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Technical Article

Evaluation of the Application of Non-Destructive Tests in Investigating the Defects of Gas Turbine Blades and Using Thermography Method as an Alternative Method

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Abstract

Blades of a gas turbine are the main and most important parts of turbine machines that work in very difficult and complex conditions. Existence of discontinuities and defects in the structure of these parts cause sudden and irreparable damage. It can completely take a turbine out of operation and impose huge costs on a power plant. Therefore, pre-installation controls and inspections for these parts are of great importance. One of the safest and most reliable methods of control and inspection is the use of non-destructive tests. One of the methods that has been considered in recent years is the use of infrared waves, which in this method; Surface defects and sometimes even internal defects can be detected by using infrared cameras that operate within a certain range of the electromagnetic wave spectrum (0.8-14 nm). In this paper, we try to review the conventional methods of non-destructive testing that are used in troubleshooting blades of gas turbines, and the method of using infrared waves as an alternative method to conventional methods to be discussed.

Keywords: Non-Destructive Tests (NDT), Thermography, Gas Turbine Blades.

1. Introduction

Gas turbines are used in different industries to generate electricity (such as aircraft engines, trains, ships, Electric generators, etc.). The life of gas turbine blades is very important in the performance and efficiency of a gas turbine. The life of these parts is very critical due to exposure to high thermal stress, corrosion, oxidation and wear. Therefore, these factors reduce the life of blades. There are also variables when producing and repairing these parts. That is why every blade is carefully inspected by non-destructive tests to ensure the health and integrity of these sensitive and expensive components guarantee the price.There are different methods of non-destructive testing that are used to examine them. They can be inspected by penetrating paints and liquids (visible to the eye and fluorescent), Ultrasound method, radiography, visual inspection, eddy currents. Each of these methods identifies various types of discontinuities and defects according to its nature. Penetrating liquids test is perhaps one of the oldest inspection methods from colored materials (usually red) defects are observed and interpreted in light. This method includes there is another technique that uses fluorescent liquids for inspection and defects with the use of ultraviolet lamps can be seen and interpreted. This, method seems simple arrives but before testing requires surface preparation and can be influenced by factors various (type of material final level under inspection, defect characteristics, selection of appropriate technique and factors human). In visual inspection is done in two direct and indirect forms. If superficial defects in places that are out of sight of the inspector, aids such as a borescope or fiberscope can be used [1].

Ultrasonic method is one of the common methods of non-destructive tests. The method uses high-frequency (MHz) sound waves to propagate into a solid discovered the heterogeneities. The local changes that occur in the properties of a material affect the energy transmitted by the sound and the amount of energy reflected to the probe or transducer receiving information about the properties of that material (thickness, density, Porosity) provides us with a black-and-white image that identifies the internal and external features of a blade. The effect is to change the density or thickness of the desired location. In the eddy current method, electromagnetic waves are used. This is the primary magnetic field with this method, structural properties (grain size, phases,...), physical properties (electrical conductivity, magnetic properties...) and hardness as well as defects in the parts can be examined [1-2].

2. Thermography

Everything emits infrared waves at temperatures above absolute zero. The image of infrared

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radiation from the surface of an object that has reached equilibrium with its surroundings is an image of surface heat and emissivity. Infrared cameras can show the surface temperature of objects in proportion to the energy radiated from that surface with a sensitivity of less than 0.1 ° C. The ability to measure temperature from distances away from the surface has caused these cameras to monitor Use condition and preventive repairs. One of the heating methods is the active heating method, in which the body is heated or cooled in different ways and the resulting temperature change is calculated and interpreted by infrared cameras as well as special software. Images obtained from this method it can reveal the structure and condition of the lower surfaces of the body to us, which can be considered competitive with the images obtained by the C-Scan method in ultrasound or radiographic testing [3]. There are different techniques in the active method for excitation of objects, which can be called Lock-in thermography, Flash thermography, Vibrio thermography, Pulse thermography.

2.1. Electromagnetic Waves

Electromagnetic radiation or electromagnetic energy according to wave theory is a type of wave that from Electric and magnetic fields are created and propagated in space.
These fields are perpendicular to each other and in the direction of wave propagation. Electromagnetic radiation is sometimes called light, but it should be noted that visible light is only part of the range of electromagnetic waves.Electromagnetic waves are called by various names depending on their frequency: radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, and gamma rays(Fig. 1). These names are arranged in order of increasing frequency and decreasing wavelength. Maxwell first predicted electromagnetic waves and then Heinrich Hertz 1 proved it experimentally[4].

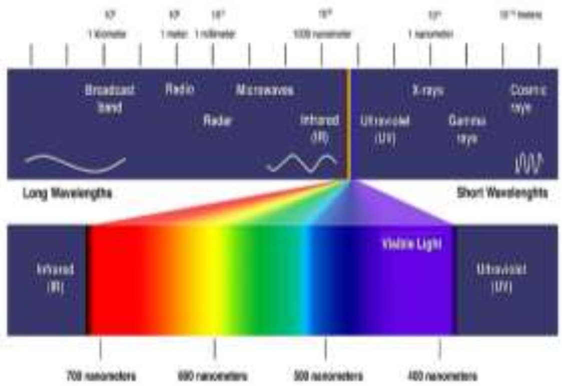

Fig. 1. Electromagnetic spectrum [4].

After completing electromagnetic theory, Maxwell obtained a form of the wave equation from the equations of this theory and thus showed that electric and magnetic fields can also behave in a wave-like manner.
The speed of propagation of electromagnetic waves was obtained from Maxwell's equations exactly equal to the speed of light, and Maxwell concluded that light must also be a kind of electromagnetic wave [4].

2.2. Thermal and Infrared Tests

Infrared thermography is a non-destructive testing method that models Draw the heat generated on the surface of an object without contact with that object This method is usually used to detect the thermal behavior by which The performance of devices and equipment can be examined, and this method can be used Realize the flawlessness of materials, products and processes. Infrared imaging equipment used in thermography is available in a variety of shapes and complexities. Thermal models obtained by thermal imaging equipment and we can interpret these temperature maps, the interpreter must be familiar with the principles of temperature and heat transfer, radiant heat flux due to infrared rays, and the operation of cameras and heating equipment [4].
Familiarity with the type of device the material used as well as the process used are very effective in interpreting and measuring tests. Methods of heat and infrared radiation used to examine materials and equipment they are considered as part of non-destructive tests and are based on the change of heat flux created by various discontinuities inside the material. This change in heat flux creates a local heat difference on the surface of the body. Study of these thermal models it is known as thermography. The intensity, frequency and wavelength of a beam can be highly dependent on the heat emitted from the heat source. The sensors that receive this heat determine the physical state of the object for us. This is the basis of thermo genic technology. Thermodynamics has different techniques. One of these techniques is the use of materials that are sensitive to heat (usually coatings) and are applied to the surface of the body. This approach is based on the thermal conductivity of heat sensitive material. The technology is called thermal technology and has nothing to do with infrared technology [5]. Techniques used to monitor the radiation emitted from the surface of an object were invented between 1962 and 1912, and in the 1982s, the technique was digitized. Thermal models created on the surface of materials it produces radiation patterns corresponding to the surface thermal design. Therefore, the heat flow in the form of conductivity and radiation determines the location of the defect and allows us to see it, but do not forget that the mechanism is the same heat flow [5].

2.3. Infrared Radiation

Heat transfer is done by three methods of conduction, convection and radiation, and sometimes by a combination of these three it can be. Conduction occurs when hot atomic particles collide with each other and transfer their energy to adjacent atoms that are cooler (slower in motion).
This action occurs from an atom (or free electron). Continues to another atom in colder regions. Therefore, heat is always transferred from a warmer environment to a colder environment. The term convection is the transfer of heat by mass transfer of a heated substance, in particular gas or liquid [6].

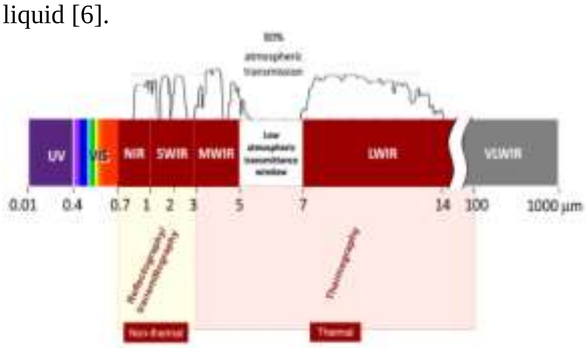

Fig. 2. Infrared spectrum range in the electromagnetic spectrum range [6].

Thermal patterns formed on the surface will be visible from a distance through beams emitted from the surface by sensors. It emits electromagnetism. The spectrum and intensity of the emitted rays depend on the temperature and the nature of the surface. Caused by thermal turbulence produces a form of radiant electromagnetic energy called infrared radiation (that is, the frequency of this ray is after the color red) [6]. They produce particles between microwaves and visible light according to Fig. 2.

2.4. Emissivity

Emissivity as the ability of an object to emit infrared energy is defined. In other words, the ratio of the energy emitted by an object to the energy emitted by a black body at the same temperature is called relative diffusivity.The black body, as mentioned earlier, is an object capable of absorbing all wavelengths of electromagnetic radiation [6].
Diffusability can vary from zero for a glossy mirror to for a black body and is known as a unit-free relative quantity. Objects can reflect, transmit, or dissipate energy, but only the emitted energy determines the temperature of the object. In general, non-metallic bodies (especially turbid bodies) have a high diffusion ability, while this ability in metals depends on the type of metal and its surface conditions. Polished metal surfaces emit less radiation, while rough or oxidized surfaces emit more radiation.
For example, the polished surface of silver has a coefficient of 0.02. Often the color of the surface is mistaken for a very influential factor in the ability to diffuse, which is not true. The thermal penetration of a material also plays an important role in the thermography technique, which is a measure of a material's ability to conduct heat compared to storing heat energy in that material. This quantity is the ratio of heat transferred to heat stored per unit volume of matter [6].

2.5. Active and Passive Thermometry

Heat transfer is generally done in two ways, passive method and active method. The passive method is performed on tests of materials and structures that naturally differ in temperature (usually higher) from the ambient temperature, while the active method requires an exciter to generate heat exchange. In most industrial processes, heat is an important indicator for evaluating the proper functioning of equipment, and the passive method helps greatly in such evaluations. Applications of passive method are in production, preventive repairs, forest fires, medicine, energy dissipation in buildings, traffic monitoring, agriculture and biology, gas leak detection and non-destructive tests. In all of these applications, the unusual temperature characteristic indicates a potential problem that needs to be addressed. Unlike the passive method, the active method requires an external stimulus that can cause a temperature difference or heat exchange. In non-destructive tests, this technique is more popular than the passive technique because in most cases, it is necessary to detect subsurface defects. The passive method has been used successfully in some industrial applications, including aircraft inspection immediately after landing to find moisture entering wings and honeycomb structures. Active heating method is a very suitable method for fast inspection of large surfaces and, as mentioned, creates thermal profiles by creating temperature differences between healthy and defective areas, which are detected by infrared detectors [4].

2.5.1. Active Thermography Category

In the active method of thermometry used in non-destructive tests, the object is stimulated by a heat source and the behavior of transient heat is monitored by a thermometer camera on the surface of the object (Fig. 3) [8].
The effect of heat waves penetrating into the moon is observed on the surface of the object and these observations are used to find the characteristics of surface and subsurface defects.

The presence of subsurface heterogeneities along with turbulence in the heat flux causes thermal contrast on the surface [7].

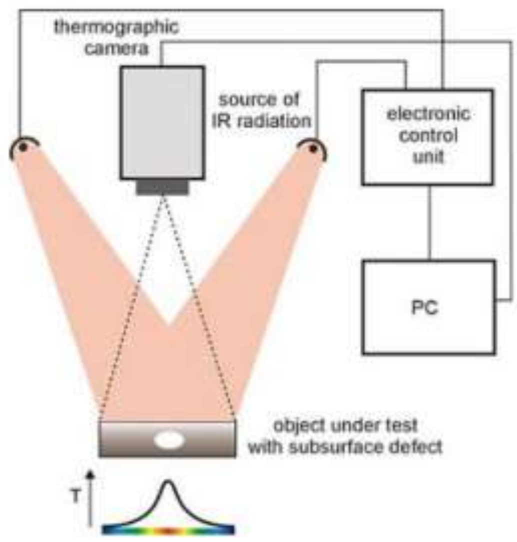

Fig. 3. Basic layout of an active heating system [8].

2.5.2. Percussive Thermography

Percussive thermography, abbreviated to PT, is one of the most common methods of thermal excitation. The reason for this popularity is the high speed of inspection, which is based on thermal excitation pulses. These actuators are usually in the form of photographic flashes and vary from a few microseconds for materials with high heat transfer properties such as metals to a few seconds for samples with low thermal conductivity such as plastics. Because the heating beats are applied in very short times, no damage is done to the part. In addition, its temperature is only a few degrees Celsius higher than the initial temperature of the test piece or sample. By applying thermal pulses, the temperature increases and this heat decreases due to the diffusion of thermal energy by penetrating the lower surfaces [9]. Now, due to a defect such as non-connection in a composite piece, the penetration rate is reduced. Therefore, when we look at the surface temperature, we see a subsurface defect with a different temperature from the healthy surfaces around it. This area is known as the heat accumulation area and is observed above the defect surface with a higher temperature than other areas. This phenomenon occurs with time, so defects that are deeper will be seen later and will have less contrast [9].

There are different forms for pulsed thermography methods which can be named as follows:

A. Spot inspection, a laser beam or focused light is used.

B- Linear inspection, linear lamps, heating elements or wires, hot air nozzles and scanning lasers are used.

C- Surface inspection, photographic lamps and scanning lasers are used.

If the temperature of the sample under test is higher than the ambient temperature, we can use cold heat sources such as cold air nozzles or water nozzles, rapid contact with ice, etc.

Heat front diffusions act similarly in both cold and hot states, so what is important is the temperature difference between the heat source and the test specimen. One of the advantages of cold heat sources is that unlike hot heat sources, we will not have heat reflection to the camera. The main limitation of excitation by cold heat sources is their practical considerations, so that heating the part is much easier than cooling it.

There are two methods of observation:

1. Reflection method, in which the heat source and the camera on one side of the part are tested

2. Passing method, in which the heat source is located on one side of the part and the camera on the other side.

The reflective method is usually used to find defects that are close to the heating surface, while the passing method is used to find defects that are located at farther levels. Percussive thermography is used for many types of materials used in aerospace, including composites, metals and polymer compounds [9].

2.5.3. Lack-in or Modulated Thermography

In Lack-in or modulated thermography, external alternating thermal excitation is used to generate heat waves inside the sample. This is usually done by sinusoidally modulated tungsten-halogen lamps. When a sample is excited by sinusoidal heat, scattered and very weak waves appear inside the material and close to the surface, which are known as "heat waves".These waves are detected non-contact and from a distance relative to the generated part and are detected by the detector. But in here means the need to monitor the exact time relationship between output signals and reference input signals. In fact, in modular thermography, the difference in heat transfer time in the work piece in the healthy and defective area is used.

Laboratory equipment has made it possible to see the amplitude and phase of the heat waves on the test sample (Fig. 4).

The images obtained from this equipment are different from the thermal images obtained by the pulse method in some respects because the phase is the same.

And the amplitude are present in these images. In a pulsed method, the images obtained are related to the thermal design emitted by the power of the infrared waves, while the phase images are related to the propagation time and the amplitude images are related to thermal penetration [10].

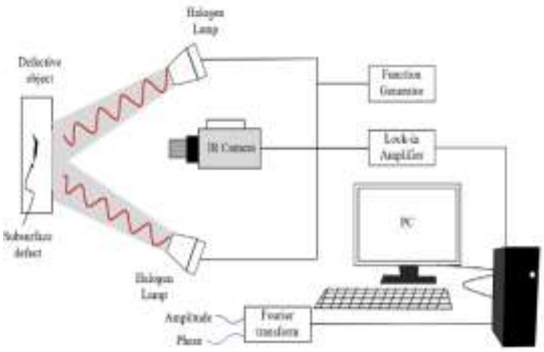

Fig. 4. Scheme of lack-in thermography [10].

The phase, which is relatively independent of the local optical and thermal properties of the surface, is a strong point for modulated thermography in non-destructive test applications [9].

The basis of lack-in method for finding subsurface defects is that internal discontinuities change the phase difference between the modulated and reflected heat waves. The images of the recorded profiles are calculated [9-10].

2.5.4. Vibrating Thermography

Vibrational thermography unlike most thermography methods in which energy is transmitted through optical equipment, the sample is mechanically stimulated using acoustic or ultrasonic oscillations. Mechanical stimulation is performed using an audio transducer that attaches to the sample surface. The propagation of the waves during the test sample is attenuated and converts the mechanical energy into thermal energy, but in the vicinity of the defect due to friction between the defect surfaces or the concentration of stress in the areas around the energy loss. In metals, sound attenuation is relatively low, and mechanical excitation acts as a selective internal heat source located within the defect, and can be detected by infrared cameras with temperature changes at the surface [9-10].

2.5.5. Thermography by Step Heating Method

This method uses a step or step pulse using a low intensity heat source. The pulses are usually applied for a long period (from a few milliseconds to a few seconds), so this is possible with a long wet the warm-up time to determine the location of defects at greater depths. Relatively slow heating creates a layer structure that provides an assessment of the connections between the layers (hidden corrosion in complex aircraft structures, as well as determining the thickness of the layers). In addition, in stepwise thermostatic, changes are made in the surface temperature distribution during the heating and cooling process [11].

Applications of this method include checking the thickness of the coating (multilayer and ceramic coatings), the health of the connection between the coating and the substrate, and evaluating composite structures [12].

3. Application of Thermography in Gas Turbine Blade Troubleshooting

In connection with gas turbine blades, there are several methods of active heating. In fact the whole the surface of a gas turbine blade can be inspected using thermography. Up to a few years in the past, thermography was only a secondary and qualitative method, but with facial improvements in technology, heating systems have been developed to the extent that they can replace old and conventional technologies and inspection methods. Today, leading companies in the gas turbine industry, such as General Electric, Pratt & Whitney, Rolls-Royce and Siemens, have added the heating method to their inspection tools. Thermography using flash is widely used in the inspection of coated and cast parts in the turbine blade manufacturing industry.

The surface of the part, especially the airfoil blade, is heated by a pulse of light that lasts only a few milliseconds, and when the heat penetrates into the metal, the surface cools, but there is a common thread between materials (such as metal-coating and metal - Air), defects (not connecting the cover to the substrate), or the inner parts of the blade (walls, inlet air humidifiers) can interrupt or cause normal cooling behavior in dealing with these cases [12].

Thermalization using the signal reconstruction method is widely used to find the details of the inner parts of the blade and also allows us to measure the thickness of ceramic coatings and the thickness of the turbine blade walls with Measure very high accuracy such as ultrasonic methods and eddy currents. Different forms of fluid flow thermometry have been used to qualitatively inspect air-cooled holes. The simplest type is that when the operator passes hot or cold fluid (usually water, water vapor or air) through the cooling channels of the turbine blade, the images of heat generated by the camera are displayed. Consider and review. Clogs are seen as discontinuities in surface temperature that form along air channels. The new generation of this thermography method has created more accuracy and sensitivity in the study of blockage of cooling channels. These systems can be designed to be fully automatic and gradually replace the method of using pins or radiographs to test for airflow obstruction. Although vibrational thermography entered the industry in the late 1912s, recently one of the non-destructive testing methods has been used to find surface cracks on the turbine blade airfoil surface.

Unlike other active thermography techniques. When the whole part is heated or cooled, high power vibration thermography injects sound energy into the part by an ultrasonic transducer (usually 12-48 kHz) and causes heating, only in cracks with openings. They are close together, which is caused by the collision of heat cracking edges. With this method, small cracks can be detected in a few seconds, which can be a very attractive technique compared to the penetrant testing method [12-13].
The use of thermography has several advantages over conventional airfoil blade inspection methods provide gas turbines.
This method is relatively fast (most inspections take a few seconds is done), has automation capability and does not require contact with the surface of the part and its preparation be. This method can also evaluate the heat transfer performance of the airfoil, which is an important and necessary task in this part. Whereas ultrasonic methods, radiography, penetrating fluids, and conventional air duct obstruction detection methods provide only structural information. Active thermodynamics offers several advantages over ultrasound and radiographic methods for applications such as measuring the thickness of the airfoil wall and the pores on its surface, as well as changes in density and the presence of foreign materials [13].

3.1. Obstruction and Misalignment of Air Ducts

Air-cooled ducts are very important for a gas turbine blade because its function is such that it increases the life of such parts. As a result, initial and continuous inspection of turbine blades is essential to avoid clogging in these ducts Air ducts can usually occur due to the presence of ceramic left over from the fish outlet, misalignment of the cool air holes and the presence of foreign matter inside the ducts, which is usually done by radiography and water or air flow test (size). Fluid outlet flow or the use of pins can be done. However, each of these methods has limitations, such as expensive radiography, time consuming and the need to comply with safety requirements, and methods of using pins or measuring the flow of fluid output are not accurate enough. Blades made of nickel-based superalloy, which are made by precision casting method, are used to create internal channels by the method of muscle insertion inside the blade, and after the melting of the ceramic fish, it is removed by the leaching process. If this process is not done completely, a part of the ceramic muscle remains inside the piece and creates an obstruction. Usually, this defect is revealed by radiography. Static hot steam stimulation can be used to detect this defect. Required equipment includes steam generator, heat source, imaging system and fixtures. Fig. 5. shows the blades with fixtures. The fixtures are designed in such a way that hot steam enters from the inlet of the ducts with pressure and after heating, it is driven out of the outlet holes that all the relevant connections must be well sealed [14].

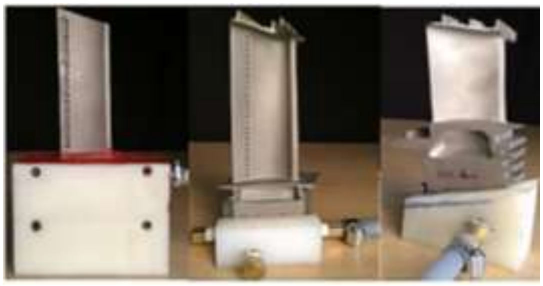

Fig. 5. Tested blades with fixing system.

Saturated steam enters the air-cooled ducts by pressing twice through the corresponding fixtures. To ensure a proper pattern, a non-clogging of the air ducts should be performed to record the reference image of the optimal state and to compare the prepared images with the condition in which the ducts are blocked. Fig. 5. shows the thermal design of an unobstructed blade sample .In the Fig. 6., it shows the surface temperature distribution of the blade as the hot fluid passes through the channel. If any of the internal parts of the obstruction are present, this obstruction should be observed as a temperature concentration (high or low temperature) on the surface.

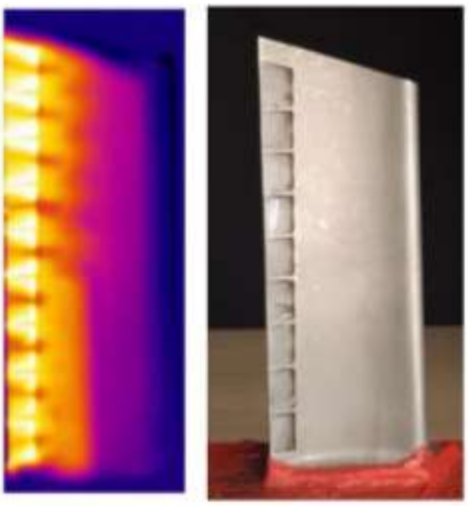

Fig. 6. The result of thermography test of blade sample without channel blockage.

Now we intentionally create an artificial obstruction (for example, by injecting a kind of obstruction adhesive, we create an air channel). After the artificial occlusion, the blade is tested again with the active scenario mentioned and is received and recorded with the help of thermal data collection systems.

The passage time is of special importance and the best time is selected and the places indicated by arrows indicate the location of defects. By comparing the thermal design of healthy and defective blades, defects can be identified and evaluated [14]. Fig. 7. shows the result of thermography test of blade sample with channel blockage.

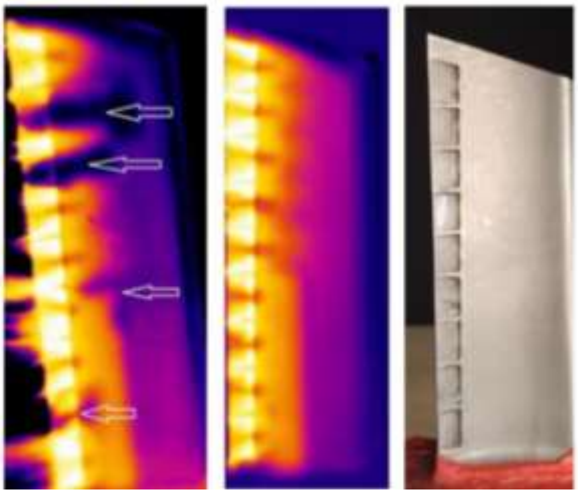

Fig. 7. The result of thermography test of blade sample with channel blockage.

The advantages of this method over conventional methods include [14]:
- High speed (test time a few seconds)
- High accuracy in troubleshooting
- Safety considerations required in radiography are not required in this method
- Non-contact inspection
- View very fine residual ceramics that cannot be detected in radiographic or pin test methods as well as fluid flow.

3.2. Crack Detection

Cracking is one of the most important defects that can occur on the moving parts of such gas turbines blades are formed. Conventional methods for cracking gas turbine blades include eye inspection and fluorescent penetrant testing, which are widely used in the industry. Today, the use of acoustic heating method is used as an innovative and special method in non-destructive tests.

This method is used to find cracks on the surfaces of turbine blades.

In this method, by entering the energy through ultrasonic waves it is provided that the crack surfaces move in front of each other and local heat is created in this area, which in the end this heat is seen as a defect. The heat generated by an infrared camera is detected and uses post-processing algorithms to help the inspector diagnose the defect well [14].

This method is widely used in the aerospace industry and gas turbines and can replace the fluorescent infiltration fluid testing and physical inspection method.

The signals received from the defect recorded by the acoustic heating system depend on specifications such as the geometry of the part, the geometry of the defect, the type of material, the degree of closure of the crack opening and its location. The acoustic heating system for the turbine blade is shown in Fig. 7. The blade is connected to the ultrasonic transducer from the end of the root and this transducer operates with a power of 3.3 kW and a frequency of 22 kHz. The blade is placed inside a fixture and is connected to the transducer at a pressure of 62 pounds from the root. Stimulation is performed for 1.5 seconds to generate heat in the defective area. With a camera operating in the range of 3-5 micrometers, it records different frames in this time frame of defect [15].

After this time, the data collected by the computer connected to the camera is synchronized. Experiments have shown that the piece was tested by penetration fluid test method with sensitivity 4 (highest sensitivity to find small discontinuities) that the number of cracks observed by acoustic heating method is much more than the penetration fluid method and the penetration fluid method by the method A visual inspection revealed more cracks. According to this finding, it can be concluded that the acoustic thermography method is more sensitive to finding cracks than the other two methods and finds the very small cracks that we mentioned in the two conventional methods more accurately [15].

It should be noted that due to the high sensitivity of the infrared camera, even very small hot spots can be detected. Accurate analysis of images must be done by an experienced and trained operator to be able to correctly interpret and properly evaluate the detection defects. Within the acceptance range to decide if the part needs repair or can be approved Fig. 8. [15].

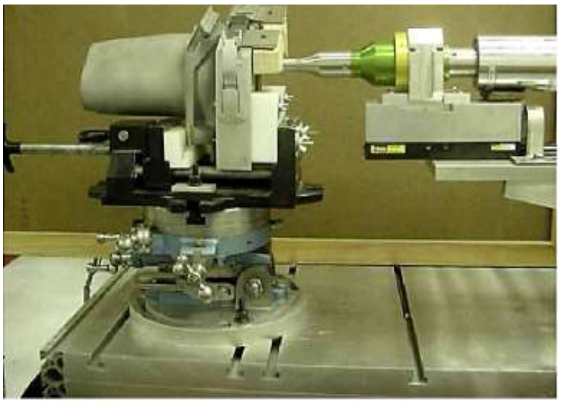

Fig. 8. Turbine blade acoustic thermography layout.

3.2.1. Open Cracks

A crack can be described by its specific length and its depth profile. Therefore, depending on the nature of the crack the current flows either around the crack tips or beneath the crack. To model this behavior, it is therefore best to look at these two alternatives individually. A model for the case where the current has to flow around the crack tip is given by a slot which is finite in length but extends completely through the sample (Fig. 9.).
In this case the current density is highest at the crack tips and lowest besides the crack. Therefore, the typical thermographic signal for such a crack is characterized by the hot-spots at the crack tips and a colder zone at the sides of the crack [16].

Fig. 9. Model and typical thermographic result of a slot-like crack [17].

For the second case, we use a notch infinite in length but finite in depth as model geometry (Fig. 10.). In this case the current has to flow beneath the crack and therefore the current density is highest at the bottom of the notch and lowest at the top edges. However, the heat from the bottom is diffusing to the surface and therefore after the induction pulse is finished the top edges tend to stay warmer than the surrounding material [16].

Fig. 10. Model and typical thermographic result of a notch-like crack (50 ms induction pulse) [17].

3.2.1. Closed Cracks

The slot and the notch already give a good model for the induction heating effects related to cracks, but looking at a real crack, as shown in Fig. 11., it becomes clear that additional heating mechanisms have to be examined and the modelling has to be modified for closed cracks.
As can be seen this crack shows a hot line along the crack with several hot spots. To model this phenomenon a sample with several adjacent drilled holes was prepared. An experiment with induction thermography shows that every material bridge between the holes leads to a hot spot (Fig. 12.).

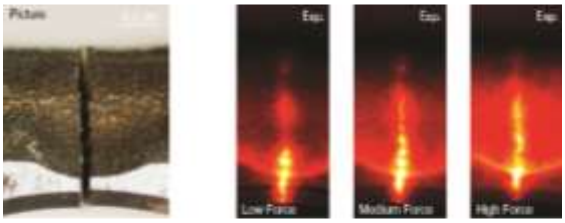

Fig. 11. Result of an induction thermography inspection of a crack closed by nut and bolt (clamping torque: 1, 2, and 10 Nm) [17].

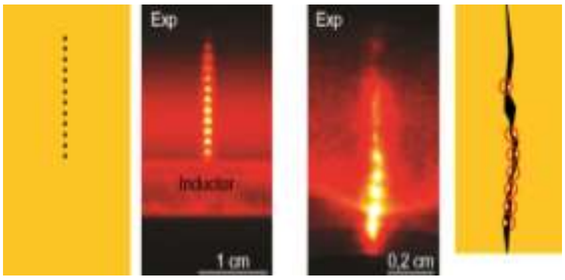

Fig. 12. Left: Indication of holes drilled in a sample; Right: Indication of the crack shown in Fig. 10. and a schematic explanation for the infrared signal (red circles in the figure on the right) [17].

An increase in the density of the contact bridges leads to a situation where the image of the spot distribution gets more and more homogeneous and finally looks like a line.
This effect can be seen in Fig. 11. By increasing the clamping force per area the density of the contacting points increases and hence the resulting infrared image of the crack looks more homogeneous.
This contrasts with acoustic thermography [18] or penetrant testing. In acoustic thermography, open cracks give no signal. With increasing residual stresses the signal gets stronger and finally decreases due to the residual stresses suppressing the movement of the crack.
This means that such cracks produce no heat and will not be detected. An experiment with the same component used in Fig. 11. show that the best signal can be obtained with acoustic thermography with a clamping torque of 5 Nm and that with 10 Nm the signal cannot be distinguished from the noise [18, 19]. Similarly, it is also very hard (or even impossible) to detect tightly closed cracks with penetrant testing.
This makes induction or conduction thermography the ideal techniques once it comes to cracks with high residual stresses.
For cracks with high residual stresses the density of contact points can be higher than what can be resolved by thermography. In that case a crack can alternatively be modelled as a zone of reduced

electric conductivity. Fig. 13. shows the result of a simulation of a slot which is filled with a material with a stepwise altered electric conductivity.

On the right hand side, the electrical conductivity of the filling material is equal to the surrounding material and the crack leads to no change in the heating. Next, the conductivity was decreased slightly and the crack shows up as a line. By further reducing the conductivity hot spots are showing up at the crack tips and finally only the crack tips can be seen. The latter situation is identical to an open crack [16].

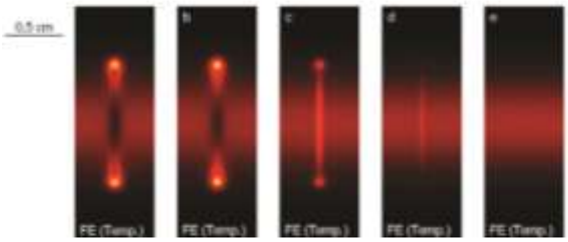

Fig. 13. Images of the temperature distribution calculated by a finite-element simulation for a slot filled with some material with an altered electrical conductivity [17].

a) σCrack = 0, b) σCrack = 1.5 10-5 σMaterial, c) σCrack = 1.4 10-3 σMaterial, d) σCrack = 0.13 σMaterial, e) σCrack = σMaterial.

4. Conclusion

In this study, common non-destructive testing methods such as fluorescent penetration inspection, eddy current, ultrasonic and visual inspection used to investigate turbine blade defects were investigated. In addition, by comparing these methods and thermography techniques, the following can be mentioned:

1. According to the three test methods of fluorescent penetration inspection, eddy current and visual inspection, the thermography method easily detects cracks created during the production process and thermal fatigue cracks that occur during operation in the turbine blade. Even small cracks that are not detectable in fluorescent inspection and visual inspection methods can be easily detected by thermography.
2. The probability of cracking detection in thermography is higher than the methods of physical inspection and testing of fluorescent fluids and eddy currents.
3. Internal defects of the turbine blade, such as the presence of residual ceramics, improper air ducts, clogged air ducts that are difficult to detect by the passage of fluid, the use of pins or radiography, can be easily detected using thermography.
4. Defects of thermal barrier coatings such as ceramic top layer and metal bonding layer and the growth of thermal oxides between the top coating and the bonding coating, which are the most common defects in ground and air turbine blades, can be detected in precision thermography with very high accuracy.
5. Very high speed and low pollution this method distinguishes it from conventional methods that are very time consuming and polluting.
6. Contaminants and consumables from radiographic methods, infiltration fluids such as emergence and stabilization materials, films, petroleum base materials, infiltrators and other consumables are reduced to zero, which is in fact an environmentally friendly method. In fact, with the increasing advancement of technology and the introduction of high-precision cameras into the industrial market, this method can be used in the very near future as the main method of non-destructive testing to check the defects of hot parts of gas turbines.

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