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Evaluation of Artificial Defects in Additively Manufactured Turbine Blade using Ultrasonic Immersion Testing

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Abstract

One of the most important components of aero engine is the turbine blade. The additive manufacturing (AM) of jet engine turbine blade is complex as the machining process involves majority of the challenging aspects of metal cutting. Due to the reason of complex component geometry, surface roughness and variable thickness it is very hard to perform the inspection on such components. Even with the probability of having several defects, various non-destructive testing (NDT) techniques may perhaps be needed to inspect the component to detect the defects. Using numerical modelling in CIVA software, the purpose of this analysis is to identify the artificial internal defects in the turbine blade using immersion non-destructive testing (NDT) technique. The flaw size and geometry can be determined from the images produced by the ultrasonic scan.

Keywords: Non-destructive testing, additive manufacturing, ultrasonic testing, turbine blade, numerical modelling

1. Introduction

A major difficulty in the extensive development of additive manufacturing by industries is linked to the complexities associated with the detection and evaluation of flaws in AM components. Advanced non-destructive testing (NDT) techniques are employed to effectively identify different flaws in different layers of additively manufactured part. The measuring systems that have been widely used conventionally for producing parts are most often insufficient to apply in additive manufacturing. The main reason for selecting the inspection of the additively manufactured turbine blade is because of the possibilities of forming various defects in the blade during its manufacturing and operation period. Additive manufacturing process has advanced such that complex components can be produced directly based on digital data without complicated tools or equipment [1, 2]. Some production line and inventory challenges could be resolved by adequately integrating 3D manufacturing into the aviation industry [3]. Substantial development in these production lines is already evident; however the lack of quality assurance and certification requirements limits the advancement of AM. The complex geometry of many 3D manufactured components need appropriate choice of non-destructive testing technique to best suit flaw detection. In some cases, a combination of NDT techniques has been performed to identify flaws adequately in vital components.

The materials are preserved free from flaws using various non-destructive testing techniques to ensure the reliability and high quality inspection [4, 5]. Different methods for the identification and assessment of flaws in AM products have been examined for non-destructive testing (NDT). These methods have been suggested both during (in-process) and following the production process (post-process). Some of the NDT methods explored in AM are computed tomography (CT), eddy current (ET), visual and ultrasonic tests (UT) [6, 9]. Ultrasonics (UT) testing is among the most effective NDT techniques in industry [10, 11]. In this paper, the turbine blade is inspected using ultrasonic immersion technique to analyze various artificial flaws present in it. The material commonly used to manufacture an aero-engine is titanium, and primarily its alloys are appreciated. The optimal relation between low density and high specific strength is the main reason for opting titanium grade 5 alloys in the manufacturing of components in aviation industry.

The main objective of this work is to investigate the additively manufactured turbine engine blade using ultrasonic immersion techniques.

The tasks to be performed during the process are listed below.

1. To study different kinds of artificial flaws present in the airfoil and dovetail section of the blade.
2. To perform a numerical analysis of ultrasonic immersion testing techniques to detect different types of defects in the turbine blade.

The experimental analysis is carried out in order to find out various flaws in the turbine engine blade. The results from the simulation will help us in designing, selecting, and applying appropriate inspection techniques to identify and analyze flaws while lowering physical investigations and mock-ups.

2. Methodology

The inspection of the turbine blade was carried out in the CIVA software with dimensions of the blade as 127 mm×50.8 mm×152.8 mm. The material used for the investigation is Ti-6Al-4V with density (ρ) = 4400 Kg/m3, young's modulus (E) = 114 GPa, Poisson ratio v = 0.37, longitudinal velocity = 6200 m/s and shear velocity = 3100 m/s [12, 13]. The turbine blade constitutes of airfoil section and the dovetail section as shown in the fig. 1 below.

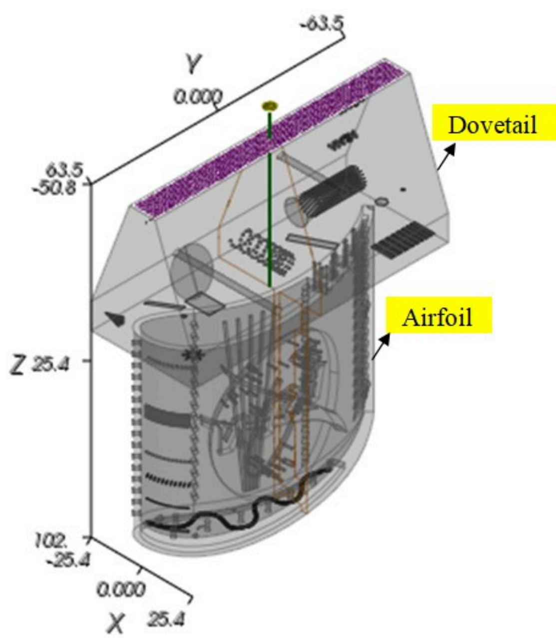

Fig. 1 Set-up of ultrasonic immersion testing of turbine Blade

The inspection was performed on the dovetail and airfoil section using immersion testing. The different kinds of flaws present in the turbine blade are varying from trapped powder with complex helical volumes, 2D and 3D arrays of trapped powder in the airfoil section, cracks formed between the dovetail and the airfoil, side drill holes of varying diameter distributed in the airfoil top section and dovetail bottom section of the turbine blade. The dimension of those defects in the turbine blade is given in the table 1 shown below.

Table 1. Defects in turbine blade [14]

Airfoil section mm	Dovetail bottom section
Curved plate inclusion 9.41 mm;	Helical spheres (0.47 to 1 mm); Circle 3.5 mm
Rods 68.56 mm; Pyramid	Star shape 2.5 mm; Two side drill holes 2 mm diameter
Rectangular slots (9.7 mm)	Rectangle plate., Rods from airfoil 4.79 mm
Cracks from hole; Rods attached to dovetail 5.1 mm	Varying thickness inclusion., Foreign object debris, Coil occupies up to 71.04 mm

2.1 Beam computation

In order to find the suitable parameters of transducer and frequency for the inspection of different kinds of flaws present in the test component beam computation is performed. The beam simulation is carried out for 5 set of frequencies ranging from 5 MHz to 20 MHz. The diameter of the transducer is 7.5 mm, signal bandwidth of 50% with 0^{o} phase difference at -6 dB gain. The beam computation results will help us with the information of direction of ultrasonic wave propagation, width of the beam and the focal spot in the component under investigation. The results of the beam simulation are shown below in fig. 2.

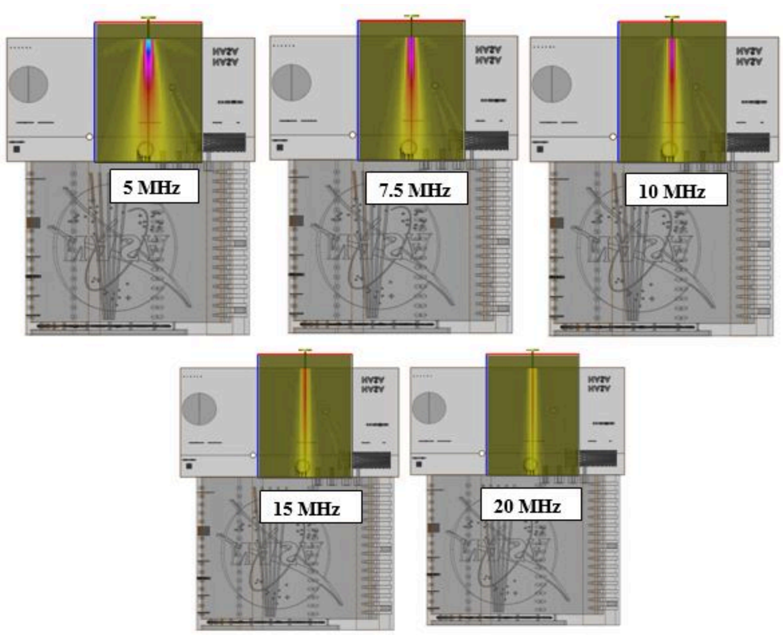

Fig. 2 Beam immersion results

From the inspection results of immersion testing, the immersion results show us that at lower frequency of 5 MHz the sideways dispersion is maximum, and at higher frequency values of 15 and 20 MHz less penetration of the beam in the specimen is observed. The suitable range of frequency was found to be in the range of 7.5 and 10 MHz for carrying out the inspection of the turbine blade. However, in our complex shaped component, the 7.5 MHz frequency gives better penetration and is suitable enough for carrying out the ultrasonic inspection.

2.1.1 Immersion testing of dovetail section

From the beam computation results the frequency of 7.5 MHz was found to be appropriate for the investigation. The parameters of the transducer for the immersion testing are gaussian signal choice with the centre of frequency as 7.5 MHz, bandwidth 50% and gain of-6dB. Water is selected as the surrounding medium, and density of water is 1 kg/cm^3, primary wave velocity of 1483 m/s and longitudinal water type. The water path of 10 mm is set for the immersion inspection. The scanning path step along the x axis and y-axis is 0.5 mm and number of steps along the axis and y-axis are 20 mm and 246 mm respectively. The 3D computation zone positioning is linked to the probe as such the computation zone moves along with the movement of the probe, and the computation mode is set to 3D with attenuation. The D-scan image depicts various flaws in the dovetail part and is shown below in fig. 3.

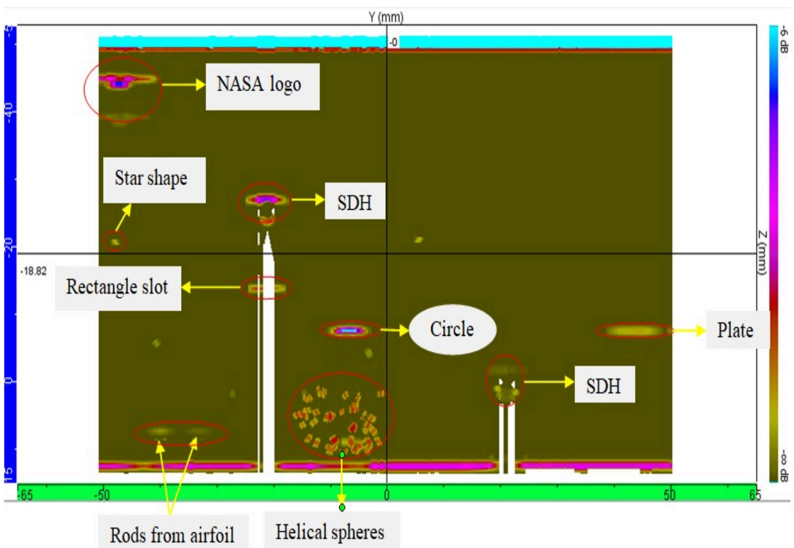

Fig. 3 Immersion inspection D-scan results

The results shown above in the dovetail part with immersion inspection shows the defects in the form of the NASA logo at the top left section, a circular section at the middle, trapped powder like holes (50 microns to 3mm) near the surface of the blade and the dovetail part, rectangular slot of length 3.07 mm in the extreme right and rods connected to the tail part from airfoil (5.18 mm).

2.1.2 Inspection simulation- Immersion testing on the backside of the blade

Following the investigation of different kinds of defects in the dovetail section of the turbine blade, the inspection is carried out on the airfoil top section to locate the artificial flaws present in the airfoil. While performing the simulation, the attenuation is neglected in this case. The gaussian signal is chosen; centre of frequency is 7.5 MHz and bandwidth 50 % at a gain of -6 dB. The water path of 14 mm and longitudinal wave type is chosen for the inspection. The surrounding medium water has a density of 1 gm/cm3 and a primary wave velocity of 1483 m/s. The setup for the inspection performed is shown in the fig. 4 below.

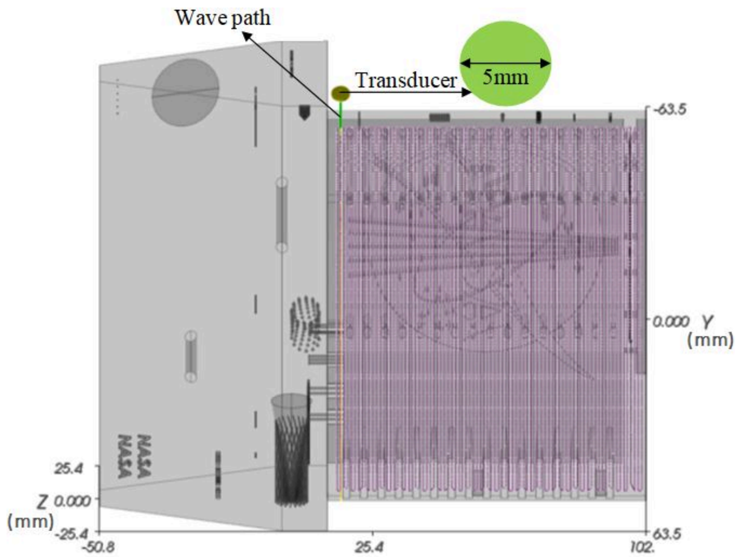

Fig. 4 Blade back side immersion inspection setup

The scanning path step along the x axis and y-axis is 0.5 mm and number of steps along the axis and y-axis are 110 mm and 185 mm respectively. The 3D computation zone positioning is linked to the probe as such the computation zone moves along with the movement of the probe, and the computation mode is set to 3D.

The scanning path step along the x axis and y-axis is 0.5 mm and number of steps along the axis and y-axis are 110 mm and 185 mm respectively. The 3D computation zone positioning is linked to the probe as such the computation zone moves along with the movement of the probe, and the computation mode is set to 3D.

3. Results and discussions

The size of side drill holes' is 2 mm in diameter. From the general rule of NDT, the defect size should be more significant than half the size of the wavelength. The calculation of wavelength for a given frequency of 7.5 MHz and theoretical wave velocity of 6100 m/s is given in table 5. The results of the wavelength are calculated using the equation of wavelength.

$$\lambda=\frac{c}{f} \quad \text{.....................................} \ (1)$$

Table 2. Wavelength calculation for frequency 7.5 MHz

Material	Frequency, f(MHz)	Theoretical velocity, c(m/s)	The wavelength, λ(mm)
Ti-6Al-4V	7.5	6100	0.81

From the above calculations, the wavelength of 0.81 mm is larger than one half of the wavelength to detect a defect size of 2 mm SDH. The result of the immersion testing of dovetail section is presented in the C-scan image and is shown below in fig. 5.

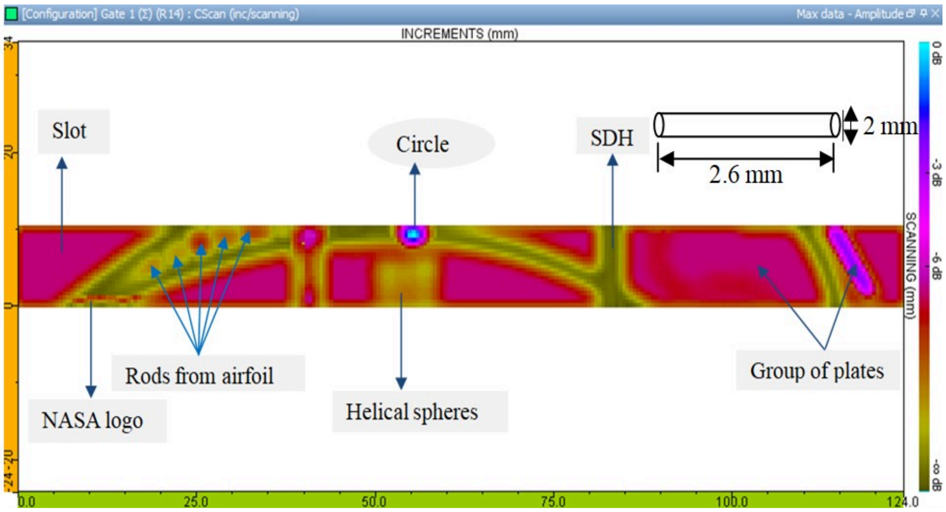

Fig. 5 C-scan immersion results

The higher amplitude intensity of C-scan is found in the defects like circle, rods from airfoil and plate at the extreme right side due to the perpendicular positioning of such defects to the scanning beam. The results of C-scan in defects like helical spheres, NASA logo, SDH and slot shows lower amplitude intensity. The reason behind the low intensity is because of these defects not positioned perpendicular to the beam path. The loss in the intensity of the amplitude of detecting artificial flaws present in the dovetail is arising because of the component's complex structure, which may influence the wave path for tracing the defects.
The results shown above (Fig. 3, 5) of the dovetail part with immersion inspection shows the defects in the form of the NASA logo at the top left section, a circular section at the middle, trapped powder like holes (50 microns to 3mm) near the surface of the blade and the dovetail part, rectangular slot of length 3.07 mm in the extreme right and rods connected to the tail part from airfoil (5.18 mm). The defects identified are plotted on a chart with their respective size and are shown below in fig. 6.

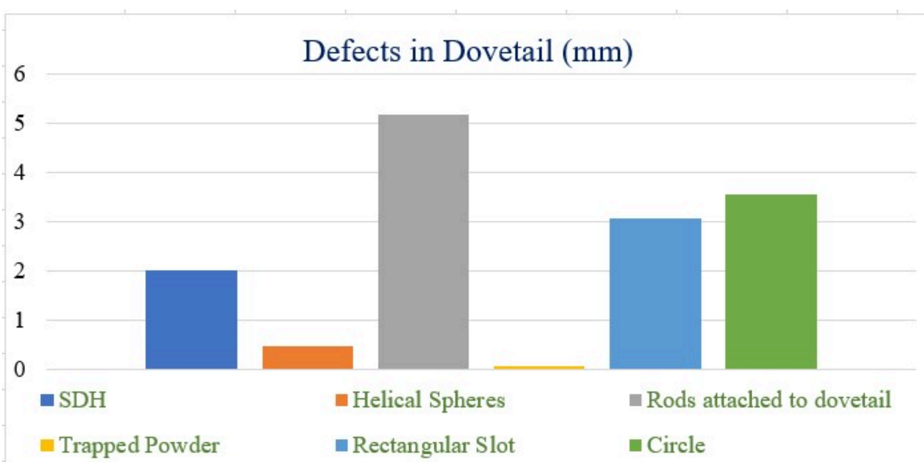

Fig. 6 Size of defects in dovetail

The results of immersion testing of airfoil section (2.1.2) are shown by the C-scan image profile (fig. 7). The presence of SDH at position 2 and 3 in the airfoil has lower amplitude because of the blade's curved shape, which results in deviation in the beam and minor focusing of the direct incident beam at such angle.

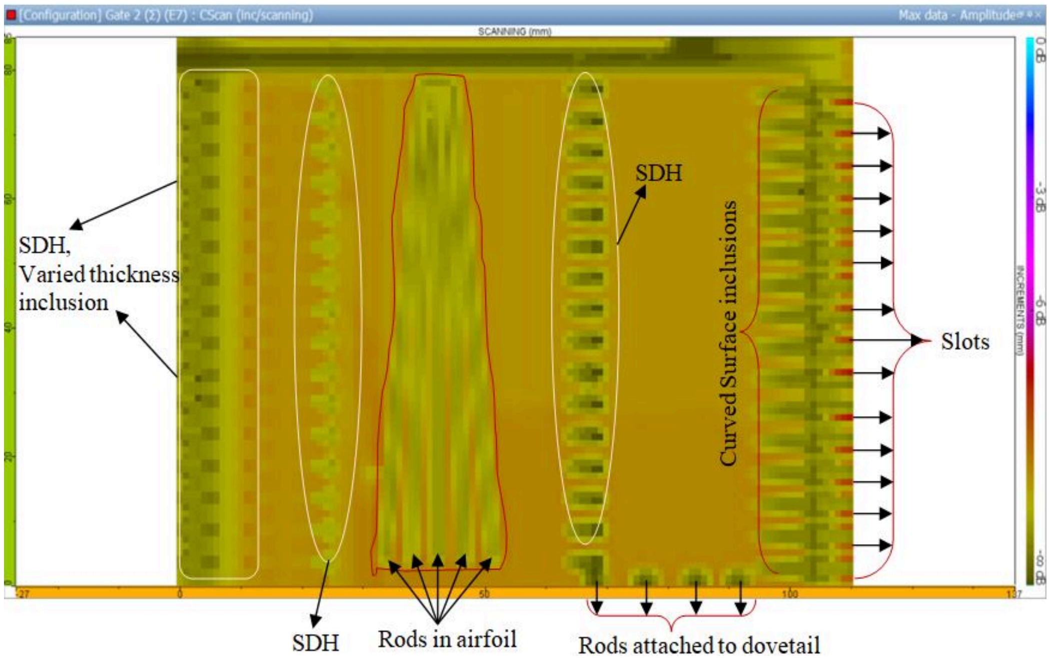

Fig. 7 Blade C-scan

The defects and the size of the defects detected in the inspection are plotted in the chart below shown in Fig 8.

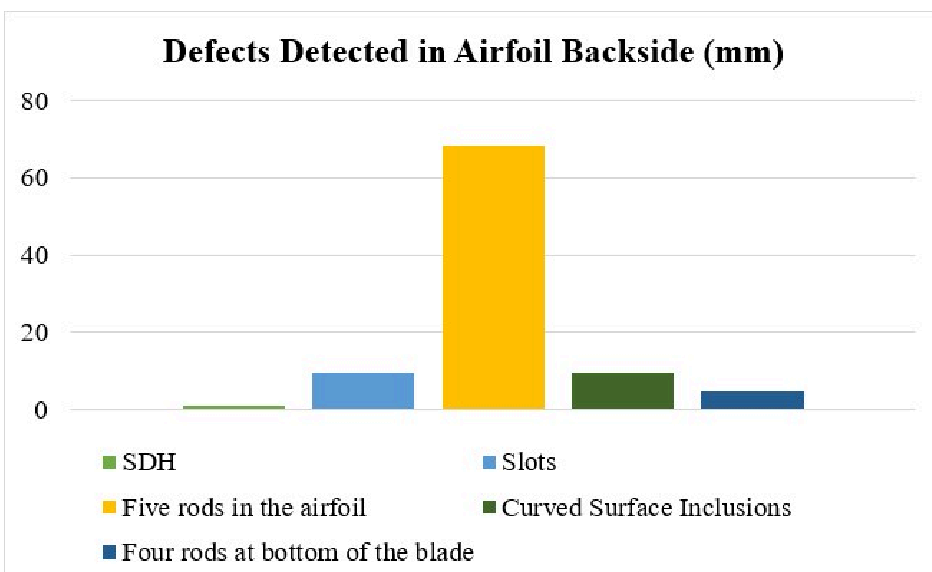

Fig. 8 Defect size in the airfoil section

The different kinds of defects present in the blade were spotted using immersion testing. For the defects like pyramid, star shape, and foreign object debris which got unnoticed using immersion testing, it is advised to use different probe positioning, inspection path and other ultrasonic testing methods to identify flaws at different positions of the blade.

4. Conclusion

In this paper, the assessment of various flaws in the turbine blade using immersion testing is presented. The beam computation results helps in selecting the optimal parameters of probe and it was found that the frequency of 7.5 MHz is appropriate for the inspection of the turbine blade. The artificial defects present in the turbine blade were inspected using immersion ultrasonic testing. The different kinds of flaws located at different positions of the dovetail part and airfoil section of the turbine blade are summarized below:

1. The defects found in the dovetail part of the blade using immersion ultrasonic testing were found as side drill holes of 2 mm diameter, helical spheres of 0.47 to 1 mm, rods of 5.18 mm length attached to the dovetail and holes in the form of trapped powder with 50 µm to 3 mm size.
2. The defects observed from the backside immersion inspection of the airfoil such as slots of 9.7 mm, curved surface inclusion of 9.41 mm, 4 rods of 4.79 mm at the bottom of the airfoil, side drill holes of 0.98 to 1 mm diameter, five rods of 68.56 mm length at the centre of the blade.

From the above-summarized results, it is evident that all the flaws present in the turbine blade can be found using immersion testing of ultrasonic technique with different probe configuration and different projection angles of beam positioning in the blade component.

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