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Failure Map generation by NDT on Metal Sprayed Multi-surfaces

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T H E S I S S H E E T

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Table of Notations

Variable	Units	Definition
$FI(x, y)$	$[-]$	Failure index
$S(x, y)$	$[-]$	Measured signal at position (x, y)
S_{ref}	$[-]$	Reference signal
FI_{crit}	$[-]$	Threshold value
RE	$[-]$	Relative error
$S_{measured}$	$[-]$	Measured signal value at a specific point
D	$[\%]$	Defective area percentage
N_{total}	$[-]$	Total number of valid measurement points
N_{def}	$[-]$	Number of defective points ($FI > FI_{crit}$)
μ_{FI}	$[-]$	Mean failure index
σ_{FI}	$[-]$	Standard deviation
x, y	$[mm]$	Spatial coordinates of measurement points

Table of Formulas

Formula	Description
$FI(x, y) = \frac{ S(x, y) - S_{ref} }{ S_{ref} }$	Failure index
$RE = \frac{ S_{measured} - S_{ref} }{S_{ref}}$	Relative error
$D = \frac{N_{def}}{N_{total}} \times 100\%$	Defective area percentage
$FI_{crit} = \mu_{FI} + 2\sigma_{FI}$	Critical threshold

Table of Abbreviations

Abbreviation	Definition
NDT	Non-destructive testing
ECT	Eddy-current testing
CT	Computed tomography
3D	Three-dimensional
2D	Two-dimensional
CAD	Computer-Aided Design
UT	Ultrasonic testing
PT	Penetrant testing
AE	Acoustic emission
PVD	Physical vapour deposition
CVD	Chemical vapour deposition
HVOF	High-velocity oxygen fuel
HVAF	High velocity air fuel
TBC	Thermal barrier coating
AI	Artificial intelligence
Mpa	Megapascal
Ksi	Kilopound per square inch

1 Introduction

“Perfection is not attainable, but if we chase perfection we can catch excellence”

— Vince Lombardi

This inspiring statement of Vince Lombardi reflects modern reality perfectly. Nowadays, every large company or organisation strives for perfection and is ready to make many sacrifices to achieve it. Modern competition is strong, the labour market is full, and the pace of development is rapid. Everyone pursues perfection because even small mistakes may lead to serious consequences and allow opponents to get ahead. In such conditions, it is simply necessary to have advanced technologies and methods that correspond to the given circumstances in which the organisation is located. In other words, everything aims towards a balance between quality and price, and in all aspects, it is obligatory to have maximum efficiency. Similarly, the maintenance engineering sphere is also no exception in this case.

1.1 Role of coating and NDT technologies in modern engineering

In pursuit of maximum efficiency, old-fashioned maintenance methods such as reactive maintenance and the “repair after failure” mindset are becoming a thing of the past, fading into the background. They are being replaced by methods of predictive and preventive maintenance strategies. Those strategies ensure early identification of potential breakdowns, their timely correction and also reduce to a minimum the risk of an unexpected failure. They also extend the lifespan of details and provide the continuous and safe operation of critical systems.

1.1.1 Coating technologies

More than 80% of structural and mechanical components in engineering are made from metals that are subject to corrosion. This makes the protection of them one of the most fundamental and crucial challenges that modern engineers must face and solve. Coating technologies are among the strongest, most efficient, and most powerful techniques of preventive maintenance. Those technologies,

particularly metallic coatings, play an essential role in mitigating wear, corrosion, fatigue, and extreme thermal conditions. These coatings not only increase the durability of machine parts but also reduce the frequency and cost of maintenance interventions.

1.1.2 NDT technologies

Another problem that comes from the above-mentioned is the need to maintain those coatings. If we have a coated part, then there is certainly a risk of other problems. Such as porosity, delamination or peeling, cracking, non-uniform layer thickness, oxide inclusion or contamination, build-up of residual stress, brittleness, etc. In such cases, non-destructive testing technologies come to our aid. With the help of non-destructive testing technology, it is possible to detect, prevent, and resolve many of the above-mentioned problems. If we are dealing with cracks (on the surface/subsurface), layer separation, non-uniform layer thickness, and even residual stresses, then Eddy-Current testing technology suits us optimally. It is a simple, cheap method that does not require advanced operator skills and can be used to quickly detect and resolve those defects. However, this method is not suitable for all problems. Problems such as porosity, internal oxidation, low adhesion strength, brittleness, etc., are hardly detectable or even impossible to detect. That is why, in some cases, it is more relevant to use other methods such as ultrasonic testing, acoustic emission testing, computed tomography, X-ray radiography, thermography and similar techniques. In certain situations, when dealing with a complex problem, it is even possible to use several methods simultaneously. The combined-techniques method allows us to discover and detect possible failures more comprehensively, from different angles. For example, at large enterprises, for a more complete technical inspection, the following combinations are most often used:

Table 1.1 – Some use cases of the NDT

Cracks	Eddy Current, Ultrasonic, X-ray CT
Porosity	X-ray CT, sometimes Thermography
Delamination	Ultrasonic, Thermography, X-ray CT
Non-uniform layer thickness	Eddy Current, Ultrasonic
Oxide/inclusion	X-ray CT
Residual stress	X-ray diffraction , sometimes AE
Poor edge coverage	X-ray CT, Visual Inspection

1.2 Aims of the work

The only way to write a truly good and high-quality work is to know and deeply understand your goal. There is a lot of research showing that information is better absorbed when presented in the form of a diagram, map, or table rather than in written form. According to Waller, R. [1], people understand and follow written instructions 323% worse than the information represented in visual form. According to another study, Bruner, J. S. states that approximately 65% of humanity learns better from pictures and absorbs visual information more effectively than written information [2]. Summarising all that has been said above, the goal of this research is, first of all, to develop a clearly understandable, accurate and appropriate method for investigating metal-sprayed multi-surfaces. Another goal is to bridge the gap between raw NDT signal acquisition and practical application of ECT by creating 3D failure maps. Provide a diagnostic tool that can help engineers locate and assess coating defects (like cracks, delamination, porosity) without damaging the component. Furthermore, the effectiveness and limitations of the ECT method for the specific use case will be evaluated, and a scalable framework that could eventually serve as a guide or be extended to industrial applications will be proposed. Also, the estimation of the future possibilities of application of ECT to metal-sprayed multi-surfaces here will be performed.

2 Literature review

2.1 Thermal spray technology

2.1.1 History and background of thermal spray technology

Surface engineering in the last 20 years has gone through three key stages of development. The first is related to the application of thermal spraying. The second includes PVD and CVD technologies, including laser treatment, ion implantation, and a number of other surface treatment methods, which, in turn, are divided into different types of coatings. The third stage is marked by the active introduction of nanotechnologies and the use of nanomaterials [3]. The various engineering approaches to surface modification are shown in Figure 2.1

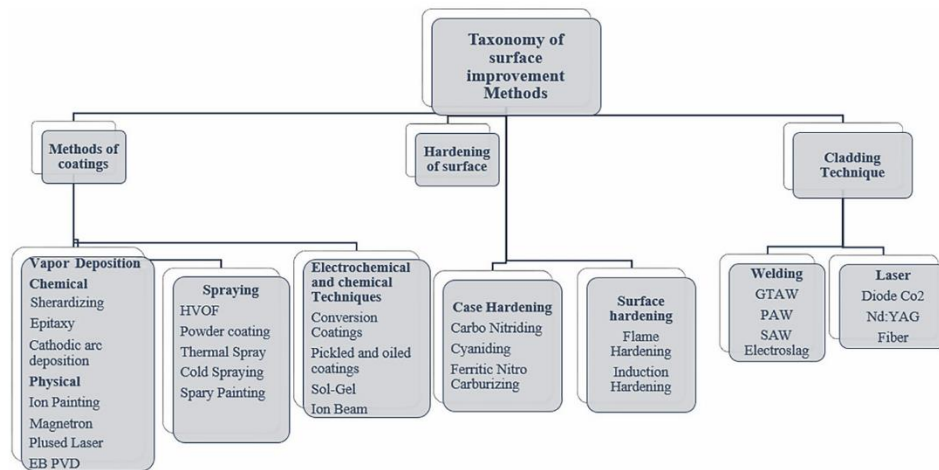


Figure 2.1 – Various engineering approaches to surface modification [3]

Thermal spraying technology has its origins in the early 20th century, when in 1910, a Swiss engineer, Dr. Max Ulrich Schoop, first used something similar to a modern thermal spraying[4]. In many of his review articles, he anticipated significant future development of this technology. He predicted the importance of the droplet velocity and temperature on the coating. Descriptions of such methods as the atomization of liquid metals by high-pressure air, the twin-wire arc spray process and the use of powders heated by a flame can be found in his early patents as well. Before the 1950s, the only representative of thermal spray technology was flame spraying technology. Later in the 1950s, the Thermal Dynamics Corporation, using developments of Metco and Plasmadyne, created the first plasma spray torch [4]. These torches laid a strong foundation for many models that are still in use today.

The evolution and improvement of the performance of thermal spray technologies can be seen on Figure 2.2

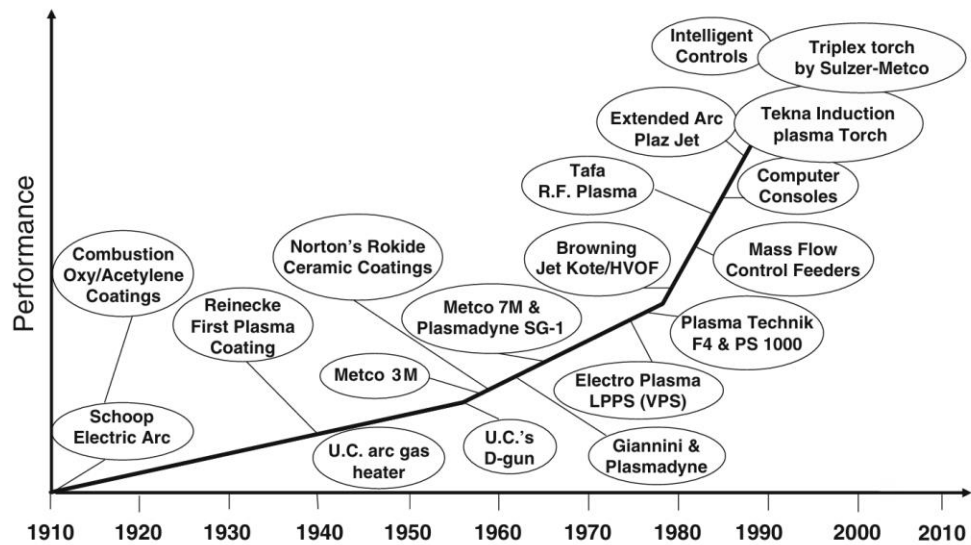


Figure 2.2 – Evolution of the Thermal spray technology [4][page 36]

In the 1960s, the development of thermal spray technology accelerated rapidly. The reason for this was the need for new materials for the space industry. Developments in the 1970s saw the introduction of HVOF, induction and low-pressure plasma spraying technologies, as well as significant process improvements. As coatings found even wider application in various industries, the need for process reliability increased. This stimulated active growth of research and development work. In response to the increasing complexity of tasks, robotic systems have been developed that are capable of applying coatings to complex-shaped products. Thermal spraying has gradually evolved into a truly interdisciplinary field, including research in areas such as plasma flow diagnostics, fluid dynamics modelling, heat transfer studies, transient and unstable phenomenon analysis, as well as particle in-flight diagnostics and coating formation mechanisms [4]. Development of the thermal spray technology through the years up to 2019 is shown in Figure 2.3

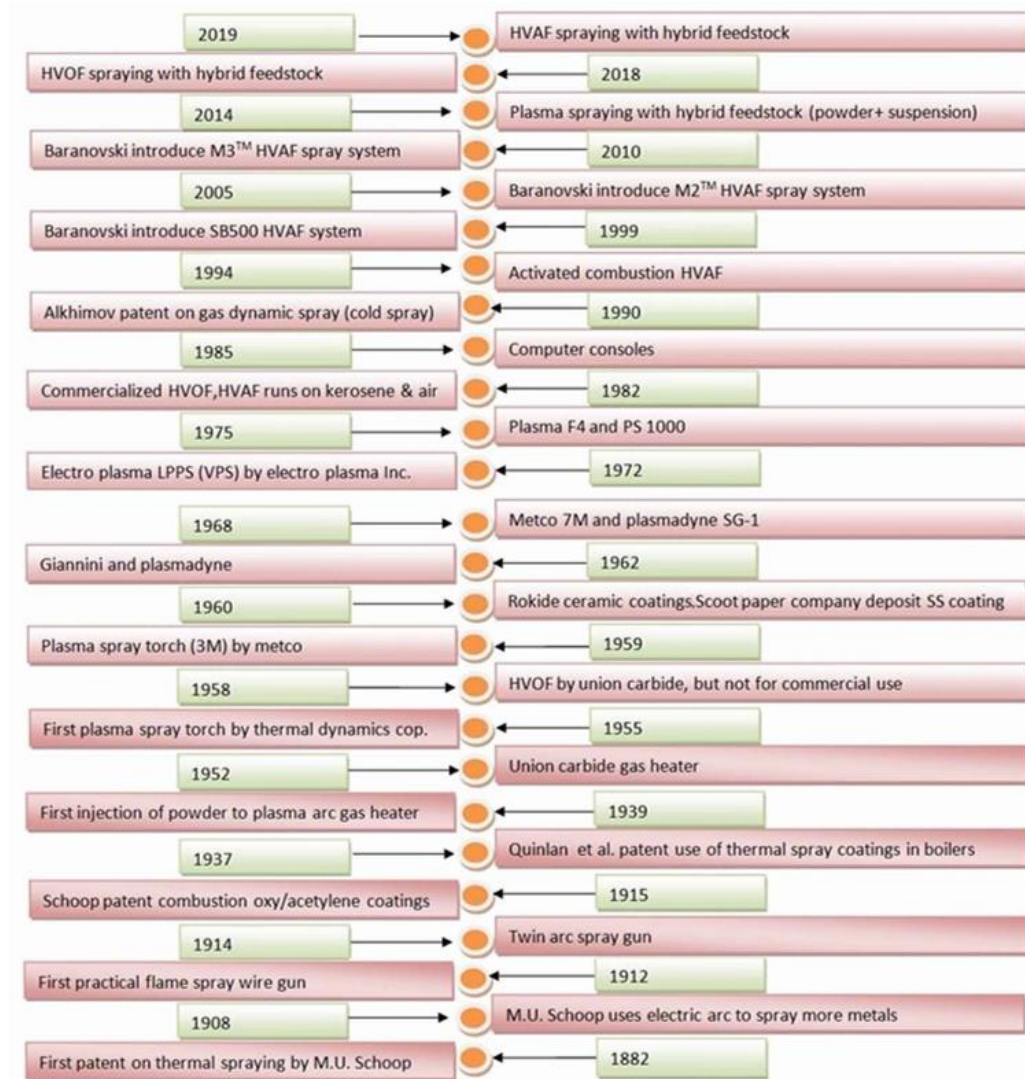


Figure 2.3 – Process of the Thermal spray development [5]

2.1.2 Definition of thermal spray

Flame spraying requires the melting of the sprayed material. The flame spray technology utilises the combustion of a gas mixture, usually a mix of oxygen or air with acetylene, to melt the feedstock material. Feedstock material particles are accelerated by the gas and melted during the flight through the flame. At high speeds in the fully or partially melted condition, particles collide with the substrate. Because of the collision, they are flattened and form a shape called „splat”. Upon impact, they mechanically adhere to the substrate, forming a coating [4]. The schematic view of this technology can be seen on Figure 2.4.

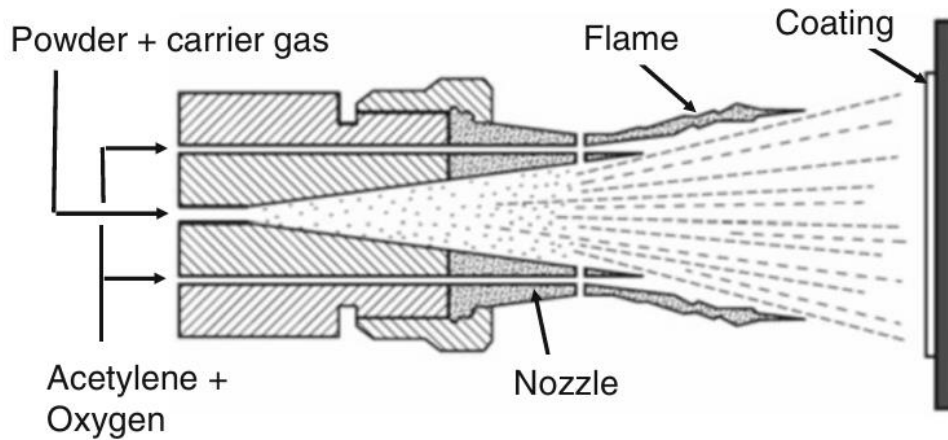


Figure 2.4 – Thermal spray technology scheme [4]

If we look at it in a more detailed view, bonding occurs through the mechanical interlocking of melted particles that solidify and interact with the substrate surface [5]. Feedstock material can vary depending on the method used. It can be powders, rods or wires. They come axially through the nozzle and pass through the flame emerging from it. Choosing the feedstock material depends on the material characteristics required. Some types of them offer different melting capabilities and thus varying coating performance [4].

Through the use of thermal spray coatings with a thickness from 20 μm to several millimetres can be achieved. In comparison, the achievable coating thickness in PVD, CVD, and electroplating is much lower. Thermal spray coatings are corrosion and wear-resistant and suitable for various applications. Those coatings have a lamellar structure with defects in the form of pores. They occur due to failures in splat stacking or when the particle is not fully melted. A more detailed look at the structure of the formed coating is presented on Figure 2.5. This process is considered one of the cheapest and simplest techniques nowadays [5].

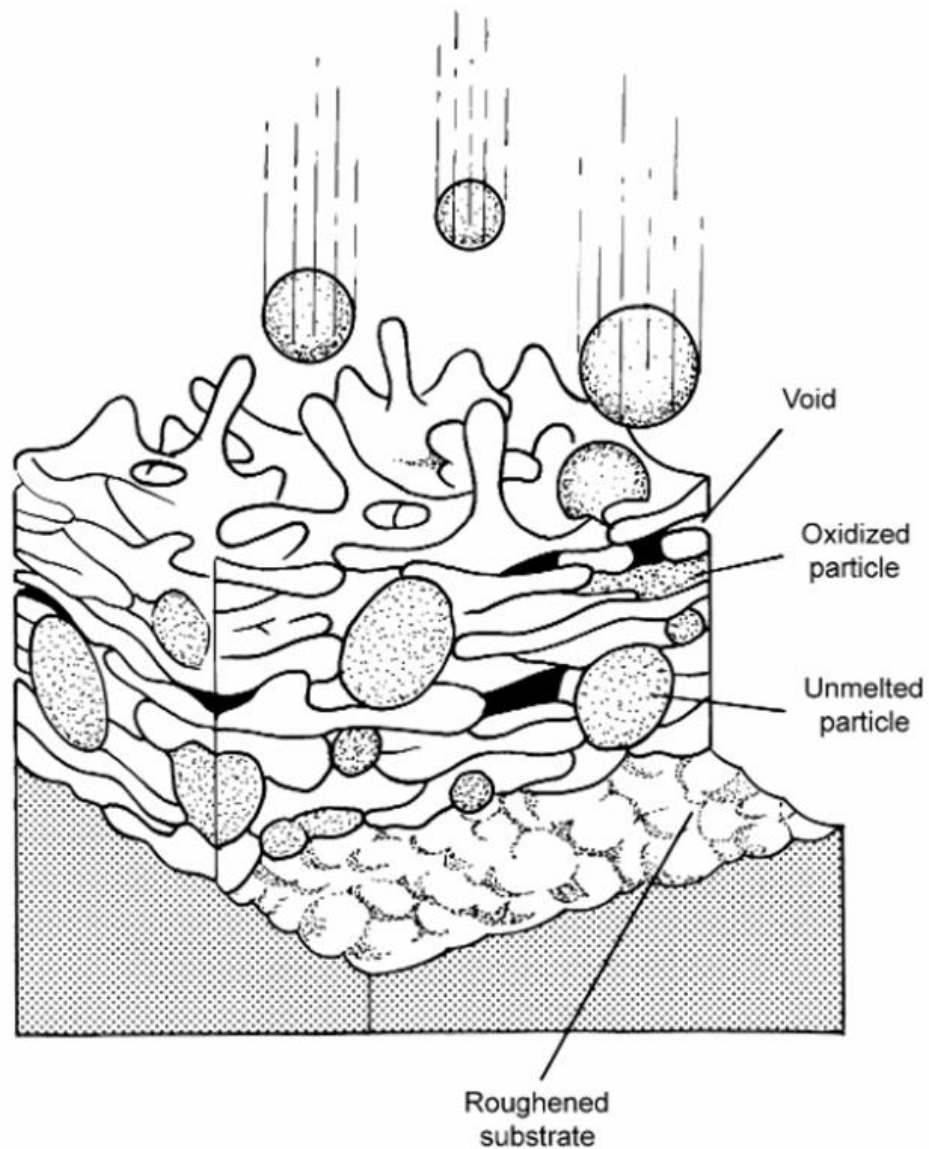


Figure 2.5 – Structure of the formed coating [6]

Classification of thermal spray processes can be very broad and varies depending on different factors, such as the types of technology to be classified and the parameters considered. But thermal spraying methods are usually classified by spray velocity and temperature. For example: HVOF (high-velocity oxygen fuel), HVOF (high-velocity oxygen fuel), cold spraying, hot spraying, flame spraying, plasma spraying, etc [5]. This classification can be seen on Figure 2.6

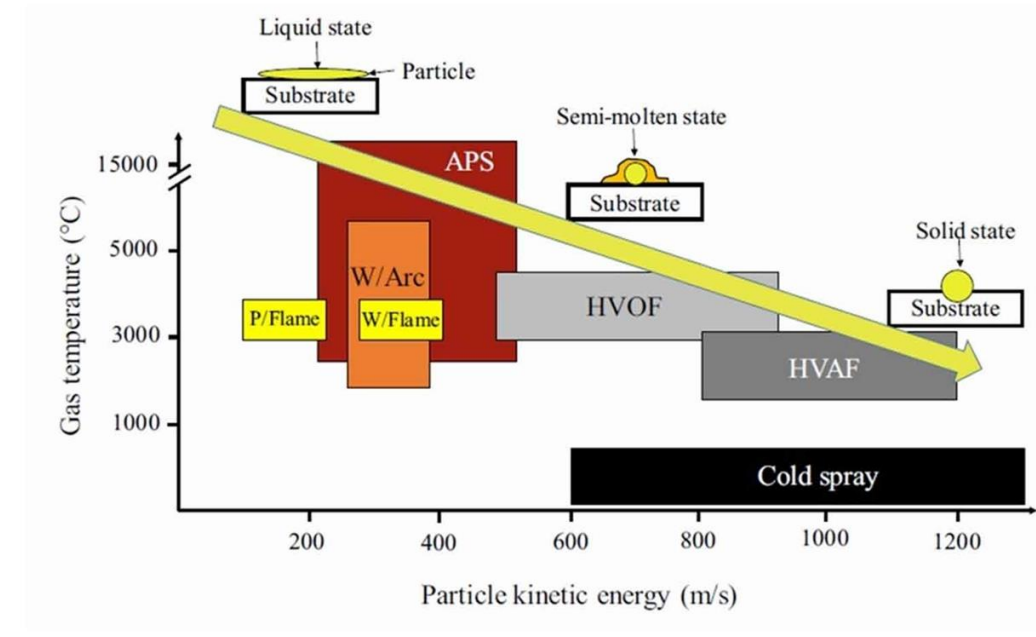


Figure 2.6 – Classification of thermal spray processes [5]

Like any engineering solution, thermal spray technologies have strengths and limitations that should be carefully considered before implementation:

- Thermal spraying allows many different materials to be used for coating, including metals, ceramics, alloys, plastics, carbides and their combinations. Competing methods do not offer this flexibility.
- It is a very efficient and cheap method. The coating can be applied quickly (up to 45 kg/h), which makes the process cost-effective. Most operations usually use 2-7 kg/h.
- This method is versatile and coatings can range from ultra-thin films (below 0.01 μm) to very thick layers (up to 6.5 mm). Thermal spraying is particularly suitable for thick coatings.
- Because this method is considered relatively low-temperature, it does not significantly damage the surface of the substrate.
- This method is relatively cheap compared to other methods. Also, it does not require very large or massive equipment. Most of the thermal sprays are portable.
- The thermal spraying method is very versatile. Its application field is very broad. Some of them are: wear and friction resistance, corrosion protection, repairing of mechanical components etc [6].

Thermal spraying has a lot of advantages, nevertheless, it has its own drawbacks as well.

- Thermal spray technology provides us with relatively weak bonding compared to other types of metal coating, such as plating or welding. The

sprayed feedstock material does not stick to the surface as strongly as in other methods. Thus, it could be less durable under certain loads. For example, the measured tensile adhesion, using the ASTM Standard C 633, is between 41 and 83 MPa (six and two ksi). Whereas plating and vapour deposition methods can provide us with adhesion of 103 MPa (15 ksi). In the case of welding technology, even higher values can be obtained.

- Coatings produced by thermal spray always have small defects in the form of pores. In most cases, such defects weaken the bond, make it less durable, and reduce its lifespan. However, in certain circumstances, pores can be useful. For example, when our goal is to achieve thermal barrier coating (TBC). But in most cases, porosity has to be reduced to minimal values. It can be obtained through the use of the Vacuum Plasma Spraying or HVOF techniques.
- Another drawback is that this method is good for simple, straight linear surfaces, but is hardly applicable to complex shapes like tubes and turbines. It requires a very high level of operator education or robots or other machines must be used, which can increase the cost of manufacturing.
- Thermal-sprayed coatings also possess anisotropic properties. They can perform up to ten times stronger in the direction along the spray than in the direction parallel to the spray. To solve this, the heat treatment must be applied afterwards [6].

2.2 NDT and Eddy-current testing methods

2.2.1 History and background of NDT and ECT

In 1820, Danish physicist Hans Christian Ørsted made an exceptional breakthrough in physics. He discovered and demonstrated, by an experiment, that a needle placed next to a wire with an electric current will move and change its direction. This incredible discovery not only linked electricity and magnetism together but also laid a foundation for future EC non-destructive testing. Eddy current testing, as we know it, is the result of the intense work done in the 19th century.

In 1824, Arago observed that a magnetic needle's oscillations were quickly dampened when placed near a conductor, though the cause remained unclear at the time. It was unclear until 1831 when, independently of each other, English scientist Michael Faraday and American physicist Joseph Henry found the phenomenon of electromagnetic induction. Both of them used a similar instrument: a toroid with two coils, a primary and a secondary, mounted on it. That was an early version of a modern transformer. The phenomenon of eddy currents was later demonstrated by J. B. Foucault in 1830, and in recognition of his work, these currents are still referred to as “Foucault currents” in France and Canada.

The history of modern eddy-current testing starts in the early 1950s, when Dr. Federico Förster introduced his discoveries in this field. He performed experiments using liquid mercury and insulating tabs that allowed the detection of defects. Over the next 20 years, Dr Federico Förster and his colleagues developed a relevant method that combined accurate theoretical and practical work. They also designed proper equipment, making ECT a very useful instrument for engineers. Hence, he can be rightfully called the „Father” of modern ECT [7].

Many types of defects can occur in manufactured components. All of them are capable of significantly influencing the component performance. Some defects can occur immediately during production, while others can occur due to wear and use. In any case, it is crucial to detect and repair them in time, before they can cause a catastrophic failure. The most popular and effective non-destructive methods nowadays are: (a) magnetic particle inspection, (b) electrical (eddy current) testing, (c) liquid penetrant inspection, (d) radiography, (e) ultrasonic testing [8].

More detailed descriptions and the applicability of those methods can be seen on Figure 2.7

<i>System</i>	<i>Features</i>	<i>Applicability</i>
Visual inspection probes	Detection of defects which break the surface, surface corrosion, etc	Interior of ducts, pipes and assemblies
Liquid penetrant	Detection of defects which break the surface	Can be used for any metal, many plastics, glass and glazed ceramics
Magnetic particle	Detection of defects which break the surface and sub-surface defects close to the surface	Can only be used for ferro-magnetic materials (most steels and irons)
Electrical methods (Eddy currents)	Detection of surface defects and some sub-surface defects. Can also be used to measure the thickness of non-conductive coatings, e.g. paint on a metal	Can be used for any metal
Ultrasonic testing	Detection of internal defects but can also detect surface flaws	Can be used for most materials
Radiography	Detection of internal defects, surface defects and to check correctness of assemblies	Can be used for most materials but there are limitations on the maximum material thickness

Figure 2.7 – Applicability of NDT [8]

2.2.2 Definition of ECT

The working principle of the ECT testing is that the small coil with the alternating current in the head of the instrument is brought close to the detail under examination. Magnetic field induces eddy currents in the workpiece. In turn, induced eddy currents produce another magnetic field around the component under examination. A schematic representation of this method is shown on the Figure 2.8. Two magnetic fields interact with each other, causing changes in the impedance value of the coil. Further, two options are considered. See figure 2.9. If the material has no defects, then the value of the impedance of the inspecting coil must be the same at all points, besides the edges of the inspected component. If the inspected detail has a defect in its structure, then the induced eddy currents will not be distributed uniformly. Thus, the produced magnetic field will be reduced, and so it will have an influence on the impedance of the inspecting coil. The impedance of the coil is assessed based on the value of the voltage across the coil [8].

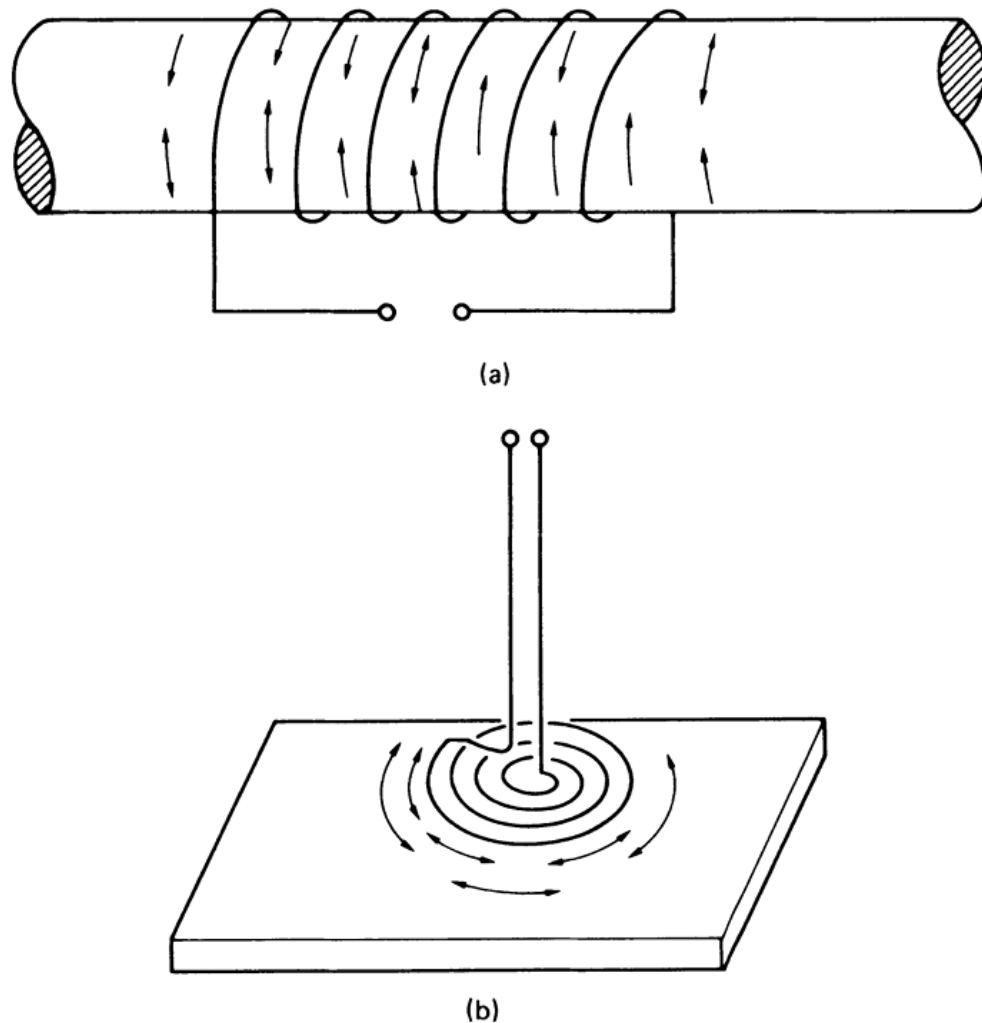


Figure 2.8 – Working principle of the ECT [8].

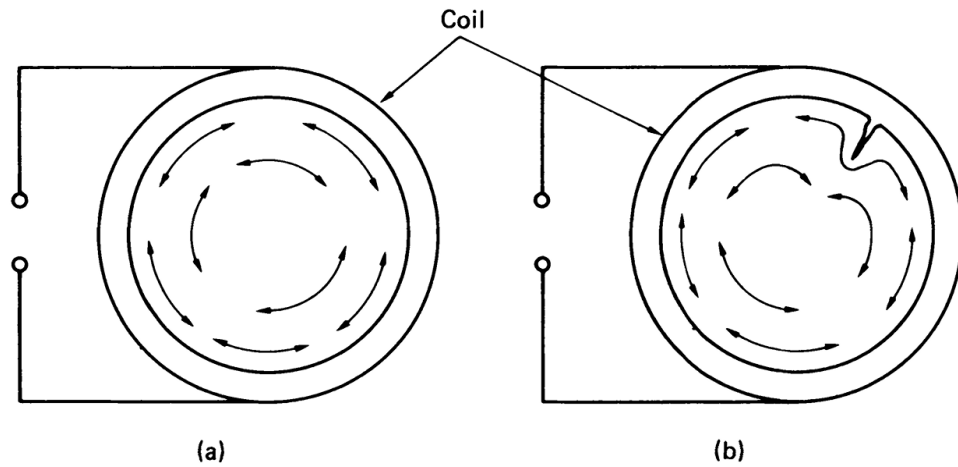


Figure 2.9 – (a) Induced eddy-current distributed uniformly across the specimen, (b) Induced eddy-current distributed uneven due to the defect [8].

During the EC inspection, the so-called skin effect must be considered. The distribution of the eddy currents is not uniform in the examined part. Their density becomes less as the depth increases. Hence, the highest density is close to the surface, and at deep layers of the component, it becomes so small that it can be neglected [8]. The schematic representation of this phenomenon can be seen on Figure 2.10.

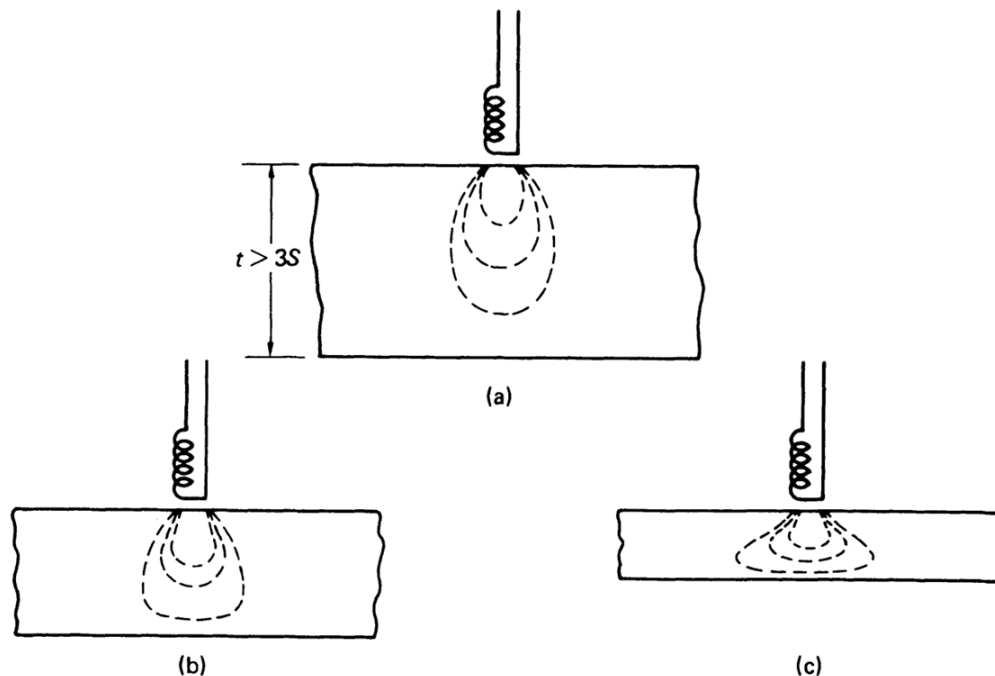


Figure 2.10 – Skin effect [8].

Like all other methods of defect inspection ECT has its own advantages as well as the shortcomings. They are represented on the Figure 2.11

Advantages	Disadvantages
Inspects conductors No safety concerns Rapid Inspection Sensitive to a large number of parameters related to conductivity, magnetic permeability, and geometry (e.g., flaws, thickness, coatings, hardness, proximity, and edges) Wide operating temperature range. Specialized off-the-shelf probes for high temperature applications Small probe size Light weight and portable Relatively low cost Can be configured in arrays Mature technology	Only inspects conductors Surface or near surface detection only (specialized forked probes for thin sheet and RFEC probes for tubing are through thickness devices. The latter is capable of inspecting carbon steel tubing thickness up to 6–10 mm thick). Sensitivity to a wide range of parameters increases complexity of interpretation Sensitive to liftoff variations Only sensitive to cracks perpendicular to the interrogating surface

Figure 2.11 – Advantages and Disadvantages of the ECT [7].

2.3 Failure maps in maintenance engineering

2.3.1 Concept of failure mapping

Different methods of component examination and failure detection, like ECT, Ultrasonic testing and radiography, are very important, but they would have no value if we were not capable of reading and processing the collected information. That is why we need failure maps. They allow engineers and maintenance professionals to spatially visualise and localise defects in the components under examination. Failure mapping enhances the interpretation of NDT results by creating a comprehensive representation of flaw distribution across the tested detail. It provides crucial information like understanding of the location, extent, and severity of damage, enabling more informed decision-making for maintenance and repair. Failure maps are especially needed when we deal with components subjected to high stress, corrosion, or wear. For example, in the aerospace industry, heavy industry. Compared to other methods of NDT, ECT is considered a very relevant method for generating such maps, particularly for conductive materials and surface or near-surface defects. Traditionally, ECT provided signal graphs or impedance plane graphs that required expert interpretation. With the help of developments in computing and signal processing, these data can now be converted into 2D or even

3D failure maps. Failure maps received from ECT are typically generated by scanning the surface of the material using a probe or a series of probes. Each measurement point records parameters like amplitude and phase of the eddy-current signal, which are then spatially compiled into a visual map.

2.3.2 Techniques and tools for failure mapping

Creation of failure maps based on the data received from NDT examination mapping relies heavily on scanning systems and data visualization software. Accuracy of failure maps depends on scanning resolution, probe sensitivity, and material properties. Key technologies include:

- **Array Probes:** Multiple coils allow simultaneous data collection over a big area, crucial for high-resolution maps.
- **Automated Scanning Systems:** Motorized stages gives us precise, repeatable probe movement.
- **Signal Processing Algorithms:** These convert impedance data into visual graphs. Can use interpolation or even machine learning
- **Visualization Tools:** MATLAB, Python, and proprietary software from device manufacturers (e.g., Zetec, Olympus) are used to generate 2D maps[9].

3 Introduction of the production technology and the possible failure modes

3.1 Introduction

In this chapter, the production technology of the mechanical components with hot metal powder spraying will be introduced, and this chapter contains an analysis and review of some of the possible failure modes as well. And also, some background and history of the manufacturing of the workpieces that will be used in the further chapters of the research are described here. A clear understanding of the manufacturing method will help us to develop a reliable, effective method for ECT examinations and will help us to estimate potential failures. It will also enhance our understanding of the failure maps.

3.2 Production technology

To better understand the performance and behaviour of the coated samples studied in this research, it is essential to examine the production technology used during their production. Here, the thermal spraying process and key parameters that influence coating quality and integrity will be defined.

Key steps in the process:

1. **Surface preparation:** Grit blasting or cleaning to increase surface roughness and adhesion. Removal of oxides, grease, and contaminants.
2. **Powder selection:** Choice of metal or alloy powder depending on desired properties (e.g., corrosion resistance, wear resistance).
3. **Heating and spraying:** Use of a spray gun (combustion flame or plasma arc) to heat and accelerate particles. Powders are melted or semi-melted before they reach the substrate.
4. **Layer formation:** Impacted particles flatten and cool rapidly, forming lamellae that build up into a cohesive coating.

Before analysing the behaviour of the coatings, it is important to discuss the production method by which the samples that will be investigated in this research were manufactured.

For the manufacturing of those components, the base material C60 hot-rolled steel was used.[10] The coating was made with hot metal powder spraying technology. A total of four samples were manufactured. In order to simplify the

referencing and notation, four samples were sequentially named with the letters „A”, „B”, „C” and „D”. They were treated by the hot metal powder spraying technology. Also, four different types of metal powders were sprayed on these metal components.

The chosen powders for:

„A” – Deloro 60 alloy powder

„B” – N40 Mogul alloy powder

„C” – N50 Mogul alloy powder

„D” – N60 Mogul alloy powder [10]

General view on the examined samples is presented on the Figure 3.1.



Figure 3.1 – General view on the specimens

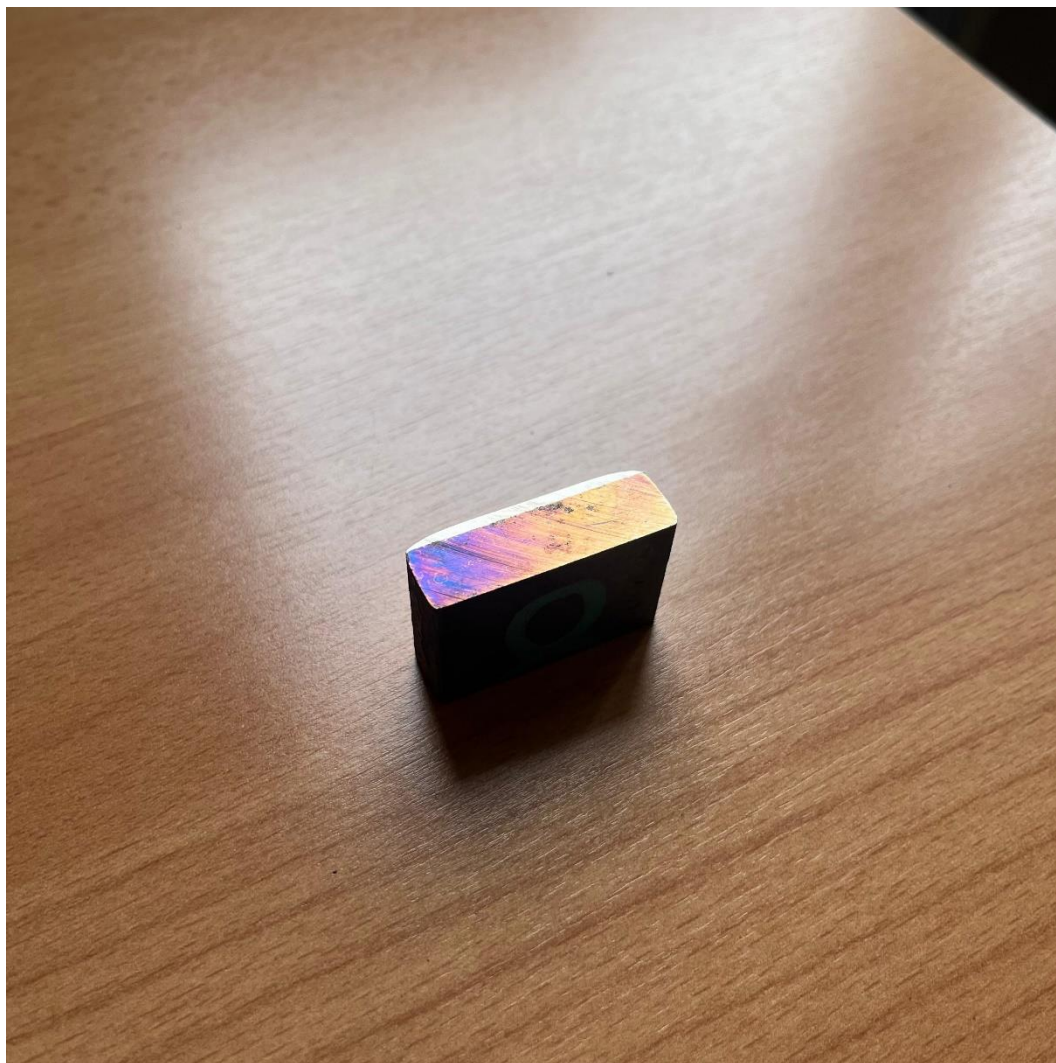


Figure 3.2 – View on the dividing line between layers of base material and coating

Distinct view on the line of connection between base material and coating is presented on the figure 3.2

Process of the application of the hot metal powder spraying can be seen on the Figure 3.3

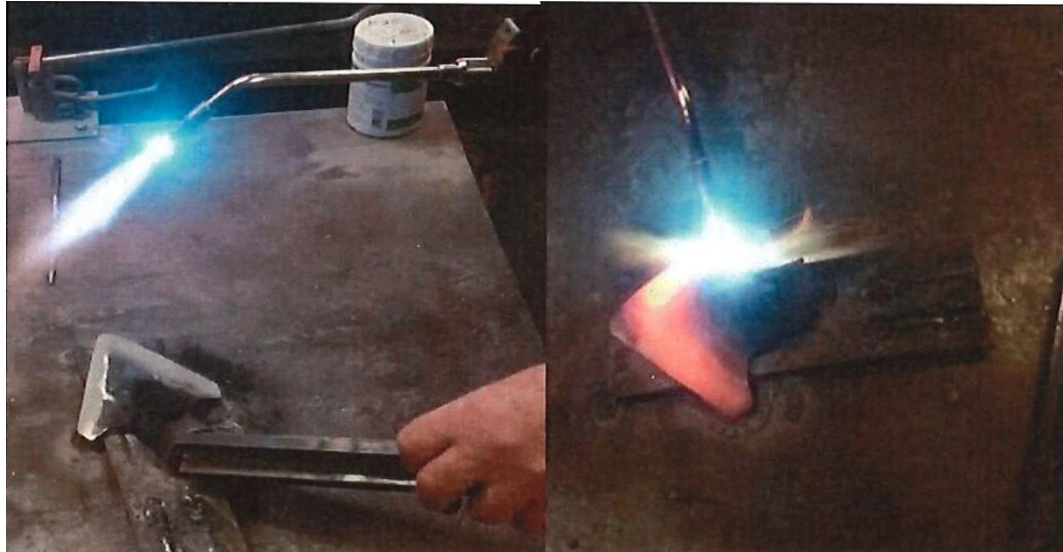


Figure 3.3 – Hot metal powder spraying utilization [10]

3.3 Typical failure modes

Despite all of their benefits metal-sprayed coatings are subjected to specific failure modes depending on operational, manufacturing and other factors.

Delamination

- **Cause:** Poor adhesion due to improper surface preparation or thermal mismatch.
- **Effect:** Layers of coating detach from the base material.

Cracking

- **Cause:** Thermal stress, impact, or shrinkage.
- **Types:** Microcracks (interlamellar), Macrocracks (through-coating)
- **Detection:** Often challenging; non-destructive testing methods like ECT are ideal.

Porosity and voids

- **Cause:** Inadequate melting, incomplete flattening of particles, or improper spray distance.
- **Effect:** Reduction in mechanical strength and corrosion resistance.

- **Critical porosity threshold:** Depends on application, but >5% is generally considered problematic.

Oxidation

- **Cause:** Reaction with oxygen during spraying.
- **Effect:** Formation of brittle oxides and reduced coating ductility.
- **Control:** Inert atmospheres or faster cooling processes.

Erosion and wear

- **Cause:** Abrasive particles or high-velocity gas/liquid flow.
- **Effect:** Gradual loss of coating material.
- **Factors:** Hardness, roughness, operating pressure.

Corrosion under the coating

- **Cause:** Porosity or cracks allowing ingress of corrosive agents.
- **Effect:** Localized pitting or crevice corrosion.
- **Control:** Use of sealants or post-treatment coatings.

Improper thickness distribution

- **Cause:** Inconsistent spraying angle or distance.
- **Effect:** Weak zones or excess material leading to imbalance or structural inefficiency.

Substrate deformation

- **Cause:** Excessive heat input or differential expansion.
- **Effect:** Warping or dimensional distortion of the component.

3.4 Influence of defects on process parameters

- **Spray Distance:** Too close may cause overheating; too far results in unmelted particles.
- **Powder Feed Rate:** Low rate may lead to thin coatings; high rate can cause overspray and waste.
- **Spray Angle:** Non-perpendicular spraying leads to shadowing and uneven coating.
- **Cooling Rate:** Influence residual stress and detail microstructure.

3.5 Environmental and service conditions

Even if applied properly, coatings may degrade due to operational conditions:

- **High Temperature Exposure:** May soften or oxidize coatings.
- **Thermal Cycling:** Induces expansion/contraction fatigue.
- **Mechanical Impact:** Brittle coatings tend to chipping.
- **Humidity and Chemicals:** Accelerate corrosion in porous coatings.

4 Description of the applied NDT Eddy-current method and the technique of reconstruction

4.1 Eddy-current testing on thermal sprayed multi-surfaces

The proper choice of an adequate NDT technique for the assessment of thermal-sprayed metallic coatings is a vital and inevitable stage in the process of detailed inspection. Hot metal powder spraying results in the formation of a conducting surface layer possessing a rather complicated microstructure. However, during the spraying process, various types of defects may emerge, including lamellar splats, oxide inclusions, pores and microcracks. These defects have a considerable effect on the functional properties and integrity of the detail. Thus, it becomes crucial to select an NDT technique which will be effective in detecting them. Sometimes, certain defects may be detected better by some NDT techniques than others. In our case, the chosen control procedure should satisfy the following conditions: it should be highly sensitive to the presence of near-surface discontinuities, differences in coating thickness, and changes in electrical properties.

Since the chosen material was the thermal spray coating and had good electrical conductivity, eddy current testing was chosen for the present analysis because of its ability to control electrically conductive specimens. Moreover, eddy currents are highly sensitive to the presence of any near-surface discontinuities, and they provide an opportunity to obtain various additional options at a relatively low cost, such as 3D images, information about defect depth, and customization of the tool according to certain detail requirements.

4.2 Experimental setup and measurement system

The study of the test object was performed via eddy current testing employing a defectoscope Foerster M 1.837, along with a computerized data acquisition module. The test object was measured in order to guarantee a stable excitation signal generation, correct data collection, and a straightforward approach to 3D mapping of the test object.

4.2.1 Eddy-current instrumentation

The main component of the measuring unit is the defectometer produced by the Institut Dr. Foerster GmbH & Co. KG firm and called the Defectometer M 1.837.

The instrument is intended for highly sensitive testing of electrically conductive materials.

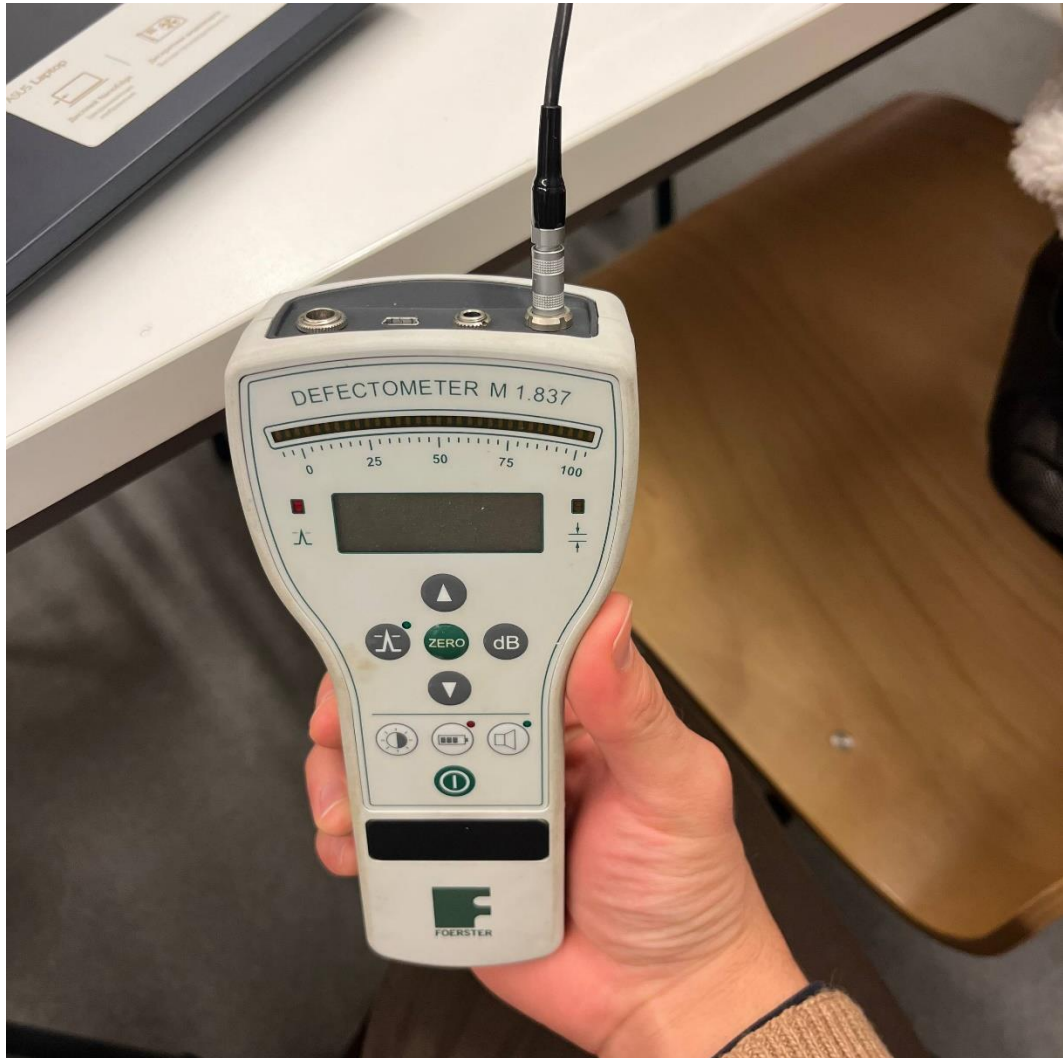


Figure 4.1 – Institut Dr. Foerster GmbH & Co. KG Defectometer M 1.837

4.2.2 Data acquisition and processing interface

The output signals from the Foerster M 1.837 instrument were transmitted to a laptop computer for data recording and further processing. The laptop served as the central unit for:

- Signal visualization
- Digital data storage
- Post-processing and reconstruction
- Creation of 3D maps

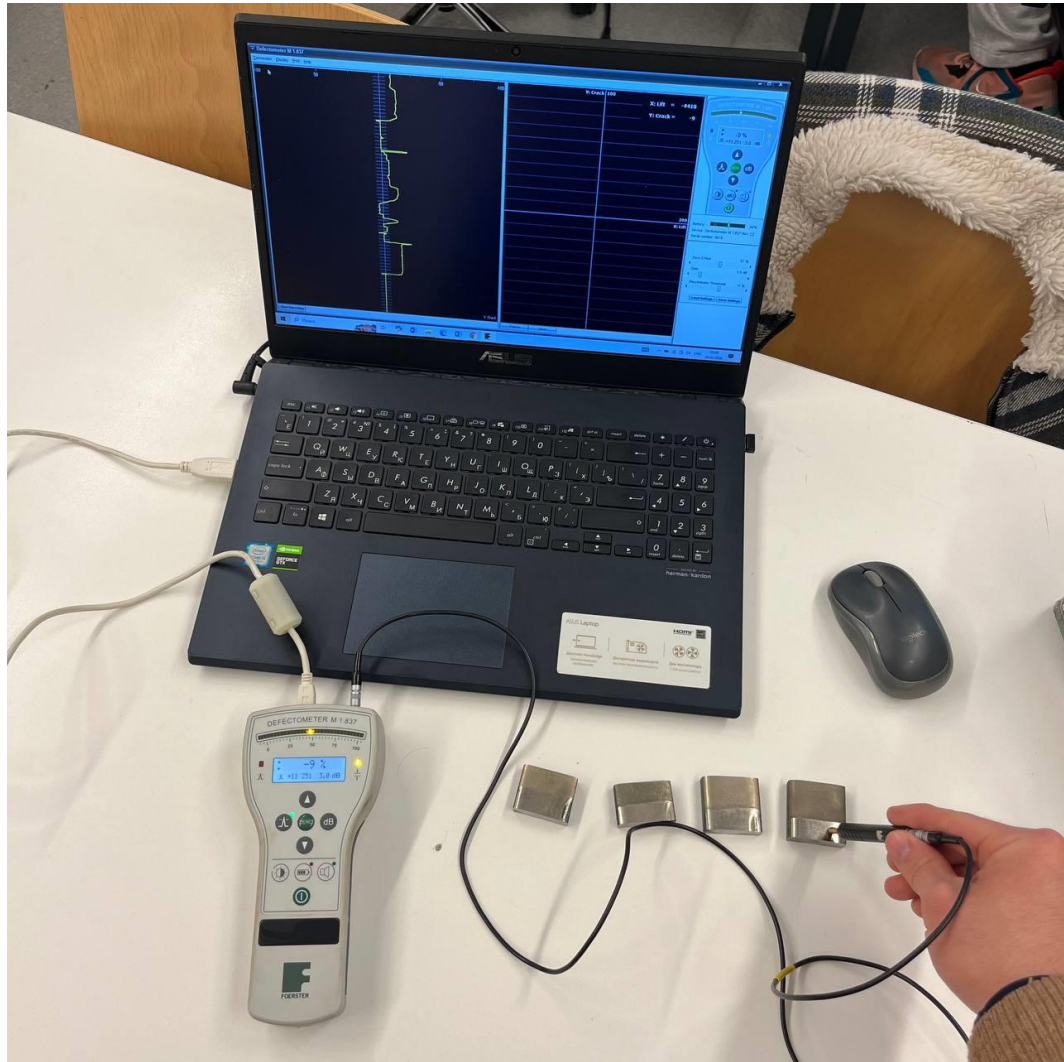


Figure 4.2 – Laptop ASUS X571 - GT

The use of a computer-based acquisition system allowed systematic recording of measurement points during inspection. Each measurement position was associated with coordinates assigned on the each specimen, allowing reconstruction of a 3D failure map.

4.3 Investigation procedure and technological considerations

Before starting the process of examining metal-coated specimens, we must first consider and identify certain important details, such as the choice of pattern, the positioning of the part during the examination, the choice of sensitivity and penetration depth.

4.3.1 Measuring device adjustment and choice of the pattern

In the first stage of the experimental process, the calibration and tuning of the eddy current meter to the properties of the test samples took place. The sensitivity of the equipment was enhanced using initial calibration tests.

As part of this process, the sensor was moved across the surface of the test sample while registering its reaction. Defects were revealed based on peak readings obtained in the output signal. The parameters of gain and threshold were tuned so as not to exceed saturation, and at the same time, not be too low to recognize defects.

The following values of the parameters yielded accurate results (see Figure 4.3):

- Gain: 3.0
- Discriminator threshold: 11
- Zero offset: 51
- High-pass filter: 0

These values were selected based on iterative testing and provided a suitable compromise between sensitivity and noise suppression.

This file was created with Foerster Defectometer 1.837				
Date of Recording = 26.02.2026				
Time of Recording = 18:10:12				
Gain = 3.0				
Diskriminator Threshold = 11				
Zero Offset = 51				
High Pass Filter = 0				

Figure 4.3 – Initial parameters of the device

One of the most critical factors affecting measurement reliability was the selection of the scanning pattern. Initially, multiple scanning strategies were evaluated.

A serpentine (zig-zag) scanning pattern was first applied. However, this approach resulted in several issues:

- Non-linear data structure complicating post-processing
- Increased probability of positioning errors due to manual probe movement
- Difficulty in correlating spatial coordinates with measured data
- Increased sensitivity to operator-induced inconsistencies

Due to these limitations, the serpentine pattern was replaced by a **linear parallel scanning strategy**, where the probe was moved consistently in one direction along parallel lines. This approach provided:

- Structured and easily interpretable data
- Improved repeatability
- Simplified reconstruction of spatial maps

Each specimen was scanned in six to nine parallel lines, ensuring sufficient spatial resolution.



Figure 4.4 – Linear parallel movement pattern

4.3.2 Certain technical solutions explanation and error analysis

During the testing for defects in metal-sprayed samples, various mistakes occurred, and many alterations were implemented in the experiment itself. An overview of these errors will aid in a deeper understanding of the decisions taken and clarify the process of the experiment.

The first mistake made was choosing an unsuitable method for inspecting our metal-coated parts for defects. Instead of using the linear pattern mentioned above, we used a serpentine (zig-zag) pattern. (See Figure 4.5)



Figure 4.5 – Serpentine movement pattern

During the inspection of parts, this type of pattern, due to the tool head moving alternately in one direction and then in the other, results not in a linear function, but

in a reverse, constantly changing function. A serpentine (zig-zag) pattern approach resulted in several issues:

- A large volume of data that is difficult to work with and makes it hard to trace errors. In other words, if a mistake is made during the inspection of a part, the entire procedure must be started from the beginning
- Increased sensitivity to inconsistencies because of the operator
- Due to the non-linear nature of the function, data recording also takes place in a non-linear manner, which significantly complicates the process of creating 3D defect maps
- Difficulty in correlating spatial coordinates with measured data

Due to these limitations, the serpentine pattern was replaced by a **linear parallel scanning strategy**, where the probe was moved consistently in one direction along parallel lines.

The orientation of the test specimen during the measurement process proved to have a big influence on the accuracy of the measurements. The first set of measurements was taken when the test specimen was placed vertically. Nevertheless, because of surface inhomogeneity, i.e., areas which could be smooth or rough (see Figure 4.6), the probe would often pass through zones with various lift-offs, creating instabilities in measurements. This problem was resolved by rotating the specimens horizontally so that:

- The probe remained in contact with a consistent surface type
- Lift-off variations were minimized
- Calibration conditions remained valid throughout the scan

That is precisely why it was decided to change the position of the component during the inspection and to choose a different pattern that would simplify our tasks. It was decided to inspect the parts from a different angle, positioning them horizontally so that, during inspections, the measuring probe would always be in contact only with the surface for which it had originally been calibrated. That final specimen position and final movement pattern can be seen on Figure 4.4



Figure 4.6 – Smooth and rough areas of the specimen

4.4 Conclusion

The final measurement methodology was formed based on repeated tests and measurement error analysis. The optimal combination of instrument settings, the implementation of a linear scanning procedure, and accurate specimen placement significantly increases the level of stability and accuracy of the process. In this chapter, the application of the eddy-current non-destructive testing approach to multi-surface metallic specimens that have undergone thermal spraying is discussed. The suitability of the method for detecting surface and near-surface discontinuities was demonstrated, taking into consideration the specific characteristics of thermally sprayed coatings, such as structural inhomogeneity, surface roughness, and variable thickness.

Using the eddy-current instrument by the manufacturer Foerster and a computer data acquisition system, the measurement process was implemented in a stable and repeatable manner. The selection of measurement parameters included probe setting, scanning procedure, and instrument settings aimed at obtaining maximum sensitivity to surface discontinuities without decreasing the accuracy of the measurements. The use of a linear parallel scanning pattern was selected as the most reliable option. It allows receiving structured data that could be used for further analysis and processing. The necessity of an appropriate probe position and correct lift-off was emphasized since they significantly affect the results of the testing. The procedure of data acquisition and post-processing is aimed at the conversion of raw information received from an eddy current into a structured set of measurements. This included removal of erroneous measurements, the structuring of the remaining measurements according to spatial coordinates, and preparing the data for further visualization. As a result of the interpolation of discrete points of measurements, the reconstruction of spatial maps showing variation in signals is achieved. Besides, the important sources of errors are identified, namely, variations in the probe lift-off, specimen surface roughness, manual scanning, and instrument background noise. All of them were considered while forming the error function and defining a failure index.

In general, the created methodology proves the effectiveness and feasibility of using eddy-current testing technology for studying thermally sprayed metal specimens. Based on a proper measurement procedure and data acquisition process, a reliable determination of the area with defects and their subsequent spatial distribution is possible. Thus, the creation of failure maps can be done. It is discussed in detail in the next chapter.

5 3D failure map of the object creation and results analysis (accuracy, error function)

5.1 Data collection and 3D failure maps generation

Once this method has been successfully adapted to the conditions of our experiment, all potential errors have been eliminated, and the entire data collection system has been carefully calibrated, we can proceed with the actual inspection of the hot metal powder - sprayed metal samples.

After the design and tuning of the measuring method presented in the previous chapter, the eddy-current measurements were performed for all metallic specimens. The acquired information formed a well-structured database, including values of signals in relation to their spatial coordinates. In the case of scanning, the scanning path consisted of a straight-line motion of the probe. To start with, a specific specimen was divided into some scanning lines along which the probe was moved with an equal step.

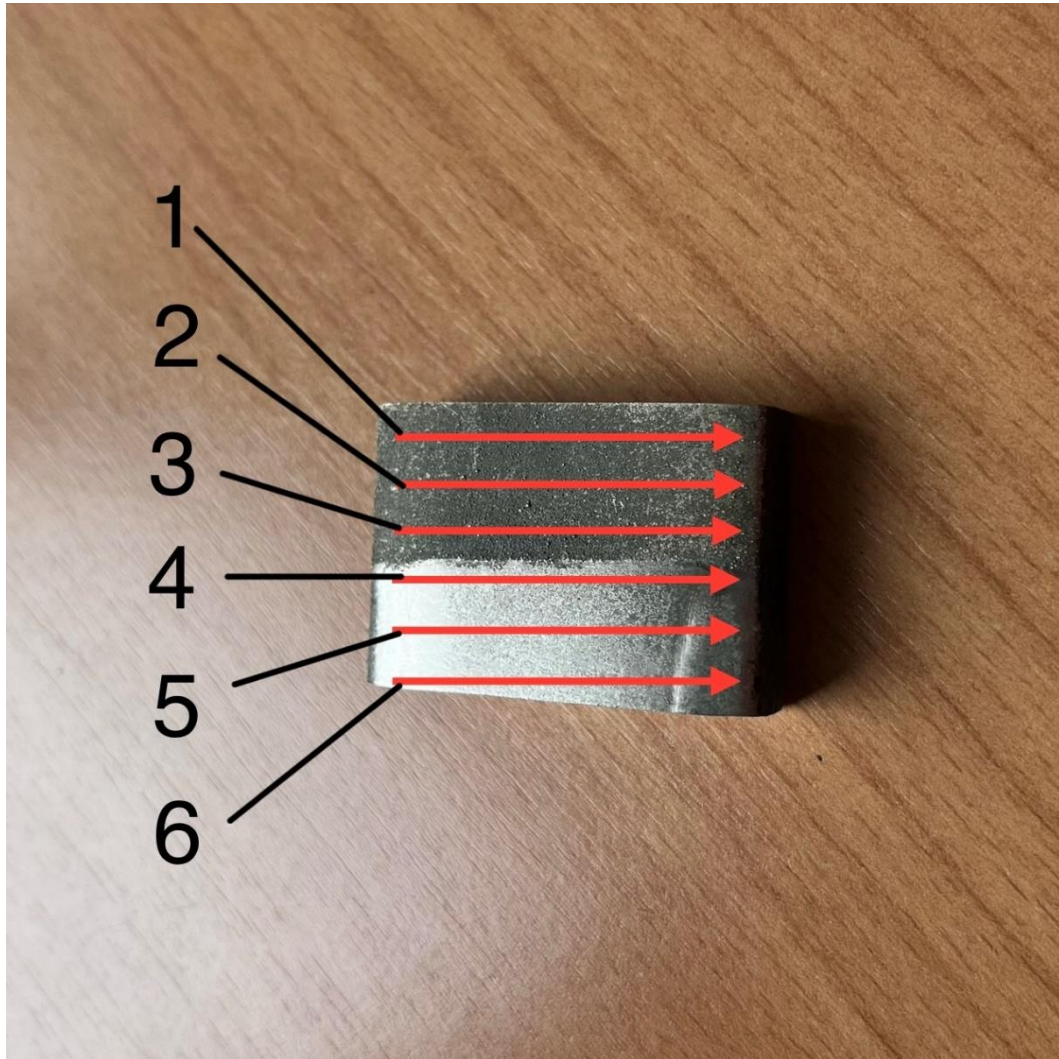


Figure 5.1 – Lines representing the path of the probe

During the data collection, fluctuations in signal amplitude served as the primary basis for detecting material anomalies like material discontinuities and structural inhomogeneities. With the aid of the software that comes with the device, Excel files were created. Within this context, each Excel file represents one particular line across which the head of the measuring device travels. For example, specimen #8 was analyzed; six lines were marked on this sample to indicate the path taken by the measuring head.

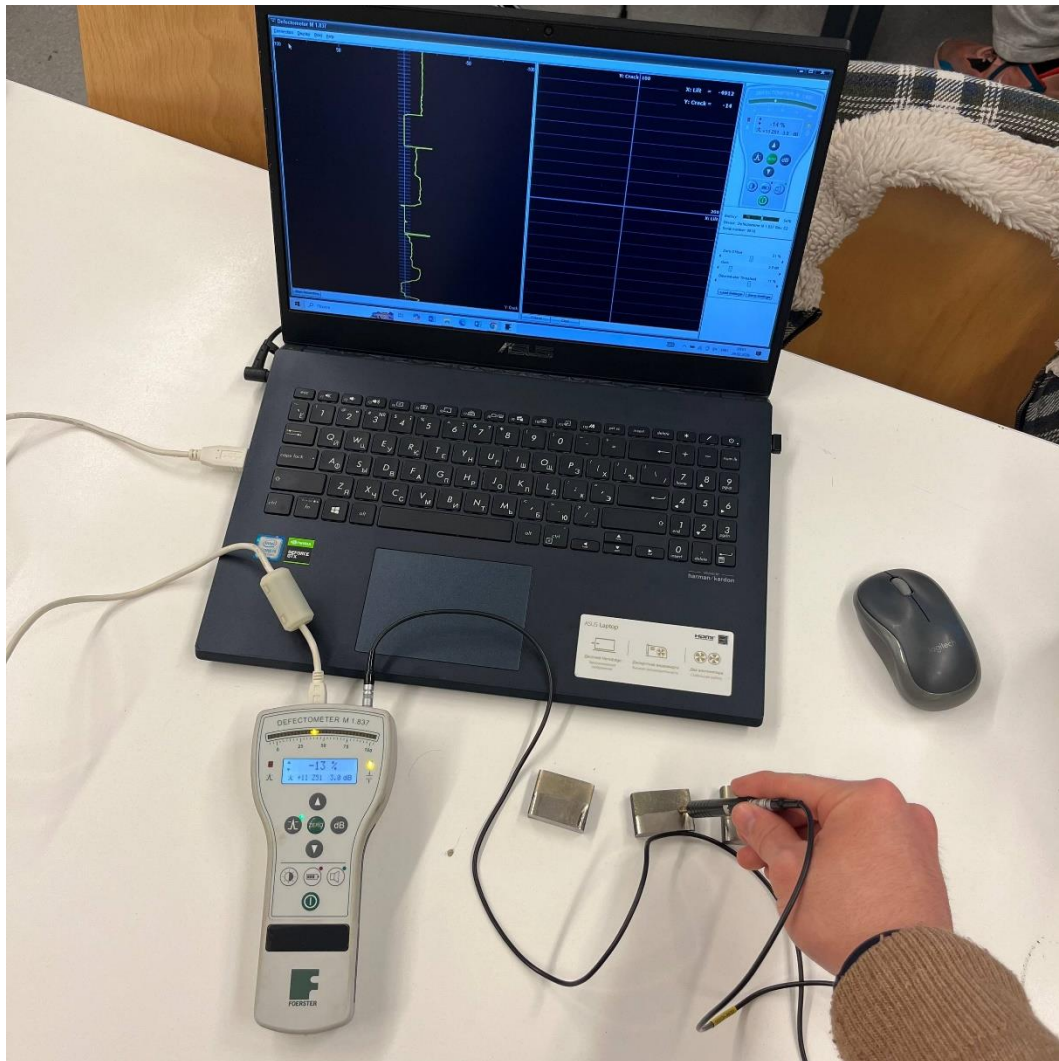


Figure 5.2 – Process of the inspection

The data were recorded using the built-in software of the measuring instrument and exported into Microsoft Excel format for further processing. For each scanning line, a separate dataset was generated.

	A	B	C	D	E	F	G
1	This file was created with Foerster Defectometer 1.837						
2	Date of Recording = 26.02.2026						
3	Time of Recording = 18:10:12						
4	Gain = 3.0						
5	Diskriminator Threshold = 11						
6	Zero Offset = 51						
7	High Pass Filter = 0						
8	Comment:						
9	S8 Crack depth #1						
10	Data:						
11	Time (ms)	X: Lift	Y: Crack				
12	0	-7962	0				
13	15	-7963	0				
14	31	-7963	0				
15	46	-7963	0				
16	62	-7963	0				
17	78	-7963	0				
18	93	-7963	0				
19	109	-7963	0				
20	125	-7963	0				
21	140	-7962	0				
22	156	-7963	0				
23	171	-7963	0				
24	187	-7963	0				
25	203	-7962	0				
26	218	-7962	0				
27	234	-7962	0				
28	250	-7962	0				
29	265	-7962	0				
30	281	-7962	0				
31	296	-7962	0				

Figure 5.3 – Excel file with the collected data on defects of the specimen

To obtain a complete representation of the specimen surface, the individual datasets were combined into a single dataset. For this purpose, the relevant measurement parameter (denoted as the “Crack” signal, corresponding to the Y-coordinate values) was extracted from each dataset and merged together.

	A	B	C	D	E	F	G
1							
191	18	21	6	18	3	1	
192	10	21	16	18	4	1	
193	10	21	26	16	4	1	
194	10	21	49	11	5	1	
195	10	21	69	9	4	1	
196	9	21	57	10	3	1	
197	10	21	58	8	4	1	
198	10	21	58	7	3	1	
199	9	20	59	6	4	1	
202	1	10	59	5	4	1	
204	-1	2	59	5	3	1	
205	-2	6	59	5	4	1	
212	-4	-3	57	6	3	-1	
230	-1	-16	1	4	1	-3	
232	-2	-18	2	4	2	-2	
246	1	-17	2	2	2	-1	
251	-4	-13	3	4	2	-2	
252	-1	-14	3	4	2	-1	
260	-4	-18	2	2	-2	-2	
263	-3	-18	1	2	-1	-2	
288	-1	-10	-1	1	-3	-4	
292	-1	-11	-2	2	-3	-3	
294	-4	-9	-4	1	-2	-2	
295	-4	-9	-4	1	-3	-3	
296	-2	-9	-4	1	-2	-3	
297	-11	-9	-4	1	-2	-2	
298	-6	-15	-4	1	-2	-2	
299	-2	-5	-3	1	-2	-2	
300	-2	-3	-3	1	-1	-1	
301	4	-7	-5	2	-1	-2	
437	-1	-21	-12	-6	1	-1	
447	-5	-27	-11	-6	1	-1	

Figure 5.4 – All the collected data merged in one excel file

In data processing, any data that would be considered invalid or non-representative was detected and removed. Measurement points having zero value were removed, either due to the lack of detectable defects or if there was no proper contact between the probe and the surface. This provided a filtered set of data that could then be used

for further analysis. The testing of the metal spray coating workpieces resulted in the creation of four Excel files regarding the defects found in the parts.

5.2 Results interpretation

Lastly, the processed dataset was used to create a spatial 3D map of defects with the help of the visual representation provided by Microsoft Excel. In that way, areas with increased variation of signal readings have been identified, which could be considered possible locations for defects within the analyzed samples.

For creating a spatial visualization, the processed data were transferred to a coordinate grid. To estimate the values between the measured points, an interpolation technique was used. On the basis of the processed dataset, a three-dimensional visualization of defects was created in Microsoft Excel, where signal intensity is presented along the vertical axis, whereas the horizontal axes show the spatial coordinates of the sample surface.

The created maps of defects demonstrate that the distribution of signal readings among the samples under investigation is uneven. High values of signals correspond to the presence of defects in the form of cracks, pores, or varying coating thicknesses.

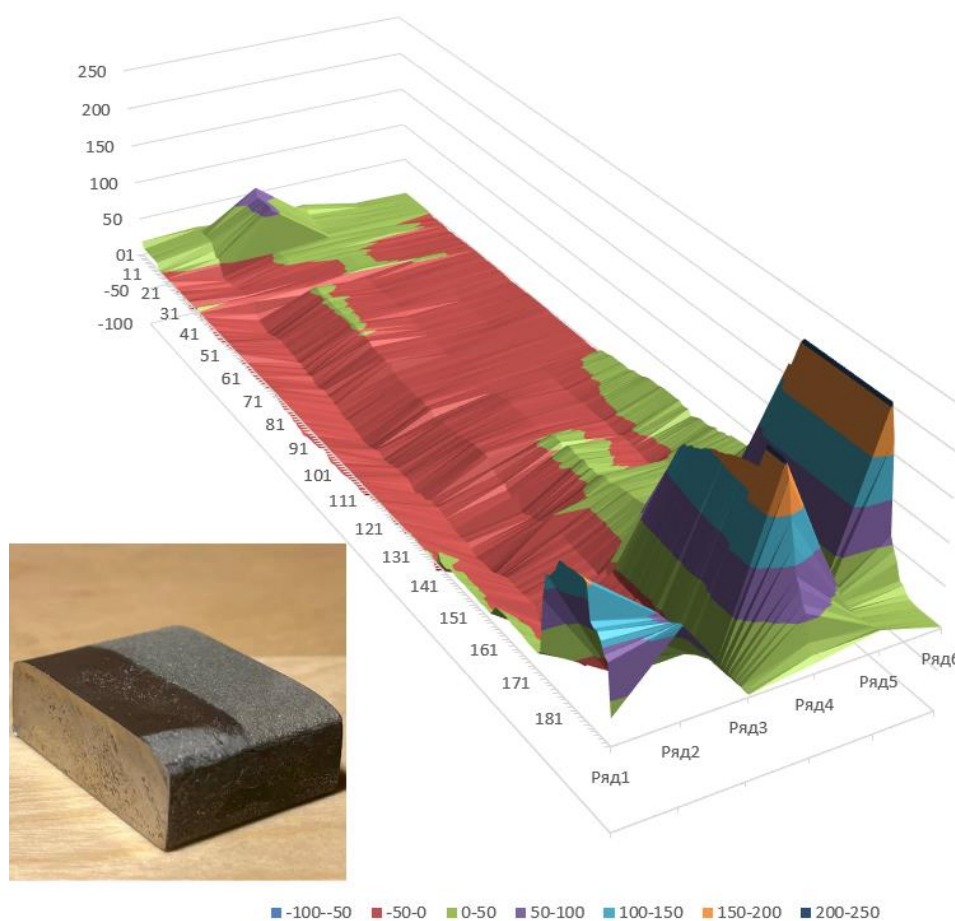


Figure 5.5 – 3D failure map of the specimen #8

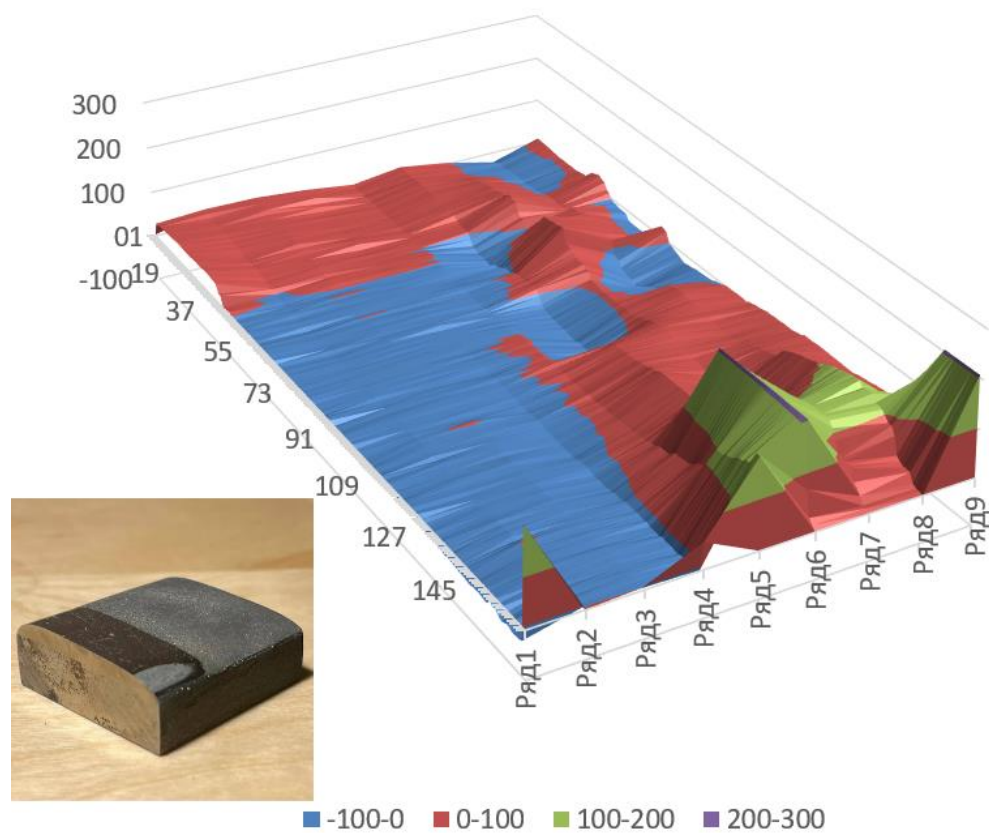


Figure 5.6 – 3D failure map of the specimen #7

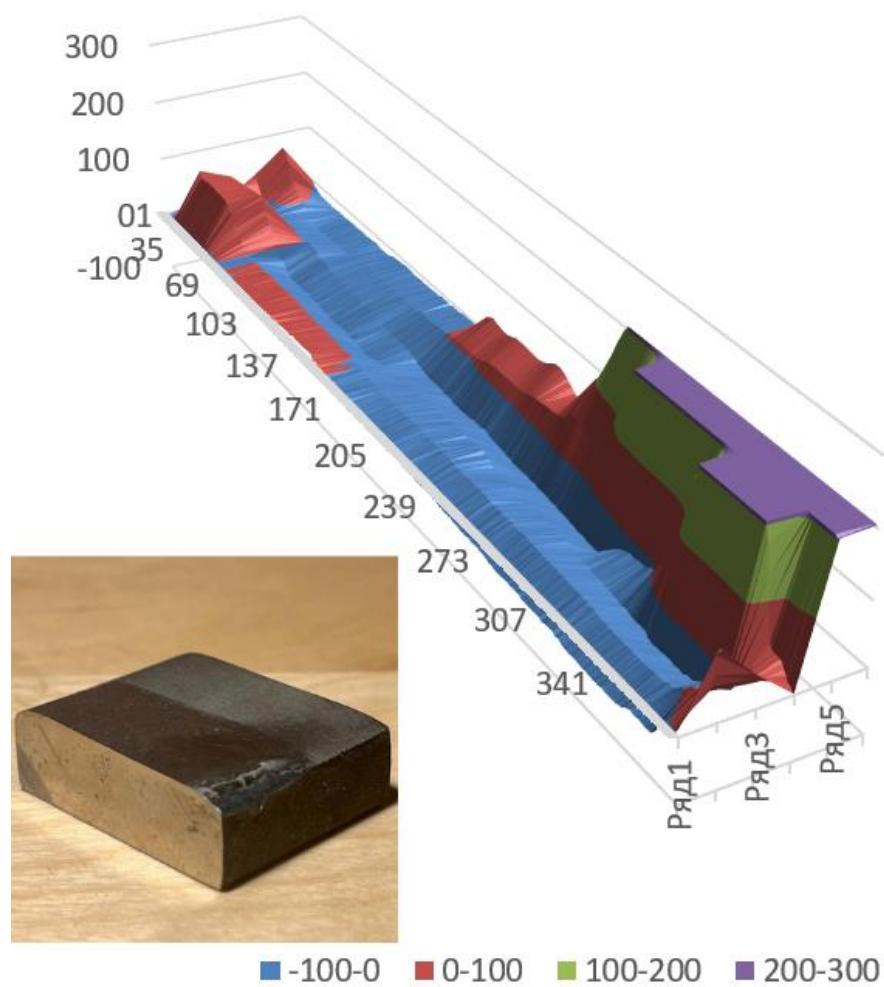


Figure 5.7 – 3D failure map of the specimen #9

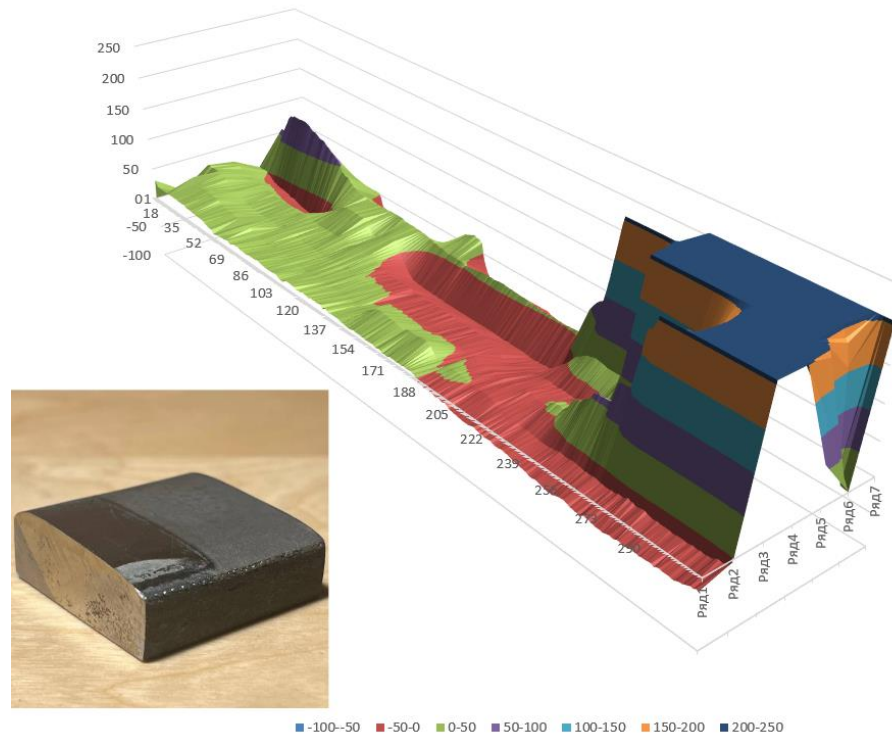


Figure 5.8 – 3D failure map of the specimen #10

On observation, there is a high probability that the defect-prone areas are often located near the edges of the samples or in the zones where a decrease in the stability of the process was observed. These results correlate with the well-known features of the thermal spray process, where the changes in particle velocity, temperature, and deposition angle may result in the development of the inhomogeneous structure of the coating. In addition to that, according to the obtained signal intensity maps, one can observe non-uniformity of the coating structure. There exist areas with rather stable and homogeneous signal values, whereas other spots show significant fluctuations, which may correspond to localized defects or irregularities. It should also be mentioned that the results achieved demonstrate that the applied methodology is very sensitive to the surface conditions. Variations in the surface structure or even in the position of the probe during its movement might significantly affect the measurements performed.

Finally, although the obtained results might vary, all observations are consistent in terms of the overall tendencies, which provide information about the structural condition of the examined surfaces. Thus, the developed maps enable to detect critical zones requiring additional investigations.

5.3 Accuracy and error function

5.3.1 Theoretical fundamentals

There are many factors that can influence the accuracy of the generated defect maps, both measurement-related and experimental. For evaluating the results obtained, the error analysis was carried out. In particular, the failure index $FI(x, y)$ was defined, which determines the relative difference between the acquired signal and its reference level:

$$FI(x, y) = \frac{|S(x, y) - S_{ref}|}{|S_{ref}|} \quad (1)$$

where $S(x, y)$ is the measured signal at position (x, y) , and S_{ref} is the reference signal obtained from a defect-free region of the specimen.

Based on this definition, regions with higher values of FI correspond to greater deviations from the reference condition and are therefore associated with a higher probability of defects. A threshold value FI_{crit} was defined to distinguish between acceptable and defective regions.

Several sources of measurement inaccuracy were identified:

- **Lift-off variations:** Changes in the distance between the probe and the surface significantly affect the signal amplitude.
- **Surface roughness:** Irregular surface topography introduces additional signal fluctuations.
- **Probe positioning:** Manual scanning may lead to inconsistencies in measurement spacing and orientation.
- **Material inhomogeneity:** Variations in conductivity and microstructure affect the eddy-current response.

The overall measurement accuracy can be estimated by considering the combined effect of these factors. Although an exact numerical value depends on experimental conditions, the relative error can be expressed as:

$$RE = \frac{|S_{measured} - S_{ref}|}{S_{ref}} \quad (2)$$

In practice, the reliability of measurements and map generation leads to a reliable analysis of the defect distribution. The applied methodology ensures sufficient precision in detecting potential zones of defects and spatial failure mapping. To

evaluate the defect distribution in the samples under study, a specific classification procedure was applied according to the calculated failure index. After calculating the failure index $FI(x,y)$ at each measurement point, a threshold-based classification algorithm was utilized using a threshold level FI_{crit} , which was established in the previous section.

Measurement points satisfying the condition:

$$FI(x,y) > FI_{crit} \quad (3)$$

were classified as defective, while points below this threshold were considered acceptable.

The classification process was carried out using Microsoft Excel. After calculating the failure index at each data point, conditional filters were used to count data points that exceeded the specified threshold. Specifically, in-built formula tools in spreadsheets were used to carry out automatic assessment of the data, thereby minimizing any chances of error that may occur through manual counting. N_{def} , which is the number of defective data points, was calculated using conditional formula counting, while N_{total} was calculated after removing invalid or zero - value data.

The percentage of defective area was then calculated as:

$$D = \frac{N_{def}}{N_{total}} \times 100\% \quad (4)$$

This approach enables an objective and reproducible evaluation of defect distribution across the specimen surface.

5.3.2 Calculation process

After optimizing the measurement procedure discussed in chapter #4, four thermally sprayed samples underwent eddy current testing. This was done by scanning the samples using a linear parallel scanning pattern to achieve systematic probe movement during data acquisition.

5.3.2.1 Specimen #8

The accuracy of the eddy-current measurements for Specimen #8 was evaluated using statistical analysis of the acquired signal data and the defined failure index.

Parameters:

- Area = 34.2 mm × 24 mm = 820.8 mm²

- Grid size = 1 mm × 2 mm
- Number of scan lines = 6
- Number of points per line = 34

Additional parameters:

- Total raw points: 4968
- Valid (non-zero) points: 2713
- Removed (zeros / no contact): ~45% of data

In order to assess deviations in the measured signal, a reference value S_{ref} was determined from stable regions of the specimen surface:

$$S_{ref} = -0.31$$

Based on this reference, the failure index $FI(x,y)$ can be calculated for each measurement point with the following equation:

$$FI(x,y) = \frac{|S(x,y) - S_{ref}|}{|S_{ref}|}$$

Statistical analysis of the failure index values gave the following results:

- Mean failure index: $\mu_{FI} = 69.56$
- Standard deviation: $\sigma_{FI} = 127.22$

To distinguish between acceptable and defective regions, a critical threshold value was defined using a statistical approach:

$$FI_{crit} = \mu_{FI} + 2\sigma_{FI} \quad (5)$$

$$FI_{crit} = 69.56 + 2 \times 127.22 = 323.99$$

The measurement data exceeding the limit value was considered defective. In this way, it is possible to determine significant changes in relation to the reference signal and ignore the insignificant changes due to noise. The relatively high standard deviation indicates a great deal of variability in the measurement data due to various reasons:

- Variations in probe lift-off distance
- Surface roughness of the coating
- Local inhomogeneities in the sprayed layer
- Manual scanning inconsistencies

To illustrate this calculation, consider a representative measurement point with a signal value of $S_{measured} = 20$. Using the reference value $S_{ref} = -0.31$, the relative error can be calculated as:

$$RE = \frac{|20 - (-0.31)|}{|-0.31|} = \frac{20.31}{0.31} \approx 65.5$$

This result indicates a significant deviation from the reference value and predicts the presence of a defect or strong material inhomogeneity at the given location.

In contrast, for a measurement point with a signal value close to the reference, for example $S_{measured} = -0.5$, the calculated error is:

$$RE = \frac{|-0.5 - (-0.31)|}{|-0.31|} = \frac{0.19}{0.31} \approx 0.61$$

This relatively low value corresponds to minor variation and can be a sign of a measurement noise or surface irregularities rather than a critical defect.

These examples demonstrate that the error function is the quantitative measurement used to distinguish between defect-free and defective regions. High error values correspond to significant deviations and indicate potential defects, while low values represent acceptable material conditions.

After processing the data, it was found that:

- 153 points satisfying the defective condition
- 2713 Total valid points

The percentage of defective area:

$$D = \frac{153}{2713} \times 100\% = 5.64\%$$

Which means approximately 5.6% of the inspected surface can be classified as defective.

5.3.2.2 Specimen #7

The accuracy of the eddy-current measurements for Specimen #7 was evaluated using statistical analysis of the acquired signal data and the defined failure index.

Parameters:

- Area = 34.2 mm × 35 mm = 1197 mm²
- Grid size = 1 mm × 1.94 mm

- Number of scan lines = 9
- Number of points per line = 34

Additional parameters:

- Total raw points: 6829
- Valid (non-zero) points: 4011
- Removed (zeros / no contact): ~41% of data

A reference signal value was determined from stable regions of the specimen:

$$S_{ref} \approx 1.0$$

Statistical analysis of the failure index values gave the following results:

- Mean signal: 18.34
- Standard deviation: 50.55
- Mean failure index: $\mu_{FI} = 28.11$
- Standard deviation: $\sigma_{FI} = 45.45$

To distinguish between acceptable and defective regions, a critical threshold value was defined using a statistical approach:

$$FI_{crit} = 28.11 + 2 \times 45.45 = 119.02$$

Measurement points exceeding this threshold were classified as defective.

To illustrate this, consider a representative measurement point with a signal value of $S_{measured} = 40$:

$$RE = \frac{|40 - 1.0|}{|1.0|} = 39$$

This high error value indicates a significant deviation from the reference signal and predicts the presence of a defect or strong material inhomogeneity.

In contrast, for a measurement point closer to the reference value, for example $S_{measured} = 1.5$, the error is:

$$RE = \frac{|1.5 - 1.0|}{|1.0|} = 0.5$$

This relatively low value corresponds to minor variations, which can be attributed to measurement noise or surface roughness rather than critical defects.

After processing the data, it was found that:

- 275 points satisfying the defective condition
- 4011 Total valid points

The percentage of defective area:

$$D = \frac{275}{4011} \times 100\% = 6.86\%$$

Which means approximately 6.9% of the inspected surface can be classified as defective.

5.3.2.3 Specimen #9

The accuracy of the eddy-current measurements for Specimen #9 was evaluated using statistical analysis of the acquired signal data and the defined failure index.

Parameters:

- Area = 34.2 mm × 28 mm = 957 mm²
- Grid size = 1 mm × 2.33 mm
- Number of scan lines = 6
- Number of points per line = 34

Additional parameters:

- Total raw points: 5286
- Valid (non-zero) points: 3110
- Removed (zeros / no contact): ~41% of data

A reference signal value was determined from stable regions of the dataset using a robust estimation approach:

$$S_{ref} \approx -50.77$$

The statistical parameters obtained from the measurement data are as follows:

- Mean signal: 27.09
- Standard deviation: 78.19
- Mean failure index: $\mu_{FI} = 1.54$
- Standard deviation of failure index: $\sigma_{FI} = 1.53$

To distinguish between acceptable and defective regions, a critical threshold value was defined using a statistical approach:

$$FI_{crit} = 1.54 + 2 \times 1.53 = 4.61$$

Measurement points exceeding this threshold were classified as defective.

To illustrate this calculation, consider a representative measurement point with a signal value of $S_{measured} = 120$:

$$RE = \frac{|120 - (-50.77)|}{50.77} = \frac{170.77}{50.77} \approx 3.36$$

Since this value is below the critical threshold $FI_{crit} = 4.61$ the corresponding region would not be classified as defective.

In contrast, for a measurement point with a higher signal value, for example $S_{measured} = 250$:

$$RE = \frac{|250 - (-50.77)|}{50.77} = \frac{300.77}{50.77} \approx 5.92$$

This value exceeds the threshold and indicates a significant deviation from the reference condition, predicting the presence of a defect or strong material inhomogeneity.

After processing the data, it was found that:

- 423 points satisfying the defective condition
- 3110 Total valid points

The percentage of defective area:

$$D = \frac{423}{3110} \times 100\% = 13.6\%$$

Which means approximately 13.6% of the inspected surface can be classified as defective.

5.3.2.4 Specimen #10

The accuracy of the eddy-current measurements for Specimen #10 was evaluated using statistical analysis of the acquired signal data and the defined failure index.

Parameters:

- Area = 34.2 mm × 32.6 mm = 1114.92 mm²
- Grid size = 1 mm × 2.39 mm
- Number of scan lines = 7
- Number of points per line = 34

Additional parameters:

- Total raw points: 5664
- Valid (non-zero) points: 3385
- Removed (zeros / no contact): ~40% of data

A reference signal value was determined from stable regions of the dataset:

$$S_{ref} \approx -3.44$$

The statistical parameters obtained from the measurement data are as follows:

- Mean signal: 12.72
- Standard deviation: 37.85
- Mean failure index: $\mu_{FI} = 4.89$
- Standard deviation of failure index: $\sigma_{FI} = 10.99$

The critical threshold for defect identification was determined using the statistical criterion:

$$FI_{crit} = 4.89 + 2 \times 10.99 = 26.87$$

Measurement points exceeding this threshold were classified as defective.

To illustrate this calculation, consider a representative measurement point with a signal value of $S_{measured} = 50$:

$$RE = \frac{|50 - (-3.44)|}{3.44} = \frac{53.44}{3.44} \approx 35.87$$

This value exceeds the threshold and therefore indicates a significant deviation from the reference condition, predicting the presence of a defect or material inhomogeneity. The values of failure indices lie in the middle zone, reflecting the average presence of defects.

After processing the data, it was found that:

- 262 points satisfying the defective condition
- 3385 Total valid points

The percentage of defective area:

$$D = \frac{262}{3385} \times 100\% = 7.74\%$$

Which means approximately 7.74% of the inspected surface can be classified as defective.

A comparison table has been created to make it even easier to use and compare the data:

Table 5.1 – Statistical results of eddy-current measurements

Specimen	S_{ref}	Mean signal	Std Dev	FI_{crit}	Defective %
#7	1.00	18.34	50.55	119.02	6.86%
#8	-0.31	9.15	43.62	323.99	5.64%
#9	-50.77	27.09	78.19	4.61	13.60%
#10	-3.44	12.72	37.85	26.87	7.74%

6 Summary of the results and introduction of future possibilities of the project

6.1 Summary of the work performed

6.1.1 Overview

Within the study, several experiments and measurements were completed with success. The main objective of this research was fulfilled: a methodology for the identification of thermal-sprayed metallic multi-surface failures using the technique of non-destructive ECT was developed and reviewed in details.

The developed method allows for relatively fast and efficient detection of defects, while the amount of equipment needed initially is minimal. Besides, the Foerster defectometer with its software allowed us to generate easily understandable failure maps, which helped us illustrate the findings. The findings of our research support the potential effectiveness of the proposed technique when applied to NDT of complex-shaped elements. Furthermore, our research contributes to bridging the gap between the acquisition of signals and their implementation in practice by engineers. This can be seen as a way to increase the accessibility of the ECT method.

Lastly, the analysis undertaken in this paper does not only showcase the advantages of the method but also evaluates its drawbacks and limiting factors.

6.1.2 Main achievements and key findings

The main achievement of this research is the successful development of a structured methodology for defect detection using ECT on thermally sprayed multi-surfaces.

The following key results were obtained:

- A reliable **linear scanning methodology** was developed and validated
- A complete workflow from **data acquisition** to **processing** to **visualization** was established
- 3D failure maps were successfully generated for all specimens
- A **failure index-based evaluation method** was introduced
- For defect detection, a **threshold-based classification approach** was implemented

From the analysis carried out on the specimens used, several types of defect patterns have been detected and classified. From the results obtained, it is evident that

defects are not evenly distributed and often concentrate around specific areas, especially along edges and unstable depositing coatings.

The comparative analysis revealed:

- Specimen #7 showed moderate defect presence (~6.9%)
- Specimen #8 exhibited the lowest defect presence (~5.6%)
- Specimen #9 showed the highest defect presence (~13.6%)
- Specimen #10 showed moderate defect presence (~7.74%)

These findings are consistent with the expected failure modes found in the literature and confirm that ECT is able to distinguish between coatings of different qualities.

6.2 Challenges and limitations

6.2.1 Technical problems

One of the main problems associated with this experiment is connected with the calibration of the measuring instrument. This measurement method is extremely sensitive to calibration and setting parameters, as the smallest deviations may lead to incorrect data obtained. The calibration problem turns out to be the most common one. Calibration must be done in strict compliance with the manufacturer's instructions, as any deviation from the procedure will have a significant effect on the result. Thus, sensitivity to the conditions under which measurements are made is clearly revealed.

In addition, for the accuracy of measurements, it is important that calibration is properly set and that there is no displacement of the probe while scanning. Therefore, this measurement method requires extreme precision and thorough preparation by the operator. Other parameters of the method, including the sensitivity of the probe and signal noise at scanning, also play a significant role, especially when dealing with a heterogeneous surface condition.

6.2.2 Equipment limitations

The resolution and accuracy of the measurement using this new method were determined by several issues associated not only with equipment but also with the way of measurement itself. First of all, it should be mentioned that this method is highly dependent on the operator since there is no automation for positioning. The accuracy will directly depend on the operator's skills in maintaining constant movement and positioning of the probe.

It is also important that the measurement method used is highly sensitive to changes in lift-off. Therefore, even a small error in lifting the probe can negatively affect the measurements.

One more critical aspect of this measurement method is the movement pattern used. As soon as an operator decides on a particular pattern of movement, he should stick to it consistently, or else the data inconsistency will emerge. Such deviation occurs because any movement pattern gives its own spatial distribution, which influences the formation of 3D maps.

It is extremely important for an operator to conduct research on possible movement strategies before conducting the measurements themselves and choosing the most suitable one. After selecting such a strategy, the operator should stick to it firmly to ensure accurate and reliable results. One more important limitation is connected with the fact that the equipment does not have deep penetration, which limits the detection of failures.

6.3 Advantages and disadvantages

6.3.1 Advantages

There are many benefits associated with the ECT approach, the foremost being the low surface preparation necessary compared to other NDT approaches such as dye penetrant inspection and ultrasonic inspection. For example, the dye penetrant method demands surfaces that are extremely smooth, close to mirrors, while ultrasonic inspection requires the use of couplant gels during signal transmission. In this experiment, surface preparation simply required minor cleaning to get rid of dust or any other particle on the surface before performing the test.

Another advantage of this method is that it can detect flaws behind surface layers such as paint and oxide films without stripping these surface layers. This is a significant advantage; however, thick surface layers due to scaling or corrosion can affect the precision of measurement, and in this case, the layer can be stripped off.

Additionally, this method provides speed and efficiency in operation, making it ideal for engineering applications. Efficiency is achieved by the portability and simplicity of the testing device used in this experiment.

The main advantages of the method can be summarized as follows:

- Minimal surface preparation required
- Fast and efficient inspection process
- Ability to detect defects through thin coatings
- No need for couplants or complex preparation procedures

- Portable and relatively simple equipment

Overall, these characteristics make ECT a convenient, time-efficient, and practical method for the inspection of thermally sprayed coatings.

6.3.2 Disadvantages

However, despite its numerous benefits, ECT technology suffers from several weaknesses. One of the weaknesses revealed by this study at the beginning is the high level of sensitivity of the system to the probe lift-off and probe movement. Any changes in the position of the probe may affect the measurement signal, resulting in false three-dimensional images of failure positions.

In practice, the aforementioned weakness may require several tests on one sample to obtain reliable results, increasing the total test time. Besides, surface condition plays an important role in the results achieved, as any cavities, surface roughness, or sharp changes in surface profile may affect lift-off values.

Another drawback associated with this type of testing is that it is highly penetrative to the sample being tested. Namely, any coatings of considerable thickness prevent testing due to the impossibility of detecting deeper flaws.

The main disadvantages of the method can be summarized as follows:

- High sensitivity to probe movement and lift-off
- Influence of surface roughness on signal accuracy
- Limited penetration depth for thick coatings
- Strong dependence on operator skill
- Potential need for repeated measurements

Considering these limitations, it can be noted that despite the effectiveness of the method, further improvements should be made regarding its measurement accuracy, automation level, and information processing techniques.

6.4 Proposed future developments

6.4.1 Automation and robotics

One of the main directions for developing this method will involve automating the scanning procedures for examining thermally sprayed objects with complex geometry.

From this study, various issues were experienced, which suggest that manual handling of the measuring device can contribute to large amounts of errors. The

precision of data obtained depends on whether the individual conducting the test maintains constant speed and scanning throughout the entire process. Even small variations may affect the precision of measurement and the 3D failure maps that result from the process. Automated techniques that use robotic arms or specific scanning stations should thus be adopted as one of the important improvements in the future.

The implementation of automation would provide several important benefits:

- Reduction of human error
- Improved repeatability of measurements
- Consistent scanning patterns across all inspections
- Increased accuracy and precision of failure maps
- More time-efficient inspection process

Additionally, automatic systems would make it possible to inspect complex shapes that are difficult to evaluate manually, thus expanding the application range of the technique. In general, automation and robotic technologies have great promise in improving the accuracy, efficiency, and practicality of ECT in thermal spray coating inspection.

6.4.2 Data analysis enhancements

Another area that should be developed is related to the improvement of data analysis and processing methods. According to the results of this research, a lot of time and effort are spent on analyzing and filtering of the obtained data. Therefore, the development of new data analysis techniques will contribute to a significant increase in productivity and effective use of the proposed method.

Firstly, one possible solution is using machine learning algorithms for automated defect categorization. Instead of conducting manual data analysis and finding areas that have high probability of defects, it is possible to use an artificial intelligence model to find patterns in data and categorize defects like cracks, delamination, and other types of failures.

Secondly, another option for developing the existing technique is based on applying sophisticated signal processing techniques. With their help, it will be possible to use computer algorithms for minimizing the impact of noise caused by lift-off and irregularities of the inspected part's surface. Another important step is creating cloud-based databases that are used to store patterns of defects. Such databases contain information about defects that were found in previous inspections, which allows for analyzing data and tracking the condition of the part during the long-term period.

Moreover, the use of real-time data analysis in the proposed system may improve its performance. Instead of waiting for the end of the inspection process to start analyzing the obtained data, it is possible to generate results right away.

The main potential improvements in data analysis can be summarized as follows:

- Application of machine learning for automatic defect classification
- Implementation of advanced noise filtering and signal processing techniques
- Development of cloud-based databases for defect pattern tracking
- Integration of real-time data analysis and visualization systems

Overall, these enhancements would make the method faster, more accurate, and more user-friendly, significantly increasing its value for practical engineering and industrial applications.

6.4.3 Methodological improvements

Improvements in the testing methods may also become another effective way to increase both effectiveness and efficiency of the method in question. One of the major approaches to ensure an improvement in the testing process via the use of ECT is multi-frequency ECT. As a result of the use of different frequencies, the penetration depth changes: high frequencies allow for the better analysis of surface defects while low frequencies provide information about deep ones. This results in the possibility of gaining additional knowledge about the internal structures of the coated material.

The employment of array probes instead of single coils is another way to improve the testing process. Compared to single probes that analyze only data inside their borders, array probes include a variety of sensors and allow analyzing much broader areas. As a result, the accuracy, measurement resolution and quality of images are increased.

Finally, it is important to mention the improvements in the processing of signals collected. For example, by using intelligent algorithms of filtering the signals collected by the probe and adjusting the information provided to compensate for possible problems, it becomes possible to minimize the effect of various sources of interference on the results.

Another important factor that should be addressed here is the issue of calibration. By developing an optimized process of calibration of ECT probes, it becomes possible to reduce the variation of measurements caused by the influence of different factors. Moreover, one of the prospective directions of further work with the technique may include using multiple inspection modalities together with ECT.

The main methodological improvements can be summarized the following way:

- Use of multi-frequency eddy-current testing for depth profiling
- Implementation of array probes for higher spatial resolution
- Development of advanced signal processing algorithms (including AI-based filtering)
- Improvement and standardization of calibration procedures
- Integration with other NDT methods for deeper analysis

Overall, these methodological enhancements will significantly improve the accuracy, flexibility, and applicability of the developed method, making it more suitable for complex and sophisticated engineering tasks.

6.5 Potential industrial applications

The developed methodology has a big potential for industrial applications, including:

- Quality control of thermally sprayed coatings
- Inspection of mechanical components
- Detection of surface and near-surface defects
- Maintenance and condition monitoring

The ability to generate failure maps allows engineers to quickly identify critical regions and optimize maintenance strategies.

6.6 Conclusion

This paper proves that the non-destructive ECT technique is a suitable way to inspect thermal-sprayed metal coatings. During this research process, it becomes obvious that such testing may be successfully used to detect and analyze various surface and subsurface defects and thus reveal structural conditions of the coatings.

As it has been proven within the process of investigation, this testing methodology implies certain stages of data acquisition, processing, and visualization which makes it possible to receive failure maps in visual form. In other words, during use of this testing method, it becomes possible to get technical data that can be easily used in the process of making some decisions related to defect under investigation.

However, there are certain limitations that should be considered while utilization of this method. It is necessary to emphasize that the accuracy of this testing depends on such external factors such as the position of the probe, the lift-off distance,

surface roughness, and other characteristics. Taking these facts into account, it seems logical to treat such testing methodology not as a way of measuring defects but as a tool that allows evaluating them relatively.

Despite all the difficulties described above, one should admit that the results obtained in the course of this research make it possible to state that the methodology developed for the purpose of the analysis can be successfully used to evaluate thermal spraying quality and make relevant conclusions. The ability to create failure maps proves to be an advantage that is worth mentioning.

In summary, this work provides an excellent background for further development of the problem. As far as it goes, with the improvement of this testing methodology and data processing procedures, the approach under consideration will gain more popularity in engineering practice.

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