 µmRMS</td>
</tr>
<tr>
<td>TA6Vα 2.2</td>
<td>0.6</td>
<td>50</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>TA6Vα 2.3</td>
<td>0.4</td>
<td>50</td>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>

Half of the samples (TA6Vα 1.1 to 1.3) have a flat surface resulting from the polishing process. For the other samples (TA6Vα 2.1 to 2.3), polishing was not applied and thus surface marks from milling are observed. A comparison between the surface conditions of two of the samples is shown in Figure 6. Much higher roughness in (TA6Vα 2.1 to 2.3) can also be observed in the profiler outputs in Figure 6 where the effect of the marking tools is also observed.
Sample TA6Vα 1.1 was used to tune the testing parameters used for the other more challenging defects. The current on the driver trace was set to 1 A amplitude (2 A$_{pp}$) and a frequency to 100 kHz. A two-dimensional sweep was performed in the zone of the defect. The probe was moved with a speed of approximately 2 mm/s in the X direction with 10 µm resolution while along Y was set to 50 µm. The resulting in the C-scans (two dimensional color scale representations) for the probe output real and imaginary of Figure 7.

Figure 8 shows the same spatial sweep, for the same sample, but with the probe being operated at a 1 MHz excitation trace current with 1 A amplitude. The defect presence
causes a typical differential ECT probe response as best seen in the center of the imaginary part.

Figure 8 - Testing results for sample TA6Vα 1.1 at 1 MHz. The 1D results were taken for Y = 10 mm.

The probe excitation trace was still increased to 10 MHz but due to a limitation of the employed ECT instrument, the driver trace current was decreased to 100 mA. In this result, as shown in Figure 9, the defect response can be clearly distinguished from the background. For 10 MHz, the standard depth of penetration is 200 µm and so it is expected that the defect causes a substantial modification of the eddy currents.

Figure 9 - Testing results for sample TA6Vα 1.1 at 10 MHz. The 1D results were taken for Y = 10 mm.
The remaining samples were tested with similar operating parameters (10 MHz, 100 mA). The results for the samples TA6Vα 1.1 to 1.3 are shown in Figure 10 where the smaller surface defect presence can still be seen. Nevertheless, for samples 1.2 and 1.3 it becomes difficult to distinguish the defect response from the background. Note that only the imaginary part is shown since this is where the defects presence is best noted.

![Figure 10](image10.png)

**Figure 10** - Testing results for sample TA6Vα 1.1 to 1.3 at 10 MHz (imaginary part of the probe output).

The results for defects TA6Vα 2.1 to 2.3 are shown in Figure 11. Here, the defect signature is difficult to identify among all the features of the background. These features essentially result from the surface machining marks and as observed completely mask the response coming from the defect. It should be noted that although the defect width is higher in comparison to samples 1.1 to 1.3, the surface tooling marks have a comparable dimension to the defect depth.

![Figure 11](image11.png)

**Figure 11** - Testing results for samples TA6Vα 2.1 to 2.3 at 10 MHz (imaginary part of the probe output).

### 4. Conclusions

The detection of surface defects in Titanium alloy mock-ups was presented, using a new ECT probe with an excitation trace and two magnetic tunnel junction sensors operated in differential mode. Defects as small as 400 µm in length, 30 µm wide, 30 µm deep were detected on polished samples, using an excitation current of 100 mA, at 10 MHz, with the sensors fed with 6.6 mA sense current.

Future work could focus on the improvement of the sensors geometry for this application. Specifically, it seems interesting to decrease the distance between the two sensors so the defect response can be better distinguished from the other signal perturbations such as lift-off and the surface conditions. Other possibility is to increase even more the operating frequency promoting greater interaction between the eddy currents and the low depth defects.
Acknowledgements

This work was supported by the European Project IMAGIC-EU-FP7-ICT-288381 and the national FCT project INSPECT PTDC/EEI-PRO/3219/2012 and the PhD scholarship FCT SFRH/BD/65860/2009. INL acknowledges partial funding from ON2 project from PO Norte. INESC-MN acknowledges FCT funding through the IN Associated Laboratory.

References