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Research Article

Evaluation Of Foreign Object Damage On The Fan Blades with Microscopic Techniques

Ayhan İsmail KIRCA [a], Seyid Fehmi DİLTEMİZ [b], Sezer YUMRUKAYA [a], Aykut BATAR [a]

[a] *1'inci Hava Bakım Fabrika Müdürlüğü, Eskişehir, TURKEY*
[b] *Department of Aeronautical Engineering, Eskisehir Osmangazi University, Eskişehir, TURKEY*
** Corresponding author's e-mail address: ayhanismailkirca@gmail.com*
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ABSTRACT

Foreign object damage (FOD) is a common problem in gas turbine engines, particularly in the fan and compressor blades. FOD generally occurs when hard body particles are ingested into an aero-engine fan and compressor blade. High-speed impact on fan titanium alloy blades leads to foreign object damage, which weakens the fatigue performance of the blades. It is important to note that FOD can also cause damage that is not visible to the naked eye, such as internal cracks or fatigue damage. Therefore, regular inspections and maintenance are crucial to detect and prevent FOD damage in gas turbine engines. Also using a microscope for the inspection of blades is important. Proper examination of blades damaged by foreign or domestic object can shed light on blade status and prevent further damage in the future. Here are some of the benefits of using a microscope for blade inspection:

Microscopes can provide high magnification and resolution, allowing for detailed inspection of the blade surface and any defects or damage.

Microscopes can help detect and identify small cracks, chips, or other forms of damage that may not be visible to the naked eye.

Microscopes can provide accurate measurements of the blade's dimensions, which can be important for quality control and maintenance purposes.

Microscopes can help identify the root cause of any damage or wear on the blade, which can inform future design and manufacturing decisions.

Microscopes can provide visual documentation of the blade's condition, which can be useful for tracking changes over time and for communicating with other stakeholders.

Overall, using a microscope for blade inspection can help ensure the safety, reliability, and performance of gas turbine engines and other equipment that relies on blades.

In this study, a comparison was made between visual inspection, borescope control, stereo microscope and SEM-EDX microscope methods used in the detection and removal of foreign material damage. The advantages and disadvantages of these 4 methods are comparatively examined and presented to the attention of the reader.

Keywords: *SEM-EDX, Foreign object damage (FOD), Stereo microscope*

Mikroskobik Tekniklerle Pale Hasarının Değerlendirilmesi

ÖZ

Yabancı cisim hasarı (FOD), gaz türbini motorlarında, özellikle fan ve kompresör kanatlarında yaygın bir sorundur. FOD genellikle, sert cisim parçacıkları bir uçak motoru hava alığından girdiğinde oluşur. Titanyum alaşımlı kanatlar üzerindeki yüksek hızlı darbe, kanatların yorulma performansını zayıflatan yabancı cisim hasarına yol açar. FOD'nin iç çatlaklar veya yorulma hasarı gibi çıplak gözle görülemeyen hasarlara da neden

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olabileceğini unutmamak gerekir. Bu nedenle, gaz türbini motorlarında FOD hasarını tespit etmek ve önlemek için düzenli denetimler ve bakım çok önemlidir. Bladelerin incelenmesi için mikroskop kullanılması da önemlidir. Harici veya dahili nesne tarafından hasar görmüş bladelerin uygun şekilde incelenmesi, bladelerin durumuna ışık tutabilir ve gelecekte oluşabilecek daha büyük hasarları önleyebilir. Rotor Blade muayenesi için mikroskop kullanmanın faydalarından bazıları şunlardır:

Kanatçık yüzeyinin ve herhangi bir kusur veya hasarın ayrıntılı olarak incelenmesine izin vererek yüksek büyütme ve çözünürlük sağlar.

Çıplak gözle görülemeyebilecek küçük çatlakları, talaşları veya diğer hasar biçimlerini tespit etmeye ve tanımlamaya yardımcı olur.

Kalite kontrol ve bakım amaçları için önemli olabilecek boyutlarının doğru ölçümlerini sağlar.

Kanatçık üzerindeki herhangi bir hasarın temel nedenini belirlemeye yardımcı olur ve bu da gelecekteki tasarım ve üretim kararları için bilgi sağlar.

Kanatçık durumunun görsel olarak belgelenmesini sağlar ve bu, zaman içindeki değişiklikleri izlemek ve diğer paydaşlarla iletişim kurmak için yararlı olur.

Genel olarak, kanat muayenesi için mikroskop kullanmak, gaz türbini motorlarının güvenilirliğini ve performansını arttırmaya yardımcı olur.

Bu çalışmada yabancı madde hasarının tespitinde ve izalesinde kullanılan göz kontrolü, boroskop kontrolü, stereo mikroskop ve SEM-EDX mikroskop yöntemleri arasında karşılaştırma yapılmıştır. Kullanılan bu 4 yöntemin avantaj ve dezavantajları karılaştırmalı olarak incelenmiş ve okuyucunun dikkatine sunulmuştur.

Anahtar Kelimeler: *: SEM-EDX, Yabancı cisim hasarı (FOD), Stereo mikroskop*

I. INTRODUCTION

Gas turbine engines are motors that operate on the principle of producing thrust or rotational energy through the combustion of pressurized gases and the expansion effect that occurs after combustion. After the primitive version developed by Heron of Alexandria, who produced power with steam reaction before the Common Era, gas turbine engines have made significant progress in modern times [1]. The gas turbine engines used today operate based on the principles of the Brayton Cycle, as formulated by George Brayton (1830-1892) [2].

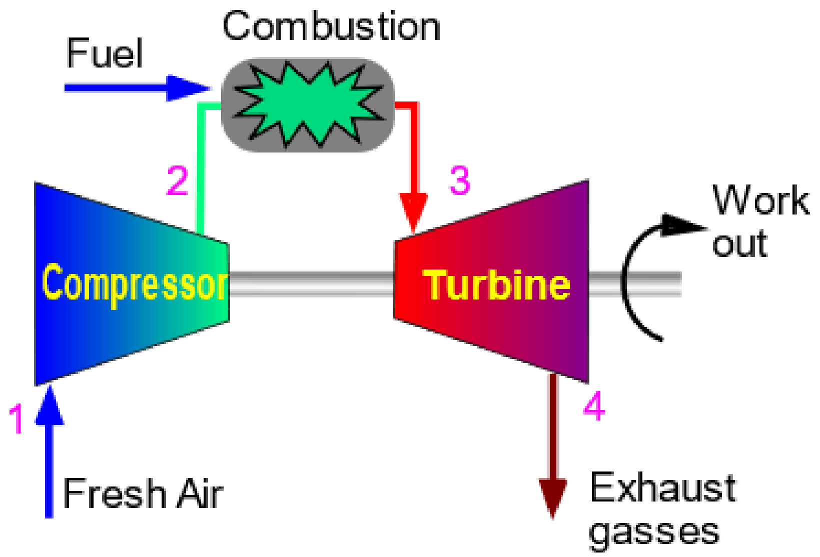

Figure 1. *Gas Turbine Engine* [1]

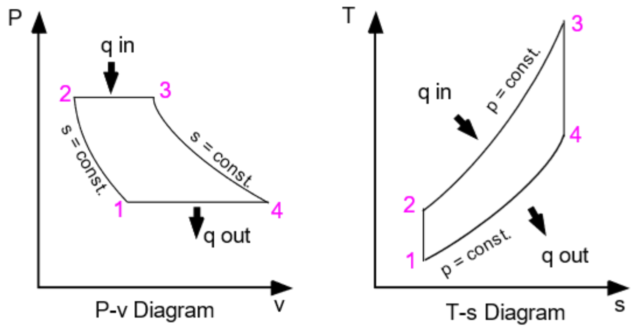

Figure 2. *Brayton Cycle* [2]

The utilization of the Brayton Cycle in aviation marked the beginning of the production of engines closely resembling today's modern counterparts [3]. These engines can generate higher power compared to piston engines and operate effectively at higher altitudes [4]. The specific fuel consumption of jet engines exhibits a decrease in correlation with a reduction in outside air temperature, while maintaining constant revolutions per minute (RPM) and true airspeed (TAS). Pilots can optimize fuel economy and attain the most advantageous cruise speed by operating at elevated flight levels during high-altitude flights [5], [6]

Gas turbine engines aim to efficiently extract work from the intake of air under atmospheric conditions, producing rotational energy or thrust. These engines generally consist of three main sections: the compressor, combustion chamber, and turbine, arranged sequentially from front to back [1]. Compressors can be axial or centrifugal, both serving the purpose of compressing air. During compression, as pressure increases, volume decreases, and the temperature rises due to the compressive effect. In the combustion chamber, compressed air is mixed with fuel and ignited under constant pressure, increasing the temperature and volume of the air. In the turbine section, the high-energy air is converted to mechanical energy to obtain rotation and is used as thrust power at the turbine outlet [5].

Gas turbine engines need to intake a large volume of air to generate high amounts of power. The ingested air may contain substances with sizes that vary based on ambient conditions [5]. This situation can lead to issues such as erosion, corrosion, and foreign object damage [7][8], [9][10]

II. THEORETICAL INFORMATION

A. FOD AND DOD

Gas turbine engines operate by intaking varying amounts of air depending on the engine type, but the ingested air always enters the engine at high speed. The environment from which this air is drawn can vary based on the engine's operating conditions and the mission profile of the aircraft. Depending on changing conditions, aircraft can pull in materials of different sizes, such as sand, gravel, tools, bolts, safety wires, clothing fragments, and even small animals, sometimes on the ground and sometimes during flight [11]. The materials drawn into the engine from the air intakes, especially rotor and stator components, can cause damage. Foreign Object Damage (FOD) refers to the smallest potential damage-causing materials drawn into the engine intakes [11]. When these materials negatively affect the safe operation or performance characteristics of the engine, it is defined as foreign object damage (FOD) [2]. Materials that strike rotor and stator components and cause damage can be from external sources or may be parts of the engine itself that are damaged and detached [12]. Such damages are referred to as

Domestic Object Damage (DOD). Examples include coating peels, breakage of rotor or stator blades, and components like safety wires or loose nuts falling into the airflow path [11].

Despite precautions such as runway cleanliness and meticulous maintenance and repair practices to prevent FOD damage, Foreign Object Damage remains a common type of damage in gas turbine engines due to its inherent nature. [7]

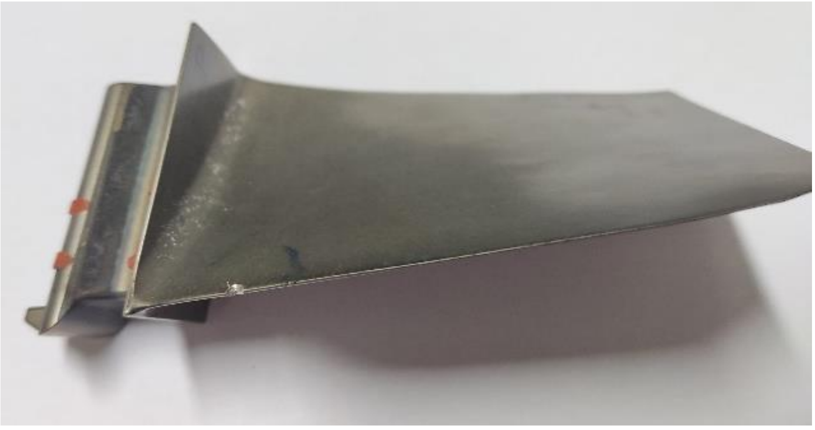

Figure 3. A blade with FOD damage

FOD damage can be within acceptable limits or reach a level that prevents the engine from continuing flight. Repairing the damage often incurs high costs and time loss. Therefore, evaluating FOD on the engine is a crucial aspect.

Various methods are employed to detect FOD damage on the engine and the removed damaged part. These include visual inspection, inspection with a borescope, stereo microscope examination, and scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDX) [10], [12].

B. VISUAL INSPECTION

The human eye can perceive an object of approximately 0.02 mm in size from a distance of 25 cm in a well-lit environment [13]. Visual inspection, which holds a significant place in FOD detection, can aid in identifying foreign objects during aircraft maintenance and cleaning. Visual inspection can be employed to detect foreign materials in critical areas of aircraft engines, such as fan blades, propellers, rims, tires, wings, and other vital components [14].

Visual inspection can be implemented not only by specialized engine personnel but also by all personnel in the aircraft, on the runway, in the aircraft hangar, and in maintenance workshops. In military areas, this visual inspection method, known as "FOD walk," involves personnel walking along taxiways and runways, inspecting the ground [15].

Visual inspection can be seen as a preventive measure against damage rather than a post-FOD occurrence check. However, there are numerous incidents where FOD is visually detected in post-flight inspections after damage has occurred [16].

Despite its advantages in terms of application speed and cost, this method has weaknesses due to the necessity of the application area being open and visually accessible, operator-dependent nature of the method, and its low precision.

C. BORESCOPE INSPECTION

Borescope is an optical and electronic tool used to visualize areas that are not accessible to the naked eye. Typically, it consists of a flexible or rigid tube with a camera at its end that can capture images and has the capability of optical and digital zoom. Additionally, it includes a screen that transmits the captured image to the operator.

Figure 4. *HPT blade borescope image* [17]

Different manufacturing companies can introduce borescope devices with evolving technical features thanks to rapidly advancing technology, and these devices find broader applications. Currently, in borescope devices, while inspections are carried out by operators, devices capable of detection through deep learning with the aid of artificial intelligence are being developed [18].

Existing borescope devices can capture images in wet or dry areas that are inaccessible to the naked eye and can perform limited measurements. For devices without measurement capabilities, a wire with a known measurement can be extended to the area for comparative measurements [19]

Inspections with a borescope are a fast and cost-effective control method. During the design of engines, various areas of the engine can be visualized through borescope ports or various openings placed for this purpose. Routine inspections often lead to the initial detection of FOD using these devices.

D. STEREO MICROSCOPE

Unlike other light microscopes, it can create a three-dimensional visual of the examined sample due to both its illumination path and oblique illumination. Besides this feature, it shares similar characteristics with other light microscopes within the framework of physical laws. Its resolution is typically limited to an average of 200-250 nm. In other words, distinguishing points closer than 200 nm is directly impossible in all light microscopes, including stereo microscopes.

The general light source of light microscopes lies within the visible spectrum, ranging from 400 nm to 700 nm. On the other hand, like other light microscopes, sample preparation is straightforward. Placing the sample on the microscope stage is sufficient to start the examination [20]. Typically, the sample is visualized at magnifications ranging from 10X to 50X. The energy source creating the image is white light through a halogen or LED bulb [21]

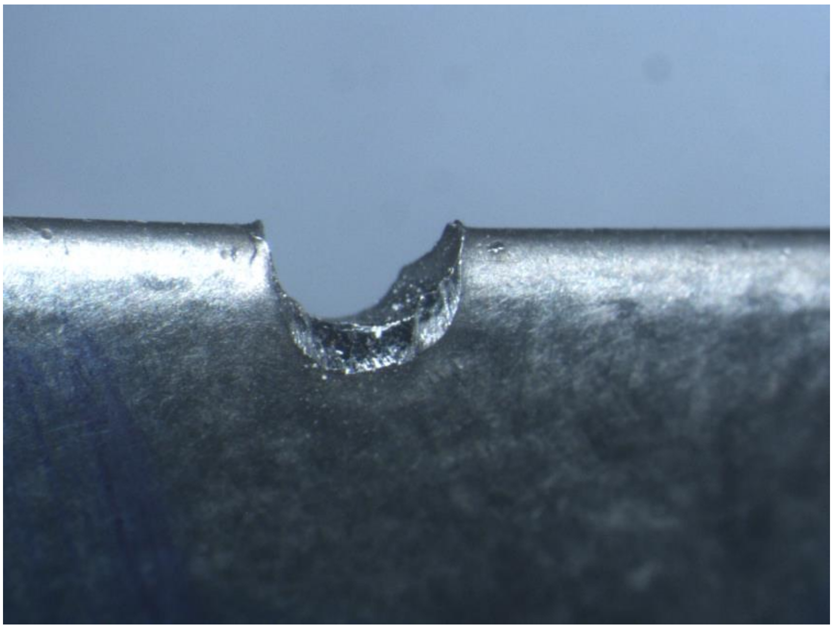

Figure 5. FOD image at 16X magnification.

E. SEM-EDX

SEM-EDX microscope is a type of microscope that surpasses the resolution limit of approximately 200 nm observed in light microscopes, allowing for nanometer-level magnification. Instead of bulbs, an electron gun is used to create the image. The resolution of electron microscopes is below 1 nm, thanks to the shorter wavelength of electrons compared to visible light [22].

In FOD examinations, electron microscopes can benefit from the Secondary Electron (SE) detector, Backscatter Electron (BSD) detector, and the Energy Dispersive X-Ray (EDX) unit that can be added to the electron microscope. These detectors and the unit are particularly useful in diagnosing the foreign object.

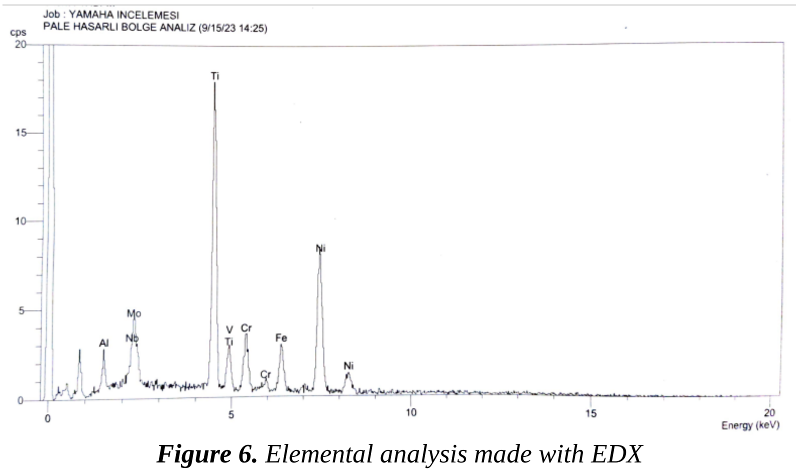

***Figure 6.** Elemental analysis made with EDX*

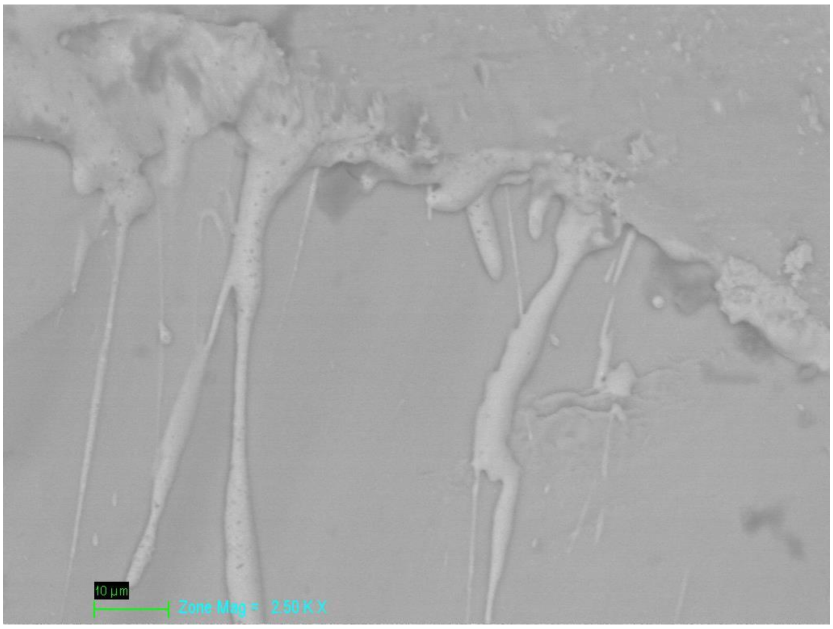

Figure 7. Blade SEM (BSD) image

SEM-EDX microscopes, providing information that cannot be obtained with other methods in FOD examinations due to their high-resolution imaging and elemental analysis capabilities, come with disadvantages such as operational complexity and sample size limitations.

III. COMPARISON

In our study, a comparative evaluation of the examination methods will be conducted in terms of FOD detection and assessment. The comparison will be made under five main categories (speed, cost, precision, subjectivity, accessibility) as discussed separately above.
The compared versions of the methods are presented in the table below, rated from 1 to 5, with 1 being the best and 5 the worst.

Table 1. Comparison of inspection methods

	Visual Inspection	Boroscope Control	Stereo Microscope	SEM-EDX Microscope
Speed	3	5	2	2
Cost	4	4	3	2
Precision	2	2	4	5
Subjectivity	2	2	4	4
Accessibility	5	4	3	2
Total Point	16	17	16	15

A. INSPECTION SPEED

In both civilian and military aviation applications, providing a quick response to encountered problems is crucial for the continuity of operations and cost control. The borescope method is an application that can be implemented without detailed disassembly, requiring only the removal of borescope plugs or parts such as sensors blocking access to the area. For the inspection of hot-section parts like HPT, it is necessary to wait for the engine to cool down [17]. In visual inspection, only the first stages of the compressor or fan part of the engine can be inspected. However, considering FOD, most damage is expected to occur in the first stages. A pre-inspection FOD check by entering through the air intake, if necessary, is crucial. Inspecting the internal parts of the engine requires disassembly, making the borescope method slower in terms of speed. On the other hand, inspections with Stereo and SEM-EDX microscopes are the slowest methods. In many cases, even assembly disassembly may not be sufficient, and part disassembly may be required.

B. INSPECTION COST

Inspection cost is evaluated not only as the cost incurred during the examination of the part but also includes examination time, pre-inspection disassembly, and sample preparation costs. In this regard, the most expensive method is SEM-EDX microscopy because maintaining the microscope constitutes a separate cost item. The maintenance costs of stereo microscopes are relatively low, but the costs of sample preparation and examination are also very low. In addition to the initial investment cost, the costs incurred due to the time spent on the arrival of the damaged part to the stereo microscope and disassembly processes constitute the basic costs of examining with the stereo microscope. Similarly, borescope devices have routine maintenance costs and are prone to damage due to working conditions. It may seem that visual inspection is cost-free, but the training of personnel to perform the inspection and maintaining their high awareness create costs. Moreover, in areas where disassembly is required for visual inspection, waiting and disassembly costs also arise.

C. INSPECTION SENSITIVITY

Among imaging and analysis techniques, the SEM-EDX unit is one of the most sensitive methods, providing an approximate resolution of 1 nm. The analysis resolution of the SEM-EDX technique can be improved by using a higher accelerator voltage that increases the penetration depth of the electron beam and optimizing sample preparation to reduce surface roughness and loading effects. Thanks to the SEM-EDX technique's ability to allow both material surface morphology and material element analysis, the characteristics of the object hitting the sample surface can be largely determined. Therefore, the SEM-EDX technique plays a significant role as a tool in determining ways to prevent FOD. Stereo microscopes usually magnify between 10X and 50X and have an approximate resolution of 200 nm. They can provide information about the direction and even the depth of FOD due to their ability to create three-dimensional images and easily change the direction of the specimen. The resolution of borescopes depends on the device used, camera length, camera diameter, and image sensor. The resolution of borescopes is usually expressed in pixels, ranging from 640 x 480 pixels to 10,000 pixels. As of yet, the measurement accuracy has not reached aviation standards. Borescopes with stereo cameras capable of creating three-dimensional images are available. With advancing technology, it is expected that devices capable of much clearer measurements will be produced in the coming years. Although research has been conducted on the resolution of the human eye, it is not possible to evaluate it as a fixed camera, and a clear resolution value has not been reached. However, a well-trained and precise human eye can yield surprising results.

D. SUBJECTIVITY

Human factors are the most important in FOD formation [23]. Similarly, in the assessment of FOD, the operator is the most critical factor. However, systems like deep learning may change this situation in the future. All mentioned inspection methods require well-trained personnel, emphasizing the importance of human factors in aviation applications. If a ranking is to be made among the methods, visual inspection is the most subjective method, often relying on a person's experiences. If possible, supporting this method with a measuring instrument will significantly reduce the problem. One of the biggest problems encountered in borescope inspections in the field is different evaluations between operators. Especially in inspections conducted with a flexible cable, the camera's approach angle, light intensity, screen resolution, and operator experience can lead to the incorrect assessment of FOD.

E. ACCESSIBILITY

Due to the difficulty of maintenance, cost, and low frequency of use, it would not be effective to have an SEM-EDX microscope at every center where an aircraft is located. Because not every FOD incident may require action; only those beyond limits need to be removed. Similarly, stereo microscopes, and even borescope devices, may not be present at every airport. Visual inspection, on the other hand, is a quick and widespread control type performed by both the mechanic and flying personnel before and after each flight.

IV. CONCLUSION

The detection of FOD damage is crucial for flight safety. Visual inspection and borescope examinations stand out as methods with application speed and ease in damage detection. Failure to detect FOD or DOD material at the right time can compromise the material's durability, leading to significant damages, including loss of life. When evaluating the importance of these two methods and their dependence on implementing personnel, the relationship between FOD and awareness becomes apparent.

After the detection of FOD, detailed evaluations highlight the control methods with Stereo microscopes and SEM-EDX microscopes. The Stereo microscope is essential in FOD inspections due to its relatively easy application, measurement precision, and reporting capabilities. SEM-EDX microscopes, while having the most challenging application, can provide highly accurate results that other methods may not reach. Moreover, they can offer insights into the source of FOD in ways not possible with other methods. Accurate efforts to eliminate FOD sources will only be possible through the correct examination of FOD.

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