IMPROVING TURBINE ENGINE COMPRESSOR PERFORMANCE RETENTION THROUGH AIRFOIL COATINGS*

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Introduction:

Alteration of compressor airfoils by the erosive action of engine ingested particulate matter is a cause of performance deterioration in commercial aircraft turbine engines. A NASA sponsored JT9D Engine Diagnostics program quantified the problem for the commercial aircraft engine fleet indicating that the performance deterioration of the compressor - and erosion of the compressor airfoils - was related to total engine cycles rather than total engine operating hours. Thus the erosion problem becomes more severe when considering short mission applications where the number of engine operating cycles builds rapidly in relation to total engine operating hours. The appearance of a set of high compressor airfoils operated for approximately 10,000 cycles is shown in Figure 1.

Erosion of turbine engine compressor components has been a serious problem for military helicopter operations. In this application the erosion problem is so severe that factors of ten improvement in erosion resistance are required for any material or coating developed to alleviate the erosion problem. The titanium carbide and titanium diboride coatings that offer this degree of protection also compromise blade fatigue strength to a level not tolerable in commercial turbine engine applications. However, since the erosion problem in commercial engine service is considerably less severe than in military helicopter operations, coating solutions are available that may provide adequate erosion resistance without critically compromising the fatigue strength margin of the airfoils.

In order to evaluate the potential effectiveness of coatings in limiting erosive damage to compressor airfoils, an effort was initiated to evaluate candidate coatings for substrate alloys typically used in commercial engine high compressor blades. Laboratory and rig erosion testing of plasma deposited and diffusion coatings described in this paper has shown the potential of a two-to four-fold improvement in erosion life. The selective application of these coatings to approximately the outer third of the airfoil - the area that is subject to erosion degradation - avoids coating the fatigue critical region of the blade, thus providing erosion resistance potentially without compromising the fatigue strength of the blade. Both the plasma and the diffusion coatings also offer the advantage of low initial cost and a multi-source production base.

*The reported work has been performed under NASA Lewis Research Center Contract titled Materials for Advanced Turbine Engine (MATE)(Contract NAS3-20072) P&WA Project 4, Erosion Resistant Compressor Airfoil Coatings.

Coating Selection:

A useful first order classification system for potential erosion resistant coatings identifies three major types of coatings. Specific coatings selected from each class for this study include:

1. Multiphase Overlay Coatings: tungsten carbide-cobalt
2. Diffusion Coatings: chromium-boron
3. Single Phase Hard Compound Overlay Coating: titanium-diboride

The tungsten carbide-cobalt composition is applied by modern plasma spraying. This type of coating has been widely used in the aircraft engine industry principally to minimize contact wear involving galling, fretting and impact. High energy thermal spray processes, the most important of which are plasma spray and detonation gun, have been developed for the application of high integrity coatings. These processes are highly commercialized and supplier facilities capable of producing these coatings exist world wide.

Representing the diffusion coating class is a chromium-boron composition. This type of coating is formed by diffusional interaction of chemical elements with substrate alloys to form erosion resistant phases at the alloy surface. An intensive commercialized technology base exists for the fabrication of diffusion coatings for the turbine engine industry.

Single phase, hard compound overlay coatings such as TiB_2, TiCN and TiC have been demonstrated to provide the greatest degree of erosion resistance, particularly at low particle impingement angles. The two most widely investigated processes for fabrication of these coatings are chemical vapor deposition and fused salt electrolysis. TiB_2 produced by fused salt electrolysis is representative of this type of coating.

Coating Evaluation:

Laboratory Erosion Testing

Coatings were produced on three alloys representing typical materials used in commercial turbine engine compressor airfoils. These alloys are the titanium base alloy Ti-6Al-4V (AMS 4928), a stainless steel alloy (AMS 5616) and a nickel base alloy (IN901). In this paper the laboratory erosion test results are reported for the coatings on stainless steel (AMS 5616). The alloy specimens were coated to a nominal thickness of 50 microns (2 mils).

The laboratory erosion testing was performed using an S.S. White Airbrasive Unit. Aluminum oxide with a nominal 27 micron particle size was used as the abrasive material. The abrasive particles are accelerated to approximately 300m/sec and impinge on the test specimen approximately 1.5cm from the nozzle. Three abrasive impingement angles were tested - 20, 45 and 90 degrees. The erosion resistance was measured by weight and volume change as a function of time, and by the time to erode 25 microns (1 mil) of coating.

Erosion data for the three types of coatings on AMS 5616 at the 20° impingement angle shows considerable improvement in terms of volume loss compared to the uncoated stainless steel alloy (Figure 2). Erosion at this angle is typical of airfoil trailing surfaces.

A comparison of test results at all three abrasive impingement angles is presented as time to erode 25 microns of material. The coatings are particularly effective at the low impingement angles (Figure 3). These data are in general agreement with the literature, with the hard coatings demonstrating greater resistance to erosion at low impingement angles than the baseline uncoated alloys. At the test condition used, the hard compound TiB_2 coating demonstrated improved resistance at a 90° abrasive impingement angle, which is not typical of this type of material in field service engine testing. These laboratory erosion tests are valuable tests to quickly and inexpensively rank coating compositional and processing variations. However, they are inadequate to provide an assessment of the potential life improvement coatings can provide on compressor airfoils.

Rig Erosion Testing

To address the challenge of establishing a test procedure that would simulate relative compressor airfoil life when subject to erosive conditions, a facility was constructed to erosion test actual compressor airfoils. A combustor system was modified to include a particle injection system (Figures 4,5). A holder was designed to place the test airfoil at controlled downstream locations with the airfoil positioned at controlled angles to the particle stream. Airfoil temperatures are monitored using an optical pyrometer. Typically, nominal twenty micron aluminum oxide is used as the erosive agent. The Laser Doppler velocimetry technique was used to determine particle velocity and particle flux in planes at a number of locations from the combustion exit nozzle. These measurements were made as a function of test rig control variables: fuel pressure, air pressure, and particle feedrate. Thus the test rig was calibrated to produce known particle velocities and test airfoil temperatures by varying the rig controls and the airfoil distance from the exit nozzle, providing the capability of simulating the temperature and velocity conditions at each stage of high compressor in gas turbine engines.

To determine the ability of this rig to reproduce erosion patterns seen in field service operated hardware, a group of blades were rig tested. Visual appearance of field service and rig tested blades was similar (Figure 6). Profiles taken at standard planes indicated similar erosion patterns with both types of testing resulting in significant reduction in blade leading and trailing edges as well as thinning of the concave airfoil.

In addition to duplicating the erosion pattern seen on field service operated compressor blades, this rig test has been able to demonstrate the blade leading edge chipping phenomenon seen in field service with titanium diboride coated blades (Figure 7). The blade leading edge blunting is an important effect to determine in screening candidate coatings as the blunt leading edge results in unacceptable aerodynamic penalties and would preclude the use of erosion resistant coatings exhibiting this effect.

Initial rig testing of AMS 5616 compressor blades with approximately 30 micron (1 mil) thick coating of plasma applied tungsten carbide-cobalt and diffusion coated chromium-boron exhibited a three fold improvement in erosion resistance measured by volume loss compared to the uncoated blades (Figure 8). The test conditions used in these tests were a blade temperature of 390°C (730°F) and a particle velocity of 290 m/sec (950 ft/sec). In these tests neither the plasma applied tungsten carbide-cobalt coating nor the diffusion chromium-boron coating eroded in a manner to produce the aerodynamically unacceptable blunted leading edge appearance seen with the titanium diboride coated blades (Figure 9).

These initial results indicate that the plasma applied coatings and the diffusion coatings offer the potential of limiting the erosive damage to high compressor airfoils.

Continuing Activity:

In the next phase of this erosion resistant coating development activity rig erosion resistance data will be generated for selected coatings on a number of airfoil stages chosen to be representative of all stages of modern turbine engine high compressors. In addition fatigue testing of coated blades has been initiated as well as surface treatments to produce blade surface finishes on the order of 20 micron AA.

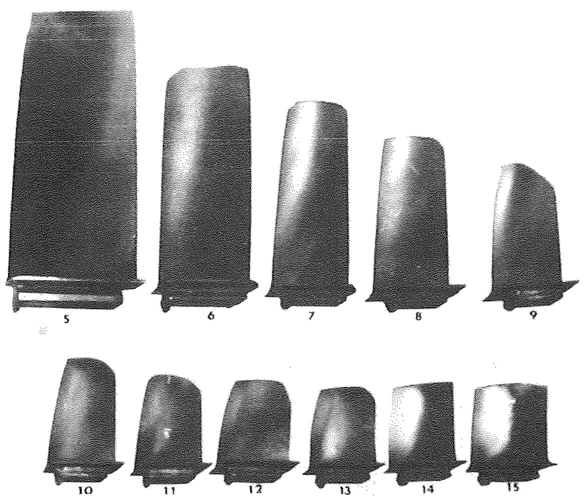


FIGURE 1 COMMERCIAL ENGINE COMPRESSOR AIRFOILS AFTER SERVICE OPERATION

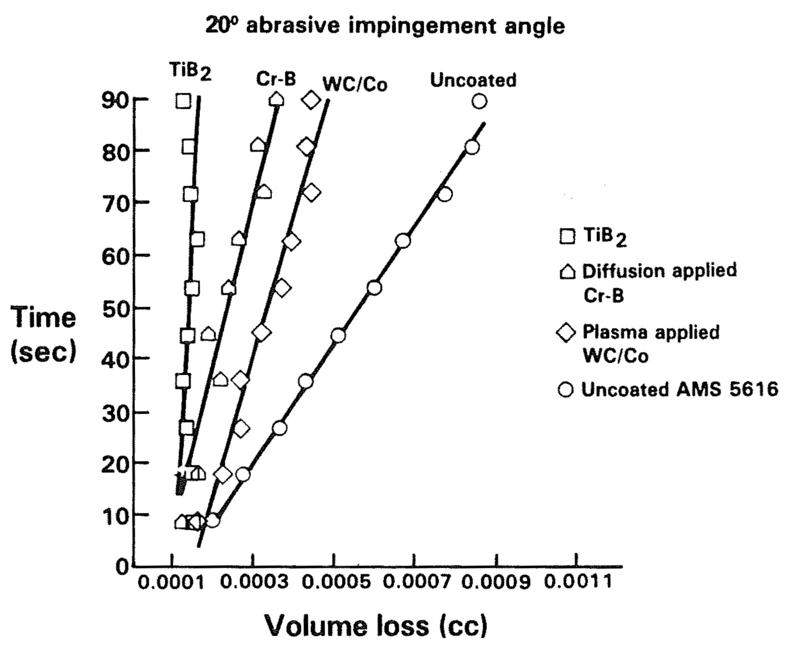


FIGURE 2 LABORATORY EROSION TEST RESULTS ON COATED AMS 5616 STAINLESS STEEL

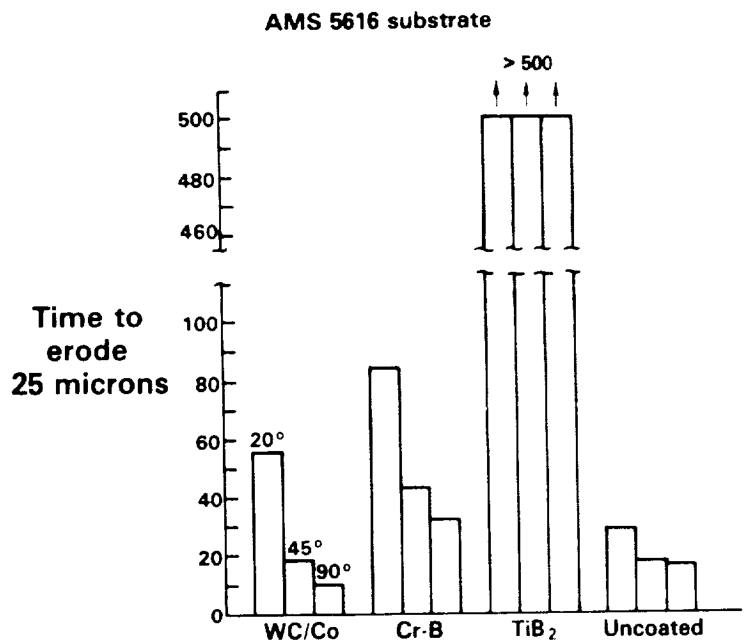


FIGURE 3 EROSION AS A FUNCTION OF ABRASIVE IMPINGEMENT ANGLE

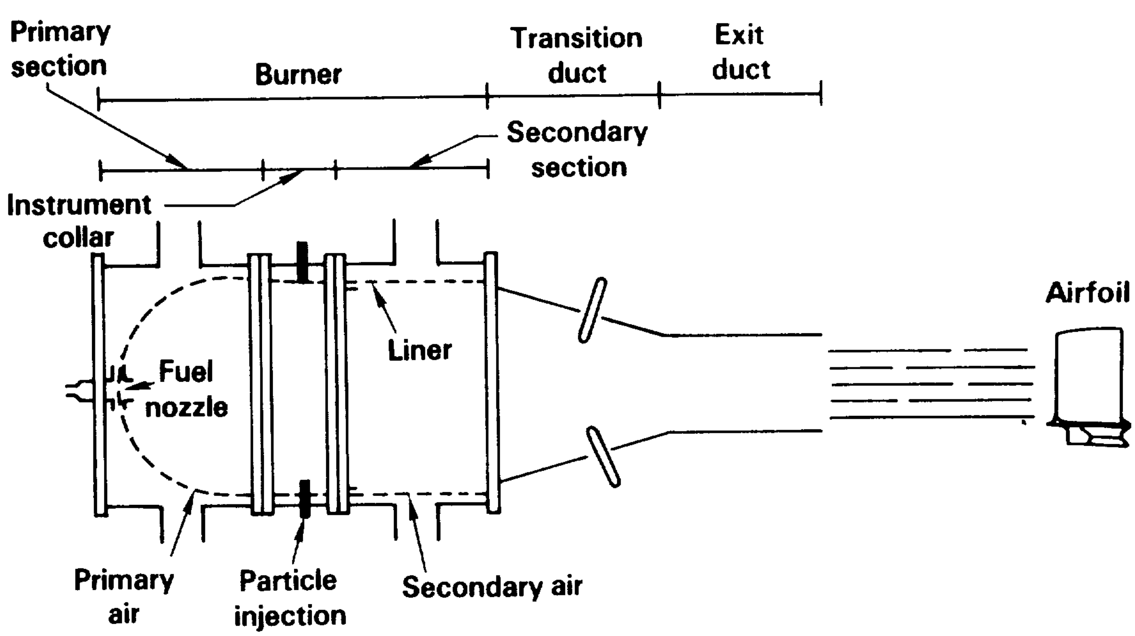


FIGURE 4 SCHEMATIC OF AIRFOIL EROSION FACILITY

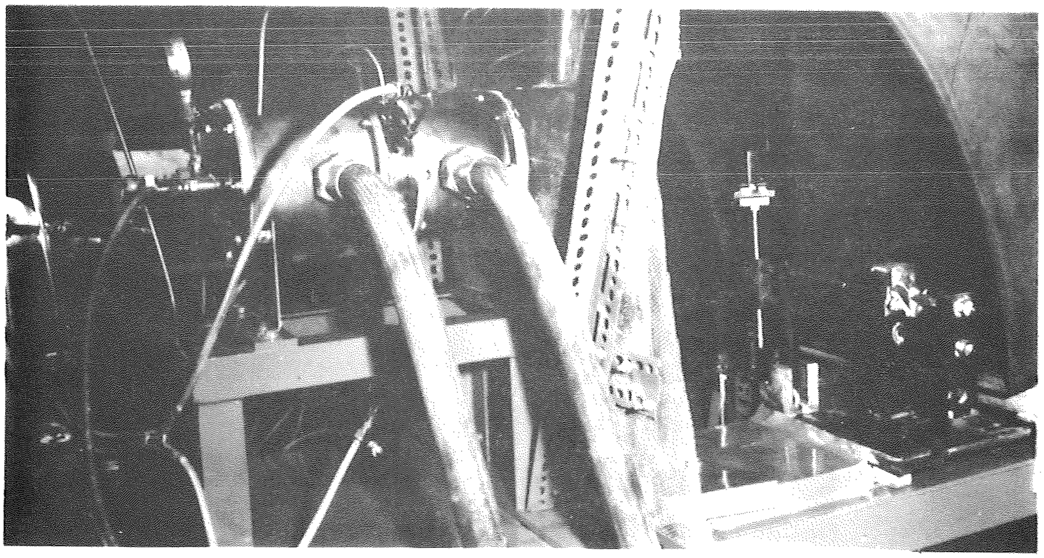


FIGURE 5 FACILITY TO TEST EROSION RESISTANCE OF COMPRESSOR AIRFOILS

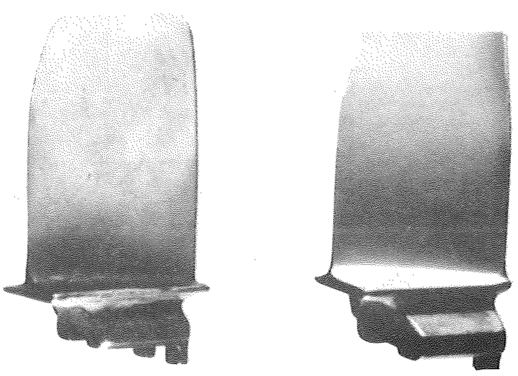


FIGURE 6 COMPONENT RIG TEST SIMULATES ENGINE SERVICE EROSION

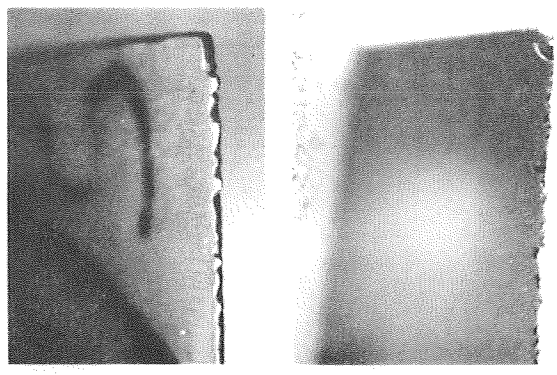


FIGURE 7 COMPONENT RIG TEST SIMULATES ENGINE SERVICE LEADING EDGE CHIPPING EROSION OF TITANIUM DIBORIDE COATED AIRFOILS

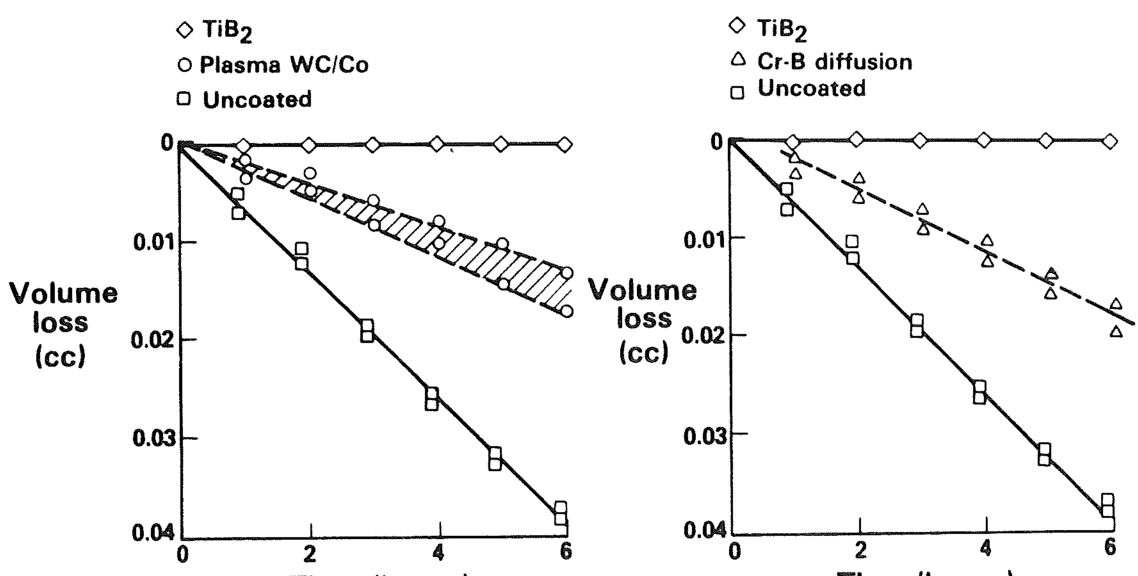
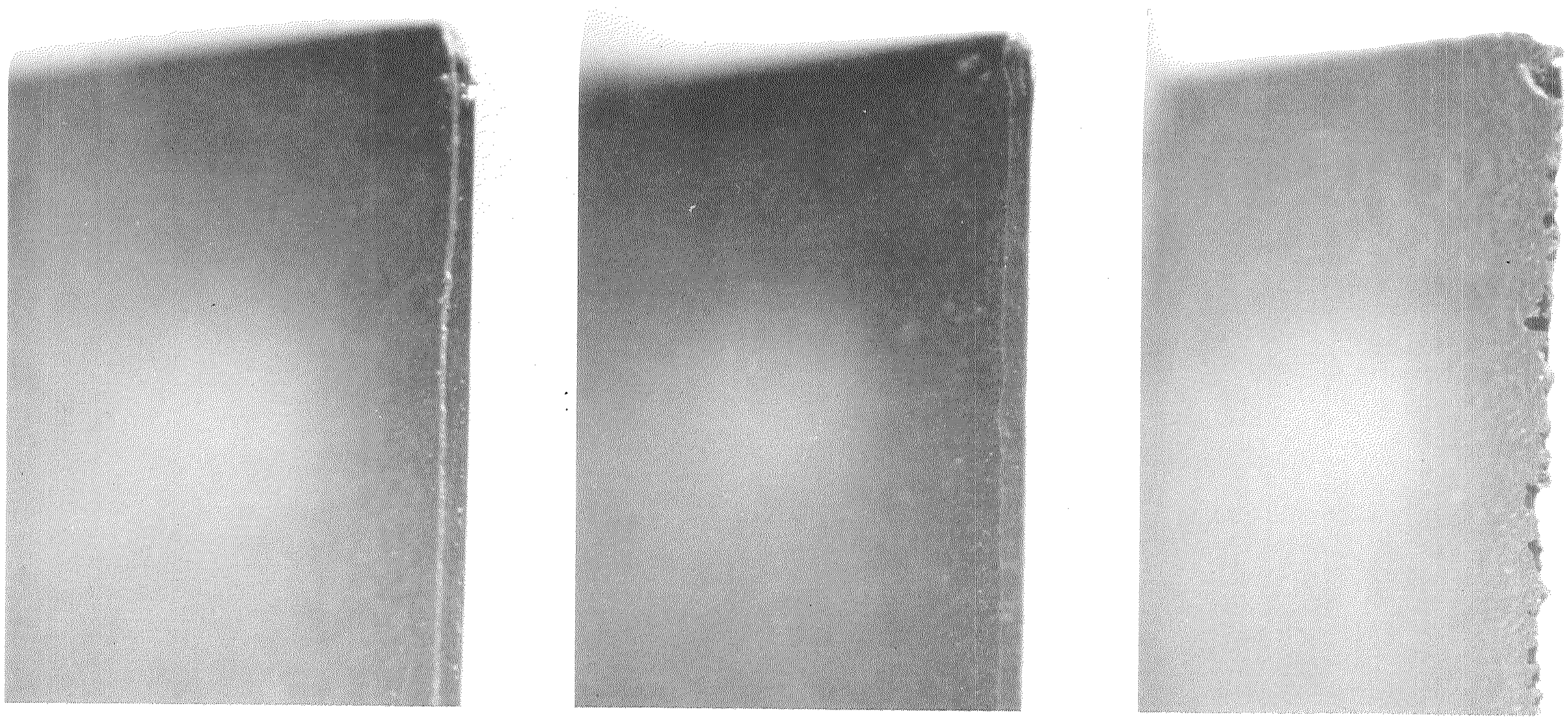


FIGURE 8 EROSION TEST RESULTS OF PLASMA AND DIFFUSION COATINGS ON AMS 5616



WC/Co   Cr-B TiB_2

FIGURE 9 PLASMA CARBIDE/METAL AND DIFFUSION Cr-B COATINGS WITHSTAND LEADING EDGE CHIPPING EROSION