Early fatigue detection in aerospace parts by means of magnetic nanoparticles

PhD Thesis Proposal

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PROVISIONAL THESIS TITLE

Early fatigue detection in aerospace parts by means of magnetic nanoparticles

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1. INTRODUCTION

Being aeronautics and astronautics a wide and multidisciplinary field of knowledge, materials science and technology has historically played a role of significant relevance, to such an extent that, in many cases, both have evolved together. Examples can be found everywhere: the rise of aluminium alloys and the intense research to improve their mechanical properties, the development of titanium alloys turbine blades for air-breathing engines, the using of advanced composite materials with structural functionality, etc.

As regards to the proposed PhD, it should be emphasized that fracture mechanics and, in particular, crack detection and monitoring has become a major concern for aerospace industry since fatigue failure caused several alarming aircraft accidents in the 1950s decade, e.g. BOAC De Havilland Comet 1 G-ALYP accident on the 10th of January, 1954. Investigators at the Royal Aircraft Establishment (RAE) concluded that the crash occurred due to a failure of the pressure cabin as a result of fatigue caused by cabin pressurization and de-pressurization cyclic loads.

Fatigue is a form of failure due to a progressive and localized structural damage that occurs in structures subjected to dynamic and fluctuating loads. These circumstances make possible for failure to occur at stress levels clearly lower than ultimate tensile stress or yield stress for structures subjected to static loads, which is fatigue's foremost special feature [1]. In particular, crack initiation and propagation expose that the material is undergoing a fatigue process.

As fatigue is responsible for a major part of metal components failure and it is a form of failure of catastrophic nature, early crack detection is hence an issue of remarkable importance in order to guarantee the safety of air transport.

Three decades ago, airworthiness regulations and manufacturers ensured safety by means of expiration dates, which stated the allowable operating life for a component, therefore determining the time that a given part needed to be replaced [2]. This way, healthy parts where being discarded and retired in spite of the fact that they had no defects, which was a waste of money.

The acceptance of non-destructive testing (NDT) methods as reliable quality control and maintenance techniques by airworthiness authorities allowed manufacturers to improve defects detection in order to reject faulty pieces. On the other hand, it provided aircraft owners the opportunity to save money by avoiding the replacement of fully operational components.

The most important airworthiness authorities worldwide are the Federal Aviation Administration (FAA) and the Joint Aviation Authorities (JAA), organizations that issue aircraft airworthiness certificates in the USA and in the EU, respectively, and mutually recognize each other's certificates. The former states NDT is defined as inspections, tests or evaluations which may be applied to a component to determine its integrity, composition, electrical or thermal properties or dimensions without causing a change in any of these characteristics [3]. Therefore NDT methods constitute a key tool for characterizing components conditions and flaws while guarantying their future usefulness once tested.

In particular, thanks to NDT methods, defects can be located and their growth can be monitored through out successive inspections, for example allowing aircraft owners to replace aviation parts only when certain defects-related parameters (for instance, crack growth rate and crack sizes) are approaching predefined critical thresholds. As can be inferred, research on suitable NDT solutions for aerospace components maintenance is to the advantage of aerospace industry, air transport safety and the reduction of maintenance costs, which are of crucial importance for the air transport industry and hence its users.

From the NDT equipment manufacturer's point of view, the strongest driver for innovation has been typically the demand of cost reductions requested by the customer industries rather than the will of the manufacturers to improve their products [4]. The proposed PhD thesis aims to take benefits of some of the recent advances in materials nanotechnology and nanoscience in order to develop an innovative NDT technique which leads to a reduction of inspection costs. This can be achieved especially through reduction of equipment cost, reduction of inspection time and several other features.

The proposed technique is thought to be suitable for surface defects detection on aerospace parts. Nevertheless, it is also suited to inspect the surface of any kind of material, except for magnetic materials. Being the challenges common for many of the NDT techniques, the main goal is therefore to develop a technique that fulfils the requirements of end-users in the form of a significant reduction of inspection costs. Later on, the partial goals that need to be fulfilled in order to achieve this cost reduction will be explained in detail.

The PhD proposal is constituted of 5 chapters, being the first one the introduction. In chapter 2, the state of the art on NDT methods and other related topics is presented. Chapter 3 deals with the definition of the thesis proposal. The thesis work planning, current status and future work are shown in chapter 4. Finally, chapter 5 concludes with the summary and the tentative calendar.

2. STATE OF THE ART

The Federal Aviation Administration (FAA), one of the foremost airworthiness authorities worldwide together with the Joint Aviation Authorities (JAA), defines NDT as a set of inspections, tests or evaluations which may be applied to a component to determine its integrity, composition, electrical or thermal properties or dimensions without causing a change in any of these characteristics [3]. Therefore NDT methods constitute a key tool for characterizing components conditions and flaws while guarantying their future usefulness once tested. As a consequence, improving NDT methods results in crucial aircraft safety improvement while saving aircraft owners considerable amounts of money.

The so-called NDT major or classic techniques are the following six:

- dye penetrant testing
- eddy current testing
- magnetic particle testing
- radiographic testing
- ultrasonic testing
- visual inspection

The most widely used for aircraft maintenance purposes are dye penetrant testing, eddy current testing, magnetic particle testing and visual inspection [2].

This chapter reviews the basic principles and the pros and cons of the above mentioned techniques. Extensive information regarding these and other NDT methods can be found in references [4-16]. Once the major techniques have been reviewed, an overview of recent and advanced NDT methods is presented in a subsequent section.

2.1. MAJOR NDT METHODS

2.1.1. Dye penetrant testing [4-7]

A dye penetrant solution is applied usually by an aerosol to the surface to be analyzed, which must have been cleaned previously with an appropriate solvent. The dye is left for a period of time and seeps into any existing surface-breaking defect by capillary action. Once dwell time is passed, excess dye is carefully removed from the surface using a solvent. A developer in liquid or powder (embedded in a spray) form is then applied which makes the trapped penetrant to seep out back to the surface and spread over. The formed stain reveals the presence of the flaw.

Advantages:

- Dye penetrant testing can be applied to any material.
- Surface cracks and porosity can be detected on large surface areas or large volumes, being the inspection a very rapid, low-cost and efficient process.
- Minimum equipment investment.
- Complex geometries can be routinely inspected.
- Indications appear directly on the testpiece surface providing information about size regarding defect length.

Disadvantages:

- Dye penetrant testing is limited to surface-breaking defects.
- Surface preparation is crucial because contaminants (dirt, grease, paint, etc.) can produce false indications.
- Smooth surface finish is required to facilitate excess penetrant removal.
- Surface post-cleaning is required.
- Several operations must be performed under controlled conditions and chemical hazardous handling is required.

2.1.2. Eddy current testing [4-6, 8]

A transducer, which is a coil carrying alternative current (AC), produces an alternating magnetic field. When brought close to the surface of a conducting material to be tested, eddy currents are induced. These eddy currents generate as well a magnetic field opposing that produced by the coil, which can either change the impedance of the coil or generate a response in a separate search coil. If a surface or near-surface defect is present, eddy currents flow is disturbed and so produces changes in the magnetic field generated by them. The alteration of this magnetic field can be sensed since the impedance of the coil or the search coil response varies.

Advantages:

- Eddy current testing can be used to detect surface and near-surface defects, but also to measure thickness of thin metal sheets or nonconducting coatings on conducting substrates and to characterize conductivity, magnetic permeability and dimensional features of conductive materials.

- The test probe or transducer does not need to contact the part.
- Minimum part preparation is required to perform the test.

Disadvantages:

- Only conducting materials can be inspected.
- Regarding sensitivity depth, eddy current testing is limited to near-surface defects detection (the final value of penetration depth is a function of frequency and material conductivity).
- The technique is very sensitive to all sort of variables, in particular to lift-off (the distance between the probe and the testpiece surface).
- Eddy current testing is a point test, this means the sensed area is limited to the region immediately surrounding the probe. Scanning is needed to inspect large areas, which is time consuming and thus expensive.
- Ferromagnetic materials require special treatment to address magnetic permeability.
- Reference standards and accurate calibration are required for set-up, as well as highly skilled and trained operators.

2.1.3. Magnetic particle testing [4-6, 9]

When a ferromagnetic component is magnetized, the magnetic field lines are confined within the material except in the vicinity of a defect, where they are distorted and forced out producing a concentration of magnetic flux leakage. The magnetization of the part may be induced by permanent magnets, electromagnets, by a current carrying coil or by the passage of a heavy current through the testpiece. A magnetic ink or powder, often a fine dispersion of magnetic particles (iron oxide) in paraffin, is then spread on the testpiece surface. The particles are attracted by the leakage field and concentrate at the discontinuities, providing a visual indication revealing the presence of a flaw.

Advantages:

- Magnetic particle testing can be used to detect surface and near-surface defects.
- Large surface areas or large volumes can be inspected rapidly.
- Equipment investment is relatively low.
- Complex geometries can be routinely inspected.

- Indications appear directly on the testpiece surface forming an image of the defect and providing information about defect length.

Disadvantages:

- Only ferromagnetic materials can be inspected.

- Surface preparation is needed although it is not as critical as in the case of dye penetrant testing.

- To detect a flaw, the magnetic field lines must be perpendicular to the flaw length, so the technique is commonly applied in two perpendicular directions to guarantee the detection of all defects.

- Large currents are required when testing large parts.

- A fairly smooth surface is required to avoid false indications.

- Sensitivity is harmfully affected by nonmagnetic coatings.

- Surface post-cleaning and testpiece demagnetization is required.

2.1.4. Radiographic testing [4-6, 10]

A source generates penetrating electromagnetic radiation that passes through the testpiece. The radiation wavelength must be of appropriate value in order to allow a proportion of radiation to reach a film behind the testpiece. As it passes through the material, the radiation undergoes attenuation and scattering due to diffraction. The film records the exiting radiation intensity and a shadowgraph that provides information regarding structure and composition is formed. This is possible thanks to the fact that the attenuation for a given radiation when going through the part is a function of its thickness and density. The presence of defects hence alters the exposure of the film. To be accepted, radiographic evidence should include an image quality indicator. This shows the achieved resolution and sensitivity and is often included and visible in the radiograph.

Factory-based radiographic testing devices usually use X-ray sources, whilst site work devices commonly use more portable gamma-ray sources.

Advantages:

- Radiographic testing can be applied to any material.

- Surface and subsurface defects can be detected. In particular, it is good at detecting volumetric non-planar flaws (porosity, inclusion, etc.) or planar defects that are parallel to the radiation beam direction.

- The radiograph provides a permanent record of the test results, so this way they can be repeatedly and carefully examined under proper viewing conditions.

- Inspection of complex shapes and multilayered structures is possible without disassembly.

- Minimum part preparation is required to perform the test.

- Easy to characterize and locate detected defects within the projected view thanks to the radiograph.

Disadvantages:

- Health hazard due to the use of radiation. Stringent safety precautions are required, for instance, expensive screening, security zones such that access is only allowed to authorized persons, disruption of operations to clear the area where the test is going to take place, etc.

- Usually it is not possible to characterize or locate defects as regards to the beam direction (through thickness direction).

- It is difficult or even impossible to detect planar defects inclined at an angle to the beam or planar defects that are aligned to the beam but closed tightly together.

- Access to both sides of the testpiece is commonly required.

- Extensively skilled and trained operators are needed.

- Expensive equipment investment is necessary.

2.1.5. Ultrasonic testing [4-6, 11]

The transducer, which is a piezo-electric crystal, generates and transmits acoustic waves or pulses into the testpiece. The frequency of the waves is usually within 0.25 to 10 MHz, although lower or higher frequencies can be used for special applications. The waves can be either transverse (shear waves) or longitudinal (compression waves).

Flaws in the path of the ultrasonic waves are detected if they produce a change in the acoustic impedance, thus reflecting back a portion of the acoustic energy. The presence of the defect can be revealed either by the increase in the echo or by the reduction in the transmitted signal. In the former case, the reflected waves are received by the transducer mentioned before or by a separate piezo-electric crystal. In the latter case, the receiver transducer is placed at the opposite side of the testpiece. In both cases, the received waves are converted into electrical signals that can be processed. Since the sound velocity is know for the tested material, the arrival time of the reflected waves allows the spatial location of the flaw along the ultrasonic beam propagation direction.

Advantages:

- Ultrasonic testing can be applied to any material.
- Surface and subsurface defects can be detected. Test penetration depth is superior to the rest of techniques.
- The electrical signals generated by the receiving transducer can be stored providing a permanent record of the test results, so this way they can be repeatedly and carefully examined.
- Minimum part preparation is required to perform the test.
- Usually only single side access is required.

Disadvantages:

- Results interpretation requires both skilled and trained operators as well as reference standards.
- Ultrasonic testing is a point test, this means the sensed area is limited to the region immediately surrounding the probe. Scanning is needed to inspect large areas, which is time consuming and thus expensive.
- A coupling fluid between the probe and the surface is required for impedance coupling. If not used, there is little or even no transmission of acoustic waves through the air interface from the transducer to the surface. Adequate gels or water are commonly used as coupling agent.
- Testpiece-transducer contact is required, so the surface to be tested must be accessible to the transducer and coupling fluid. In addition, surface finish and roughness can affect the results.
- Planar or linear defects parallel to the wave propagation direction cannot often be detected.
- Need to maintain the correct alignment of the ultrasonic beam, which is difficult in curved parts.
- Difficult to interpret the results of the inspection for complex shapes.

2.1.6. Visual testing [4-6, 12]

Visual inspection is often used and is often the simplest technique. It can be used as an initial approach to locate gross flaws or to target subsequent inspections by other techniques.

Advantages:

- Visual inspection can be applied to any material.
- Minimum equipment investment.
- No part preparation is required to perform the test.
- Complex geometries can be routinely inspected.

Disadvantages:

- Visual inspection is limited to surface-breaking defects and to areas that are accessible to the naked eye or to the ancillary optical devices.
- Appropriate lighting is required.
- Visual inspection is highly dependent on operator's skill and training.
- Visual inspection is a point test.

2.2. RECENT AND ADVANCED NDT METHODS

Once the basic principles and pros and cons of the major techniques have been reviewed, here follows an overview of recent and advanced NDT methods for detecting defects. In this section, no in-depth analysis is done on these methods but they are reviewed superficially due the following reasons.

The first reason is that the below mentioned methods are far from the author's thesis scope, as will be seen in detail in chapter 3, where the thesis proposal is defined. The second reason is that the joint expenditure on the major techniques represents almost the totality of the NDT market. For instance, it clearly exceeded 90% of the market in the beginning of the 1990s decade [13]. See Fig. 2.1.

In addition, some of the following methods are nowadays immature technologies or are only viable and useful for laboratory purposes due to their high degree of sophistication and complexity.

The first method to be presented is the Acoustic Emission (AE) technique. This method achieves the detection of cracks through the detection of acoustic emission signals. These transient elastic stress waves are generated when elastic strain energy stored in the material is suddenly released due to dynamic processes like crack initiation or propagation [14].

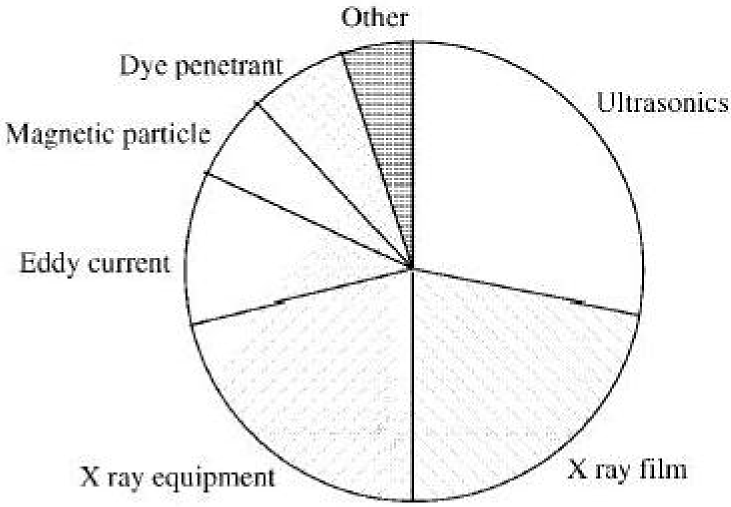

Fig. 2.1: NDT market share by technique in the beginning of the 1990s decade [13].

Laser scattering techniques such as holography [14, 15] and speckle pattern [14] can also be utilised to sense superficial flaws.

The micromagnetic techniques can be used to sense fatigue damage too [14]. These techniques are Acoustic Barkhausen Emission (ABE) and Magnetic Barkhausen Noise (MBN) or Magnetic Barkhausen Emission (MBE).

Positron Annihilation (PA) technique is based on the fact that the positron annihilation rate of positrons penetrating into a material is different for a region with flaws than for a defect-free region [14].

Reflection Anisotropy Spectroscopy (RAS) is a NDT optical technique to probe surfaces. The RAS spectrum can be correlated to the surface electronic structure of the material which in turn can reveal the presence of flaws [16].

Microcracks and voids can be detected by Small Angle Neutron Scattering (SANS). This technique is based on the scattering that a neutron beam suffers when penetrating into a material and interacting with microstructural features [14].

Temperature Sensitive Paint (TSP) allows detection of cracks because the stress concentrations at the crack tip can be observed as temperature increases due to frictional heating [17].

Extensive information relative to other alternative NDT methods to the so-called major techniques can be found in reference [18].

3. DEFINITION OF THE THESIS PROPOSAL

In this chapter, a brief background on aerospace industry and interesting data is presented firstly. Next follows the definition of the thesis main objective and a brief description of the proposed NDT method.

3.1. AEROSPACE INDUSTRY BACKGROUND

Maintenance costs represent around 17-21% of an aircraft's Direct Operating Cost (DOC), which are the costs derived from the aircraft utilization, and even reach 40% in some cases. These costs usually rise up to 60,000-120,000 euros per year per aircraft and significantly more for large turbine aircraft [9]. It is worth to mention that the total world NDT market was estimated to be 770 million euros in the early 1990s and that the split between industrial sectors showed that aerospace sector was the largest customer, covering just over 25% of the total market [13]. See Fig. 3.1.

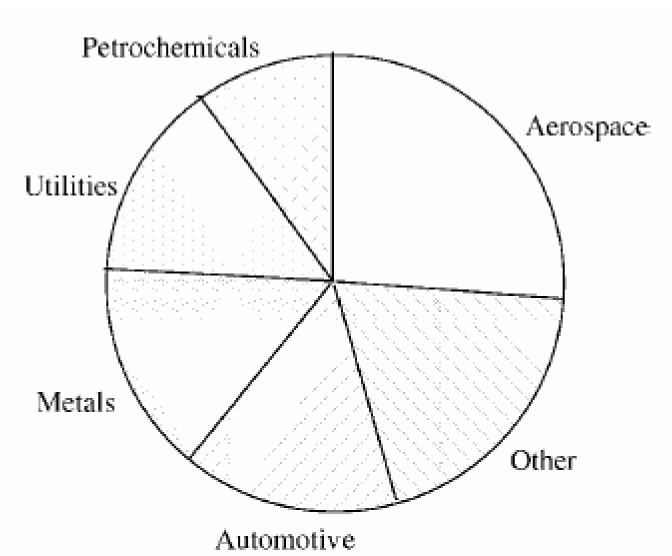

Fig. 3.1: NDT market share by customer industry in the beginning of the 1990s decade [13].

These numbers show on one hand the importance of the maintenance activities and the derived costs in air transport industry and on the other hand the importance of NDT for maintenance purposes in aerospace industry. As a consequence, research on suitable NDT solutions for aerospace components maintenance is to the advantage of aerospace industry, the air transport safety and the reduction of maintenance costs, which are of crucial importance for the air transport industry and hence its users.

3.2. THESIS OBJECTIVES

From the NDT equipment manufacturer's point of view, the strongest driver for innovation has been typically the demand of cost reductions requested by the customer industries rather than the will of the manufacturers to improve their products [4]. In accordance, the proposed PhD thesis aims to take benefits of some of the recent advances in materials nanotechnology and nanoscience in order to develop an innovative NDT technique which leads to a reduction of inspection costs.

Being the challenges common for many of the NDT techniques, the main goal of this thesis is therefore to develop a technique that fulfils the requirements of end-users in the form of a significant reduction of inspection costs.

3.3. DEFINITION OF THE PROPOSED NDT METHOD

The operator spreads a solution made of iron oxide magnetic nanoparticles and a low surface tension highly volatile solvent on the surface of the testpiece by means of an aerosol. The solution is left for a period of time (which will be called residence time from now on) and seeps into any existing surface-breaking defect by capillary action. Magnetic nanoparticles are supposed to concentrate inside the defects. The most suitable nanoparticles, the most suitable solvent and the value of residence time are still to be determined. Whether it is necessary or not to force somehow nanoparticles to concentrate inside the surface-breaking defect will be checked later on, depending on the first experimental results with the selected nanoparticles and solvent.

Once the residence time has gone by, the operator begins scanning the surface with the transducer, which is a Hall probe or magnetometer. At this early stage, it is supposed there is neither need for testpiece preparation nor carefully removing excess solution from the surface after residence time, prior to performing the scan. If experimental results prove the contrary, a suitable testpiece preparation method and/or an excess removal method will also be developed.

The Hall probe senses the local value of magnetic flux density. When scanning the testpiece surface, the presence of any existing surface-breaking defect will be revealed to the operator as an abnormal reading in the transducer, due to the magnetic field generated by magnetic nanoparticles concentrated inside the defect.

The whole procedure will be referred in the following as Magnetic Early Defect Detection, MEDD. Early refers to the fact that one of the goals of the technique is to enable the detection of defects before they reach a reference initial length. Given that one of the most important target applications of MEDD will be aircraft skin panel inspection, the reference initial length will be the well accepted in aircraft structural design for meeting damage tolerance requirements. This length is agreed on 50 mm [35]. It refers to the expected crack length to be reliably detected by visual inspections (General Visual

Inspections, GVI), the most widely used NDT technique in aircraft crack monitoring.

If effective early crack detection could be achieved by means of MEDD, cracks could be identified and located well before they reach the initial length and crack monitoring could began earlier. Safety would be improved consequently. Also the number of overlooked cracks could be reduced. In order to achieve economical viability for this specific application, advantages should overcome appreciably those of GVI and balance the undesired increase in costs as regards to GVI.

Considering the advantages and disadvantages of the major NDT techniques that have already been presented in chapter 2, the target advantages and the predicted disadvantages of the proposed technique would be the following, as a first approach:

Advantages of MEDD:

- Applicable to any non-magnetic material: polymers, composites, metals, either conducting or non-conducting.

- In situ applicability, for example on aircrafts parked outdoors or indoors at an airport.

- Minimum equipment investment and minimum data processing.

- A permanent record of the test results could also be provided by MEDD, so results can be repeatedly and carefully examined under proper viewing conditions. Further research is required to see whether readings can be correlated to defect features or not, which is out of the scope of the author’s thesis.

- Simplicity of operation and results interpretation. Operation and results interpretation do not require highly skilled and trained operators as well as reference standards.

- No part preparation is required to perform the test.

- No part cleaning or postprocessing is required after performing the test.

- Inspection of complex geometries is routinely possible without testpiece disassembly.

- Only single side access to testpiece is required.

- Test probe or transducer does not need to contact the testpiece. From now on, the distance between the probe and the testpiece surface will be called lift-off, as it is done in the case of eddy current testing.

- There is neither need for operation under controlled conditions, nor chemical hazardous handling nor stringent safety precautions.

- The technique is not only limited to areas that are accessible to the naked eye.

Disadvantages of MEDD:

- Only surface-breaking defects detection capability.

- The technique is a point test, this means the sensed area is limited to the region immediately surrounding the probe. Scanning is needed to inspect large areas, which could be time consuming and thus expensive. In this sense, the inspection process does not allow rapid inspection of large surface areas or volumes.

- Indications do not appear directly on the testpiece surface. MEDD only allows prove of defect existence. Alternative methods should be used to fully characterize the flaw. Further research is required to see whether readings can be correlated to defect features or not, which is out of the scope of the author’s thesis. If possible, the method could be able to provide additional information regarding the defect.

- The technique is limited to areas that are accessible to the probe.

If MEDD finally meets the above mentioned specifications, with the consequent predicted advantages and disadvantages, it is possible to achieve the cost reduction demanded by end-users for a certain range of NDT tests and applications.

Finally, it is important to mention that neither reference has been found regarding any NDT method similar to the one proposed in this PhD. Proposal, nor work already done that could be included in the framework or scope of the author’s thesis.

3.4. PREDICTABLE MEDD PROBLEMS AND SOLUTIONS

Predictable problems as well as possible solutions are presented. Solutions are only at a conceptual stage.

Should any of these problems turn into reality, some of the predicted technique advantages could be seriously compromised or even vanish.

3.4.1. Problem 1

Testpiece preparation is needed before performing the test because contaminants (dirt, grease, paint, etc.) produce false indications. Nevertheless, this problem is hardly expected since contaminants are not usually magnetized.

Possible solution to problem 1:
A proper cleaning method should be developed.

3.4.2. Problem 2

Nanoparticles do not enter or concentrate inside the defect. It is necessary to force nanoparticles to concentrate inside the surface-breaking defect.

Possible solution to problem 2:
A proper method to force nanoparticles to concentrate inside the surface-breaking defects should be studied.

3.4.3. Problem 3

It is not possible to find a suitable solvent for such application.

Possible solution to problem 3:
An alternative deposition method should be considered.

3.4.4. Problem 4

It is necessary to remove carefully excess solution from the part surface after residence time, prior to performing the scan, because otherwise produces false indications.

Possible solution to problem 4:
A suitable method to remove carefully excess solution from the surface after residence time should be developed.

3.4.5. Problem 5

The technique performance is very sensitive to unforeseen variables: scanning velocity, etc.

Possible solution to problem 5:
The solutions could be the specification of operation procedures and the training of operators to minimize errors derived from human factors (operator errors), and the utilization of alternative probes with better performances than the probes selected at the very early stage of development.

3.4.6. Problem 6

Magnetic fields of near sources (for example, electronic equipment in the vicinity of the part to be tested) distort the test results.

Possible solution to problem 6:
A signal filter or processor should be studied to distinguish between noise and signal generated inside defects. The signal should be processed before being displayed to operator. Also a sort of shielding procedure could be developed.

3.4.7. Problem 7

Lift-off distance is already known to be a variable with a major influence on MEDD detection capability. Analytical/experimental evidence shows probe lift-off distance is close to zero, so probe should almost contact the surface to sense the defect.

Possible solution to problem 7:
The solutions are the same for previously considered problems, for instance, the utilization of alternative probes with better performances (sensitivity) than the probes selected at the very early stage of development, and the development of a proper method to force nanoparticles to concentrate inside the surface-breaking defects.

4. THESIS DEVELOPMENT

Once the thesis objectives and the basis of the MEDD method have been defined, in this section the attention is focused on the thesis development. The thesis work planning is presented in the first section. In the following sections, the current status of the thesis work and the future work are shown respectively.

4.1. THESIS WORK ROADMAP

A thesis work roadmap is presented in this first section (see Fig. 4.1). The diagram shows the different topics to be covered and the sequential steps or partial objectives to be fulfilled in temporal order, from top to bottom. A tentative calendar is shown later on in section [4.4.] by means of a Gantt Diagram.

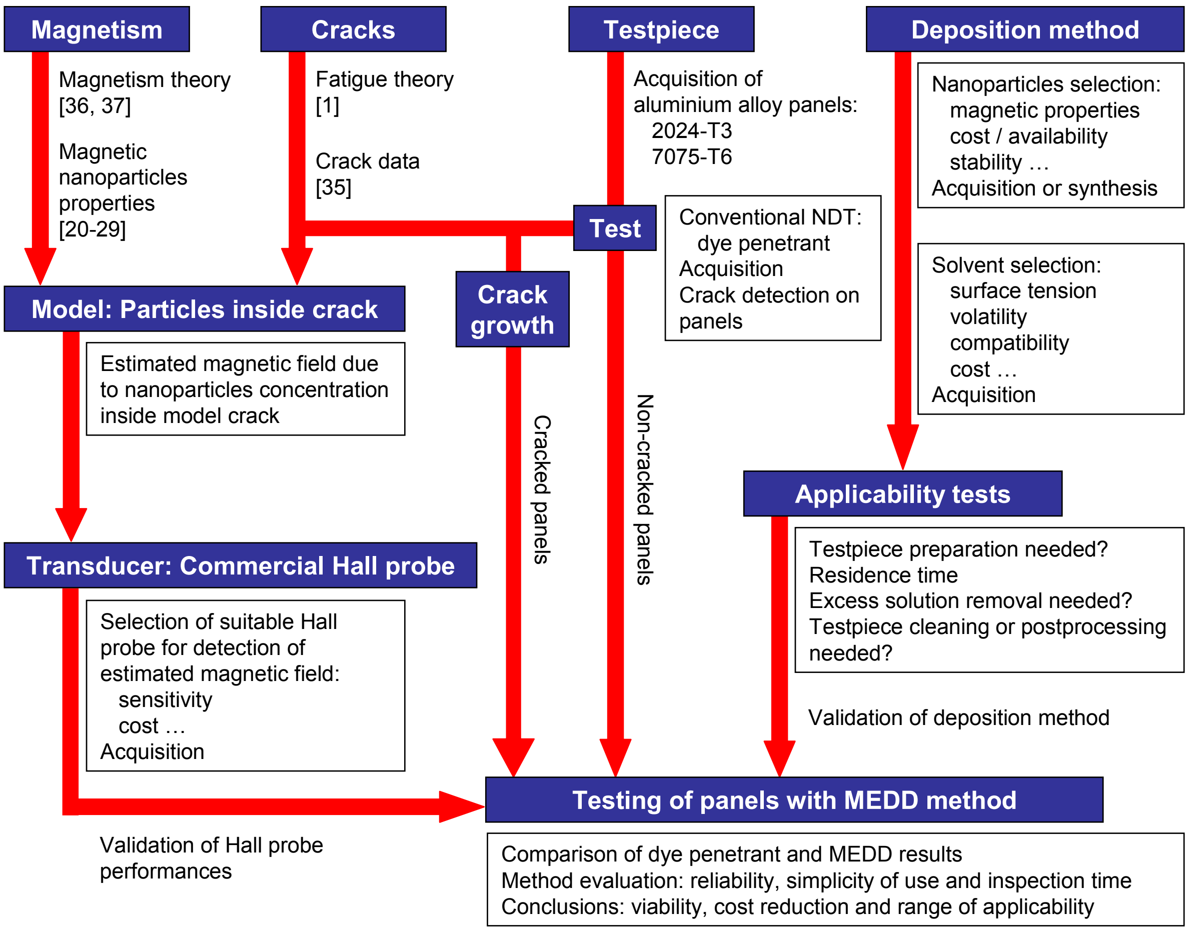

Fig. 4.1: Thesis work roadmap.

4.2. CURRENT STATUS

Next follows a summary of the thesis work that has already been realized. As far as is possible, the tasks are presented in temporal order. Several tasks are still in progress. Depending on each case, these tasks will finish sooner or will remain in progress until the end of the thesis.

4.2.1. Research on NDT state of the art

Research on the NDT state of the art has been the first task to be undertaken. The results have already been presented in chapter 2. During this process, focus was placed especially on the search of a conceptually similar NDT method to the one that is being proposed. As said before, no evidence of existence or current or past research on such a NDT method was found.

Research on the NDT state of the art is planned to be performed periodically (every 6 months). The aim is to know whether research that could be included in the framework or scope of the author's thesis is done or not. This process will not end until the finishing of the thesis.

4.2.2. Nanoparticles selection

Research has been done on magnetic nanoparticles aiming to find the most appropriated for this specific application [20-22]. The selection criteria are magnetic properties (saturation magnetization, magnetic remanence, Curie temperature, etc.), chemical stability, biocompatibility (non toxicity), cost and availability. Compatibility with solvent will be taken into account during solvent selection, once the final nanoparticles to be used have been selected.

The possibility of synthesizing nanoparticles with properties on demand was taken into account. Therefore simplicity of production would have been another criterion in this case. Finally this option was discarded because the utilization of commercially available mass-produced nanoparticles was to the advantage of the proposed NDT method cost reduction.

According to the above mentioned criteria, the chosen alternatives are α-Fe nanoparticles, magnetite nanoparticles (Fe_3O_4) and maghemite nanoparticles (gamma-Fe_2O_3). Among the three options, pure α-Fe nanoparticles have the best magnetic properties, but they are highly unstable in the presence of oxygen. A priori, this would make them probably unacceptable for MEDD in view of chemical stability if considering the requirements specified in chapter 3, namely in situ applicability outdoors.

To overcome this problem, instead of pure α-Fe nanoparticles, core-shell particles where the core consists of iron and the protecting shell is composed of iron oxides will be considered [23]. In fact, this should be the natural product of α-Fe exposed to the atmosphere. The shell guarantees stability but as a consequence the magnetic properties are diminished.

On the other hand, both magnetite and maghemite nanoparticles have high chemical stability at atmospheric conditions and acceptable magnetic properties for the proposed application. They are also completely biocompatible (non toxic) [24]. Magnetite nanoparticles have slightly better magnetic properties while maghemite nanoparticles are slightly more stable regarding oxygen presence. Information regarding their properties can be found in references [20, 24-29].

Considering the two latter criteria, it is worthy to mention that all these alternatives are suitable enough since iron and iron oxide nanoparticles are low-cost and highly available, in terms of nanoparticles market. Several commercial providers can be found in references [30-32].

The three alternatives will be experimentally tested to determine which one leads to the highest NDT method performances. If experimental evidence shows that these types of particles are not suitable for the proposed target, further research on this topic should be done.

4.2.3. Acquisition of testpieces

In order to perform the NDT tests with the innovative method, 2024-T3 and 7075-T6 aluminium alloy sheets have been acquired. The reason behind the selection of these specific aluminium alloys is that they are commonly used in aircraft skin panels (especially in military aircraft [33, 34]). In addition, aircraft skin panel testing has been identified potentially as one of the most important target applications for MEDD technique.

Aircraft flat skin panels without holes are usually 1.0 to 1.6 mm thick while skin panels on critical locations are usually 2.0 to 3.0 mm thick. The latter are for example the fuselage skin panels near the wing root, near the Horizontal Tail Plane root and near Vertical Tail Plane root. Among the possibilities, the finally acquired 2024-T3 and 7075-T6 aluminium alloy sheets are 2.0 mm thick.

Nevertheless, it must be remembered that one of the goal specifications for the proposed technique is applicability to any material, so testpiece material is not critical.

4.3. PUBLICATIONS AND CONGRESSES

Presentation of a poster in the frame of the 8th Minerva Winter School and meeting of EU Networks on ‘Physics of Nonequilibrium and Complex Systems’ and on ‘Fluid Mechanical Stirring and Mixing: the Lagrangian Approach’. Both events took place at Weizmann Institute of Science, Rehovot (Israel), February 2006.

- J. Rojas and D. Crespo. Nondestructive Testing (NDT) in aerospace sector. 8th Minerva Winter School and meeting of EU Networks on ‘Physics of Nonequilibrium and Complex Systems’ and on ‘Fluid

Mechanical Stirring and Mixing: the Lagrangian Approach'. Rehovot (Israel), February 2006.

4.4. FUTURE WORK

The sections above summarize the thesis work that is already done at this moment. Next follows a summary of the planned future work in order to achieve thesis objectives. Again, as far as is possible, the tasks are presented in a hypothetical temporal order. Several tasks are already in progress but at a very early stage.

1. Further study on fracture mechanics and fatigue theory. Work in progress.

2. Extensive research on target crack data in aerospace parts to completely characterize model crack: depth, length, width, morphology, etc.). Work in progress (reference [35]).

3. Get further information on magnetism theory. Work in progress (reference [36, 37]).

4. Development of a model crack. Filling of the model crack with selected nanoparticles. Analytical calculation of magnetic field around the crack generated by nanoparticles inside the crack. Work in progress.

5. Selection of suitable commercial Hall probe for detection of estimated magnetic field around model crack filled with nanoparticles. Work in progress. Several commercial providers can be found in references [38, 39].

6. Further research on commercial magnetic nanoparticles and acquisition of selected ones. Work in progress [30-32].

7. Research on suitable solvent and acquisition of selected one.

8. Testing of acquired aluminium panels to detect already existing surface defects. Dye penetrant testing has been selected since it is the most cost-effective NDT for surface defects detection in this particular case: simplicity of utilization, equipment investment is minimal and time of inspection is not critical. Partial goals or tasks to be performed:

   i) Research on information regarding dye penetrant testing [4-7]
   ii) Research on commercial dye penetrant testing equipment
   iii) Selection and acquisition of proper equipment
   iv) Inspection of acquired aluminium panels
   v) Cracks characterization and location
   vi) Classify: cracked panels/areas and non-cracked panels/areas

9. Generation of sample specimens. Available methods for crack initiation and propagation: search for dynamic testing machines among UPC research groups and beyond.
10. Perform MEDD applicability tests with acquired solvent and magnetic nanoparticles. Experimental evaluation of:

    i) Influence of contaminants and need for testpiece preparation
    ii) Residence time
    iii) Influence of excess solution and need for excess solution removal
    iv) Need for testpiece cleaning or postprocessing

11. Perform MEDD testing of cracked and non-cracked panels/areas. Measurements and data acquisition.

12. Results and MEDD technique evaluation:

    i) Comparison of test results on cracked and non-cracked areas
    ii) Comparison of dye penetrant and MEDD results: reliability and sensitivity
    iii) Simplicity of use
    iv) Time of inspection
    v) Definition of range applicability
    vi) Degree of fulfilling of predicted specifications/advantages
    vii) Viability
    viii) Effective and enabling reduction costs

13. Problems solving. Iteration. Method improvement.

Next follows a Gantt Diagram showing the tentative calendar of the thesis development (see Fig. 4.2). Major tasks are shown as well as the expected time of activity beginning and activity finish.

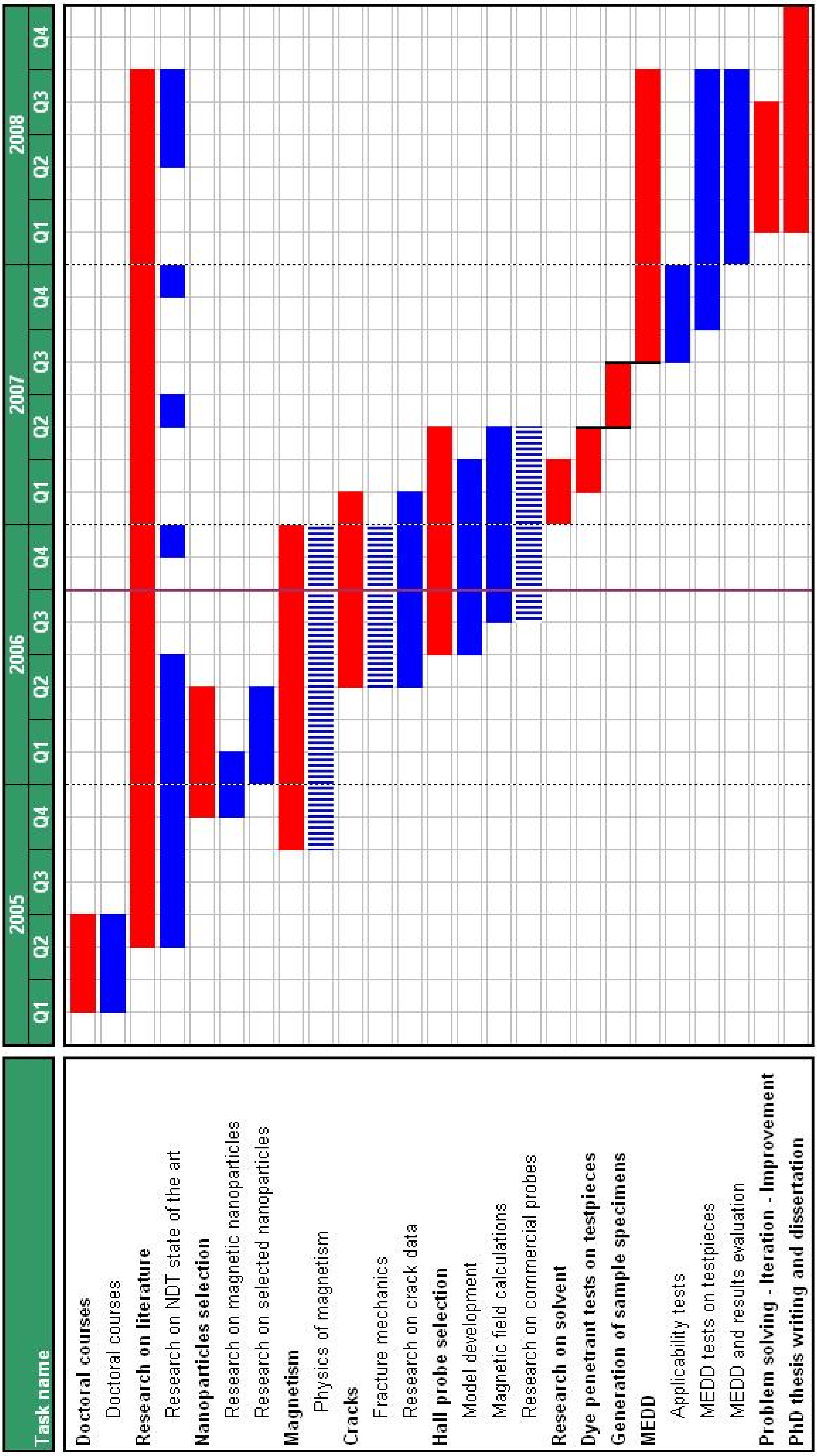

Fig. 4.2: Thesis work roadmap.

4.5. FUNDING

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5. SUMMARY

The goal of the proposed PhD thesis is to develop an innovative NDT technique which fulfils the requirements of end-users in the form of a significant reduction of inspection costs, for a certain range of aerospace NDT applications. The goal should be achieved especially through reduction of equipment costs and reduction of inspection time. The proposed NDT method is called Magnetic Early Defect Detection (MEDD) and aims to bring somebenefits of the recent advances in materials nanotechnology and nanoscience to the aerospace NDT sector.

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