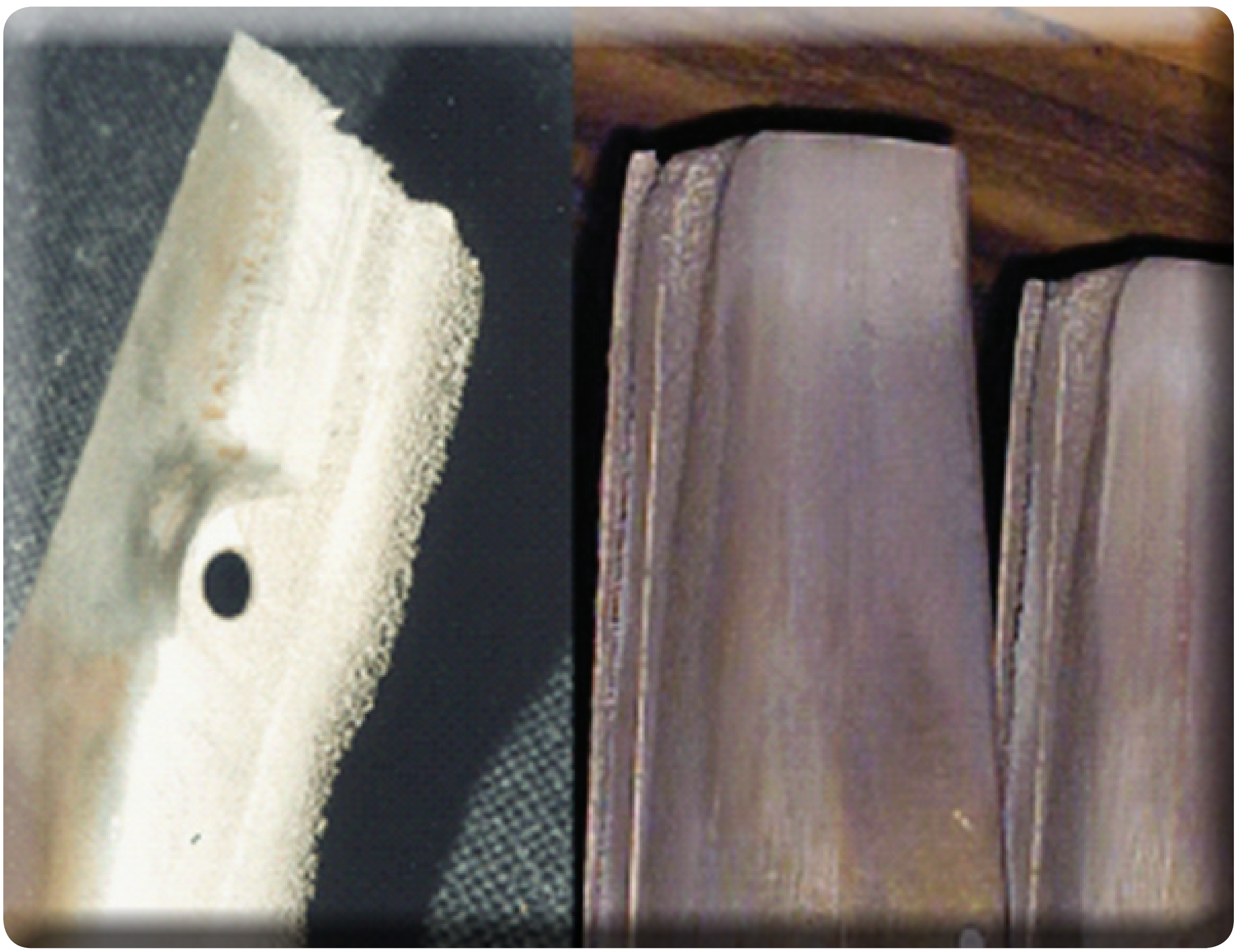
SOLID PARTICLE AND LIQUID DROPLET EROSION:
TESTING, MODELING, AND APPLICATIONS

CONFERENCE PROGRAM

June 18–19, 2012 • Milan, Italy

Co-Sponsored by the EPRI and RSE S.p.A.



BACKGROUND

Solid particle erosion (SPE) of steam turbine blades, nozzles, control valves, and radial seals has been a problem of concern for steam turbine operators for many decades. Reports on the effects of SPE on turbine efficiency and maintenance date back over 50 years now and involve steam turbine units that operate at and above 1000F (538C). SPE is the direct result of exfoliation of oxide scale from high temperature boiler components (superheat and reheat tubing, main and hot reheat piping, and headers) that becomes entrained in the steam flow path and eventually impacts steam turbine components at a high velocity resulting in steam path and turbine SPE damage. Additionally, SPE of aero-engine components and coatings significantly reduce the life and reliability of these engines in harsh flying environments.

Similarly, liquid droplet erosion (LDE) also generates concerns for both steam and gas turbine operators for steam path and compressor blades respectively. In a steam turbine, moisture created as droplets from the steam as it expands through the last stages of the low pressure (LP) turbine can result in significant blade erosion. In recent years, gas turbine compressor blades have also been shown to be susceptible to LDE. Other forms of high-temperature erosion can be found in gasifiers, aero-engines blades, gas turbine hot section blades and coatings.

This conference will focus on two forms of erosion damage, SPE and LDE, methods used to test materials exposed to these forms of damage, as well as field experience and observations

TECHNICAL SCOPE

EPRI and RSE S.p.A will host the 2-day conference. This Conference is being assembled to bring experts and researchers from around the world to discuss the latest developments/ methods for testing materials exposed to solid particle- and liquid droplet-erosion damage. Specifically the Conference will:

- Review equipment and methods used to control and measure particle/ droplet dynamics (size, feed rate, flow conditions, impact angle, and velocity)
- Investigate variables affecting the erosion rates
- Examine modeling of erosion rates under various test conditions, materials and erodents
- Highlight measurement and comparison of erosion rates using various erosion media on selected materials and coatings
- Discuss small specimen and full scale component testing methods and results
- Identify applications of erosion test methods
- Discuss development of test standards and general guidelines for erosion testing with a specific emphasis on high temperature erosion testing.

EPRI has identified a number of experts from around the globe that have been invited to participate in this open industry forum. These experts have been selected from equipment manufacturers, academia, research organizations, national laboratories, and consultants. The experts include individuals with expertise in steam and gas turbine blade/disc metallurgy, erosion testing, modeling and turbine operation.

Conference sessions will be aligned along five central themes:

- Session 1 – SPE: Historical Perspective and SPE Characterization
- Session 2 – SPE Testing and Standardization Issues
- Session 3 – LDE: Test Methods and Erosion Mechanisms
- Session 4 – lDE: Test Methods, Erosion Mechanisms and Modeling
- Session 5 – Protective Coatings, Verification and Field Tests

We look forward to your participation in this important International Conference.

KEY CONTACTS

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SUNDAY, JUNE 17, 2012	
6:30 p.m. – 8:30 p.m.	Registration and meet & greet at the bar
DAY 1: SOLID PARTICLE EROSION – MONDAY, JUNE 18, 2012	
8:30 a.m.	Welcome and Conference Goals *David Gandy* and *Federico Cernuschi*
8:45 a.m.	Opening and Introduction by all participants
SESSION 1 – SPE: HISTORICAL PERSPECTIVE AND SPE CHARACTERIZATION	
	Co-Chairs: David Gandy and Federico Cernushi
9:00 a.m.	Solid Particle Erosion Characterization of Materials for Power Generation (Key note Presentation) *F. Cernuschi, C. Guardamagna, L. Lorenzoni, S. Capelli, RSE, Italy*
9:30 a.m.	A Study Comparing the Erosivity of Volcanic ash and Silica (Invited Presentation) *John Nicholls, L.N. Ndamka* and *R.G Wellman, Cranfield University, U.K.*
10:00 a.m.	Development of an Elevated Temperature Solid Particle Erosion Testing Standard *Jeff Smith, Materials Processing Technology; Swami Swaminathan, Turbomet International* and *David Gandy, Electric Power Research Institute, USA*
10:30 a.m.	**BREAK**
SESSION 2 – SPE TESTING AND STANDARDIZATION ISSUES	
	Co-Chairs: Swami Swaminathan and Mark Gee
10:50 a.m.	Use of the ASTM G 76 Solid Particle Erosion Test for Screening Engineering Materials (Invited Presentation), *Ken Budinski, BUD Labs, USA*
11:20 a.m.	Test Rig for Elevated Temperature Solid Particle Erosion and Test Procedure *Shun-sen Wang, Jin-ru Mao, Liu-xi Cai* and *Yong-qiang Han, Institute of Turbomachinery, Xi'an Jiaotong University, China*
11:50 a.m.	Development of Erosion Resitant Coatings and Erosion Testing for multi-stage Blisk Geometries *B. Ulrichsohn, Rolls Royce Deutschland; R. Cremer, KCS Europe; K. Ortner, Fraunhofer,* and *M. Naveed, Brandenburgische Technische Universtat Cottbus, Germany*
12:20 p.m.	High Temperature Erosion Studies on Carbon Fabric Reinforced Polyetheretherketone Composites *Mohit Sharma* and *Jayashree Bijwe, IIT, Delhi, India*
12:50 p.m. – 1:50 p.m.	LUNCH
2:00 p.m.	High Accuracy Particle Velocity Measurement Using Optical Methods (Invited Presentation) *Cliff Weissman, Dantec Dynamics, USA*
2:30 p.m.	Design Challenges in Development of High Temperature Solid Particle Erosion Test Rig *Narendra M. Dube* and *Abshuman Dube et al, DUCOM, Bangalore, India*
3:00 p.m. – 6:00 p.m.	RSE LAB TOUR AND DANTEC LDV DEMO AT RSE
7:30 p.m.	RECEPTION
DAY 2: LIQUID DROPLET EROSION – TUESDAY, JUNE 19, 2012	
SESSION 3 – LDE: TEST METHODS AND EROSION MECHANISMS	
	Co-Chairs: Jeff Smith and John Nicholls
8:00 a.m.	Overview of Liquid Droplet and Solid Particulate Erosion Testing Illustrated by Design, Installation and Validation of WDE Test System at NPL (Invited Presentation) *Mark Gee, National Physical Laboratory, UK*
8:30 a.m.	Water-Droplet-Erosion in Steam Turbines - Testing Method & Validation *A. Uihlein, C. M. Maggi, I Keisker, Alstom, Switzerland*
9:00 a.m.	Liquid Impact Erosion Testing and Modeling for Steam Turbine Lifetime Estimation *Z. Ruml. Hreben, J. Mach, L.Prchlik, , et al, SKODA Power, Czech Republic*

SESSION 3 – LDE: TEST METHODS AND EROSION MECHANISMS (CONTINUED)	
9:30 a.m.	LDE Testing of Steam Turbine Blades, Erosion Rate Prediction and Protection Development *Tomohiko Tsukuda, Toshiba, Development Center Toshiba Corporation Power Systems Company, Japan*
10:00 a.m.	Application of Stress Wave Analysis in Multi-Layer Coating Design *Wei Chen* and *Mamoun Medraj, Concordia University, Montreal, Quebec* *Pawel Jedrzejowski, Rolls-Royce Canada, Ltd. Montreal, Canada*
10:30 a.m.	BREAK
DAY 2: LIQUID DROPLET EROSION – TUESDAY, JUNE 19, 2012 (CONTINUED)	
SESSION 4 – LDE: TEST METHODS, EROSION MECHANISMS AND MODELING	
	Co-Chairs: Andreas Uihlein and Sungbo Shim
10:50 a.m.	Erosion Mechanisms During Water Droplets Impingement of Forged Ti-6Al-4V *N. Kamkar, F. Bridler, P. Bocher, Ecole de Technologie Superieure* and *P. Jedrzejowski, Rolls-Royce Canada Ltd, Canada*
11:20 a.m.	Design and Development of a Laboratory-Scale Water Impact Test Rig *Ed Tobin* and *Trevor Young, Department of Mechanical, Aeronautical and Biomedical Engineering, Irish Centre for Composites Research (IComp), Materials and Surface Science Institute (MSSI), University of Limerick, Ireland*
11:50 a.m.	Improvement of Water Droplet Erosion Resistance of Steam Turbine blade by Ceramics Coating *Ryuichiro Ebara, Institute of Materials Science and Technology, Fukuoka University, Japan*
12:20 p.m.	Influence of Sand and Rain Erosion on the Surface Roughness of Aerodynamic Surfaces *Oliver Rohr, Stefanie Naumann, Franz J. Gammel, EADS Deutschland GmbH, Germany*
12:50 p.m.	Water Impingement Modeling and Testing *S.N. Marzbali, A. Dolatabadi, P. Jedrzeowski* and *M. Medraj Concordia University & Rolls-Royce Canada Ltd., Canada*
12:50 p.m. – 2:00 p.m.	LUNCH
SESSION 5 – PROTECTIVE COATINGS, VERIFICATION AND FIELD TESTS	
	Co-Chairs: David Gandy and Ryuichiro Ebara
2:00 p.m.	TiN Multilayer Systems for 7FA Compressor Airfoil Liquid Droplet Erosion Protection (Invited Presentation) *Albert Feuerstein, Michael Brennan* and *Michael Romero, Praxair Surface Technologies, Inc., USA*
2:30 p.m.	SPE and LDE Evaluation of Erosion Resistant Nanocoatings *Swami Swaminathan, Turbomet International* and *David Gandy, EPRI, USA*
3:00 p.m.	The Development and Evaluation of Erosion and Corrosion Resistant Coating in Gas Turbine Compressors *Sungbo Shim, Rolls Royce Corp., Indianapolis, USA*
3:30 p.m.	BREAK
3:50 p.m.	Beyond Standard Testing: The Pitfalls of Coupon Erosion Results and the Need for Component Assessment *J.M. Méndez, P. Rodger, J.P. Huot, S. Durham, J. Cheverie, MDS Coating Technologies Corp., Canada*
4:20 p.m.	Aircraft Engine Anti-Erosion Coatings Successfully Transition to Industrial Turbines *Robert Tolett, Liburdi Eng., Canada*
4:50 p.m. – 5:10 p.m.	CONCLUDING REMARKS, DAVID GANDY and FEDERICO CERNUSCHI
5:10 p.m. – 6:00 p.m.	ASTM TASK GROUP MEETING *Led by Jeff Smith, Materials Processing Technology* and *Swami Swaminathan, Turbomet International, USA*

SESSION 1 – SPE: HISTORICAL PERSPECTIVE AND SPE CHARACTERIZATION

SOLID PARTICLE EROSION CHARACTERISATION OF MATERIALS FOR POWER GENERATION

F. Cernuschi, C. Guardamagna, L. Lorenzoni, S. Capelli

Ricerca sul Sistema Energetico , RSE SpA, Milano, Italy

Solid particle erosion (SPE) has been outlined as one of the main problems concerning both steam power plant and land based gas turbines. In steam power plants, candidate alloys for manufacturing high pressure steam turbine diaphragms, buckets, radial seals and control valves should exhibit, among other properties, even a good resistance at the erosion phenomena induced by hard solid particles: in fact ferric oxide (magnetite) scales cause SPE by exfoliating from boiler tubes and steam pipes (mainly super-heaters and re-heaters) and being transported within the steam flow to the turbine. In coal-fired utility power stations very large quantities of solid fuel and ash products are present. Therefore most of coal-fired power plants suffer from abrasion and erosion wear caused by pulverised coal and fly ashes. Thermal barrier coatings (TBC) are used to protect hot path components gas turbines from hot combustion gases. Volcanic ashes and sand present in air are the main causes of solid particle erosion failure for TBC in gas turbines, this is true especially in the case of aero engines although some occurrences even on land based turbines are reported. This work reports the experiences at RSE in the field of high temperature solid particle erosion carried out on metallic materials and ceramic coatings for power generation.

A STUDY COMPARING THE EROSIVITY OF VOLCANIC ASH AND SILICA

J. R. Nicholls, L. N. Ndamka and **R. G. Wellman**

Cranfield University, United Kingdom

Aircraft encounters with volcanic ash clouds are more common than most people realise. Since 1935 there have been well over 100 reported incidents with 7 class 4 encounters between 1980 and 1991 involving temporary engine failures, where Class 0 is classified as acrid odour and electrostatic discharge and Class 5 as engine failure or other damage leading to a crash. To date there have been no Class 5 encounters.

While there are numerous ways in which volcanic ash can damage both the airframe and an engine this paper is purely focussed on the effect of ash ingestion on compressor blade erosion. This paper reports on the relative erosion rates of IN718 and Ti64 impacted with different size fractions of volcanic ash at three different impact angles and different impact velocities. Selected tests were repeated using silica as the erodent in order to compare the relative erosivity of the two erodents at room temperature and 450°C.

The volcanic ash used in this programme was obtained from the 2010 Eyjafjallajökull eruption approximately 6 miles from the volcano. In order to determine the effect of particle size and erosion the ash was sieved into three size fractions for testing 0-53μm, 53-106μm and 106-212μm. Two size fractions of silica were used 0-150μm and 76-212μm.

Both the Ti64 and the IN718 showed a maximum erosion rate at the 30° impact angle, and the fine silica sand was found to be marginally more erosive than the volcanic ash. Overall the results indicated that the volcanic ash behaved in a similar manner to the fine silica at both room temperature and 450°C.

DEVELOPMENT OF AN ELEVATED TEMPERATURE SOLID PARTICLE EROSION TESTING STANDARD

Jeffery S. Smith, *Material Processing Technology, LLC, USA*

V.P. "Swami" Swaminathan, *TurboMet International, USA*

Dave Gandy, *Electric Power Research Institute, USA*

Solid Particle Erosion (SPE) of hardware remains an ongoing concern with the operation of Steam Turbine power plants as well as Aero engine and Land Based Gas Turbines. SPE of both rotating and stationary components leads to loss of efficiency, higher cost of operation and maintenance of turbines. Ultra Supercritical (USC) and advanced USC programs underway in North America, Europe and Asia have created renewed interest in the understanding of the effects of SPE on the advanced alloys at high temperature. The Gas Turbine industry has also been conducting studies for improving the elevated temperature erosion resistance of compressor and hot section components and coatings. ASTM's G76 "Standard Test Method for Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets" defines a standard test method for conducting room temperature SPE erosion testing but has many limitations that restrict its usefulness.

The objective of the current Electric Power Research Institute (EPRI) sponsored program is to develop an elevated temperature SPE standard that will provide more appropriate reference parameters for SPE conditions encountered in current and next generation steam turbine and gas turbine applications. Currently such test standard is not available from any of the standards organizations. Various laboratories around the world have developed their own equipment and procedures to conduct their elevated temperature (ET) SPE tests. This makes it difficult to compare these inter-laboratory test results for the purpose of screening and selecting alloys and coatings for erosion mitigation. Organizations from the United States, United Kingdom, China, Germany, Italy and India are participating in the EPRI inter-laboratory "Round Robin" test program to develop a new ASTM ET erosion test standard. This presentation will describe the program structure, test conditions used, erosion test results received to date and the status of the development of a new ASTM ET SPE test standard.

SESSION 2 – SPE TESTING AND STANDARDIZATION ISSUES

USE OF THE ASTM G 76 SOLID PARTICLE EROSION TEST FOR SCREENING ENGINEERING MATERIALS

Kenneth G. Budinski, *Bud Labs, USA*

There are many industrial, aerospace, and military applications where erosion by solid particle impact is a limiting factor. This problem is addressed by laboratory tests to evaluate candidate materials to resist this form of erosion. Various solid particle erosion testing approaches and rigs are described and the ASTM G76 gas jet test is described in detail.

This test uses 90-degree impingement of air-born aluminum oxide particles on a test surface and the measurement of the resulting erosion rate. There are some significant problems that are encountered in using this test and they are described. The foremost problem is that the single procedure in the test method is too aggressive to distinguish differences in engineering materials. Typically the test shows no erosion differences between a soft steel and the same steel hardened with a millimeter-deep 60HRC carburized case.

This paper describes experiments that have been conducted to develop less aggressive procedures (and media) that can be added to a revision of the test method. The goal is to develop tests that more closely simulate real–life solid particle erosion conditions.

TEST RIG OF ELEVATED TEMPERATURE SOLID PARTICLE EROSION AND TEST PROCEDURE

Shun-sen Wang, Jing-ru Mao, Liu-xi Cai, Yong-qiang Han
Institute of Turbomachinery, Xi'an Jiaotong University, China

An elevated temperature erosion test facility was designed and built at the Xi'an Jiaotong University of China to examine the erosion resistance of various materials and coatings subjected to particulate flow. The erosion test facility consists of high-temperature gas system, particles feeding system, and erosion testing system. The work flow is: the main air flows into a long nozzle after being heated to the required temperature in a combustion chamber, and the solid particles from a screw feeder are transported to the throat of long nozzle by secondary air. Then, the particles is accelerated and heated by the main air with high temperature in the long nozzle. Eventually, the solid particles impinge on the surface of sample at a required incidence angle (β).

The test section consists of rotary device, protective casing, and top plate. The incidence angle can be varied by rotating the top plate around the point R2. Four test samples are mounted on a rotary device in the test section. However, only one sample is exposed to the high-velocity particulate flow, and other samples are protected by a protective casing. The position of the test samples can be varied by rotating the device around the point R1. The sample No.1 is used to calibrate the test conditions. When the test temperature, particles velocity and mass flow rate of the particles meet the required conditions of erosion test, the rotary device is turned 90 degrees to conduct the erosion test on sample No.2. Then, sample No.3 and No.4 is conducted the erosion test in turn.

DEVELOPMENT OF EROSION RESISTANT COATINGS FOR MULTI-STAGE BLISK-GEOMETRIES

B. Ulrichsohn, *Rolls-Royce Deutschland Ltd & Co KG, Germany*

R. Cremer, *KCS Europe GmbH, Germany*

K. Ortner, *Fraunhofer IST, Germany*

M. Naveed, *Brandenburgische Technische Universität Cottbus, Germany*

The airfoil design and performance of modern jet engine compressors is more and more susceptible to erosion wear. One reason are less wear resistant lightweight materials like titanium alloys. Furthermore the airfoil thickness is reduced more and more, leading to less material to be worn. In the past it was possible to replace single blades, which have been worn over a critical tolerance. For weight and fuel saving reasons, in future engines the usage of the blisk technology will increase. The extremely high costs for these components and for potential repair processes show the necessity for an effective protection against erosive wear.

Most PVD processes are "line of sight" processes. For the application of hard thin film coatings on complex 3-dimensional geometries like multi-stage blisks, current technologies are not sufficient. Gas flow sputtering is a PVD coating process that has been developed especially for application on more complex geometries. An ionized gas is pushed through the sputter targets with high pressure. Reaching the substrate with a high velocity, the atoms are not immediately absorbed by the surface. Supported by the ionized gas, the atoms of the coating material can penetrate deeper into the interspace between two blades.

For the development of the coating process and the coating itself it is necessary to test these coatings under realistic conditions. Therefore Rolls-Royce has built-up a particle erosion test rig. In this test rig it is possible to accelerate an arbitrary erodent up to about 300 m/s. With two heaters the compressed air can be heated to a maximum of around 830°C. The test output is the dependence of the mass loss of the specimen on the mass of used erodent. Typically, the graph of coated specimen can be divided into three regions indicating three different erosion mechanisms.

Caused by the geometry of a blade and the particle flow through an engine, the full range of impact angles between 0° and 90° is possible. For flat test specimen a fixture allows to vary the impact angle between 15°, 30°, 45°, 75° and 90°. But for the final coating evaluation it is not sufficient to test flat coupons, because the erosion behaviour can change significantly by changing the coated geometry, especially in case of sharp edges.

HIGH TEMPERATURE EROSION STUDIES ON CARBON FABRIC REINFORCED POLYETHERETHERKETONE COMPOSITES

Mohit Sharma and **Jayashree Bijwe,** *Industrial Tribology Machine Dynamics and Maintenance Engineering Centre (ITMMEC) Indian Institute of Technology, Delhi, Hauz Khas, New Delhi, India*

Two composites based on carbon fabric (CF) reinforcement in Polyetherether ketone (PEEK) were developed and designated as P_{KFU} (which contained CF as received) while other was designated as P_{KFT} (which contained CF treated with cold remote nitrogen plasma). The treated fabric composite proved superior to the other one in strength properties as a result of better fiber-matrix bonding. Erosion studies at high temperature were done by bombarding with alumina particles at selected angles (15°, 30°, 45°, 60° and 90°). For both the composites, the angles of impingement at which the wear rates were lowest (α_{min}) and highest (α_{max}) were 90° and 45° respectively indicating semi-ductile failure. P_{KFT} showed higher resistance to wear.

Further studies at 45° and various temperatures (25–2000°C) indicated increased wear rate with temperature almost uniformly up to 125°C followed by a slight dip around 143°C. At glass transition temperature (T_g) of PEEK (143°C),when segmental motion starts, some flexibility is imparted in the chain leading to more wear resistance as a result of more efficient absorption of impact energy. Further increase in temperature resulted in an abrupt increase in wear till 200°C due to more fiber-matrix debonding. Wear of P_{KFU} was more than 2 times higher at 200°C that that of P_{KFT} while at ambient temperature, difference was marginal. Thus the functional groups added on fibers due to the treatment and enhanced roughening led to the enhanced fiber-matrix adhesion which was responsible to hold the fabric by the matrix more tightly even at elevated temperatures and hence ease in fiber removal by breakage, cutting, cracking etc. during erosion got reduced.

Based on the erosive wear studies on PEEK composites, following conclusions were drawn:

- Cold remote nitrogen plasma treatment of CF led to enhanced fiber-matrix adhesion and effectively improved the mechanical and erosive wear properties of the composites.
- α_{max} at 45° of impingement indicated semi-ductile failure of both the composites.
- With increase in temperature both erosion wear resistance and tensile strength decreased, indicating a correlation (though not perfectly linear). Glass transition temperature (T_g) played an important role in this relationship. Beyond T_g erosion increased very fast because increase in temperature leads to more fiber-matrix debonding.

HIGH ACCURACY PARTICLE VELOCITY MEASUREMENTS USING OPTICAL METHODS

Clifford Weissman, *Dantec Dynamics USA*

The accurate measurement of particle and/or droplet velocity is critical for numerous applications including fuel sprays, multiphase flows, and particle erosion studies. Particle velocity measurements in erosion applications present unique challenges. To obtain reliable and accurate particle velocity measurements, optical methods such as laser Doppler and Particle Image Velocimetry systems are well suited solutions. An overview of both Laser Doppler and Particle Image Velocimetry theory and application is presented with discussion on uncertainty analysis and expected accuracy of the measurements. As particle size is also an important parameter in erosion applications, extension of the Laser Doppler to Phase Doppler for size measurements as well as Shadow Sizing by imaging is also discussed.

DESIGN CHALLENGES IN DEVELOPMENT OF HIGH TEMPERATURE SOLID PARTICLE EROSION TEST RIG

Narendra M. Dube and **Anshuman Dube,** *DUCOM Instruments (P) Ltd., Bangalore, India*

Gas jet carrying controlled fraction of erodent are commonly used for solid particle erosion (SPE) testing. ASTM G76 – 07 provides standard test method for conducting erosion test by solid particle material using gas jets. In several applications erosion occurs under conditions which are widely different from recommended in this standard. Standard test method is useful in ranking of different materials, but fails to provide data for estimation of service life of components. This calls for customized testing depending on type of erodent, particle size distribution, temperature, particle velocity, flux and nature of carrier gas. Case study of development of a 1000°C, 150 m/s SPE air jet tester will be presented. It will highlight some of the issues encountered while simulating realistic conditions. They include nozzle design, erodent feeder, and particle flux and velocity measurement.

SESSION 3 – LDE: TEST METHODS AND EROSION MECHANISMS

OVERVIEW OF SOLID PARTICULATE AND LIQUID DROPLET EROSION TESTING ILLUSTRATED BY DESIGN, INSTALLATION AND VALIDATION OF WDE TEST SYSTEM AT NPL

M. G. Gee, A. J. Gant, and **P. Lovelock**
National Physical Laboratory, United Kingdom

Solid particulate and liquid droplet erosion are key degradation mechanisms for materials in many sectors. This talk will start by discussing the main parameters that control wear in gas borne solid particulate and water droplet erosion and how they can be measured and controlled. Results will be given of ambient temperature particulate erosion of ceramics, hard-metals and steels including the results of incremental erosion that reveals the step-by step degradation of the structure of the material at a microstructural scale.

The talk will conclude with a description of the recent experience at NPL of designing, building and initial experiments with a rotating arm water droplet erosion test system. The system, which has a design speed of 500 ms^{-1}, is currently operating at a rotor arm speed of 300 ms-1 whilst experience in operation is gained. The experience of a catastrophic failure of the rotor at a speed of 250 ms^{-1} due to choice of inadequate fixtures in the design will be described. The use of 3D optical microscopy for the evaluation of damage will also be explored.

WATER DROPLET EROSION IN STEAM TURBINES – TESTING METHOD AND VALIDATION

Andreas Uihlein, Carlo M. Maggi, Ingo Keisker,
ALSTOM (Switzerland) Ltd., Switzerland

The destruction of material by water-droplet erosion (WDE) is caused by repeated surface loading from the small and short-term impingements of fluid water droplets. This fatigue damage process leads to surface destruction with a similar appearance to that of cavitations, pitting and selective corrosion processes.

Low pressure steam-turbines blades are in particular significantly affected by water droplet erosion leading to damage at the tip region of the turbine blade during standard operation mode, as well as to the trailing edge during ventilation mode. Several years ago a test rig was established at the Alstom materials department to characterize the behavior of materials and bondings due to water droplet erosion using the volume loss.

The erosion behavior is significantly influenced by the droplet-velocity and size. Therefore one of the main considerations for the test rig is the reproducibility of the droplet size and the influencing parameters. Different studies were carried out to determine these and it was found that the handling of the water droplet generation nozzle is particularly critical. A further parameter-study was carried out together with Lechler GmbH to determine the influence of different test-rig setup on the droplet size which was measured using PDA (Phase Doppler Anemometry). The investigations show the influence on droplet size of nozzle back-pressure and chamber vacuum-pressure as well as the impact of poor cleaning and water residues.

LIQUID IMPACT EROSION TESTING AND MODELING FOR STEAM TURBINE LIFETIME ESTIMATION

Z. Ruml, S. Hřeben, J. Mach, L. Prchlík
SKODA POWER,Czech Republic

Water droplet erosion of the blades is one of the serious problems affecting lifetime and overhaul frequency of steam turbines. Moisture in droplet form causes erosion of last stage blades (LSB) in low pressure (LP) turbines leading to performance degradation.

Understanding of erosion process and testing and modeling of erosion resistance of various materials has key importance in choice of proper materials for last stages of LP turbines. Suitably chosen material or proper surface treatment of LSB can minimize risk of damage and increase lifetime and efficiency of turbine set.

SKODA POWER utilizes a unique erosion stand allowing close simulation of water droplet erosion process taking place at last stages of LP turbines. Based on the testing of erosion resistance of various materials, erosion model allowing prediction of the erosion damage after certain operating time has been created. This model is used for erosion damage prediction and contributes to lifetime estimation of entire turbine. Recently, SKODA POWER is focused on development and testing of laser beam deposited coatings that will be used for erosion protection of titanium LP blades.

LDE TESTING OF STEAM TURBINE BLADES, EROSION RATE PREDICTION AND PROTECTION DEVELOPMENT

Tomohiko Tsukuda, *Turbo Machinery Group, Rotating Machine Technology R&D Department Power and Industrial Systems Research and Development Center Toshiba Corporation Power Systems Company, Japan*

In the low pressure section of the steam turbine, steam condenses and generates water droplets which cause a various problems such as decreasing of stage efficiency and last stage blade erosion. Particularly, last stage blade erosion is a one of key phenomena for the reliability and efficiency of the steam turbine. Toshiba has vast experience with the last stage blade erosion. In this presentation, we explain our development of countermeasures against the last stage blade erosion. Toshiba has implemented the material test to reveal the erosion resistant characteristic of the various materials for last stage blade.

Toshiba has also developed various techniques such as erosion shield, flame hardening of the leading edge of blade and slit nozzle as the countermeasure against the erosion. In model scale steam turbine, with and without slit nozzle tests wear implemented and slit nozzle effects are revealed. Water droplet size in the low pressure steam turbine was also measured by using special measurements system. Based on the knowledge obtained from above experiments, Toshiba has developed the method which can predict the amount of erosion of the last stage blade in the actual steam turbine. The prediction has agreed well to the result of erosion at the actual steam turbine.

Recently, Toshiba has developed fabrication technique for new type erosion shield for the last stage blade. This technique has great advantage that it can reuse the last stage blade eroded through long time operation in the actual steam turbine. This technique was validated in the full scale steam turbine test facility.

APPLICATION OF STRESS WAVE ANALYSIS IN MULTI-LAYER COATING DESIGN

Wei Chen and **Mamoun Medraj**
Concordia University, Mechanical Engineering Department, Canada

Pawel Jedrzejowski, *Rolls-Royce Canada Ltd., Canada*

Upon the collision between water droplet and solid surface, consecutive impact loads are applied and stress waves are generated at the surface of the solid. The stress waves transmit in the homogeneous solid, and are partially reflected at the discontinuities, such as microcracks or other discontinuities. Due to the accumulation of both the transmitted and the reflected stress waves, strong tensile stresses may be generated at some specific locations, in spite of the fact that the initial impact loads result in compressive stresses, and cause the failure of materials. In the case of multi-layer coatings, extra discontinuities, specifically the interfaces, are intentionally introduced in the materials. These added discontinuities will greatly change the distribution of the stresses in the materials, and lead to additional damping effect due to the extra transmission and reflection, which may potentially provide protection to the substrate materials. Meanwhile, within the multi-layer structure of the coatings, it is necessary to optimize the stress distribution to make sure that the distributed stresses do not reach the strength limit within each layer and more importantly at each interface. Based on this consideration, stress wave analysis is used as a design tool to adjust the thickness of different layers or the stacking sequence in order to minimize the tensile stresses through the coatings and at the interfaces. Under the same impact load and for the same Ti64 substrate, the stress distribution in three coating scenarios with different layer thicknesses is investigated. In the optimized design the stress at all the interfaces behaves as moderate compressive stress, which indicates that an improved stress distribution has been obtained. Similar effect may also be achieved by changing the stacking sequence of layers.

SESSION 4 – LDE: TEST METHODS, EROSION MECHANISMS AND MODELING

EROSION MECHANISMS DURING WATER DROPLETS IMPINGEMENT OF FORGED TI-6AL-4V

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The erosion mechanisms during water droplets impingement have been investigated in the case of two commercial duplex Ti-6Al-4V from a rolled plate and a forged part, respectively. Erosion testing has been performed on coupons exposed to high speed water impact with two droplet sizes.

In the present work, original characterization methods have been developed to analyze the final state of the coupons. The methods are based on both exhaustive observations and quantitative measurements coupling scanning electron microscopy (SEM) and electron back-scattered diffraction (EBSD). Observations were done by imaging the eroded surface craters but also by progressive cross-sectional polishing to reveal both surface and sub-surface damage features at different scales. The size of cracks as well as their inclination relative to droplets impingement direction have been measured and synthetized. The occurrence of sub-tunneling mechanisms has also been documented. The observed damage features (cracks, sub-tunnels, striations) appear to be dependent on the local microstructure morphology and the crystallographic texture of the base material, i.e., either rolled or forged.

A mechanism is proposed for water droplet erosion of investigated alloys. Erosion involves cyclically the nucleation of networks of cracks, followed by their propagation and/or merging, leading to the loss of materials chips, and finally to potential water polishing of the rough craters surfaces left by material loss. The mechanisms observed are discussed relative to the droplet size and the crystallographic texture of both base materials.

DESIGN AND DEVELOPMENT OF A LABORATORY-SCALE WATER DROPLET IMPACT TEST RIG

Edmond F. Tobin and **Trevor M. Young,** *University of Limerick, Ireland, Department of Mechanical, Aeronautical and Biomedical Engineering, Irish Centre for Composite Materials (IComp), Materials and Surface Science Institute (MSSI), Ireland*

A laboratory-scale whirling-arm water droplet impact facility has been designed and developed at the University of Limerick. The primary function of the facility is to test materials and coatings used on aircraft leading edges. Tests are undertaken on circular samples (27 mm Ø) at impact speeds of up to 178 ms^{-1}. A localised stream of droplets, with a nominal droplet diameter of 2 mm, is produced along the central region of the sample. One of the major issues with water droplet impact testing is correlating the results from one test facility to another; a particular difficulty occurs when comparing results from whirling arm and water jet tests. Whirling arm test rigs produce droplets that are impacted by a rotating sample while jet test rigs produce jets that have a similar rounded leading edge to a droplet that impact a stationary sample. An initial comparison between a whirling arm and a water jet test rig has been completed using AA2024 clad aluminium alloy. A correlation of 1000 impacts to 15 minute test duration was found between the test rigs based on roughness measurements of the material surface. An experimental study was also completed to provide a relationship between velocity and erosion rate. It was found that the erosion rate varied as a function of the number of cycles through the droplet field. An evaluation has been completed into the variation in the droplet impact density over the eroded area of the sample. Images of AA2024 clad material have been analysed to provide experimental data on how the damaged area increases with time. An empirical model of the variation in impact density over the sample test face has been developed and validated using the experimental results.

IMPROVEMENT IN WATER DROPLET EROSION RESISTANCE OF STEAM TURBINE BLADE BY CERAMICS COATINGS

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A stellite plate is normally soldered with silver alloy on to the blade surface.to prevent drain erosion damage in turbine blades. However, the following three problems remain in silver soldering. (1)Cadmium in the silver solder is harmful to human body. (2)The high cost is required for skillful silver soldering. (3) Small defects in the thicker soldered layer cause fatigue crack initiation.

In this presentation it is focused upon the Cr-TiN ceramics coating to prevent drain erosion damage in steam turbine blade. Fundamental properties such as coating method, structure of coating and adhesion to blade material are related to the erosion resistance of Cr-TiN coating based upon the cavitation erosion testing data. Mechanical properties, fatigue strength, corrosion fatigue strength, thermal shock resistance and steam oxidation resistance are presented for safety use of ceramics coated blades. The Cr-TiN coatings were applied to actual compressor drive turbines. The result of long term nonstop operation for 7.5 years in compressor drive turbine is demonstrated. Finally recommended works for coatings with higher erosion resistance are touched in brief.

INFLUENCE OF SAND AND RAIN EROSION ON THE SURFACE ROUGHNESS OF AERODYNAMIC SURFACES

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The worldwide increasing civil air traffic demands new, high-efficient aircrafts with low fuel consumption and low CO_2 and NOx emissions. Besides weight reduction by the use of new materials like CFRP and advanced engine concepts, there are approaches to reduce the fuel consumption by new aerodynamic concepts such as laminar flow wings. Erosion resistance is a basic requirement to ensure laminar flow conditions since roughening caused by the impact of rain drops and sand particles will change the flow conditions from laminar to turbulent resulting in higher friction drag.

The presentation shows results of laboratory sand and rain erosion tests. The aim of the erosion tests was to investigate the influence of test parameters such as droplet or particle velocity and impact angle on the surface roughness on materials which are currently used for erosion protection of aircrafts (steel, anodised aluminium, paint and elastomeric tape). The rain erosion tests were performed on the PJET, a water jet erosion facility developed at EADS Innovation works. Water jets with a diameter of 2 mm and a jet velocity of 145, 155, 185 and 225 m/s were used. The number of impacts (similar to incubation time) which have struck the surface was varied from 20 to 100,000. The impact angle was 90°. The sand erosion tests were performed on a sand blast device with a cylindrical nozzle with an inner diameter of 5 mm and length of 308 mm. The particle velocity was 55 and 80 m/s at impact angles of 20° and 90°. Four different types of particles were used: Rounded silica sand with a diameter of 220 µm and angular corundum particles with a diameter of 50 µm, 108 µm and 215 µm.

The erosion progress was evaluated by surface roughness measurements using a confocal laser microscope, investigation of failure mechanism by optical microscope and SEM and, for sand erosion, weight loss measurements to determine the erosion rate. The sand erosion tests show a nearly linear increase of the surface roughness Ra with increasing diameter of sand particles. For particles of uniform size, harder and sharper-edged particles cause a higher mass loss (fig. 4) and roughness However, the mass loss also depends on the substrate material. The smaller but harder and sharper-edged corundum particles cause a higher mass loss on steel, titanium and anti erosion paint compared to silica particles. For those materials the hardness/shape of the particles is the dominating factor. On elastomeric tape the particle size is the predominant factor. With rain erosion testing the surface roughness caused by droplet impact shows on steel a nearly linear increase with increasing number of impacts. Up to 185 m/s jet velocity the roughness increases linearly with increasing jet velocity. Above the roughness stays constant. On anodised aluminium the surface roughness increases linearly with increasing number of impacts However, the influence of jet velocity on surface roughness is different to steel. On anodised Al the surface roughness stays constant up to a jet velocity of 185 m/s. Then the roughness jump up. A possible explanation for this different behaviour could be the different wear mechanism on steel and anodised aluminium. As can be seen in SEM images, the predominating wear mechanism on steel is pitting. On anodised aluminium, cracking and flaking of the anodic oxide are the predominant wear mechanism.

WATER IMPINGEMENT MODELING AND TESTING

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Water impingement erosion of solid surfaces is a phenomenon observed among others on steam turbine blades, compressor blades of jet engines, and high speed missiles. Although the water or liquid impingement erosion has been known for long time and several research groups were investigating various aspects of this phenomenon, testing facilities and equipment are relatively rare. This work describes water impingement testing rig that has been recently developed by joint effort of Concordia University in Montreal (Canada) and Rolls-Royce Canada and water impact modeling efforts.

The rig is capable of evaluating the resistance to water impingement erosion of various materials, including samples simulating leading edge geometry of a blade. Samples can be rotated at high linear speed, up to 500 m/s to impact water droplets of known and controlled size distribution. Water droplet impingement on the sample's surface can be monitored either by a high speed camera or by a stroboscope. Various testing approaches and common problems are discussed.

Low speed single droplet impingements onto flat plates with various wettabilities at normal and oblique angles have been investigated. Volume of Fluid (VOF) method was employed to capture the interface between two phases. In order to validate the accuracy of the numerical model, the results were compared against experimental and theoretical data for perpendicular impact. A splash regime map was established based on pre-impact conditions.

For the high speed impact, the dynamic response of a metallic disk has been studied. In order to address the parameters that influence such a phenomenon, two widely used materials are chosen for the disk, namely, martensitic stainless steel and Ti-6Al-4V. The pressure in the fluid region and the stress distribution in the solid part are obtained simultaneously by solving the coupled equations of motion. The deformation and spreading of the droplet upon impacting the solid surface are captured by VOF method. The structural equations are solved for elastic solid to obtain the stress field in the disk. A 2-D axisymmetric model is utilized as the computational domain for fluid and solid parts. The pressure and stress distributions are investigated along the solid-fluid interface and along the disk center axis over time. The results revealed the peak transient stress in the solid can reach very high magnitudes even at relatively low impact velocities. Moreover, tensile stress appeared in solid at later stage of impact.

SESSION 5 – PROTECTIVE COATINGS, VERIFICATION AND FIELD TESTS

TIN MULTILAYER SYSTEMS FOR 7FA GAS TURBINE-COMPRESSOR AIRFOIL LIQUID DROPLET EROSION PROTECTION

Albert Feuerstein, Michael Brennan, and **Michael Romero**

Praxair Surface Technologies, Inc., USA

In modern power generation gas turbines water fogging, i.e., the injection of water mist into the turbine is used to augment the performance and efficiency by reducing the air temperature and increasing the compression ratio. The water droplets hit the leading edge of the first stage compressor with app. the speed of sound and can cause liquid droplet erosion (LDE) of the base metal. This leading edge erosion can lead to a reduction of the cord width over extended periods of operation. With some blade designs, this can lead to fatigue cracks which shorten the life of the blades. Various abatement solutions are presently under investigation: redesign of the airfoil shape to allow more material removal, laser peening to reduce the impact on fatigue life and protective coatings. We have investigated the effectiveness of sub-stoichiometric TiN multilayer coating systems to protect the leading edge of the compressor blades against liquid droplet erosion. A full set of 7FA 1st stage compressor blades has been coated with two different substoichiometric TiN multilayer architectures. The erosion damage progression in both coatings was evaluated after 10,000 hrs and 25,000 hrs of field service. In a parallel effort an accelerated water jet test procedure has been developed to simulate the LDE process. A semi-quantitative correlation between the damage progression in the field test and the water jet test confirmed the effectiveness of the water jet test as a meaningful tool to predict the coating performance in an LDE environment. The accelerated water jet testing is capable of simulating the LDE damage progression. The better performing coating of the two types investigated has a predicted life in excess of 50,000 hrs for the current environment.

SOLID PARTICLE AND LIQUID DROPLET EROSION EVALUATION OF EROSION RESISTANT NANOCOATINGS

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David Gandy, *Electric Power Research Institute, USA*

Under a program funded by the Electric Power Research Institute (EPRI), nanocoatings with thickness ranging from 15 to 25 microns were developed and tested for application in steam and gas turbines to mitigate the adverse effects of solid particle erosion (SPE) and liquid droplet erosion (LDE on rotating blades and stationary vanes. Based on a thorough study of the available information, most promising coatings such as nano-structured titanium silicon carbo-nitride (TiSiCN), titanium nitride (TiN) and multilayered nano coatings were selected.

TurboMet International teamed with Southwest Research Institute with state-of-the-art nano-technology coating facilities with plasma enhanced magnetron sputtering (PEMS) method to apply these coatings on various substrates. Ti-6V-4Al, 12Cr, 17-4PH, and Custom 450 stainless steel substrates were selected based on the current alloys used in gas turbine compressors and steam turbine blades and vanes. Coatings with up to 25 micron thickness were deposited on small test coupons. The erosion resistance under both SPE and LDE test conditions evaluated using the ASTM G-76 standard test method with alumina erodent and also a custom built water droplet erosion test rig using high-pressure water jet with velocity of 230 m/s were employed. Four other commercially available coatings were also tested under this program. These tests showed that the nano-structured coatings have higher erosion resistance compared to other commercially produced erosion resistance coatings. Tension and high-cycle fatigue test results revealed that the hard nano-coatings do not have any adverse effect on these properties but may provide positive contribution.

THE DEVELOPMENT AND EVALUATION OF EROSION AND CORROSION RESISTANT COATING IN GAS TURBINE COMPRESSORS

S Shim, *Rolls-Royce Corporation, USA*

Gas turbine engine components, especially compressor airfoils, suffer from airfoil material loss by erosion when operating in sandy and dusty environments. In addition, aqueous corrosion can occur when an engine is operated in a marine environment. There is a significant need for a surface engineering solution that can provide both erosion and corrosion protection. There are a number of surface engineering processes and coating systems which are currently being investigated by Rolls- Royce for the protection of compressor blades and vanes against both erosion and corrosion. One of the approaches used is to apply alternating hard and soft coating layers for erosion protection. The hard layer provides for erosion protection and the soft layer absorbs energy and help to arrest crack growth into the coating. However, with the advent of improved coating process control systems and equipment the development of monolayer coatings with enhanced properties is possible. Recent testing by Rolls-Royce has shown that in some instances monolayer coating systems can perform better than multilayer systems.

Blade airfoil geometry is a critical feature which can affect both the coating structural features and properties. The manufacturing process can affect the subsequent performance of the coating and a poorly applied coating can result in significantly reduced engine life. For many years conventional physical vapour deposition (PVD) processing methods such those using a cathodic arc or electron beam have been used to apply erosion resistant coatings for compressor airfoil components. However, conventional PVD processes have not been generally successful at coating leading edges, creating high residual stresses and out of plane stresses due to the small radius of curvature at these features. In addition, conventional PVD technologies have an inherent "line of sight" limitation which makes the coating of components with complex geometries difficult. The development of processes which can coat sharp edges and have some degree of 3-D coating capability is therefore a major need for such components.

Several different tests, including both those at the coupon and component level, are used at Rolls- Royce to determine coating erosion and corrosion resistant. Coupon level testing is an effective tool during the initial stage of coating development, but results from coupon testing are not always consistent with component level test results. Hence, component level testing that allows for testing the actual airfoil geometry is required to complete development. It is also important that component testing results replicate the failure modes observed in airfoils in actual gas turbine engines.

BEYOND STANDARD TESTING: THE PITFALLS OF COUPON EROSION RESULTS AND THE NEED FOR COMPONENT ASSESSMENT

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MDS Coating Technologies Corporation, Canada

Gas Turbine Engines operating in aggressive erosive environments are subject to solid particle impingement that leads to detrimental engine compressor airfoil conditions such as; blade thinning, leading edge curl, airfoil chord loss and other conditions that are weakly related to what is observed during standard testing done on flat coupons like in ASTM-G76. MDS Coating Technologies Corporation (MCT) has developed laboratory tests that reproduce such erosive conditions observed on real compressor blades and vanes, as well as methodologies to measure their deterioration effects, hence allowing to quantitatively evaluate the coating solutions designed by MCT. The presentation describes how some metrics have been developed and correlated with field data, as well as with data from flat coupons exposed to different erosive conditions by varying the erodent type, size and speed, as well as impingement angle and intensity. This methodology has allowed MCT to evaluate and compare various coating designs and their effectiveness at reducing or eliminating erosive damage in real operating conditions.

AIRCRAFT ENGINE ANTI EROSION COATINGS SUCCESSFULLY TRANSITION TO INDUSTRIAL TURBINES

Robert Tolett, *Liburdi Engineering. Canada*

The use of mechanical erosion protection on blades dates back to WWI when the use of wooden propellers and impellers were sheathed of plated with brass for erosion and cavitations protection. The use of coatings and in particular, Physical Vapour Deposition (PVD) coatings in Aerospace applications goes back over thirty years to the 1970's when they were used on Russian helicopters in Afganistan. The technology is mature in this area and well established as a viable means of protecting compressor components against premature wear from solid particulate erosion in the intake air stream of flight gas turbines. Liburdi has a history of on-wing flight performance with erosion coatings that spans several decades.

The need for these coatings in Industrial gas turbines was less apparent due to the use of filtration on the land based units. However, the recent blade failures several years ago of industrial rotating compressor parts in service have exposed the need for both Solid Particle Erosion (SPE) & Liquid Droplet Erosion (LDE) resistance in the industrial engines.

The use of water washing to clean the industrial turbines and the need for power augmentation through the use of water droplet spray systems commonly referred to as "fogging" or "evaporative cooling" systems expose hardware to cavitation erosion that posses an unacceptable risk to owners and companies. In many cases water augmentation is not used at all or is turned off due to these risks. In addition, the critical design issues surrounding larger rotating compressor components leaves little margin for error when erosion pitting can cause potential failures in compressor components and systems.

Coatings with high surface finishes can provide anti fouling characteristics while improving compressor efficiency and turbine performance over a long period of time. Liburdi has pioneered new coatings for enhanced erosion resistance and augment performance on industrial rotating hardware and has demonstrated their effective use in service.

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