Sudan University of Science and Technology

College of Graduate Studies

Effect of Eddy Currents on Discontinuity of Different Metals

تأثير التيارات الدوامية على الانقطاعات لمعادن مختلفة

A Thesis submitted in Fulfillment for requirement of the Degree of master in physics

By

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الآيـــــــة

بسم الله الرحمن الرحيم

قال الله تعالى:

﴿ يَرْفَعِ اللَّهُ الَّذِينَ آمَنُوا مِنْكُمْ وَ الَّذِينَ أُوتُوا الْعِلْمَ دَرَجَات ﴿11﴾﴾

صدق الله العظيم

سورة المجادلة

Dedication

I dedicate you this research to my dear father, my dear mother, my brothers and sisters, my dear husband, all my teachers and all my friends

Acknowledgements

Firstly thanks to Allah for reconciling me, Thanks to my beautiful family, my teachers and especially the supervisor of this research; **Dr. Rawia Abdelgani Elobaid,** Thanks to Tarco Corporation

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Abstract

The objective of thesis to inspect discontinuities such as cracks, scores, Corrosion pits, seams, laps, inclusions etc. will disrupt the eddy currents and may cause an indication. Study design: The learner will use the descriptive analytic and experimental approaches to carry out this research. Alternating electrical current is passed through a coil producing a magnetic field. When the coil is placed near conductive material, the changing magnetic field induces current flow in the material .these currents travel in closed loops and are called eddy currents. Eddy currents produce their own magnetic field that can be measured and used to find flaws and characterize conductivity, permeability, and dimensional features. In this study eddy current testing technique was used Defect meter 2.837 to study defect on some selected samples and report was considered.

This thesis reviews the state-of-the-art methods of eddy current testing which is one of the most widely used non-destructive forms of testing. Eddy current testing permits crack detection and measurements that are beyond the scope of other techniques such as non-conductive coating thickness, alloy composition and hardness in a large variety of materials. The only need is that the materials being tested must be electrical conductors where eddy currents can flow. Eddy current sensors are insensitive to dirt, dust, humidity, oil or dielectric material in the measuring gap and have been proven reliable in a wide range. In conclusion, as researchers and developers of solutions based on eddy current testing, it was found that eddy current techniques can provide the industry with reliable quality control systems. Although there are excellent improvements due to the effort of the many scientists during the last several years, we believe that more research in eddy current techniques, in terms of sensors, equipment and signal processing, will lead to even more applications of these techniques. From inspection done in the Khartoum

International Airport it was concluded that there is defect on the samples that inspected under Defect meter 2.837 as prescribed in the report.

It is necessary trying to develop new coil probes and research the use of other magnetometers such as superconducting quantum interference devices (SQUIDs), Hall-effect and magneto resistive sensors that also provide very interesting responses.

المستخلص

الهدف من البحث فحص الانقطاعات مثل الشقوق ، والنتائج ، وحفر التآكل ، والدرزات ، واللف ، والشوائب ، وما إلى ذلك ، سوف يعطل التيارات الدوامة وقد يسبب إشارة. تصميم الدراسة: يستخدم المتعلم المنهج الوصفي التحليلي والتجريبي لإجراء هذا البحث. يتم تمرير التيار الكهربائي المتردد عبر ملف ينتج مجالًا مغناطيسيًا. عندما يتم وضع الملف بالقرب من مادة موصلة ، فإن المجال المغناطيسي المتغير يحث على تدفق التيار في المادة ، وتنتقل هذه التيارات في حلقات مغلقة وتسمى تيارات إيدي. تنتج تيارات إيدي مجالها المغناطيسي الخاص الذي يمكن قياسه واستخدامه للعثور على العيوب وتمييز الموصلية والنفاذية وخصائص الأبعاد. في هذه الدراسة تم استخدام تقنية اختبار تيار الدوامة العيب مقياس 2.837 لدراسة الخلل في بعض العينات المختارة وتم النظر في التقرير. إتسعرضت هذه الرسالة الأساليب الحديثة لاختبار التيار الدوامي الذي يعد أحد أكثر أشكال الاختبار غير المدمرة استخدامًا. يسمح اختبار تيار إيدي باكتشاف الشقوق والقياسات التي تتجاوز نطاق التقنيات الأخرى مثل سماكة الطلاء غير الموصلة وتكوين السبيكة والصلابة في مجموعة كبيرة ومتنوعة من المواد. الحاجة الوحيدة هي أن المواد التي يتم اختبارها يجب أن تكون موصلات كهربائية حيث يمكن أن تتدفق التيارات الدوامة. مستشعرات التيار إيدي غير حساسة للأوساخ أو الغبار أو الرطوبة أو الزيت أو المواد العازلة في فجوة القياس وقد ثبت أنها موثوقة في نطاق واسع. في الختام ، بصفتنا باحثين ومطورين للحلول القائمة على اختبار التيار الدوامي ، فقد وجد أن تقنيات التيار الدوامي يمكن أن تزود الصناعة بأنظمة موثوقة لمراقبة الجودة. على الرغم من وجود تحسينات ممتازة بسبب الجهود التي بذلها العديد من العلماء خلال السنوات العديدة الماضية ، لذا يجب إجراء المزيد من البحث في تقنيات التيار الدوامي ، من حيث المستشعرات والمعدات ومعالجة الإشارات ، سيؤدي إلى المزيد من التطبيقات لهذه التقنيات. من المعاينة التي تم إجراؤها في مطار الخرطوم الدولي تبين وجود خلل في العينات التي تم فحصها تحت عداد العيب 2.837 كما هو محدد في التقرير .من الضروري محاولة تطوير مجسات ملف جديدة والبحث في استخدام مقاييس مغناطيسية أخرى مثل أجهزة التداخل الكمومي فائقة التوصيل (SQUIDs) ، وأجهزة استشعار تأثير هول وأجهزة استشعار المقاومة المغناطيسية التي توفر أيضًا استجابات مثيرة جدًا للاهتمام.

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CHAPTER ONE
INTRODUCTION

1.1Preface

Nondestructive testing (NDT) has been defined as comprising those methods used to test a part or material or system without impairing its future usefulness. The term is generally applied to nonmedical investigations of material integrity. Strictly speaking, this definition of nondestructive testing includes noninvasive medical diagnostics. Ultrasound X-rays and endoscopes are used by both medical and industrial nondestructive testing. Medical nondestructive testing, however, has come to be treated by a body of learning so separate from industrial nondestructive testing that today most physicians do not use the word nondestructive.

Nondestructive testing is used to investigate specifically the material integrity or properties of the test object. A number of other technologies — for instance, radio astronomy, voltage and amperage measurement and rheometry (flow measurement) — are nondestructive but are not used specifically to evaluate material properties. Radar and sonar are classified as nondestructive testing when used to inspect dams, for instance, but not when they are used to chart a river bottom. Nondestructive testing asks "Is there something wrong with this material?" In contrast, performance and proof tests ask "Does this component work?" It is not considered nondestructive testing when an inspector checks a circuit by running electric current through it. Hydrostatic pressure testing is another form of proof testing, one that sometimes destroys the test object [1].

Another gray area that invites various interpretations in defining nondestructive testing is future usefulness. Some material investigations involve taking a sample of the tested part for a test that is inherently destructive. A noncritical part of a pressure vessel may be scraped or shaved to get a sample for electron microscopy, for example. Although future usefulness of the vessel is not impaired by the loss of material, the procedure is inherently destructive and the shaving itself — in one sense the true test object — has been removed from service permanently.

The idea of future usefulness is relevant to the quality control practice of sampling. Sampling (that is, less than 100 percent testing to draw inferences about the ensample lots) *is* nondestructive testing if the tested sample is returned to service. If the steel is tested to verify the alloy in some bolts that can then be returned to service, then the test is nondestructive. In contrast, even if spectroscopy used in the chemical testing of many fluids is inherently nondestructive, the testing is destructive if the samples are poured down the drain after testing. Nondestructive testing is not confined to crack detection. Other discontinuities include porosity, wall thinning from corrosion and many sorts of disbands. Nondestructive material characterization is a growing field concerned with material properties including material identification and microstructural characteristics — such as resin curing, case hardening and stress — that have a direct influence on the service life of the test object [1].

1.2 Methods and Techniques

Nondestructive testing has also been defined by listing or classifying the various techniques. This sense of nondestructive testing is practical in that it typically highlights methods in use by industry.

In the Nondestructive Testing Handbook, the word method is used for a group of test techniques that share a form of probing energy. Ultrasonic test methods, for example, use acoustic waves faster than sound. Infrared and thermal testing and radiographic testing both use electromagnetic radiation, each in a defined wavelength range. A technique, in contrast, has features that adapt the method to the application. Through-transmission immersion testing is a technique of the ultrasonic method, for example [2].

1.3 Purposes of Nondestructive Testing

Since the 1920s, the art of testing without destroying the test object has developed from a laboratory curiosity to an indispensable tool of fabrication, construction, manufacturing and maintenance processes. No longer is visual testing of materials, parts and complete products the principal means of determining adequate quality.

Nondestructive tests in great variety are in worldwide use to detect variations in structure, minute changes in surface finish, the presence of cracks or other physical discontinuities, to measure the thickness of materials and coatings and to determine other characteristics of industrial products. Scientists and engineers of many countries have contributed greatly to nondestructive test development and applications. The various nondestructive testing methods are covered in detail in the literature but it is always wise to consider objectives before details. How is nondestructive testing useful, why do thousands of industrial concerns buy the testing equipment, pay the subsequent operating costs of the testing and even reshape manufacturing processes to fit the needs and findings of nondestructive testing, Modern nondestructive tests are used by manufacturers to ensure product integrity and in turn reliability, to avoid failures, prevent accidents and save human life, to make a profit for the user to ensure customer satisfaction and maintain the manufacturer’s reputation, [3] to aid in better product design, to control manufacturing processes, to lower manufacturing costs, to maintain uniform quality level and to ensure operational readiness.

These reasons for widespread and profitable nondestructive testing are sufficient in themselves but parallel developments have contributed to its growth and acceptance.

1.4 Applications of Nondestructive Testing

Nondestructive testing is a branch of the materials sciences that is concerned with all aspects of the uniformity, quality and serviceability of materials and structures.

The science of nondestructive testing incorporates all the technology for detection and measurement of significant properties, including discontinuities, in items ranging from research specimens to finished hardware and products in service.

By definition nondestructive test methods provide a means for examining materials and structures without disruption or impairment of serviceability.

Nondestructive testing makes it possible for internal properties or hidden discontinuities to be revealed or inferred. Nondestructive testing is becoming increasingly vital in the effective conduct of research, development, design and manufacturing programs. Only with appropriate nondestructive testing methods can the benefits of advanced materials science be fully realized. The information required for appreciating the broad scope of nondestructive testing is available in many publications and reports [4].

1.5 Classification of Methods

The National Materials Advisory Board (NMAB) Ad Hoc Committee on Nondestructive Evaluation adopted a system that classified techniques into six major method categories: visual, penetrating radiation, magnetic-electrical, mechanical vibration, thermal and chemical/electrochemical. Each method can be completely characterized in terms of five principal factors: (1) energy source or medium used to probe the object (such as X-rays, ultrasonic waves or thermal radiation); (2) nature of the signals, image or signature resulting from interaction with the object (attenuation of X-rays or reflection of ultrasound, for example);

(3) Means of detecting or sensing resultant signals (photo emulsion, piezoelectric crystal or inductance coil); (4) means of indicating or recording signals (meter

deflection, oscilloscope trace or radiograph); and (5) basis for interpreting the results (direct or indirect indication, qualitative or quantitative and pertinent dependencies).

The objective of each method is to provide information about one or more of The following material parameters: (1) discontinuities and separations (cracks, Voids, inclusions, eliminations and others); (2) structure or malstructure (Crystalline structure, grain size, segregation, misalignment and others); (3) dimensions and metrology (thickness) [5].

1.6 The Problem

The problem in this research is concentrated on the increased demand on machines In the interest of greater performance and reduced cost for materials, the design engineer is often under pressure to reduce weight. This can sometimes be done by substituting aluminum alloys, magnesium alloys or composite materials for steel or iron but such light parts may not be the same size or design as those they replace.

Beside engineering demands for sounder materials which is another justification for nondestructive tests. Materials as size and weight decrease and the factor of safety is lowered, more emphasis is placed on better raw material control and higher quality of materials, manufacturing processes and workmanship.

Also public demands for greater safety are apparent everywhere. Review the record of the courts in granting high awards to injured persons.

1.7 The Objective

The main objective of this study to inspect discontinuities such as cracks, scores, Corrosion pits, seams, laps, inclusions etc. will disrupt the eddy currents and may cause an indication.

1.8 Literature Review

H. JAEGER and J. V. SANDERS,(1967), Studied the Surface Structure of Defects In Crystals.

The structures of surfaces off c. c. crystals containing faults and defects are represented by ball models. Illustrations show the atomic arrangements of surfaces around points of emergence of dislocations, stacking faults, and twin and grain boundaries. The way in which these faults and defects may modify the surface activity is discussed [6].

1.9 Thesis Lay out

This thesis is consist of four chapters, Chapter one is introduction. The fundamentals of eddy current inspection and the main variables of this technique are presented in chapter two. Chapter three reviews the probes and transducer used in this research. Chapter four material and methods was discussed.

CHAPTER TWO

EDDY CURRENT INSPECTION FACTORS AFFECTING EDDY CURRUNTS

2.1 Introduction

This method used the effect of electromagnetic induction to induce currents in the components being tested. In turn, these currents are affected by the presence of faults which can be detected by electronic means.

2.2 Electromagnetic Induction

When an electrically conducting circuit is linked by changing magnetic field an electromotive force (EMF) is induced in this circuit. In accordance with Faraday's law, an electromotive force (EMF) is induced within an electric circuit whenever the magnetic flux linking the circuit changes in magnitude. The induced EMF is proportional to the rate of change of the flux linkage.

2.3 Production of Eddy Currents

The changing magnetic field for our purpose is produced by passing an alternating current through a coil wound around a ferritic core. We call this the primary field. When the alternating magnetic field from the coil is near to a conducting component, EMF's are induced in the component which cause currents to flow in circular paths linking the flux from the coil, these are known as eddy currents.

2.4 Advantages of Eddy Current Testing

• Suitable for the determination of a wide range of conditions of conducting material, such as defect detection, composition, hardness, conductivity, permeability etc. in a wide variety of engineering metals.

• Information can be provided in simple terms: often go/no go. Phase display electronic units can be used to obtain much greater product information.

• Extremely compact and portable units are available.

• No consumables (except probes – which can sometimes be repaired) [7].

• Flexibility in selection of probes and test frequencies to suit different applications.

• Suitable for total automation.

2.5 Disadvantages of Eddy Current Testing

• The wide range of parameters which affect the eddy current responses means that the signal from a desired material characteristic, e.g. a crack, can be masked by an unwanted parameter, e.g. hardness change. Careful selection of probe and electronics will be needed in some applications.

• Generally tests restricted to surface breaking conditions and slightly subsurface flaws.

2.6 Magnetic Effects of Eddy Currents

The eddy currents produce a magnetic field around them, we call this the secondary field. This secondary field is always in such a direction as to oppose the change in the primary field, which induced the eddy currents.

This is an example of Lenz's law which states that the direction of an induced EMF is such that the magnetic field from the current it produces will oppose the change in the field inducing EMF Fig (2.1).

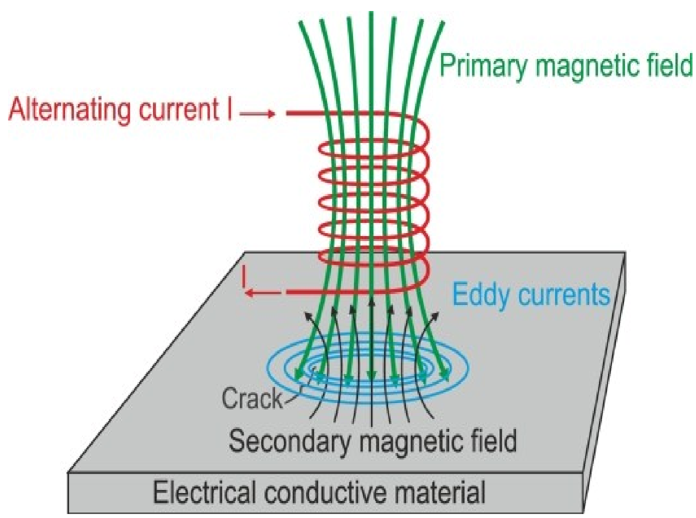

Figure (2.1) Magnetic flux produced by the eddy currents (secondary field) tries to oppose changes in the primary field [8]

2.7 Coil Impedance

Impedance is the opposition to the current flow. In a coil this impedance is partly due to the resistance of the wire and partly to the EMF induced by the changing magnetic field linking the coil windings, opposing the applied voltage. Therefore as the secondary field opposes the change in the primary field the eddy currents will change the impedance of the coil. The instrument displays this change in impedance.

2.8 Factors Affecting Eddy Currents

2.8.1 Conductivity

Electrical conductivity of a material is a measure of the ease with which electrons will flow within it. A material having a high conductivity, e.g. copper, will permit eddy currents to flow more than a material having a low conductivity, e.g. lead or nonmetals. Resistivity (p) is the reciprocal of conductivity, it is defined as the resistance offered by a 1 meter cube of the material at 0 degrees C. Thus resistivity:

$$\rho = \frac{RA}{L} \tag{2.1}$$

Where R is the resistance of the uniform conductor of length L and cross sectional area A. Usually expressed in ohm meters. Conductivity changes in materials can be caused by variations in:

i) Heat treatment.

ii) Chemical composition.

iii) Temperature.

Eddy currents can be used to measure conductivity, for the purpose of metal sorting or defining areas of heat damage. Eddy current instruments designed for measuring conductivity are usually calibrated in Percentage International Annealed Copper Standard (lACS). This is a standard whereby a certain pure copper is said to be 100% lACS, all other conductivities being compared with it. Table 1 gives examples of typical values.

2.8.2 Permeability

Absolute magnetic permeabilityμ) is the ratio of magnetic flux density (B) in a body of the external magnetic field strength (H) which produces it.

$$B = \mu H \qquad (2.2)$$

It is usual to refer to the relative permeability μ of materials. That is absolute permeability μ_r divided by permeability of a vacuum (μ_0)' Non-magnetic materials have relative perm abilities of 1, magnetic materials have values as shown in Table (2.1). If the magnetic field from the coil couples with a ferromagnetic component the flux density will be greater than if the material was non-magnetic, the actual density will depend on the permeability. This in turn will produce a stronger eddy current and have a greater effect on the coil's impedance.

Testing of ferromagnetic materials is possible however. Problems arise in practice when ferromagnetic items such as steel bolts or ferrous swarf in non-magnetic structures have a large affect when scanning near them. This is known as ferrous effect.

2.8.3 Frequency

When direct current flows through a conductor the current density is uniform through its cross section. With alternating current the current density is greater near the surface and gets less with distance into the material (Figure 2).This is known as skin effect. The higher the frequency the more quickly the current density decreases with depth. Thus, eddy currents are affected more by faults near to the surface. To give a measure of depth of penetration we regard the standard depth of penetration (SOP) as being the depth where the current density is 37% of the value at the surface. In practice the effective depth of penetration (EOP) is greater than SOP.

Table (2.1) shows conductivity, resistivity and relative permeability for Non-magnetic materials magnetic materials.

Metals Alloy	Conductivity % lACS	Resistivity Micro Ohms Meter	Relative permeability
Aluminium	65.1	0.0265	1
Cadmium	25	0.069	1
Copper	100	0.017	1
Gold	71.8	0.024	1
Lead	8.2	0.21	1
Magnesium	43.1	0.04	1
Silver	107.8	0.016	1
Titanium	3.3	0.53	1
Soft Iron	18.9	0.01	10000
Mild Steel	11.5	0.15	20000
Stainless Steel (18%Crand 8% Ni)	1.79	0.96	1.02
Typical Aluminium alloy aircraft skin	34 -42	0.051 - 0.041	1
Typical Aluminium alloy aircraft forging	34 -42	0.051 - .0.041	1
Typical Aluminium alloy aircraft wheels	9 - 36	0.192 - 0.048	1

2.9Component Under Test will Arrest Eddy Currents

2.9.1 Edge effect

As the probe approaches an edge the eddy current will be limited and cause a spurious indication. To scan near the edge of a component, the equipment must be balanced at a set distance from the edge and a scan path carried parallel to the edge.

2.9.2 Mass Effect

If a scan is carried out near to a large mass the magnetic field around the sides of the probe will couple with the mass increasing the total amount of eddy current induced. Scanning towards or away from a mass will affect the impedance of the coil, causing a spurious indication. Practical methods of overcoming this problem will be dealt with later.

2.9.3 Thickness Effect

When the frequency is such that the eddy current penetrates the full thickness of the material, any changes in thickness will give rise to indications.

2.10 Proximity

The distance of the probe to the material being tested will determine how much of the coil's flux couples with the material. Any change in this distance can cause indications. This is referred to as lift off.

2.11 Discontinuities

Any discontinuities such as cracks, scores, corrosion pits, seams, laps, inclusions etc. will disrupt the eddy currents and may cause an indication.

2.12 Probe Handling

Variations in the angle that the probe makes with the surface being scanned can alter the coupling. The probe should therefore be held perpendicular to the surface both during calibration and during scanning of the component to ensure consistent results. Some probes can be susceptible to hand capacity and must be held the same way throughout.

2.13 Classification of Eddy Current Transducers

The number of different types of eddy current transducers and the even larger number of variations on basic types make it necessary to classify them according to some convenient and meaningful factors.

The most basic distinction between transducers can be made on the basis of their mode of operation, and includes three classes:

2.13.1 Absolute Eddy Current Transducers

These consist of a single coil or its equivalent. A winding separated into two or more sections, as it is sometimes done to compensate for coil capacitance, would still be considered absolute if it performs as such. In this type of transducer the impedance or the induced voltage in the coil are measured directly (their absolute value rather than changes in impedance or induced voltage is considered). In general, absolute eddy current transducers are the simplest available and, perhaps because of this, the most widely used.

2.13.2 Differential Eddy Current Transducers

These consist of a pair of coils connected in opposition so that the net measured impedance or induced voltage is cancelled out when both coils experience identical conditions. The coils can sense only changes in the test material and therefore differential eddy current transducers are used to react to changes in test materials while cancelling out noise and other unwanted signals that affect both coils. Their sensitivity to discontinuities in materials is higher than that of absolute transducers while sensitivity to lift-off variations and probe wobble is reduced because these factors tend to affect both coils equally.

2.13.3 Absolute and Differential Eddy Current Array Transducers

Array transducers are listed separately although they may be used either in an absolute or differential mode. Depending on the exact configuration of the coils, and their connection, the output will differ greatly. Thus, for example, a number of small coils on the outer surface of a transducer could be connected in series. In this case, the transducer qualifies as an absolute transducer. The same transducer may be used in a differential configuration by connecting pairs of coils in a differential mode. It is also feasible to use the transducer as a multiple absolute (or multiple differential) transducer, where each coil (or pair of test material.

2.12 Secondary Classification of Transducers

A second kind of transducer classification is based on the method used for sensing changes in Probe characteristics:

a) Impedance method

In the impedance method, the driving coil is monitored. Because changes in coil voltage (for a constant current source) or coil current (for a constant voltage source) are due to impedance changes in the coil, it is possible to use this method for sensing any material parameters that result in impedance changes. These all relate to changes in the real part of the impedance (conductivity, losses, etc.) or changes in the imaginary part of the impedance (changes in permeability) or both.

b) Transmit-receive method

The Transmit-receive method consists of separate driving coil (or coils). In this case, the induced voltage across the pickup coils is measured. There is little fundamental distinction between the two methods since, in the limit, they are identical. For practical purposes, one may be more convenient or more sensitive than the other. Both methods may be used with absolute or differential eddy current transducers.

2.14 Classification by Probe Usage

A third important method of probe classification is based on usage. Although identical or similar transducers may be used for different testing situations, the following major types may be distinguished.

a) Feed-through transducers.

Feed-through transducers consist of circular coils used to test the interior of tubes or circular holes. Sometimes, the term feed-through is used for encircling coils (the test material is fed through the coils) but it is more common to refer to inside probes as feed-through probes.

b) Encircling transducers.

Encircling coils are similar in structure to feed-through transducers except for the fact that the test material is passed inside the coils. They are primarily used to test the outer surface of round material such as tubes and rods.

c) Surface transducers.

Surface coils (or probe coil transducers) are some of the most widely used eddy current probes. In most cases, they consist of flat coils and are used to test flat surfaces of surfaces with relatively large curvatures. Surface probes may also be curved to fit contours of the test object.

d) Forked transducers.

Forked coils are usually used to test flat, thin sheets of metal. The test material is passed between the coils. This type of probe is particularly appropriate for testing thin steel since they have excellent lift-off characteristics and are very sensitive to material thickness. They also represent the through-transmission probes, in which the coils are located at opposite sides of the test material, compared to reflection type probes where both the exciting and the pickup coil (or Coils) are located on the same side of the test object.

All these transducers may be used in any of the configurations mentioned above. Thus, for example, a feed-through probe may be absolute or differential and either the impedance or the induced voltage may be measured. For this reason, any classification of eddy current transducers is at best more of a convenience than a true statement of the differences between the various transducers. Secondary methods of classification may also be employed to further distinguish between various transducers. For example, it is quite common to refer to particular transducers by describing their shape. Examples of this practice are U-core probes, E-core probes, mushroom probes and pencil probes. A name such as pencil probes refers to the fact that the coils are very small on a pencil shaped holder but it adds little to our knowledge of the probe characteristics. Still other probes are commonly named according to some feature of their design which may have even less importance. For example, winding an absolute probe in the cavity of one half of a ferrite potcore produces a superior probe that is sometimes called a pot-core probe or cup-core probe.

2.15 Surface Structure of Defects in Crystals

Defects in crystals are known to control many of the mechanical properties of solids, and it has been suggested that they may also be important as active sites in the surface1 Their influence in catalytic reactions has been investigated experimentally2-4 and the effect reviewed by THOMAS.5 As an aid to understanding how and when this may occur, we give here descriptions of the structures of the surfaces of crystals containing defects. We will assume that one knows the ideal atomic structure of the surface of a crystal, i. e. the distribution of atoms in steps and kinks, or more precisely, the distribution of atoms with various numbers of broken bonds. We shall introduce crystal defects into such a surface and describe the change of structure which they produce. Because they may have unusual chemical properties, it is important to define when surface steps are produced and to describe the nature of the steps. We shall consider in turn point defects (vacancies, interstitials), line defects (dislocations), and planar faults (grain boundaries, stacking faults, twin boundaries), and give models or drawings of their intersections with surfaces of otherwise ideal crystals. The surface structure of defects can be derived mathematically from a knowledge of the orientation of the surface and the vectors characterizing the defects. However, models that can be handled and modified should be of more immediate value to the practicing surface chemist interested in how the surface influences the reactivity of adsorbed molecules or atoms. The models which have been constructed indicate the types of surface structures which are produced by intersecting faults, but the treatment does not include all possible combinations. All models were constructed from balls of identical size, the diameterbeing a measure of the spacing between nearest neighbor atoms. An initial layer of balls was placed in a close-packed fashion in a square or hexagonal array in a tray, with suitably shaped spacers beneath part of the layer to produce the displacement of atoms appropriate for the faults intersecting a (100) or (111) surface. The models were then built up, layer by layer, by placing balls in the correct interstices of the layer beneath. The intersections of faults and defects with surfaces of various orientations were then modeled by following the instructions given in "An Atlas of Models of Crystal Surface"6 and taking into consideration the shear displacement produced by the faults. Relaxation at the surface is generally ignored because of a lack of knowledge of how it would affect the structure and because it is difficult to incorporate in a model made of inelastic balls. Also the elastic strains around dislocations are difficult to introduce into ball models and therefore a sketch is given of a surface containing a dislocation with its Burgers vector in the surface.

2.15.1 Description of Surfaces

Ideal Surface of a Perfect Crystal: if a plane surface is created by removing all atoms whose centers lie on one side of a plane through a crystal, the positions of the atoms left in the surface are determined by the crystal structure. The surface structure is periodic and contains a unit cell, within which the surface atoms have calculable positions and numbers of broken bonds. Thus atoms in the surface are bonded to the crystal by a number of nearest neighbor bonds which is less than the maximum. This number we call the coordination number of the surface atoms, *e.g.* all the atoms in a (111) surface of a f. c. c. crystal have a coordination number of 12 - 3 = 9. The simplest surfaces are the close packed planes forming the atomically smooth (100) or (Ill) surfaces. There is a. restricted range of orientations like (110) which contain only atomic ledges, but surfaces of other orientations contain ledges of height h, and generally kinks in these ledges, and we shall call all such surfaces atomically rough. The structures of surfaces defined in this sense can be determined for any orientation and examples have been given with ball models.

2.15.2 Point Defects

Figure 1 shows a model of a close-packed (Ill) surface containing a natural step S-S' with kinks K in it. It also shows an adatom vacancy pair AI > VI on the close packed surface, created by an atom jumping from its normal position in the close-packed plane onto the surface, and a vacancy Vz in a step and an ada tom adsorbed on the step Az. The vacancies and adatoms do not occur in ideal surfaces, but can result from atomic rearrangements, and will generally exist on real surfaces. It should be noted that if a kink atom moves Fig. 1. Photograph of a ball model of a close-packed (1l1) surface in f. c. c. crystal containing a natural step S-S' in which there are kinks K, and a vacancy Vz. VI is a vacancy in the close packed plane and AJ and Az represent adatoms. Away from its position in a step, it generally leaves another kink atom, and correspondingly a kink site may not be lost by adsorption of an atom at it. A surface vacancy VI may be created when a vacancy in the bulk diffuses to the surface, and in the presence of mobile adatoms will easily be filled. If vacancies diffuse to an atomically rough surface, and emerge on a step, they will create kinks or step vacancies. Similarly interstitial atoms will emerge as adatoms on close-packed surfaces or be incorporated on steps in atomically rough surfaces.

2.15.3 Dislocations

If a dislocation is introduced into a crystal, it must terminate at the surface if it does not form a closed loop or part of a network within the crystal. It creates a point of strain where it emerges at the surface and may also produce a surface step. There is no step when the Burgers vector of the dislocation is parallel to the surface; the strain around such a dislocation in an atomically smooth surface is sketched in Fig (2.2) In real crystals this dislocation may split into two separated partial dislocations, thereby producing a length of step between them, of the type discussed in the section on stacking faults. Whenever the Burgers vector is not parallel to the surface a step is formed, and Figure 3 shows a ball model of a surface containing such a step produced by a dislocation emerging at point D.

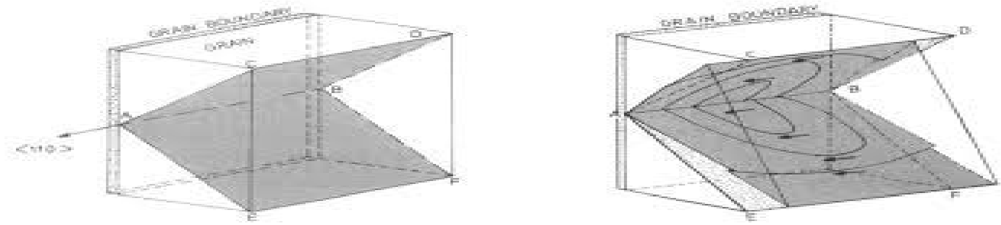

Figure (2.2) Sketch of a dislocation terminating in a (100) surface of a copper crystal without producing a surface step, based on calculations by Cotterill and Doyama.

For whole dislocations the smallest Burgers vectors possible in f. c. c. crystals point along the various [110] directions and the length of these Burgers vectors is the distance from the center of one atom to the Centre of the next atom along any of these directions. When a whole dislocation moves along its slip plane, it leaves the atoms in positions equivalent to those they occupied originally and a step produced by such a dislocation is identical to a natural step except near the dislocation where its height decreases to zero Fig (2.3) Consequently, apart from near the dislocation lines, any displacements at the surface will always be of atomic dimensions.

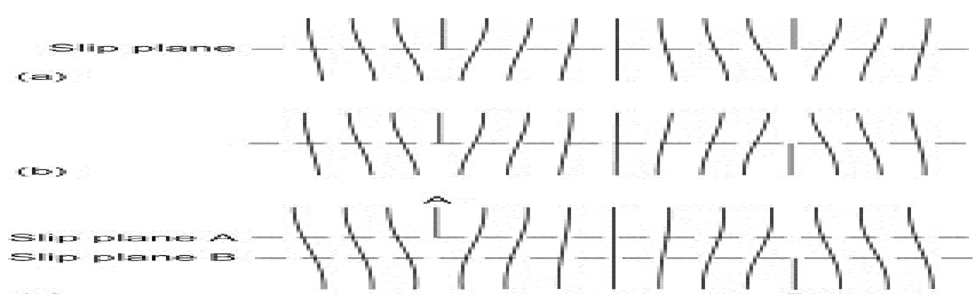

Figure (2.3) Arrangement of edge dislocations with parallel Burgers vectors lying in parallel slip planes. (a) Like dislocations on the same slip plane, (b) unlike dislocations on the same slip plane, and (c) unlike dislocations on slip planes separated by a few atomic spacings

When such a dislocation moves on its glide plane, it will extend the step until it moves out of the crystal or until the orientation of the surface changes in such a way, that it becomes parallel to the Burgers vector of the dislocation. Figure 3 shows that the slip step is a continuous ledge in an atomically smooth surface. However, if it crosses a natural step a kink is incorporated into the slip step so that on flat surfaces of other orientations, slip steps will contain rows of equally spaced kinks unless the dislocation moves parallel to the existing ledges.

Partial dislocations have Burgers vectors such that as they move, atoms are shifted into new positions that are not lattice sites and thus create an area of faulty stacking. The steps created are different from natural steps and are discussed in the section dealing with stacking faults.

2.15.4 Twin Boundaries

Fig (2.4) shows a twinned region included within a (100) surface. It is bounded by coherent (CTB) and non-coherent (NCTB) twin boundaries. Twins can be considered to be introduced into a f. c. c. crystal by moving twinning (partial) dislocations and creating intrinsic stacking faults on adjacent (111) planes. The twinning dislocations form the non-coherent boundaries and the model Fig (2.4) shows that here the atomic fit across the boundary is bad.

However, the atoms forming the coherent boundary belong equally to both lattices and no misfit exists. The displacement of the layer adjacent to the coherent boundary is the same as that across a stacking fault, but the orientation changes across the boundary and therefore subsequent layers are in different positions. If the plane of a (100) surface is extended into the twinned region, it exposes a surface which is 16° from (111), *i. e.* a (221) surface which consists of equally spaced ledges on a (111) surface. A similar situation exists on a (111) surface, where the twin exposes a (511) surface. Which consists of similar ledges on a (100) surface. As with a stacking fault the row adjacent to the coherent twin boundary may be displaced by either (1/3) h or (2/3) h. If a coherent twin boundary crosses a natural step, it creates kinks of configurations similar to those generated in natural steps by stacking faults.

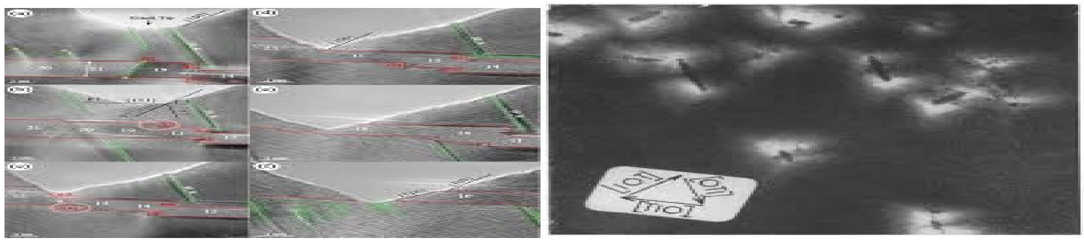

Figure (2.4) Twin included in a (100) surface; CTB, coherent twin Boundary; NCTB, no coherent twin boundary

Parallel to the surface, which can occur whenever the surface orientation is (111). In this case only the non-coherent twin boundaries can intersect the surface. The model shows the intersection with three consecutive layers. In the foreground the atomic misfit across the boundary is indicated in the model by a gap in a <110> direction. A similar gap occurs in the next layer. However, as the back half of the model shows, every third layer can cross the boundary without misfit. Thus in a (111) surface lines of misfit occur except that the boundary would disappear in every third layer.

2.15.5 Grain Boundaries

Disorientation between grains in polycrystalline solids produces atomic misfit at the common boundaries of grains. If the difference in orientation is small, the boundary can be considered to consist of an array of dislocations which may be of different types. Therefore such a boundary may be a source of steps which will run across the surface of the grains to account for the misorientation. A number of models have been suggested for large angle boundaries, but it is not clear which is the more accurate.[9]) the boundary intersects the

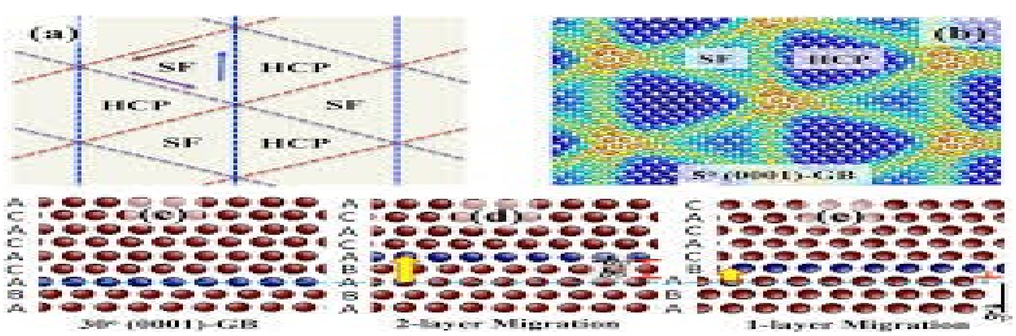

Figure (2.5) Model of grain boundary, showing the atomic misfit.

Surface in a line which will contain atoms with various numbers of mlssmgneighbours, and hence may have bonding properties approximating those of atoms in steps. The extent of the misfit can be seen by the gaps in ball models, shows a grain with a (111) surface surrounded by a (100) grain.

2.15.6 Real Surfaces

We have started by defining an ideal surface in a perfect crystal and then shown how the atomic arrangement in such a surface is modified by the introduction of faults and crystal defects. If one knows the orientation of the surface and the nature and vectors characterizing the defects one can in principle determine the ideal surface structure at the intersection, and construct a model. However, in real crystals surface diffusion causes rearrangements of the surface and leads to deviations from the ideal structure. It produces the point defects which we have already mentioned. BURTON *et al. lO)* have shown that the relative concentrations of the adatoms and vacancies can be obtained from thermodynamic considerations and that the creation of AI> VI pairs is not likely at temperatures much below the melting point of the material, and that A2, V2 pairs are more easily produced (see Fig(2.1). Similarly surface diffusion will lead to the breaking up of the straight slip steps and the ideally sharp intersections of different slip steps become rounded. ll) The steps produced by dislocations may subsequently wander across the surface and it is therefore difficult to know how many surface atoms are affected by dislocations. On a macroscopic scale minimization of the surface energy produces observable grooves at coherent and non-coherent twin boundaries and at grain boundaries which will slightly increase the total area of exposed surface and also produce a change of orientation at the surface intersection of these boundaries. Adsorbed impurities and chemical reactions occurring at the surface may either reduce or enhance the rate of surface diffusion and can also lead to the development of characteristic surface structures.12) The concentrations of defects in real crystals can be varied widely and depend upon the physical conditions during preparation of the crystals. By using single crystals, grain boundaries can be avoided and suitably oriented bicrystals can provide specimens with grain boundaries of defined orientation. In metal crystals prepared by solidification from the melt followed by slow cooling, one can expect some dislocations (105 to 107 cm-2) and point defects. Deformation can increase the concentrations of dislocations (~lOIOcm -2) and some stacking faults may be formed as well as aditional point defects. In some metals deformation may also produce twins. Subsequent annealing will lower the concentrations of dislocations; the point defects may aggregate or migrate to the surface, and twins may be formed by recrystallization. On the other hand thin films of metals prepared by vapour deposition in vacuum usually contain much higher concentrations of all these defects, even when single crystals are formed epitaxially. Typical values which have been reported for silver films3 ,13) show that 1 cm2 of film surface was intersected by 108 to 1012 dislocations, 103 to 104 cm of stacking faults or coherent twin boundaries, and 103 to 104 cm of non-coherent twin boundaries. There are a number of ways of determining the defect concentrations in metal crystals, but if one is interested in the influence of surface structure and defects on chemical reactivity, then only those methods which give the number of defects intersecting the surface are of interest in the first instance. As we have pointed out, the surface structure of the defects depends upon the surface orientation and the nature of the defect, and therefore both these factors must be determined. Ideally, atomically smooth surfaces seem to be necessary for experimental work of this type, and epitaxially grown films provide, up to now, the closest approach to this situation, in spite of their high defect concentrations.

CHAPTER THREE
PROBES FOR ELECTROMAGNETIC TESTING

3.1 Basic Operation of Eddy Current Probes

Nondestructive testing involves the application of a suitable form of energy to a test object and measuring the manner in which the energy interacts with the material. An electromagnetic measurement is usually made with a probe, or transducer, that converts the energy into an electrical signal. The probe output is fed to an appropriate instrument, which calculates the measurement variable of interest. The measured variable or signal is then either manually interpreted or analyzed by using signal processing algorithms to determine the state of the test object. The probes typically used in electromagnetic nondestructive testing are described below. In nondestructive testing, the words probe and transducer are synonymous. Electromagnetic testing probes come in several forms, types and sizes. The most common types are coils, Hall Effect detectors and magnetic particles.

The electromagnetic field that is measured in nondestructive testing is usually three-dimensional and varies as a function of space. In most cases, the field varies as a function of time. Full characterization of the state of the test object usually makes it necessary to obtain as much information about the field as possible. Because the field varies as a function of time and space, the test object is usually scanned and measurements are taken at multiple points along the surface of the test object. In the case of magnetic particle testing, the particles are sprayed over the test area. Another approach is to use an array of sensors to cover the area of interest. An alternate technique is to use magneto optic imaging devices. When the field varies as a function of time, the probe and the associated instrumentation should have the necessary bandwidth to support the measurement. Inadequate bandwidth can lead to erroneous measurements [10]. The field, being three-dimensional, is characterized by three independent components. An appropriate coordinate system (Cartesian, cylindrical or spherical) is usually chosen and the field values are referenced accordingly. It is customary to use a point in the test object as the origin of the coordinate system and align one of the coordinates along the surface of the test object. Most probes are directional, sensitive to fields along a specific direction. Thus, a flat or pancake eddy current coil is sensitive to fields that are perpendicular (normal) to the plane of the coil. Similarly, a hall element detector output is proportional to the plane of the hall element. Both devices are insensitive to components of the field in the other directions. It is possible to use two or more of these devices to measure components in the field in other directions. The orientation of the probe with respect to the test object is critical.. If the flux density components along the axial, normal and tangential components are denoted by B_X, B_Y and B_Z, respectively, then the magnitude of the total flux density is:

$$B = \sqrt{B_X^2 + B_Y^2 + B_Z^2} \tag{3.2}$$

- **Forms of Coil Probes1**

Coil probes are used extensively in eddy current as well as magnetic flux leakage nondestructive test applications. The popularity of these probes can be attributed to their simple and robust construction, low cost and design flexibility [10].

3.2 Configuration

Design flexibility lets probes be configured in different ways. Three of the most common eddy current configurations are (1) absolute probes, (2) differential probes and (3) absolute and differential array probes. Absolute eddy current probes consist of a single coil. In this type of probe, the impedance or the induced voltage in the coil is measured directly (the absolute value rather than changes in impedance or induced voltage is considered). In general, absolute eddy current probes are the simplest and perhaps for this reason are widely used. Differential eddy current probes consist of a pair of coils connected in opposition so that the net measured impedance or induced voltage is cancelled out when both coils experience identical conditions.

The coils sense changes in the test material, so differential eddy current probes are used to react to changes in test materials while canceling out noise andother unwanted signals that affect both coils. Their sensitivity to discontinuities in materials is higher than that of absolute probes. Their sensitivity to liftoff variations and probe wobble is reduced because those effects tend to affect both coils equally. Array probes consist of coils arranged in a circular, rectangular or some other form of an array.

3.3 Sensing Technique

A second kind of probe classification is based on the technique used for sensing changes in probe characteristics: either

(1) The impedance technique or

(2) The transmit-receive technique. Because impedance changes in the coil cause changes in the coil voltage (for a constant current source) or in the coil current (for a constant voltage source), it is possible to monitor the driving coil to sense any material parameters that result in impedance changes. The Transmit-receive technique uses a separate driving coil (or coils) and pickup coil (or coils). In this case, the voltage induced across the pickup coils is measured.

- **Geometry**

A third way to classify probes is according to geometry. Common probe designs include (1) inside diameter probes, (2) encircling coils (outside diameter probes), (3) surface probes such as pancake units and (4) special designs such as plus point probes. The pancake probe has a coil whose axis is normal to the surface of the test material and whose length is not larger than the radius. The plus point probe consists of two coils that lie at a right angle to each other. Inside diameter probes consist of circular coils inserted in tubes or circular holes. Encircling coils are similar in structure to inside diameter probes except for the fact that the test material is passed inside the coils. They are primarily used to test the outside surface of round materials such as tubes and rods. Surface coils are some of the most widely used eddy current probes. In most cases, they consist of flat coils and are used to test flat surfaces or surfaces with relatively large curvatures relative to their size. Surface probes may be curved to fit contours of the test object.

All of these probes may be used in any of the configurations described above. Thus, for example, an inside surface probe may be absolute or differential and either the impedance or the induced voltage may be measured [10].

3.4 Factors Affecting Eddy Current Probes

- **Liftoff Curve**

An eddy current probe has an initial impedance (quiescent impedance) that depends on the design of the probe itself. This is an intrinsic characteristic of any eddy current probe and is sometimes called infinite liftoff impedance. As the probe is moved closer to the test object, the real and imaginary parts of the impedance begin to change until the probe touches the material surface. This is called the zero liftoff impedance. The impedance curve described by the probe as it moves between these two points is the liftoff curve and is a very important factor to consider in eddy current testing. Because of the nature of the eddy current probes, the curve is not linear (the change in the field is larger close to the coils). In many cases, especially with small diameter probes for which the field decays rapidly, the range in which measurements may be taken is very small and the effect of liftoff can be pronounced. In other cases, such as with large diameter probes or with forked probes, the effect may be considerably smaller. Liftoff, because it is troublesome in many cases, is often considered an effect to be minimized. Liftoff effects may be reduced by techniques such as surface riding probes2 or compensated for by making multi frequency measurements.3 at the same time, some important eddy current tests depend on the liftoff effect. Measurements of nonconductive coating thicknesses over conducting surfaces and testing for surface evenness are two such tests.

3.5 Fill Factor

For encircling coils, the coupling factor, analogous to the liftoff effect, is referred to as fill factor. Fill factor is a measure of how well the tested article fills the coil. The largest signal is obtained with the material completely filling the coil — fill factor is almost equal to 1.0. Although it is usually desirable to maximize fill factor, some tests rely on fill factor variations. Fill factor is determined by the intersection of the impedance curve with the vertical or imaginary axis of the impedance plane.

- **Depth of Penetration**

When the eddy current probe is placed on the test object, the eddy currents induced in the test object are not uniformly distributed throughout the material. The eddy current density is high at the surface and decays exponentially with depth in the material; the phenomenon that accounts for this density difference is called the skin effect. A measure of the depth to which eddy currents penetrate the material is called the depth of penetration, or skin depth. The standard depth of penetration can be defined as:

$$\delta = \sqrt{\frac{1}{\pi f \mu_0 \mu_r \sigma}} \tag{3.1}$$

Where *f* is frequency (hertz),δ is the standard depth of penetration (meter), μ_0 is the magnetic permeability of free space,μ_r is the relative magnetic permeability and σ is the conductivity of the material. The standard depth of penetration is a convenient figure at which, under precisely controlled conditions, the eddy current density has decayed to 1·*e*–1 (37 percent) of its surface value. It is an important figure for practical purposes because, at about five standard depths of penetration (under precisely defined conditions), the eddy current density ism less than 0.7 percent of the surface value. As Eq. 2 shows, the standard depth of penetration depends on conductivity, permeability and frequency but is relatively small for most metals, about 0.2 mm (0.008 in.) for copper at 100 kHz. The skin effect has two important effects on the design of eddy current probes: (1) the probes are more useful for surface testing and (2) lower frequencies may be necessary for subsurface testing. The standard depth of penetration can be increased in the case of ferromagnetic test objects by magnetically saturating them, thereby reducing their relative magnetic permeability μ_r [10].

3.6 Design of Eddy Current Probes

Eddy current probes are based on relatively simple principles and consist of one or more coils. The shape of the coils, their cross section, size, configuration and sources are all parameters that are chosen by the designer to accomplish a particular purpose. Practical eddy current probes may range from tiny coils less than 0.5 mm (0.02 in.) to over 300 mm (12 in.) in diameter, may be long or short and may have square, round or elliptical cross sections, with magnetic or nonmagnetic cores or shields. Parameters of interest in the design may include (1) coil inductance, (2) coil resistance, (3) field distribution in space, (4) Coil response to relevant material property changes, (5) liftoff characteristics and (6) response to a notch, drilled hole or other simulated discontinuities, In addition, the design may be influenced by other constraints intrinsic to the test environment, such as weather or access requirements for a specific shape or size. Some of these requirements may in fact be contradictory. The design process is usually iterative, proceeding by trial and error. There are three basic techniques of probe design. Although these will be considered separately, a combination of the techniques is perhaps the most appropriate approach. The techniques can be classified as follows: (1) experimental or empirical design, (2) analytical design and (3) numerical design. A practical way to design a probe would be to start with analytical expressions (exact or approximate), design a probe based on some set of initial requirements, construct the probe and then evaluate its performance experimentally. If necessary, the process can be repeated until an acceptable design is obtained. Analytical expressions are not accurate except for the simplest probe geometries and numerical tools are often used in practice. The numerical design of probes has several advantages.

1. The probe, with all its components (coils, core and shield) and the surrounding medium are analyzed. The probe characteristics in the actual test environment can be obtained.

2. A more accurate design is obtained before the probe is actually built by numerically experimenting with the probe parameters.

3. The numerical technique is applicable to situations that cannot be analyzed analytically or simulated experimentally (subsurface discontinuities, layered materials and others). The following discussion focuses on analytical and numerical approaches involving an iterative approach in which the test results from a specific design lead to improvements to that design. Some of the avenues available to a designer are outlined below. In particular, a numerical approach to probe design is highlighted. The discussion below uses the finite element technique but the considerations and the treatment of the problem are similar for other numerical techniques [10].

3.7 Experimental Design of Eddy Current Probes

Probe design literature4-9 reveals the experimental nature of eddy current research. This approach was dominant in the early days of nondestructive testing.

3.8 Analytical Design of Eddy Current Probes

The design of an eddy current probe may proceed either (1) by calculating the Coil

Impedances for a given geometry or (2) by determining the appropriate dimensions for a probe with a predetermined impedance. Not all probe parameters may be designed independently. For example, if a certain probe diameter and reactance at a given frequency are required, it may not be possible to design such a probe or the design may not be acceptable for the test at hand. In the following discussion, the basic relations necessary for probe design are outlined. First, the design of air core coils is presented for single-coil and multiple-coil probes. The discussion on air core coils is followed by remarks on magnetic (ferritic) core probes and a short section on probe shielding.

3.9 Calculation of Probe Resistance

The impedance *Z* of any coil consists of a real part *R* and imaginary part *iwL*:

$$\boldsymbol{Z = R + jwL} \qquad (3.2)$$

Where *j* is √ (–1), *L* is inductance (henry) and $\boldsymbol{w}$ is angular frequency ($\boldsymbol{w}$= 2*πf,* Where *f* is frequency in hertz). The real component of impedance *Z* is the direct Current resistance *R* (ohm). *R* is calculated from Ohm's law:

$$\boldsymbol{R = \frac{\rho L}{a}} \qquad (3.3)$$

Where *a* is the cross sectional area of the wire (square meter), l is the total length (meter) of wire and $\boldsymbol{\rho}$ is the conductor resistivity (ohm meter).

Because the diameter of the coil is important in probe design, the equation may be written in terms of the probe mean diameter:

$$\boldsymbol{R = \frac{\pi \rho d N}{a}} \qquad \mathbf{(3.4)}$$

where*d* is mean coil diameter (meter), *N* is the number of turns in the coil and *dN*is the total wire length (meter). In the more general case of conducting materials in the vicinity of the coil, the real part of the impedance also includes the effects of eddy current losses in the conducting bodies.

The simple calculation of the real part of the probe impedance is applicable only to air core coils at low frequencies. It cannot be used if the cores are magnetic or conducting or if the impedance of an air coil in the vicinity of conducting or magnetic bodies is required. The effective resistance increases due to losses in the core and winding. These losses can be estimated but no general, simple expressions exist for their calculation. In particular, losses in ferrites are difficult to estimate except for particular shapes (such as cup cores) for which empirically derived estimates of the losses may be available. Where *d* is mean coil diameter (meter), *N* is the number of turns in the coil and *dN* is the total wire length (meter). In the more general case of conducting materials in the vicinity of the coil, the real part of the impedance also includes the effects of eddy current losses in the conducting bodies [10].

- **Calculation of Probe Reactance**

In its simplest form, coil reactance can be calculated by assuming (1) that only the inductive reactance (ohm) in Eq. 3 exists and (2) that the mutual inductance is negligible. Then, the coil inductance in air may be calculated using well known formulas. As a start, consider the inductance *L* (henry) of a long, circular current sheet:

$$\boldsymbol{L = \frac{4\pi a \times 10^{-7}}{l}} \qquad \mathbf{(3.5)}$$

Where *a* is the cross sectional area of the coil (square meter) and l is the length (meter) of the current sheet. (A current sheet is a conductive surface, such as a flat, energized sheet of copper foil, in which the current density measured in ampere per square meter is uniform at every point.) This expression's usefulness for design purposes is limited because actual coils are made of individual wires of round cross section and are usually relatively short.

Thus, the assumptions of uniform current distribution and long coil in Eq (3.5) are seldom met. The equation is useful, however, insofar as the expressions found in the literature for a variety of coils are written as corrections to this simple expression. If the length l of the solenoid is not large compared with the coil mean radius *r* (that is, if *r*·l–1 is not small compared to unity) the nagaoka end correction must be used in Eq (3.6) and inductance *L* for a short solenoidal current sheet becomes:

$$\boldsymbol{L = \frac{4\pi a \times 10^{-7}}{l} k} \quad (3.6)$$

The *K* value may be found from the nagaoka formula12 or from tables11 where *K* is customarily expressed in terms of the *r*·l–1 value. The value for *K* tends toward unity as *r*·l–1 approaches zero. A further correction is necessary to account for the differences between a current sheet and an equivalent solenoid made of round, insulated wires:

$$\boldsymbol{L = \frac{4\pi^2 r^2 N^2}{l} k \left[1 - \frac{l(A+B)}{\pi r N k}\right]} \quad (3.7)$$

Where *A* = 2.3 log10 1.73 *d*·*p*–1;

B = 0.336 (1 – 2.5·*N*–1 + 3.8·*N*–2); *K* is the nagaoka constant; *p* is the winding pitch; and *r* is the coil mean radius (meter). The factor *A* depends on wire diameter *d* and pitch *p; B* depends on the number of turns *N*. These factors may be found in tables elsewhere. Eddy current probes are usually made of short, multilayered coils of rectangular cross section. For rectangular cross section coils with any desired proportion between length and thickness of the windings two expressions exist: one for relatively long coils (*b* > *c*) and one for short, flat coils (*b* < *c*).11 in the intermediate range (*b* ≅□*c*), both formulas are useful. The formula for the first case is:

$$\boldsymbol{L = 0.019739 r \frac{N^2 r (K-k)}{b}} \quad (3.8)$$

The *K* value is again the nagaoka constant for a solenoid of length *b* and may be found tabulated as a function of 2*r*·*b*–1 or *b*·(2*r*)–1. The quantity *k* takes into account the decrease in inductance caused by the separation of turns in the radial direction. Again, *k* may be found tabulated as a function of *c*·(2*a*)–1, *b*·*c*–1 or *c*·*b*–1. A similar expression exists for pancake coils [11]:

$$\boldsymbol{L = 0.001(N^2 r p f)} \quad (3.9)$$

The term P is a function of $c \cdot (2a)–1$ whereas F takes into account the inductance reduction caused by turn separation in the radial direction. It is a function of $c \cdot (2r)–1$ and either $b \cdot c–1$ or $c \cdot b–1$.

These formulas are very accurate but require values to be interpolated from tables or graphs. In many cases, it is more convenient and almost as accurate to use simplified, approximate formulas. Two of the more popular formulas are summarized elsewhere.12, 14 For a long, thin coil ($b \cdot c–1 > 10$), the inductance may be approximated by Eq (3.9):

For short coils, where both b and c are smaller than the radius of the coil, a useful formula is:

- **Multiple Coil Probes**

In the case of multiple coils, the calculation of inductance is somewhat more complicated because the mutual inductance of the coils may have to be taken into account. This is not always the case. For example, in the case of coils spaced relatively far apart, the mutual inductance may be very small. No general solution to this problem exists but, for the most common arrangement of two coils close together, the mutual inductance may be found:

Where f tab is a tabulated value that depends on the dimensions of the two coils, N_1 and N_2 are the number of turns in the coils and r_1 and r_2 are the mean radii (meter) of the two coils.

The total inductance of the two coils is altered by the value of the mutual inductance depending on the way the coils are connected. If the configuration is series aiding, the mutual inductance is added. If their configuration is series opposing, the mutual inductance is subtracted:

Where L_1 and L_2 are the self-inductances of the two coils and $M_{1,\ 2}$ is their mutual inductance. The same relation may be applied for multiple-coil arrangements by calculating the mutual inductance of each pair of coils as separate values and then summing them.

CHAPTER FOUR

EXPERIMENTAL WORK

4.1 Introduction

The aim of this chapter is to present the experiment that was carried out at Khartoum international airport (Sudanese air lines) to find surface defects in some samples using the eddy current techniques.

4.2 Principle of Eddy Current

The principle of the Eddy Current sensor inducing a primary field, according to Lenz Law, 90 degree to the original field lines of the coil.

Due to the further induction of the Eddy Current in the primary field of the electric conductive material, a secondary field is induced (again according to the Lenz law) and this has an effect to the coil impedance.

In case of a defect in the tube wall, the secondary field is changed in comparison to its origin. The change of the Eddy Current field lines causes a change of the impedance of the Eddy Current probe coil, which can be displayed in the impedance screen of the Eddy Current equipment.

The impedance screen displays the change of the coil impedance in amplitude change and phase change. This is evaluated in comparison to a calibration with known artificial defects at a calibration sample which has the same electric conductive and dimension properties as the inspected tube.

Eddy Current based inspection of Ferro and Non-Ferromagnetic materials

The standard depth of penetration is described as the following function:

$$\delta = \frac{1}{\sqrt{\sigma \mu_0 \mu_r f}} \quad (4.1)$$

Whereδ: standard depth penetrant [mm]σ material electricconductivity $[\frac{\Omega}{mm}]$

μ_0 = absolute permeability, μ_r = relative permeability, f = frequency

4.3 Material

Defectometer model 2.837 was used in this inspection, some defected samples steel, aluminum, iron Lead and Tutia surface inspection probe.

(a) **(b)**

Figure (4.1) Types of probes used in the thesis (a) and standard hole calibration (b)

4.4 Method

The device was opened (switched on) and then the probe was raised to the upper position then it was placed in the standard sample which attached to the calibration device at the depth(1mm) the probe was then placed in the sample to be inspected and the probe was passed at a vertical angle (90 degrees) for all sample parts

CHAPTER FIVE

RESULTS AND DISCUSSION

5.1 Introduction

In this chapter review the result and discussion

5.2Results

When the probe passes in the place of defect, there is a complete signal in the device and an acoustic alarm at the same time. If the sensor passes in the area without defect it reads zero which indicate no defect in this region.

4.5.1 Eddy Current Report

Customer TARCO:

Order no: Method of inspection: eddy current

- ✓ **Type inspection:** surface

Equipment used: Defect meter type 2.837

Probe: Range 350 KHz up to 3MHz

Reference stander: P|NN Fe 2 (69 55)

Cable: P/ N 2 07050444709

Examination standard: any discontinuity indication is to be considered as defect and reported

Component identification Steel, AL, Pb Fe and tutia see figure (4.1)

- ✓ **Area to be inspection:**

Different material different thickness and area see fig (4.2,3,4,5,6..7.8.9 and4.10).

Technique no used: 73-32-E

- ✓ **Inspection procedure**

The sample cleaned and dried at 60c in circulating machine. The Defectometer checked (function cheek) using the reference standard P/N 2-164-SSS we carried but visual in spectrum and eddy current inspection for inspection area see fig (4.11, 12,13,and 4.14).

- ✓ **Test report**

At the time of inspection a 1mm discontinuity indication was found in the. See fig (4.2, 3, 4, 5, 6.7.8.9 and4.10).

- ✓ **Man hours**

  1hrs for every sample

- ✓ **Report compiled by**

  1. Engineer Aboelgasim Mohamed Osman
  2. Marwa Nour aldaiem Hussein
  3. Idriss Abass Mohamed
  4. Sami Mohamed Ahmed Mahgoub

Figure (4.2) shows the Defect meter 2.837 with samples to be inspected

Figure (4.3) shows Pb samples inspected with defect 30%

Figure (4.4) shows Al sample inspected with defect 60%

Figure (4.5) shows Fe sample inspected with defect zero

Figure (4.6) shows Tutia sample inspected with defect 100%

Figure (4.7) shows steel sample inspected with defect 80%

Figure (4.8) steel sample inspected with defect 30%

Figure (4.9) shows Pb sample with defect 40%

Figure (4. 10) shows Fe sample with defect 50%

Figure (4.11) shows steel sample defect 30%

Figure (4.12) shows the samples without defect (equal to zero)

Table (4.1) relation between defect percentage D and dimension for linear scratches L

Sample	Thickness	Resistivity $P\times10^{-7}\ \frac{\Omega}{m}$	Valance v	Atomic Number Z	Scratches Length L	Percentage D (%)	dimm
Al	0.41	0.282	3	13	60	82.09	1.68
Zn	0.44	0.590	2	30	50	24.63	2.87
Fe	2.87	1.000	3	26	80	52.77	2.03
Sn		1.090	2.4	50		27.95	
Pb	0.54	2.200	2.4	82	40	71.12	0.44

Table (4.2) relation between defect percentage D and dimension for holes L

Sample	Thickness	Resistivity $P \times 10^{-7} \frac{\Omega}{m}$	Valance v	Atomic Number Z	Scratches Length L	Percentage D (%)	dimm
Al	0.41	0.282	3	13	60	82	1.68
Zn	0.44	0.590	2	30	100	52	2.87
Fe	2.87	1.000	3	26	50	24.6	2.03
Sn		1.090	2.4	50	30	27	
Pb	0.54	2.200	2.4	82	30	71	0.44

Table (4.3) Relation between defect holes and Scratch defect

Metal	Defect holes	Metal	Scratch defect
AL	13	AL	60%
Zn	80%‹100%	Zn	30%
Fe	zero	Fe	50‹80%
Pb	30%	Pb	40%
Sn	30%	Sn	80%‹50%

- **Defect perunitom**

$$\text{For} \quad AL = \frac{30}{1.68} \div \frac{60}{0.41} = \frac{17.85}{146.34} = 0.1219$$

$$Zn = \frac{30}{1.07} \div \frac{80}{2.87} = \frac{28.037}{278.74} = 0.1005$$

$$Fe = \frac{zero}{zero} \div \frac{50}{2.03} = \frac{zero}{24.63} = 0$$

$$Pb = \frac{30}{0.44} \div \frac{40}{0.54} = \frac{68.18}{74.07} = 0.92$$

$$Sn = \frac{100}{1.29} \div \frac{30}{1.07} = \frac{77.51}{28.03} = 27$$

Table (4.4) Relation between atomic number and Par number

Metal	Z atomic number	Par number	$Fx10^{-7}$	%
AL	13	+3	0.282	82
Zn	30	2	0.59	52
Fe	26	0،2،+3	1.00	24.6
Pb	82	2,4	2.2	71
Sn	50	2,4	1.09	27

Table (4.5) Relation between atomic number and R

Metal	Z atomic number	X% percentage	R=(x%+1) *r0
AL_1	0.41 cm	60%	(60+1)*0.41=61*0.41=25.01
AL_2	1.68 cm	30%	(30+1)*1.68=31*1.68=52.08
Fe_1	2.03 cm	50%	(50+1)*2.03=51*2.03=103.53
Fe_2	2.87cm	80%	(80+1)*2.87=81*2.78=232.47
Zn_1	zero	Zero	(zero+1)*zero=zero
Zn_2	1.07cm	30%	(30+1)*1.07=31*1.07=33.17
Pb_1	0.44cm	30%	(30+1)*0.44=31*0.44=13.64
Pb_2	0.54cm	40%	(40+1)*0.54=41*0.54=22.14
Sn_1	1.29cm	100%	(100+1)*1.29=101*1.29=1.419
Sn_2	1.07cm	30%	(30+1)*1.07=31*1.07=33.17

5.3 Conclusion

Nowadays, destructive or non-destructive techniques are more frequently used to test products due to the increase prevalence of quality controls. While destructive techniques verify only some samples that are destroyed and make some invalid in other industrial processes, it was found that non-destructive techniques more interesting than destructive ones since all production can be tested without permanent alterations.

This thesis reviews the state-of-the-art methods of eddy current testing which is one of the most widely used non-destructive forms of testing. Eddy current testing permits crack detection and measurements that are beyond the scope of other techniques such as non-conductive coating thickness, alloy composition and hardness in a large variety of materials. The only need is that the materials being tested must be electrical conductors where eddy currents can flow.

Eddy current sensors are insensitive to dirt, dust, humidity, oil or dielectric material in the measuring gap and have been proven reliable in a wide range.

In conclusion, as researchers and developers of solutions based on eddy current testing, it was found that eddy current techniques can provide the industry with reliable quality control systems. Although there are excellent improvements due to the effort of the many scientists during the last several years, we believe that more research in eddy current techniques, in terms of sensors, equipment and signal processing, will lead to even more applications of these techniques.

From inspection done in the Khartoum International Airport it was concluded that there is defect on the samples that inspected under Defect meter 2.837 as prescribed in the report.

5.4 Recommendation

There are many recommendations such as:

1. Although eddy current testing has been developed for several decades, research into developing new probes, techniques and instrumentation is currently must be conducted by manufacturers and research groups around the world in order to satisfy the increasingly higher quality standards required in almost every industry.

2. it is necessary trying to develop new coil probes and research the use of other magnetometers such as superconducting quantum interference devices (SQUIDs), Hall-effect and magneto resistive sensors that also provide very interesting responses.

3. The review of research into electromagnetic models and powerful simulators that help the probe designer to solve the forward and inverse flaw-probe

problems is essential to optimal crack detection in terms of sensors and the operating variables such as frequency and signal-to-noise ratio.

Non ferromagnetic materials have relative and absolute permeability value of 1. The standard depth penetration of the Eddy Current field lines depends on the material electric conductivity and the selected frequency. Therefore, non-ferromagnetic materials can be well inspected with the modes and channels as described in the Multiple Frequency Eddy Current Technique.

Ferromagnetic materials, on the other hand, have relative and absolute permeability values far larger than 1. Consequently, the Eddy Current field line depth of penetration is very limited. This is sufficient for surface defect detection such as surface braking crack detection in carbon steel materials.

This formula shows that the conventional Eddy Current technique is not capable of inspecting and detecting on either side of the ferromagnetic tube walls. Therefore, other extended Eddy Current techniques like the Magnetic Biased Eddy Current Technique and Remote Field Eddy Current Technique are used to overcome the described limitation.

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