NON-DESTRUCTIVE EVALUATION OF MANUFACTURING ANOMALIES IN AERO-ENGINE ROTOR DISKS

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Abstract: Manufacturing anomalies introduced during machining of critical parts, although rare in occurrence, have become a significant cause of gas turbine disk cracking events in the aero-engine. These non- geometric anomaly types are usually different to those commonly targeted by current production NDI efforts. A European Union funded programme 'MANHIRP' has been set up to address this issue by introduction of quantitative NDI results into probabilistic lifing concepts. A selection of the efforts undertaken to expand the capability of NDI is described in this paper.

1. Introduction: Rotor disk ruptures in aero-engines must be prevented with the highest possible probability. Statistics show that, although the aero-engine industry invests high efforts into quality assurance, manufacturing induced anomalies mainly caused by "rare events" are becoming the most important reason for disk failures. The international development programme "Integrating Process Controls with Manufacturing to Produce High Integrity Rotating Parts for Modern Gas Turbines" (MANHIRP), funded by the European Union, has been set up to address this issue. Engine manufacturers, institutes and universities from seven European countries are working together to investigate the most life limiting manufacturing anomalies. Three manufacturing methods producing the appropriate geometric features are under investigation: hole making (holes), turning (flat surfaces) and broaching (shaped slots). Commonly used NDI techniques as well as near term and longer term techniques are investigated to assess their potential for detecting and quantifying the most life limiting anomalies. In this paper these techniques are outlined along with some of the programme results and some open questions are posed.

2. Objectives of the NDI efforts within the MANHIRP Programme: During the first trials to create manufacturing anomalies, currently used production NDI techniques were applied to detect and quantify the anomalies, where possible. At this stage, eddy current and some optical methods were effective for detection of geometric anomalies, while etch inspection could detect some non-geometric anomalies. Following this, samples were metallographically cut up or fatigue tested to enable further characterization.

The next step was to adapt so called near-term NDI methods, already discussed within the NDI community, to meet the needs of manufacturing anomaly detection. In addition, new inspection ideas were also investigated to determine whether the techniques were applicable or at least show promise, after further investigation, for use in future projects. However it was not the intention of the programme to spend the major effort on the development of new NDI techniques.

3. Definition of the Most Important Manufacturing Anomalies

3.1 Non-Geometric Anomalies: Inclusion of foreign (e.g. tool) material: During machining , breakage of the machine tool cutting edge can lead to residual tool particles being impacted in the surface of the component. Incomplete removal of impacted tool material can cause a significant deficit in fatigue life (Fig. 1).

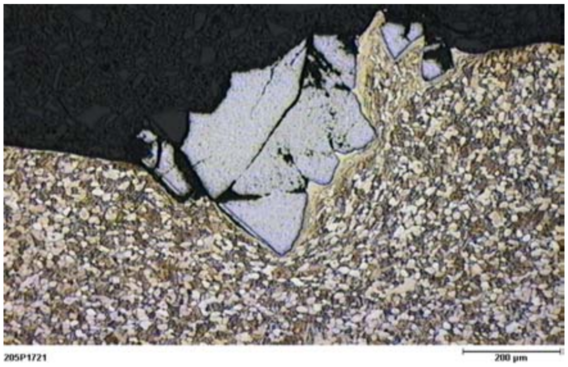


Fig. 1: Micro section of broken cutting insert in titanium matrix showing microstuctural distortion and phase transformation through adiabatic shear

Distorted microstructure and/or adiabatic shear bands through tool breakage: Even when no tool material is left behind after tool breakage, there will be micro structural distortion and local residual stress concentration at the reworked surface. Furthermore, titanium-base alloys tend to form adiabatic shear bands under the influence of the high energy released during a high velocity impact into the material, as caused by a tool breakage (Fig. 2).

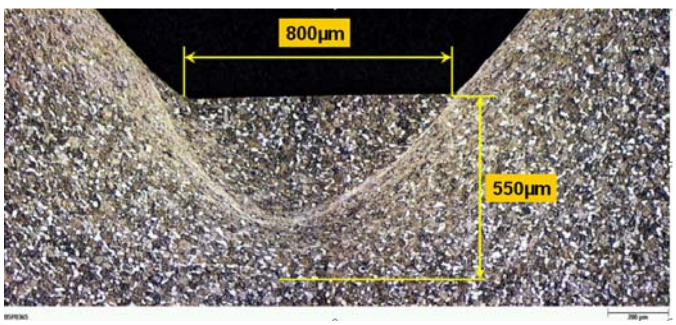


Fig. 2: Micro section of artificially created impact causing adiabatic shear bands and microstructural distortion in Ti 64 material

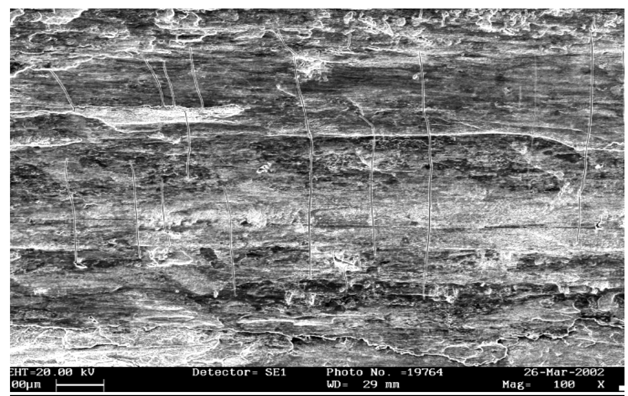


Fig. 3: Heavily smeared surface with "grinding cracks" through friction with tool fixture before rework

Microstructural distortion due to friction with non-cutting tool material: Programming errors or tool selection errors can lead to contact of non cutting tool parts with the machined surface. This usually rare event could lead to overheating and/or microstructural distortion and even cracks at the component surface. Provided that such events will of course be noticed it must be taken into account that there could remain some damage after rework of the surface (Fig. 3).

3.2 Geometric Anomalies: Plucking is a phenomenon where small volumes of material are torn out of the surface. This leads to very small surface depressions, which are open to the surface and so not reliably detected by penetrant inspection. Plucking is mainly observed on broached surfaces using aggressive cutting parameters.

Re-depositing of parent material also called "smearing" is the bonding of chip material to the surface under high pressure and local heat generation. It happens mainly when chip material is prevented from escaping the cutting surface (Fig. 4).

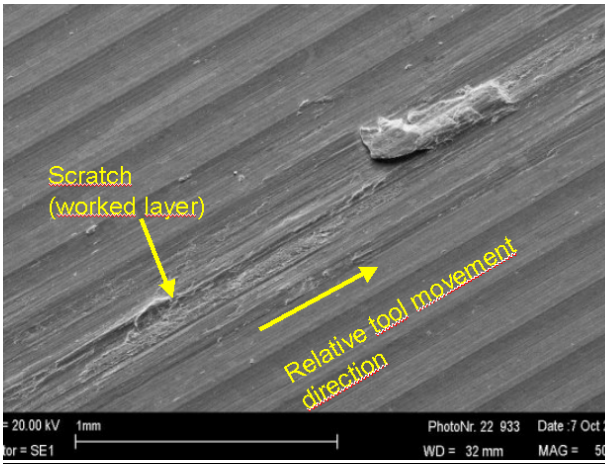


Fig. 4: Re-deposited parent material on turned titanium surface

Scores and scratches usually arise in manufacturing from unplanned tool contact with the surface. Contact between machine tool and surface during tool retraction in hole making is a common example of this.

4. NDI Methods used: Current methods: All aero-engine manufacturing companies apply visual inspection, fluorescent penetrant inspection (FPI) and different chemical and/or anodic etch methods to 100% of their highly stressed components before releasing them into service. In addition some companies inspect critical geometries such as bore features with the eddy current method.

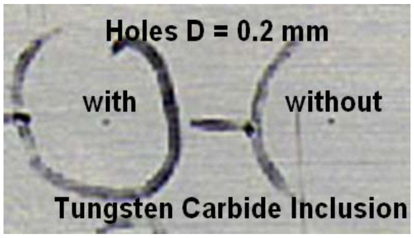
Near term methods: Some currently available NDI methods are not used in the production environment of participating manufacturers. Where this is the case, those methods are referred to as "near term" for the particular manufacturer. They should be adapted to either the anomaly type or the feature geometry within the MANHIRP program. In this category is seen scanning eddy current techniques with special kinds of signal enhancement for the detection of small defects and/or defects with a low impedance change. Also, a special "gap probe" was used, made of an old hard disk head.

New methods: Feasibility studies were initialized with meandering winding magnetometry (MWM) /1/, a special eddy current technique for holes defined by Volvo Aero Corporation /2/, a highly sensitive magnetometric scanning method /3, 4/ and some optical scanning methods especially for the inspection of inaccessible areas.

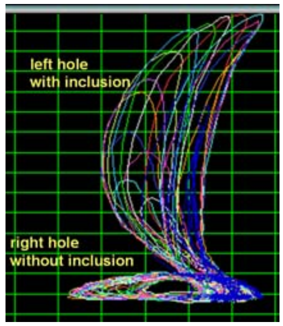
5. Results: In the following paragraphs those cases are highlighted where some success occurred in detection of the specific anomaly reported.

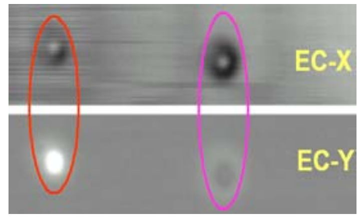
5.1 Inclusion of foreign material after tool breakage: Bits of broken tool material could be detected by FPI, but in some cases they might not be visually accessible or are smeared with parent material from the rework process. It is very important to detect and remove residual impacted tool material that remained in or just under the surface of highly stressed parts. Therefore trials with different NDI methods where undertaken to reduce the probability of this rare event.

5.1.1 Eddy Current: Test blocks were prepared with inclusions of tungsten carbide cutting material. To provide defined inclusion sizes, tungsten carbide micro drills were drilled into the material and in some cases were broken at specified depths. The phase of the eddy current signal shows very clear differences between the filled and the empty holes. This effect is caused by the change in permeability due to the ferromagnetic nature of the cobalt content of the cutting material (Fig 5).



Section of test block with TC inclusion left





Eddy current c-scan

Fig 5:
EC detection of TC inclusion, phase shift in complex plain due to ferromagnetism of tungsten carbide cutting material

5.1.2 Detection of the remanence magnetism by a fluxgate gradiometer: The test blocks, including tungsten carbide tool material as described before, were magnetized and then scanned with a fluxgate gradiometer. The University of Magdeburg-Stendal (Germany) and the University of Cincinnati (USA) carried out the highly sensitive measurements. Drill bits down to 0.05 mm diameter and a length of 0.14 mm (volume app. 2x10 Exp -4 mm³) introduced in titanium could be detected by this method with reasonable signal to noise ratio (Fig. 6).

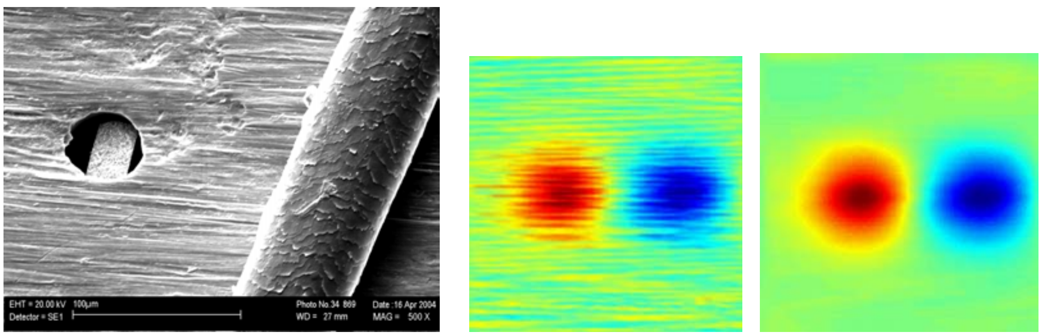
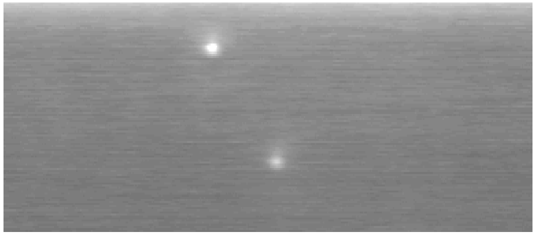
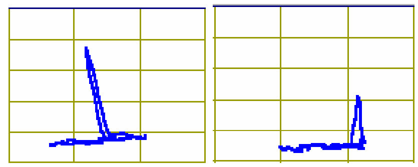


Fig. 6: 50µm hole with broken tungsten carbide drill inclusion in titanium sheet in comparison with human hair (left) magnetometric images before (middle) and after image processing (right)

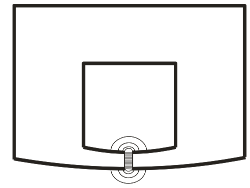
5.1.3 Eddy current inspection of holes: A special tube shaped test block was prepared to simulate inclusions of tungsten carbide in a drilled hole (Fig 7). The inclusions were made by breaking a micro drill coming through the tube wall just before entering into the
hole. The drill diameters were 0.07 and 0.15 mm. Both could be detected with a special probe made of a hard disk head /5/.



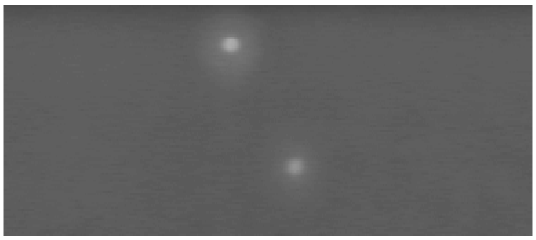
Gap-probe EC-Y-image of the TC inclusions



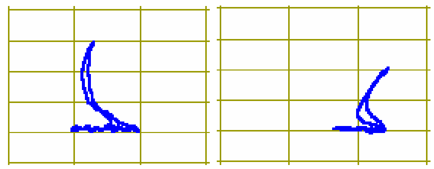
Impedance plane signals, horizontal direction: lift-off



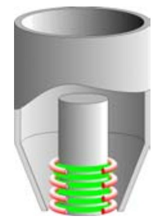
EC gap-probe principle



Cylinder-core probe EC-Y-image of the TC inclusions



Impedance plane signals, horizontal direction: lift-off



EC cylinder core probe principle

Fig. 7: Eddy current rotating probe images of hidden tungsten carbide inclusions in a titanium tube

5.2 Distorted microstructure and adiabatic shear bands through tool breakage: Tool breakage, particularly during turning with high cutting speeds can cause local microstructural distortion and adiabatic shear bands (titanium). Where phase transformation under high temperature may take place in small parts of the volume, transformed material can be left behind, even after rework, when the event takes place just before reaching the final contour of the part. As tool breakage with reproducible results is difficult to initiate this kind of anomaly was created using a reproducible punching process. After rework, non geometric affected zones were left behind in the surface (Fig 2).

5.2.1 Blue Etch Anodize (BEA): The BEA process is usually used on new titanium parts to detect non-geometric anomalies like segregations and worked layer. It was shown that adiabatic shear bands could also detected by this method, although there is some uncertainty arising from the possibility of small defect sizes and because it is based on visual interpretation by an individual inspector (human factor) (Fig. 8)

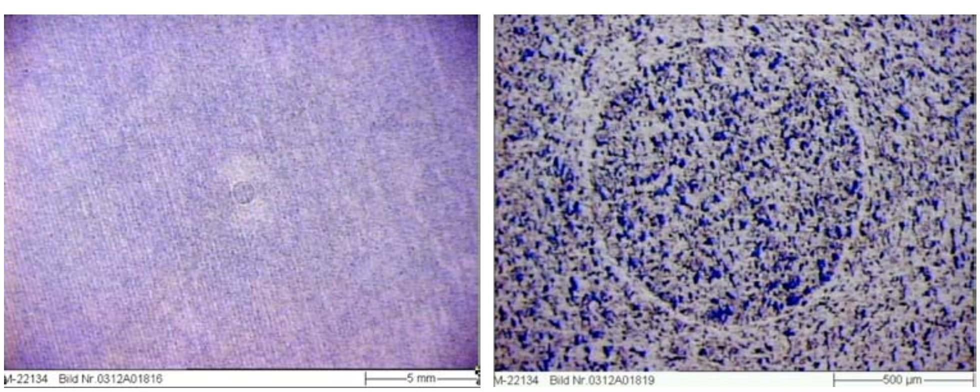


Fig 8: BEA image of artificially created adiabatic shear band in Ti 6-4 under light microscope

5.2.3 Eddy Current Inspection with C-scan presentation: Eddy current could detect the microstuctural distortion due to a slight change of the conductivity. Due to the rather low EC signal a poor signal to noise ratio was observed that made signal processing a very useful tool.

Fig. 9 shows two EC c-scans of the same distortion zone filtered with a whitening filter, based on linear predictor in the horizontal direction, and a 2D matched filter using a selected EC response

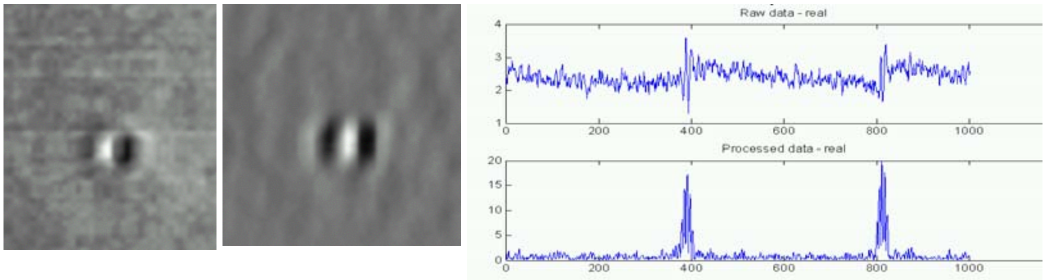


Fig 9: Two step filtering of complex EC data. Unfiltered C-scan (left), filtered (middle), unfiltered EC signal (right upper diagram), filtered (right lower diagram)

5.2.4 Meandering Winding Magnetometry (MWM): In a feasibility study carried out at Jentek Sensors it was shown that this method has potential to detect zones with microstructural distortion /1/ (Fig. 10).

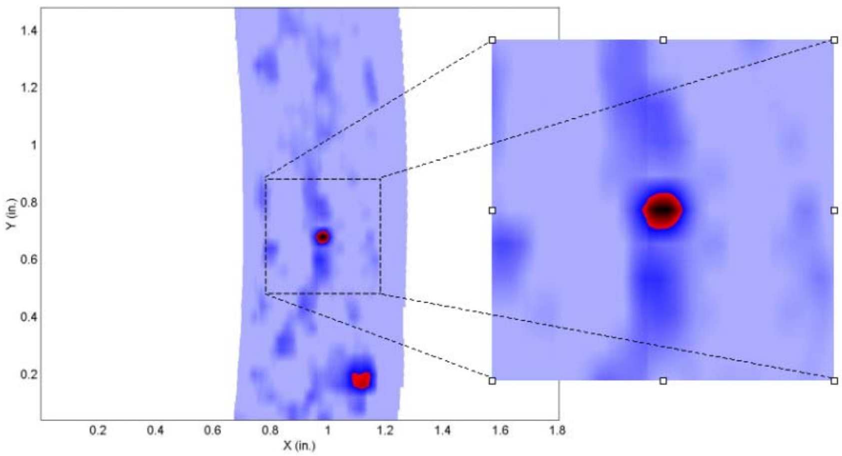


Fig. 10: Image of affected zone from simulated tool breakage (distorted microstructure and adiabatic shear bands) and unknown "natural" indication lower right edge

5.3 Microstructural Distortion of Titanium Due to Friction with Non-Cutting Tool Material: To create this anomaly a tool fixture was pressed against a turning Titanium 6-4 part. A heavily smeared surface was the result with zones of shallow "grinding cracks" (Fig. 3). This surface was then reworked with the lowest possible cutting depth to obtain a smooth surface that showed no visible anomaly.

5.3.1 Eddy current: No indication could be detected by eddy current inspection using high resolution scanning with highest possible crack detection capability and c-scan presentation.

5.3.2 Blue Etch Anodize: The BEA process showed up streaks of different color that correspond to zones of different affected micro structure (Fig. 11).

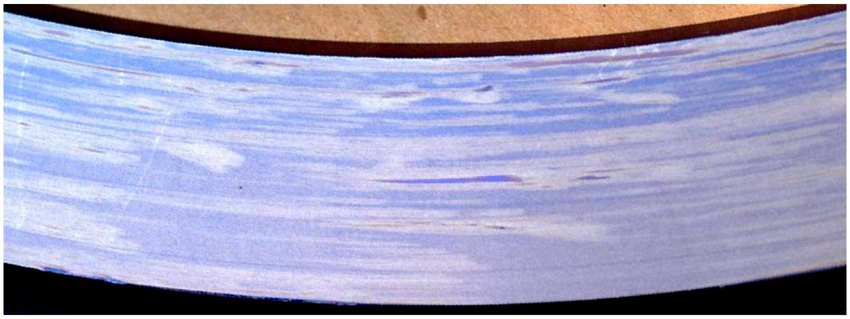


Fig 11: BEA image of distorted surface from friction with non cutting tool material after rework (no anomaly visible before the etch treatment)
(prior to rework: see Fig. 3)

5.4 Plucking

5.4.1 Eddy current inspection: FPI showed some, but not all indications that could be seen with the scanning electron microscope (SEM), as does EC inspection with the special "gap probe". Not one of the pluckings in this slot can be assumed to be detectable with state of the art EC equipment (probes and scanner).

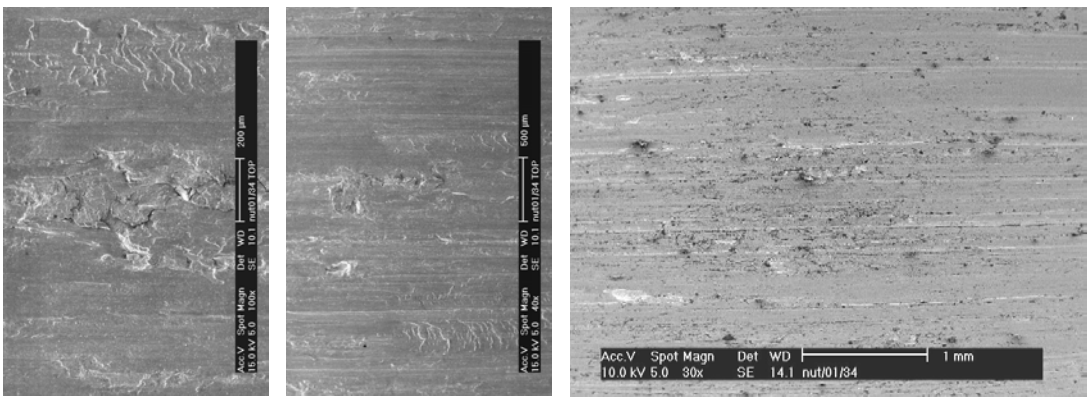


Fig. 12a: SEM images showing pluckings of indications in Fig. 12c: 1, 2, 5 (from left)

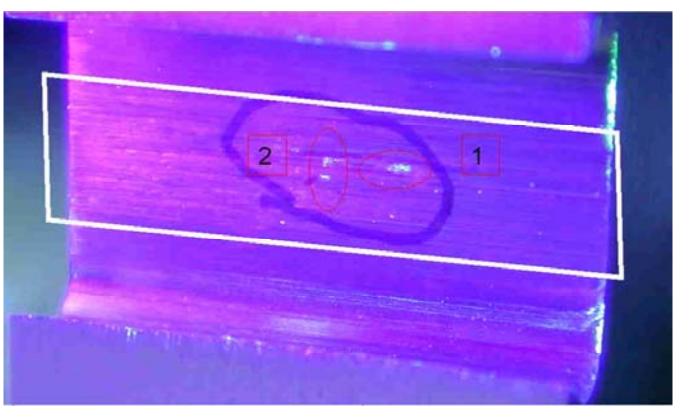


Fig 12b: Broached slot with pluckings, two of five indicated by FPI

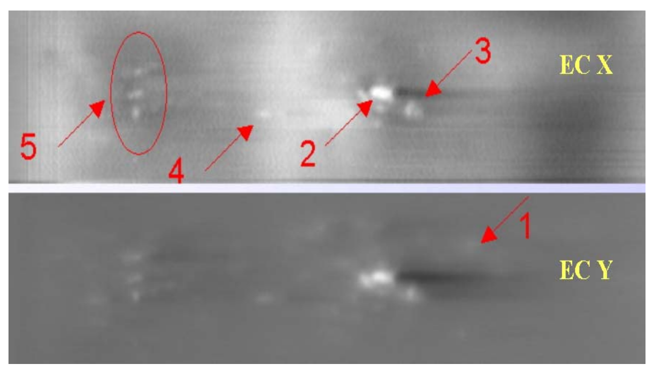


Fig 12c : EC images of area in Fig. 12b with five indications

5.5 Re-deposited Parent Material

5.51 Automated optical inspection: An automated laser based optical inspection was tested for this kind of anomaly in a feasibility study. Defects, smaller than 0.2 mm were detected on a flat surface /6/. However due to the spatial resolution of the technique a vast amount of data must be acquired, which makes the application ineffective for larger areas. However this technique might have a potential for hole inspection.

5.5.2 Eddy current inspection: Eddy current inspection can detect this anomaly. Due to its geometric nature a lift off signal is generated when the probe moves over the re-deposited material. EC is particularly advantageous in visually inaccessible areas and in part areas where EC inspection is applied anyway because of component or feature criticality.

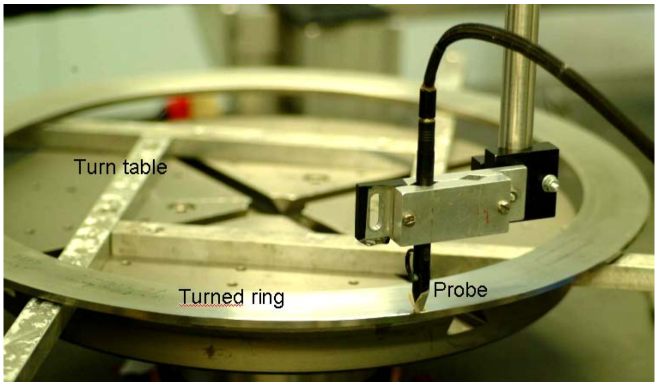


Fig. 13a: EC-inspection with standard differential probe with sample part on turntable

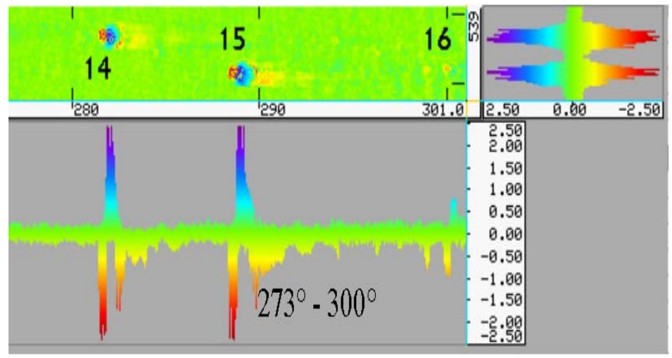


Fig. 13b: **C-scan image of three indications of re-deposited parent material**

6. Conclusions: The experiments carried out so far have shown possibilities to increase the probability of detecting both geometric and non-geometric manufacturing induced anomalies with NDI to prevent their escape into service. Some examples, like the MWM method or the adaptation of eddy current probes with high resolution capability, may not be practical immediately but show a potential for further efforts.

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