

TAXONOMY OF GAS TURBINE BLADE DEFECTS

Introduction

1. **Context.** Maintenance of aero engines is intricate, time-consuming, and costly and has significant functional and safety implications. Engine blades and vanes are the most rejected parts during engine maintenance. Consequently, there is an ongoing need for more effective and efficient inspection processes.
2. **Purpose.** This paper defines engine blade defects, assigns root-causes, shows probable causes and cascade effects and provides a taxonomy system.
3. **Background.** The operation of modern gas turbines demands ever higher temperatures, pressures and rotational speeds to increase power and improve efficiency. This ultimately creates a strenuous environment for engine parts, particularly engine blades. Those blades are subject to high stress resulting from exposure to extreme operating conditions, such as high centrifugal loads, high temperatures, high pressures and vibration. Blade failure and severe damage to the engine and airframe can be caused by each of these factors which can result in loss of life of aircraft occupants. Most defects that can lead to failures are detected during maintenance inspection before any negative effects appear on flight operations. The maintenance inspection is primarily by visual means. The most rejected engine parts are blades and vanes from compressor and turbine sections. During engine maintenance, the first step of the inspection process comprises that all blades are visually inspected for defects or indications of damages. Boroscopes are the most important optical aid to visually inspect the inside of the engine, which is otherwise inaccessible.
4. The inspector has to examine the blades and identify surface discontinuities, deviations or anomalies, and quantify their intensity. In order to make a final decision on whether a part is serviceable, repairable or has to be replaced, NDT methods are employed. For simplification, here the term '**blade**' is used for both blades in the compressor and turbine section, and for turbine vanes.

Defects and Causes

5. **Defect.** In the aircraft maintenance discipline, the term 'defect' is used to represent a component failure mode, which arises either from an intrinsic defect or an external event, and which becomes evident over time.
6. **Defect Categorization.** The defect categories include 'Surface Damage, Wear, Material Separation and Material Deformation'. In parallel, potential causes grouped by the nature of the root cause are described. This list includes such items as 'Environmental Impact, Operational Failure and Fatigue'. Four main damage categories are enumerated below:-
 - a. **Surface damage.** Surface damages describe deviations from the nominal surface, such as roughness, waviness, lay and flaws. This may include material separation and/or loss of base material or coating. It is often aggravated by high air temperature, humidity, moisture and contaminated environments, such as salt from sea or de-icing treatments.
 - b. **Wear.** The material removal from the part by mechanical means is called wear. This can be caused by foreign object impact, such as grit, sand or ground debris.
 - c. **Material separation.** This describes a condition whereby material is split but not removed. An example for this damage is crack. Material separation is often caused by foreign object impact and operational means leading to overheating or loss of cooling.
 - d. **Material deformation.** Material deformation is notable by significant change of the original contour of the part. The deformation can be caused by mechanical or thermal means.
7. The resulting categorized defects are attached as **Annex A**.
8. **Categories of Causes.** There is a myriad of potential items that can cause a defect. The structured cause list is attached as **Annex B**.
9. **Defect versus Cause.** The inter-relations of defects with causes were then identified and the causes assigned to the defects. The cause-defect list is believed to be adequate for the maintenance audience since it has been validated in that field, but it may not be sufficiently exhaustive for the accident investigation audience. The defect-cause relation is explained in **Annex C**.

BLADE DEFECT LIST

1. Surface Damage (Material separation and/or loss)

1.1. Corrosion

1.1.1. Oxidation

1.1.2. Pitting

1.1.3. Sulfidation

1.2. Burns

1.3. Blistering

1.4. Erosion

1.4.1. Guttering

1.5. Deposits (No material separation or loss, but additional particles on surface)

2. Wear (Material removal)

2.1. Abrasion

2.2. Gouge

2.3. Groove

2.4. Score

3. Material separation

3.1. Chipping

3.2. Crack

3.3. Breaking

3.4. Nick

3.5. Tear

4. Material Deformation (Change of contour)

4.1. Bent

4.2. Bow

4.3. Bulge

4.4. Burr

4.5. Battered

4.6. Creep

4.7. Curl

4.8. Dent

4.9. Peening

4.10. Scratch

4.11. Waviness

CATEGORIZATION OF DEFECT CAUSES

1. Impact

1.1. Foreign Object Damage (FOD)

- 1.1.1. Grit
- 1.1.2. Fine sand
- 1.1.3. Dust
- 1.1.4. Ground debris
- 1.1.5. Left-behind items

1.2. Known Object Damage (KOD)

- 1.2.1. Broken off pieces from upstream engine parts
- 1.2.2. Abrasion from worn parts

1.3. Organic

- 1.3.1. Birds
- 1.3.2. Wildlife

1.4. Weather

- 1.4.1. Ice
- 1.4.2. Hail

2. Environmental

2.1. Intake air contaminants

- 2.1.1. Polluted air
- 2.1.2. Volcanic ash
- 2.1.3. Deposited salts from sea or runway de-icing
- 2.1.4. Agricultural chemicals
- 2.1.5. Moisture

2.2. Accelerated by:

- 2.2.1. Warm air temperatures
- 2.2.2. Acids

3. Operational

3.1. Overheating

- 3.1.1. Abnormal flame pattern
- 3.1.2. Incorrect burning process
- 3.1.3. Lack of lubrication
- 3.1.4. Improper clearance
- 3.1.5. Complex thermal and mechanical loads

- 3.1.6. Overload
- 3.1.7. Heavy landings
- 3.1.8. Turbulences
- 3.1.9. Compressor surge
- 3.1.10. Aggressive environment

3.2. Loss of cooling

- 3.2.1. Blocked cooling passages
- 3.2.2. Blockage or malfunction of the cooling airflow

3.3. Sulphur deposits

- 3.3.1. Sulphurous jet fuel
- 3.3.2. Sulphur oxides from combustion or airborne salts

3.4. Damaged bonding caused by:

- 3.4.1. Aggressive gases
- 3.4.2. Pressure
- 3.4.3. Excessive heat

3.5. KOD as by-products of operation

- 3.5.1. Excessive oil burn
- 3.5.2. Carbon particles
- 3.5.3. Particles of ceramic thermal barrier coatings
- 3.5.4. Fuel (ash content)
- 3.5.5. Particles resulting from wear

3.6. Vibrations

- 3.6.1. Improper operation
- 3.6.2. Hard landing

3.7. Aggravated by massive air flow

- 3.7.1. Hot gases
- 3.7.2. Corroding liquids
- 3.7.3. Dirt-laden oil
- 3.7.4. Turbulences

4. Poor Maintenance

- 4.1. Improper assembly or disassembly
- 4.2. Careless handling of part or tools
- 4.3. Left behind hand tools or parts in engine
- 4.4. Disregard of (inspection) procedures
 - 4.4.1. Use of prohibited metallic pencils (for markings)
 - 4.4.2. Missed tip clearance check

4.4.3. Not performed or improper repair

4.5. Use of corrosive agent

4.5.1. Fire extinguisher agents

5. Poor Manufacturing

5.1. Improper bond

5.2. Incomplete bonding

5.3. Defective coating

5.4. Internal stresses (from machining)

5.5. Defective (raw) material (This could be a material defect, e.g., wrong alloy, composition, microstructure

or inclusions, or a faulty process, such as casting or forging or heat treatment.)

5.6. Missed or improper deburring after machining

6. Fatigue

6.1. Random stress fluctuations

6.2. Stress concentrations

6.3. Surface finish

6.4. Residual stresses

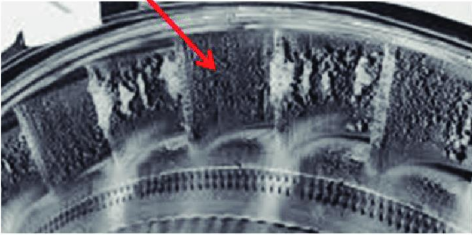

6.5. High cycle fatigue


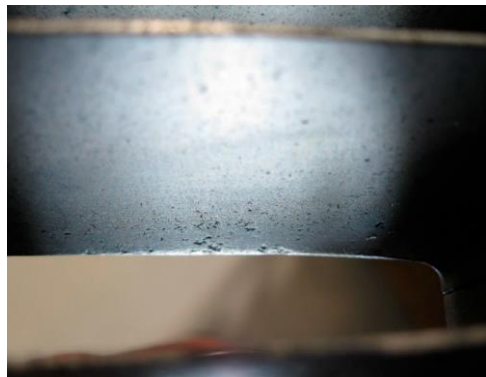
6.6. Thermal fatigue



6.7. Life time of part exceeded

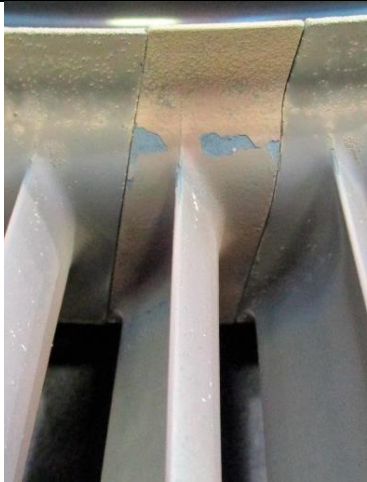

6.8. Shorten lifecycle caused by operational means



ROOT - CAUSE AND DEFECT LIST

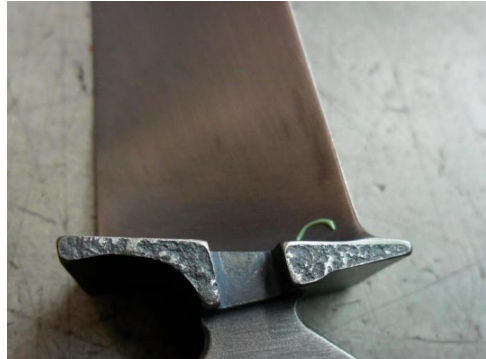
Defect	Equally Used Terms	Description	Potential Causes	Sources of Cause	Image
1. Surface Damage	Surface texture	Deviations from the nominal surface, such as waviness, roughness, lay and flaws [60]. May include material separation and/or loss of material or coating.	-	-	 <p>An Example of Surface damage</p>
1.1. Corrosion		Definition: Slow deterioration of part surface or its coating by a chemical or electrochemical reaction with atmospheric or hot gas contaminants in the working environment. Parts made of aluminium and high strength alloys, as well as some stainless steels can corrode when exposed to tensile stresses.	1. Environmental 2. Poor Maintenance 3. Operational	1.1. Intake air contaminants 1.1.1. Pollution and soot from industry or forest fires 1.1.2. Volcanic ash 1.1.3. Salt deposits from sea air or de-icing treatments 1.1.4. Agricultural chemicals 1.2. Accelerated by: 1.2.1. Warm temperatures 1.2.2. Salts 1.2.3. Acids 2.1. Carbon alloy or metallic pencils (used for markings) 2.2. Corrosive agent 2.2.1. Fire extinguisher Agents 3.1. Higher burning temperatures 3.1.1. Complex thermal and mechanical loads 3.1.2. Overload 3.1.3. Aggressive environment	 <p>Corrosion pitting and de-colorization of stage 4 vane</p>



Defect	Equally Used Terms	Description	Potential Causes	Sources of Cause	Image
1.1.1. Oxidation	Rusted	Definition: Chemical reaction between oxidants or other corrosive contaminants in the hot gases and the blade surface (coating), or in its absences, with the base alloy.	1. Pre-existing damages	1.1. Missing coating 1.1.1. Impact	 <p>Oxidized deposits on Blades</p>
			2. Environmental	2.1. Salt deposited on the surface reacts with ferrous-based metals or deposits when getting into contact with moisture-laden air 2.2. Chemical reactions of the part with intake are contaminants	
1.1.2. Pitting	Pustules	Definition: Small, irregularly shaped cavities or hollows, usually dark bottomed, in the blade surface, whereby material has been removed by corrosion or chipping. Sulphidation of pitting holes is called sulphidation pits or pustules.	1. Pre-existing damages	1.1. Corrosion 1.1.1. Breakdown of surface by oxidation 1.1.2. Chemical reaction due to corrosive contaminants	 <p>Pitting on stator vane airfoil</p>
			2. Operational	2.1. Overloading 2.2. Inclusion removal in operation mode 2.3. Presence of unwanted particles	
			3. Impact	3.1. FOD 3.2. KOD (Para 1.2, Anx B) 3.3. Organic damage	




Defect	Equally Used Terms	Description	Potential Causes	Sources of Cause	Image
1.1.3. Sulfidation	Sulphidation	<p>Definition: Sulfidation, or sulphur corrosion describes a chemical process whereby sulphur containments in the ingested air reacts with the coating and/or base material of engine blades under heat influence. This defect can be found in the engine's turbine hot section where temperatures are high. It appears as a greenish to pale blue discolouration and as raised, blistered surface similar to corrosion pits.</p>	<ol style="list-style-type: none"> 1. Environmental 2. Operational 	<p>1.1. Sulphur containments in intake air in form of: 1.1.1. Deposited salts 1.1.2. Agricultural chemicals 1.1.3. Airborne particles from forest fires 1.1.4. Polluted air</p> <p>2.1. Sulphurous jet fuel 2.2. Sulphur oxides from combustion and airborne salts, such as sodium, react with water (by-product of fuel combustion) and creates a sulfuric acid.</p>	 <p>Sulfidation on blade root</p>
1.2. Burns	<ul style="list-style-type: none"> •Burnings •Charred •Overheated 	<p>Definition: Surface and/or structural damage due to excessive heat, visible as stain or discoloration and, in severe cases, by loss or flow of material. Often the term 'overheated' is misleadingly used as a defect. In fact, 'overheated' is the cause and 'burns' are one possible consequence of it. The V2500 Engine Manual further distinguishes between:</p> <ol style="list-style-type: none"> 1. Burn through: Local burn area that has continued through the aerofoil surface. 2. Trailing edge burns: Burns or burn through that start at the airfoil trailing edge and continue forward to the airfoil leading edge. 3. Lift-up: Surface on one side of the crack is higher than on the other side. 4. Coating damage: See: '1. Surface Damage' 5. Connected loop crack: A crack or a group of cracks that show an isolated area of vane metal. 	<ol style="list-style-type: none"> 1. Operational 2. Environmental 	<p>1.1. Excessive heat 1.1.1. Abnormal flame pattern 1.1.2. Incorrect burning process or parameters 1.1.3. Lack of lubrication 1.1.4. Improper clearance 1.1.5. Overloaded 1.1.6. Hard landing 1.2. Insufficient cooling 1.2.1. Blocked cooling passages 1.2.2. Blockage or malfunction of the cooling airflow</p> <p>2.1. Aggravated by high air temperature 2.2. Aggravated by heat, moisture, and contaminated environment</p>	



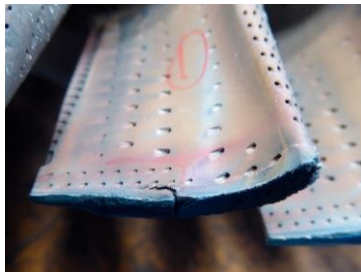
Defect	Equally Used Terms	Description	Potential Causes	Sources of Cause	Image
					Burned blade with burn through
1.3. Blistering	Exfoliation Flaking Peeling	Definition: Raised areas that indicate a separation of pieces of a coated surface from a base metal, often evident as peeling and/or flaking.	1. Operational	1.1. Damaged bonding by: 1.1.1. Aggressive gases 1.1.2. Pressure 1.1.3. Excessive heat	
			2. Environmental	2.1. Contaminants in airborne	
			3. Poor manufacturing	3.1. Improper bond 3.2. Incomplete bonding 3.3. Defective coating	
1.4. Erosion		Erosion describes the surficial abrasion of material by the flow of fluids or gases and thus leads to wear and destruction of engine parts. Heat or particles in the hot gases accelerates this process. The impact of particles typically larger than 20 fm is especially apparent on the leading edge of the blade. It is visually recognizable by a rough surface with stripes or marks in the direction of the particle; often in the air flow direction. The amount of particles entering the engine and leading to erosion is significantly higher during landing and take-off	1. impact	FOD: Solid particle impacts 1.1.1. Grit 1.1.2. Fine sand 1.1.3. Dust 1.1.4. Ground debris 1.2. KOD: Broken-pieces from upstream engine parts	
			2. Environment	2.1. Moisture 2.1.1. Water droplets on inlet edge of a rotating blade 2.2. Salty air 2.3. Polluted air	
			3. Operational	3.1. KOD: By-products of operation 3.1.1. Excessive oil burn 3.1.2. Carbon particles (from fuel injection) 3.1.3. Particles of ceramic thermal carrier coatings (detaching due to thermal shock) 3.2. Aggravated by massive air flow	



Defect	Equally Used Terms	Description	Potential Causes	Sources of Cause	Image
					<div><p>Deposits on vane</p></div> <div><p>Deposits on blade</p></div>



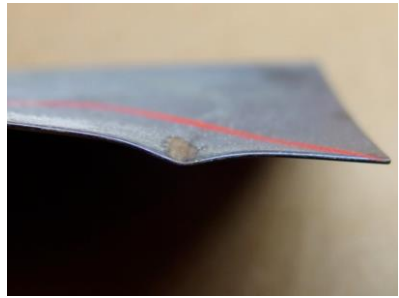
Defect	Equally Used Terms	Description	Potential Causes	Sources of Cause	Image
2. Wear		Material removal from the part by mechanical means.			
2.1. Abrasion	<ul style="list-style-type: none"> •Chafing •Fretted •Galling •Scuffed •Scraped 	<p>Definition: Abrasion or galling describes a roughened area usually caused by severe chafing or fretting action resulting from slight relative movement of two surfaces under high contact pressure during engine operation. The damage characteristics include microstructure changes of the part surface material or coating, surfaces debris, wear or material removal and reduced fatigue capability. The degree of abrasion varies from 'light' to 'heavy' depending upon the extent of reconditioning required to restore the worn surface. The abrasion effect is accelerated by the presence of foreign material in addition to the detached abrasion material. Chafing is often used as synonym for the same defect description. However, chafing shall be understood as action resulting in deterioration of the surface condition rather than as the description of the damage itself.</p> <p>Note: Not to be confused with scores, scratches or gouges.</p> <p>Example:</p> <ul style="list-style-type: none"> • Relative motion between blade lock or lock nut and dovetail slot. Also called 'blade platform frettage'. • Movement and rubbing of clappers. 	1. Operational	1.1. Wear 1.1.1. Particles from abrasion are self-accelerating 1.2. Abnormal relative movement of parts 1.3. Parts out of alignment	 <p>Abrasion of blade cheeks</p>
			2. Environmental	2.1. FOD 2.1.1. Unwanted material between parts	

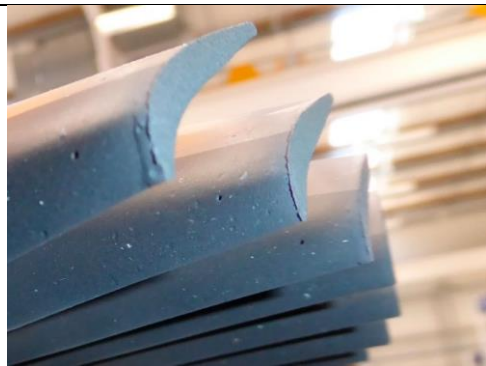

Defect	Equally Used Terms	Description	Potential Causes	Sources of Cause	Image
2.2. Gouge	Gouging	Definition: A furrowing condition where material from the surface has been displaced and removed by cutting or tearing action.	1. Impact	.1. FOD 1.1.1. Large, sharp unwanted foreign object 1.2. KOD	 <p>Gouge on retaining slot of a blade</p>
			2. Poor Maintenance	2.1. Improper (dis-) assembly 2.2. Careless handling	
2.3. Groove	<ul style="list-style-type: none"> •Fluted •Furrowed 	Definition: A smooth, rounded furrows, such as tear marks, whose edges have been polished due to concentrated wear.	1. Operational	1.1. Concentrated wear 1.2. Abnormal relative motion of parts 1.3. Parts out of alignment	

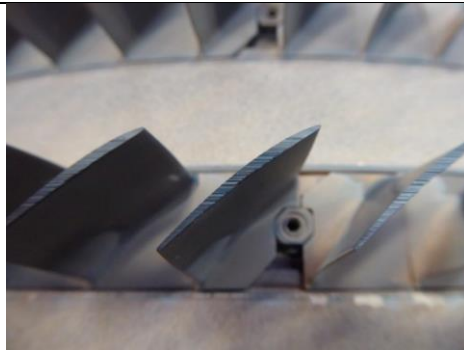
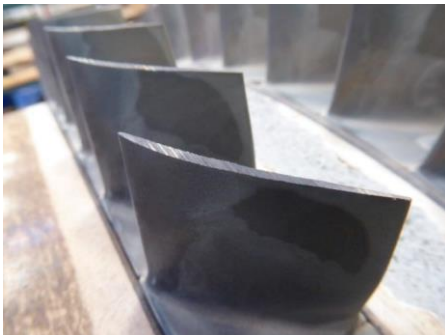
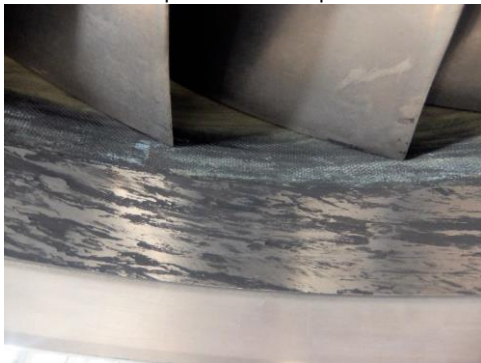
Defect	Equally Used Terms	Description	Potential Causes	Sources of Cause	Image
					 <p>Groove in retaining slot of blade</p>
2.4. Score		Definition: Multiple scratches of significant depth are called a score, which is often caused by sharp objects during engine operation. Contrary to scratches, scores show some removal of material.	1. Operational	1.1. KOD 1.1.1. Presence of chips between parts	
			2. Poor Maintenance	2.1. Careless assembly or disassembly techniques	
			3. Impact	3.1. FOD 3.2. KOD 3.3. Organic damage	 <p>Fan blade scoring</p>



Defect	Equally Used Terms	Description	Potential Causes	Sources of Cause	Image
3. Material Separation		Material is split but not removed.			
3.1. Chipping	Spalling	<p>Definition: Chipping describes mechanical separation of small pieces of blade material or coating often apparent on edges, corners or surfaces leaving a sharply roughened area of irregular shape. Often apparent on clappers.</p> <p>Note: Not to be confused with flaking.</p>	<p>1. Pre-existing defects</p> <p>2. Poor maintenance</p> <p>3. Impact</p>	<p>1.1. Excessive stress concentration 1.1.1. Nicks 1.1.2. Surface cracks 1.1.3. Scratches 1.1.4. Peening 1.2. Fatigue 1.3. Subsurface inclusions</p> <p>2.1. Careless handling 2.2. Improper (dis-)assembly</p> <p>3.1. FOD 3.2. KOD</p>	 <p>Clapper wear on rotor blade</p>
3.2. Crack	Fissure	<p>Definition: A material separation or partial fracture of material evidenced as a linear opening that can easily be seen and which can cause the material to break. The depth can vary from a few thousandths of the full part's thickness to its full thickness. The latter usually leads to full breakage of the part into one or more pieces. A crack is often an expansion of a pre-existing defect such as a nick, scratch or gouge.</p> <p>Note: Not to be confused with a hairline crack, which cannot be detected by the naked eye and where special fluorescent or magnetic penetrants are required to detect the defect.</p>	<p>1. Impact</p> <p>2. Operational</p> <p>3. Pre-existing defects</p> <p>4. Fatigue</p> <p>5. Poor maintenance</p> <p>6. Poor</p>	<p>1.1. FOD 1.2. KOD 1.3. Organic damage</p> <p>2. Overheating 2.1.1. Localised hot spots 2.1.2. Overload 2.1.3. Hard landing 2.2. Vibrations</p> <p>3.1. Corrosion 3.2. Nicks 3.3. Scratches 3.4. Scores 3.5. Gouges</p> <p>4.1. Random stress fluctuations 4.2. Stress concentrations 4.3. Surface finish 4.4. Residual stresses 4.5. High cycle fatigue 4.6. Thermal fatigue</p> <p>5.1. Careless handling of parts or tools 5.2. Improper disassembly 5.3. Left behind hand tools</p> <p>6.1 Internal stresses (from machining)</p>	 <p>Blade cracked airfoil</p>  <p>Crack in blade tip</p>

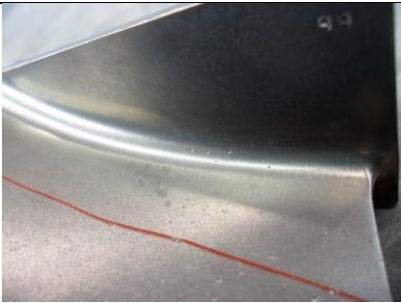


Defect	Equally Used Terms	Description	Potential Causes	Sources of Cause	Image
3.3. Breaking	<ul style="list-style-type: none"> •Burst •Breakage •Break-off •Broken •Cut •Fracture •Liberation •Rupture 	Definition: Complete separation of a blade into two or more large-sized pieces by an external force or internal stresses. Different defects, such as cracks, nicks, dents and notches, often precede and lead in combination with one of the causes to material separation and a broken engine blade.	manufacturing Resulting from pre-existing defects in combination with: 1. Impact 2. Fatigue	6.2. Defective (raw) material Cracks, nicks, dents, notches! 1.1. FOD 1.1.1. Left behind items 1.2. KOD 1.3. Organic impact 2.1. Thermo-mechanical creep 3.1. Stresses caused by heat 3.2. Sudden overload	 <p>Broken blade</p>
3.4. Nick	Notch	Definition: A small, sharp cut on the surface or edge of a part caused by a striking object. A nick has a characteristic V-shaped bottom, breaks the material flow and concentrates stresses. This weak point may initiate the development of cracks, leading to a decreased lifetime of the blade. The damage occurs often at or close to the leading edge of a blade.	1. Impact 2. Poor maintenance	1.1. FOD 1.1.1. Sand 1.1.2. Fine unwanted particles 1.2. KOD 1.3. Organic damage 1.3.1. Birds 1.3.2. Wildlife 2.1. Careless handling of parts or tools 2.2. Improper (dis-)assembly	 <p>Fan blade trailing edge nick</p> <p>Compressor stage 8 blade</p>


Defect	Equally Used Terms	Description	Potential Causes	Sources of Cause	Image
3.5. Tear		Definition: Separation of material by tensile stresses imposed by a sharp object. A nick may have been pre-existent and was enlarged by a heavy impact. It is apparent by ragged or irregular edges.	May result from pre-existing defects in combination with or by: Impact	1.1. FOD 1.1.1. Significant tough and sharp foreign object 1.1.2. Left-behind items 1.2. KOD	 <p>blade tear after organic impact</p>
4. Material Deformation		Extensive change of the original contour of a part.			
4.1. Bent	<ul style="list-style-type: none"> •Creased •Distorted •Folded •Kinked •Leaning 	Definition: Angular change from the original shape or contour usually the cause is a lateral force.	1. Impact (lateral)	1.1. FOD 1.2. Organic impact 1.2.1. Bird ingestion	 <p>Blade bent</p>  <p>Blade bent</p>

Defect	Equally Used Terms	Description	Potential Causes	Sources of Cause	Image
4.2. Bow	Bowed	Definition: A bow is a stress-included bent or curve in the blade or vane contour. In comparison to bent damage, bows are indicated by larger curve radii. Additionally, the damage is caused by internal stresses arising from excessive heat, pressure, or forming, rather than by lateral impact resulting from foreign object hits.	1. Operational	1.1. Excessive heat 1.2. Uneven application of heat 1.3. Structural stresses 1.4. Thermal overload	
4.3. Bulge	<ul style="list-style-type: none"> •Ballooned •Bulged •Swelling 	Definition: An outward bending or swelling of displaced material without separation resulting from excessive heat. This defect often occurs on the leading edge.	1. Impact	1.1. FOD (dull objects) 1.2. Organic impact	
			2. Operational	2.1. Excessive heat	
4.4. Burr	<ul style="list-style-type: none"> •Raised edge •Raised imperfection •Ridge 	Definition: A narrow ridge of material, roughed edge or imperfection on the surface of a material raised above the general contour of the part. It is most likely appears along an edge	1. Poor manufacturing	1.1. Missed or improper deburring after machining	 <p>Burr on blade tip resulting from tip rub</p>
			2. Environmental	2.1. Excessive wear 2.2. Deposits	
			3. Impact (sharp hitting object during operation)	3.1. FOD 3.1.1. Ice or hail 3.1.2. Sharp objects 3.1.3. Left-behind items 3.2. KOD	
4.5. Battered		Definition: Damage on a part that is repeatedly hit and as a consequence severely deformed.	1. Impact	1.1. FOD 1.1.1. Hail 1.1.2. Ice 1.1.3. Ground debris	 <p>Heavy battered fan blade</p>

Defect	Equally Used Terms	Description	Potential Causes	Sources of Cause	Image
4.6. Creep	<ul style="list-style-type: none"> •Elongation •Growth •Stretched 	<p>Definition: Continuous stretch or deformation of a part in operation under high temperatures, and/or centrifugal loads and high rotational speeds (latter impacts rotating parts only). Creep is predominant in the engine's hot section (turbine) and in the last blade stages of high-pressure compressors (HPC), whereby the blades elongate towards the surrounding shroud case, and the shrouds expand under thermal influence. In order to improve the engine efficiency, the clearance between blades and casing shall be kept as minimal as possible. When heavy operations cause severe blade elongation, the blade tips rub against the non-moving shrouds. The resulting damage is known as tip rub. The V2500 engine manual further distinguished between:</p> <ul style="list-style-type: none"> • Leading edge tip rub • Mid chord tip rub • Trailing edge tip rub 	1. Operational	1.1. Loss of cooling 1.1.1. Blocked cooling passages 1.1.2. Blockage or malfunction of the cooling airflow 1.2. Continued and/or extensive heat accelerated by high rotating speeds and centrifugal forces 1.2.1. Turbulences 1.2.2. Heavy landings 1.2.3. Overloaded 1.3. Deposits on casing 1.4. Compressor surge	
			2. Fatigue	2.1. Creep cracking 2.1.1. Random stress fluctuations 2.1.2. Stress concentrations 2.2. Life time of part exceeded 2.3. Shortened lifecycle caused by operational means	
			3. Poor maintenance	3.1. Inspection procedures not correctly followed 3.1.1. Missed tip clearance check 3.1.2. Not performed or improper repair, e.g., blades not trimmed to restore minimum tip clearance	<p>Compressor blade Tip rub</p>  <p>Fan blade tip rub against fan case</p>

Defect	Equally Used Terms	Description	Potential Causes	Sources of Cause	Image
4.7. Curl	<ul style="list-style-type: none"> •Twisted •Warped 	Definition: A rounded fold in a rotating part after contact with a fixed, non-moving part. This defect can be observed after a blade tip rubbed against the engine case (see 'tip rub').	1. Tip-rub	1.1. Elongation/creep of blade 1.1.1. Heavy landings 1.1.2. Overloaded 1.2. Deposits on casing 1.3. Compressor surge 1.4. Missed maintenance inspection or incorrect procedures during maintenance inspection of tip clearance	 <p>Compressor blade tip curl</p>
4.8. Dent		Definition: Damage to the surface of a part caused by mechanical impact of a dull object. A dent is visible as small, smooth indentation with rounded edges, corners and bottom. Material is displaced but not removed. Often, dents can be found at or close to the leading edge of a blade. A cluster of multiple dents on the leading edge can result in waviness of the blade.	1. Impact	1.1. FOD 1.1.1. Hail 1.1.2. Ice 1.1.3. Left-behind items 1.2. KOD 1.3. Organic damage 1.3.1. Birds 1.3.2. Wildlife	 <p>Dent on leading edge of vane</p>

Defect	Equally Used Terms	Description	Potential Causes	Sources of Cause	Image
4.9. Peening		A group of very small dents caused when a part is repeatedly hit is called peening	1. Impact	1.1. FOD 1.1.1. Hail 1.1.2. Ice	 <p>Blade root</p>  <p>Compressor blade</p>
4.10. Scratch		Definition: Shallow, thin lines, marks or dragged indentations on either the coating (if present) or the material surface caused by movement of sharp foreign objects, careless handling or improper assembly. Scratches have a sharp bottom and material is usually not removed.	1. Impact 2. Poor maintenance	1.1. FOD (fine foreign particles) 1.1.1. Airborne particles 1.1.2. Fine sand and dust 1.1.3. Polluted air 1.1.4. Volcano ash 2.1. Careless handling of parts or tools 2.2. Improper (dis-) assembly	 <p>blade scratched on airfoil surface</p>

Defect	Equally Used Terms	Description	Potential Causes	Sources of Cause	Image
4.11. Waviness		An engine blade that has been deformed under influence of high temperatures is called waviness (The term 'waviness' originates from the FAA Aviation Maintenance Handbook).	1. Operational	1.1. Loss of cooling 1.2. Continued and/or extensive heat accelerated by high rotating speeds and centrifugal forces 1.2.1. Turbulences 1.2.2. Heavy landings 1.2.3. Overloaded	

BIBLIOGRAPHY

1. Yusra Abdulrahman, M. A. Mohammed Eltoum. Aero-Engine Blade Defect Detection: A Systematic Review of Deep Learning Models, 12 May 2023.
2. Available online at <https://www.linkedin.com/pulse/aircraft-engine-blade-damages-contribution-health-tanmay-palei>
3. Jonas Aust and Dirk Pons. Taxonomy of Gas Turbine Blade Defects, 4 April 2019
4. Maria Grazia De Giorgi, Nicola Menga and Antonio Ficarella. Exploring Prognostic and Diagnostic Techniques for Jet Engine Health Monitoring: A Review of Degradation Mechanisms and Advanced Prediction Strategies, 31 January 2023
5. Poppy Puspitasari, Andoko Andoko, Pradhana Kurniawan. Failure analysis of a gas turbine blade: A review, 2020.
6. Xubo Li, Wenqing Wang, Lihua Sun, Bin Hu, Liang Zhu & Jincheng Zhang. Deep learning-based defects detection of certain aero-engine blades and vanes with DDSC-YOLOv5s, 2022.
7. Jonas Aust, Sam Shankland, Ramakrishnan Mukundan, Antonija Mitrovic. Automated Defect Detection and Decision-Support in Gas Turbine Blade Inspection, January 2021