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ADVANCING ABRADABLE EVALUATION: A COMPREHENSIVE REVIEW AND DEVELOPMENT OF AN INNOVATIVE COST- EFFECTIVE METHODOLOGY

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Abstract. *Abradable coatings have been proven to significantly improve the performance of gas turbine engines by serving as a protective barrier between rotating blades and stationary casing. While a significant amount of research has been performed on the development of novel abradable coatings over the last few decades, there is limited work focusing on the wear mechanisms within the abradable-blade tip interaction. Therefore, the main purpose of this study is to critically review alternative methodologies to assess abradable coatings and their interactions with the blade tips, simulating an application-relevant environment. Various abradable test rigs are discussed with a wide range of inputs and outputs, such as blade tip velocity, incursion rates, incursion depths, reaction forces, rubbing temperatures, and smoothness of cutting. Throughout this study, by a meticulous selection of mechanical and electronic components, low-cost promising equipment was designed and developed. The cost-effective abradable test rig can provide valuable insights into the wear behaviour of abradable coatings and can aid in the development of more effective wear-resistant coatings by a pre-screening methodology.*

Keywords: *Abradable Test Rig, Abradable Coatings, Cost-effective Equipment, Pre-screening, Tribology.*

1. INTRODUCTION

Abradable materials serve a crucial role in gas turbine aircraft engines by reducing the clearance between stationary and rotating parts. This enhances engine efficiency, diminishes power loss, curbs polluting gas emissions, and augments operational safety (Dorfman et al., 2022; Rathmann et al., 2007). Achieving these outcomes requires abradable materials to wear smoothly against a more abrasive material in motion, ensuring the stationary part wears while the moving abrasive material remains unscathed (Smiarowski et al., 2005). Abradable coatings must have good sealing abilities while being easily scrubbed off, indicating low hardness and elastic modulus. These characteristics enable smooth rubbing against blade tips, without causing significant tip damage. Simultaneously, the coatings must exhibit strong bonding strength and resilience against solid particle erosion and corrosion, presenting a challenge to integrate these competing attributes within one material system (Bounazef et al., 2004; Hardwicke and Lau, 2013).

While research has focused on novel plasma-sprayed abradable coatings, limited work has delved into wear mechanisms within the interaction of abradable coatings and blade tips, particularly under application-relevant conditions. High-speed abradable test rigs have emerged as a solution to simplify and economize evaluation processes (Dorfman et al., 2022; Oerlikon Metco, 2012). These rigs simulate rubbing processes within aero-engine systems, mimicking the conditions of a rotating blade within a stator component. Some facilities stand out for their sophistication and ability to replicate representative rubbing systems, such as rigs developed by: Oerlikon Metco, Beijing General Research Institute of Mining & Metallurgy (BGRIMM), Pratt and Whitney (P' & W), and the National Research Council Canada (NRC).

Despite the advancement of high-velocity abradable test rigs, conducting tribological evaluations on abradable coatings remains cost-intensive. The study's primary aim is to devise a cost-effective test rig methodology to pre-screen different abradable materials. This approach emulates application-relevant conditions and could significantly aid the tribological selection of new abradable.

2. STATE OF ART ABRADABLE MATERIAL ASSESSMENT

Extensive research efforts are currently focused on the development of materials employed as abrasive coatings on both blade tips and the inner surface of shrouds. To conduct these evaluations, numerous studies have introduced various testing rigs designed specifically for assessing abradable materials (Dadouche et al., 2008; Dorfman et al., 2022; Padova et al., 2005). Broadly, a testing rig is a device that emulates the dynamic conditions of a rotating blade within a shroud, facilitating experiments to gauge the material's resistance to rub wear (Oerlikon Metco, 2020; Padova et al., 2005). A frequently used method involves utilizing a high-speed abradable test rig.

2.1 High-Speed Abradable Test Rig

High-speed abradable test rigs can decrease time and expenses during the evaluation process of abradable rubbing systems. It can be used to precisely assess coating abradability. The main idea of the equipment is to simulate the rubbing process that happens in an aero-engine system on a small scale. It simulates the condition of a rotating blade inside a stator component. High-speed friction and wear processes between blade tips and seal coatings are usually assessed (Oerlikon Metco, 2012; Zhang et al., 2016).

Abradability testing can be used to investigate the wear mechanisms of abradable coatings and obtain more precise test results. This is because the simulated conditions closely resemble real-life working situations (Zhang et al., 2016). Several companies and research institutions have developed dedicated rig capabilities to understand the physics of abradable rub interaction (Lu et al., 2013; Oerlikon Metco, 2020; Rathmann et al., 2007; Zhang et al., 2016).

The following topics provide detailed information on some of the most famous high-speed abradable test rig facilities.

2.1.1 Abradable Test Rig Developed by Sulzer Metco

Oerlikon Metco operates a dedicated incursion test facility capable of replicating engine rub conditions, offering blade tip velocities of up to 500 m/s (1640 ft/s) and rotor incursion rates into the stator of up to 2000 $\mu\text{m/s}$ (0.079 in/s), all at elevated temperatures reaching 1200 $^{\circ}\text{C}$ (2192 $^{\circ}\text{F}$) (Oerlikon Metco, 2020). Figure 1 shows a schematic of Metco's rig.

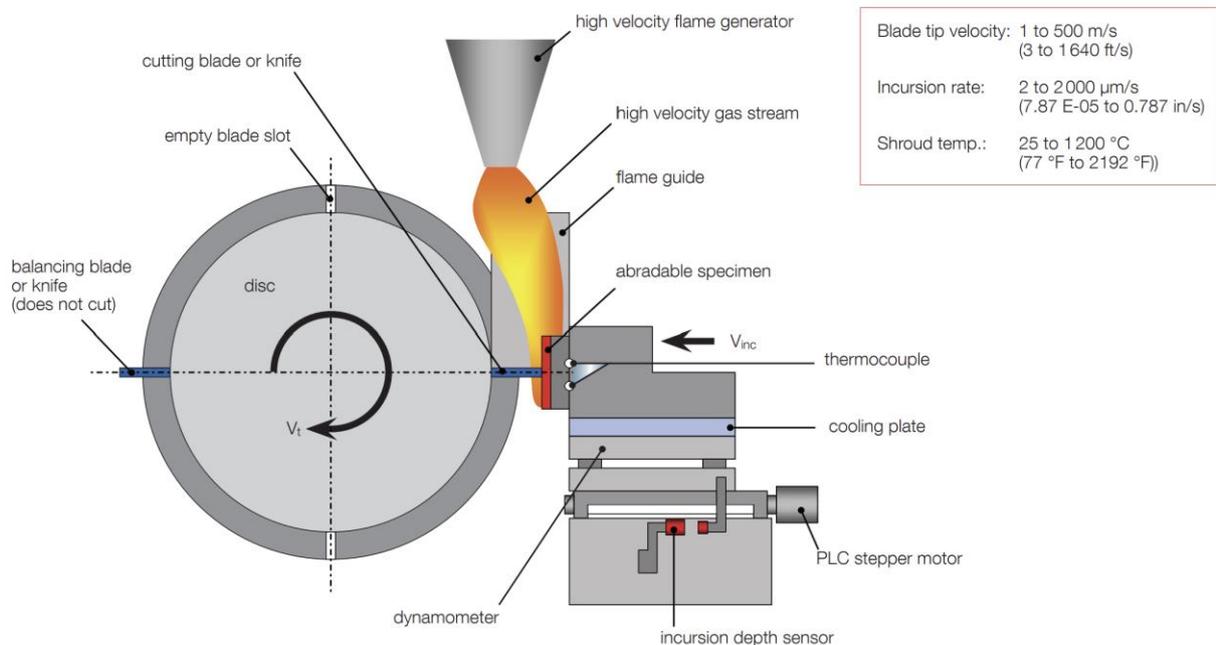


Figure 1. Schematic of the abradable test rig developed by Sulzer Metco (Oerlikon Metco, 2020).

This facility plays a pivotal role in identifying shroud wear mechanisms, blade wear under varied operational conditions, and essential factors like frictional heating temperature and rubbing forces. These insights are vital for validating the effectiveness of developed abradable systems. Notably, beyond its internal use for testing and validating its own abradable material products, Oerlikon Metco's test stand has evolved into an industry reference point within the

turbomachinery sector. Multiple Original Equipment Manufacturers (OEMs) in aviation and power generation sectors utilize it as a risk mitigation tool for new clearance control systems in gas and steam turbines (Oerlikon Metco, 2020).

The utilization of Oerlikon Metco's test rig enables swift abrasible coating testing across diverse conditions, yielding highly correlatable results. Its testing approach can replace some in-situ assessments, including test cells, on-wing evaluations, and assessments on actual turbine engines (Oerlikon Metco, 2020, 2012).

Routinely, the test facility serves as a benchmarking platform for candidate material compositions and systems. Furthermore, it is instrumental in testing actual sprayed abrasible coatings, gathering data that can be leveraged to optimize spray parameters for maximum effectiveness (Oerlikon Metco, 2020).

2.1.2 Abradable Test Rig Developed by NRC Canada

The high-speed abrasible test rig from the National Research Council of Canada (NRC) effectively replicates operational wear by employing a simulated turbine blade or knife edge. It comprises a rotor powered by an air turbine and supported by hybrid rolling-element bearings. Capable of reaching speeds of up to 40,000 rpm, equivalent to a blade speed of 425 m/s, the rig's table, supporting the test coupon holder, is controlled axially and radially through two servo motors. This stage provides incursion rates from 2.5 $\mu\text{m/s}$ to 760 $\mu\text{m/s}$, and the fixture is adaptable to accommodate both flat and curved profiles of test coupons (Dadouche et al., 2008; Irissou et al., 2014). Figure 2 presents an image of the aforementioned abrasible test rig.

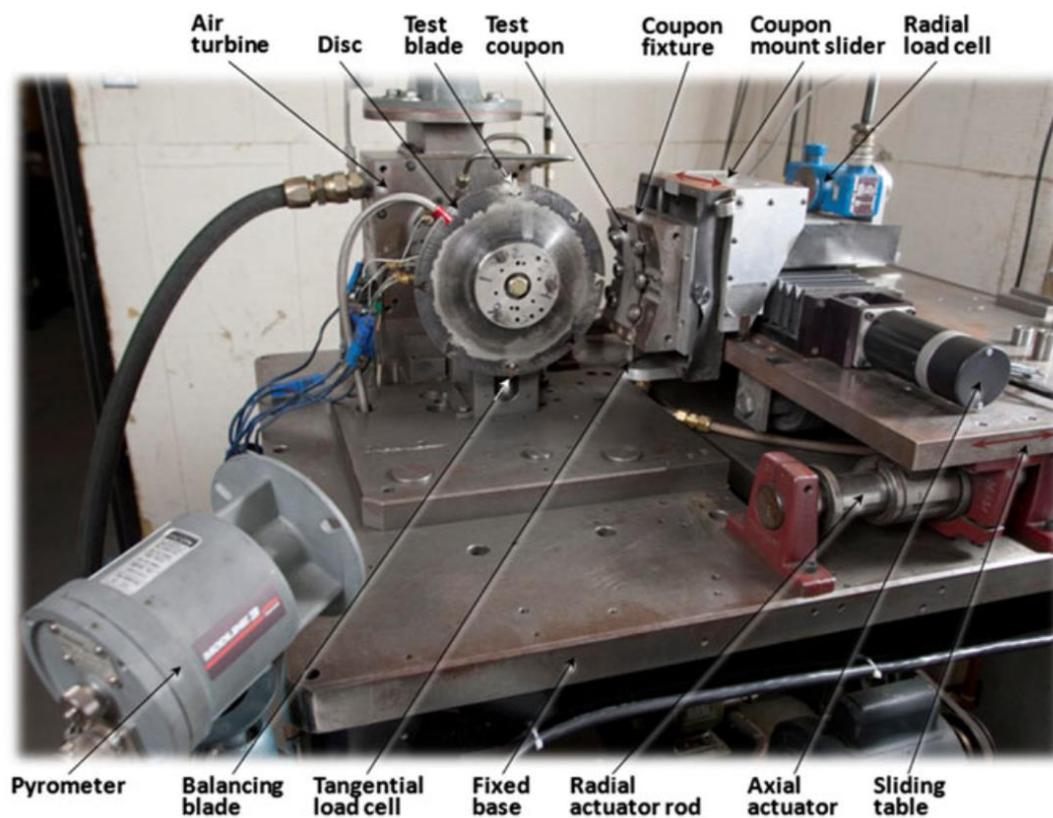


Figure 2. Abradable test rig developed by NRC (Irissou et al., 2014).

Furthermore, the rig can assess heated abrasible materials up to 600°C using a ceramic-encased, wire-wound resistor situated at the test coupon's rear (Dadouche et al., 2008; Irissou et al., 2014).

According to (Irissou et al., 2014), the pivotal parameters for evaluating abrasible seal performance encompass blade tip speed, incursion rate, and working temperature. These parameters need to faithfully replicate the typical operational conditions endured by abrasible seals. Generally, such specifications are outlined by end users or manufacturers.

Equipped with diverse sensors, the rig captures rub temperature, radial and tangential rubbing forces, speed, and seal incursion rate. Subsequent to each test, the wear on both the blade and abrasible seal is quantified. Parameters like vibration and bearing temperature are also closely monitored throughout testing. Data collection is facilitated by a computerized data acquisition system (Dadouche et al., 2008; Irissou et al., 2014).

2.1.3 Abradable Test Rig Developed at University of Sheffield (UK)

The University of Sheffield (UK) test rig comprises several integral components, these components include a spindle, a stage, bearing supports, a disk, which is positioned between the front and rear bearings, and a rig containment structure constructed from steel plates and blocks filled with concrete (Rahimov et al., 2022). Images of the high-speed abradable test rig can be seen in Figure 3 and 4.



Figure 3. Abradable test rig developed at University of Sheffield (UK) (Stringer and Marshall, 2012).

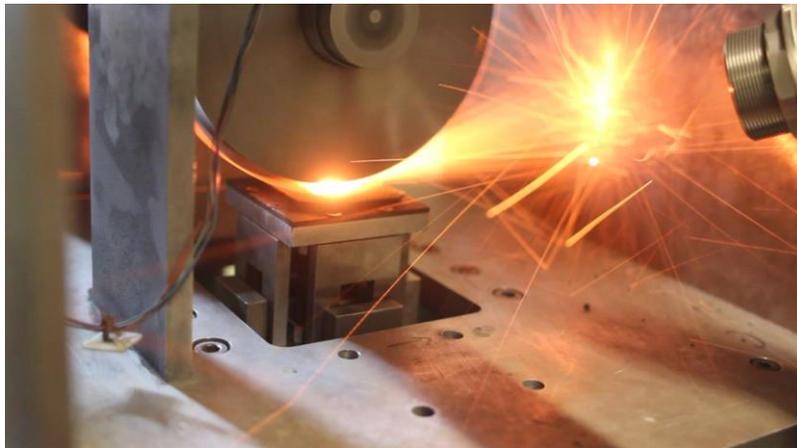


Figure 4. Abradable test rig developed at University of Sheffield (UK) in operation (Watson and Marshall, 2018).

The disk is linked to the spindle through a flexible coupling. Within the disk, slots are situated 180 degrees apart to accommodate both cutting and dummy blades, the latter being used for disk balancing purposes. The maximum achievable blade tip speed with this configuration reaches 200 m/s (Rahimov et al., 2022; Stringer and Marshall, 2012; Watson and Marshall, 2018).

In addition, the incursion stage serves the purpose of advancing abradable samples toward the rotating disk at a constant velocity. It encompasses several key components, including a front plate attached to a force dynamometer and sample holder. The stage is driven by a ball screw and a system of gearboxes (Rahimov et al., 2022; Stringer and Marshall, 2012; Watson and Marshall, 2018).

2.1.4 Abradable Test Rig Developed by BGRIMM

BGRIMM is also actively working on the improvement of the material used as an abrasive in the turbomachines. One of the machines, developed by Beijing General Research Institute of Mining & Metallurgy (BGRIMM), China, can be seen in Figure 5.



Figure 5. Abradable test rig developed by BGRIMM (Liu et al., 2017).

The test rig, developed by the BGRIMM, replicates the operational conditions of aero-turbine engines. This rig encompasses four essential components: Rotor, incursion system, heating device, and controlling system. A Schematic of the abradable test rig developed by BGRIMM is shown in Figure 6.

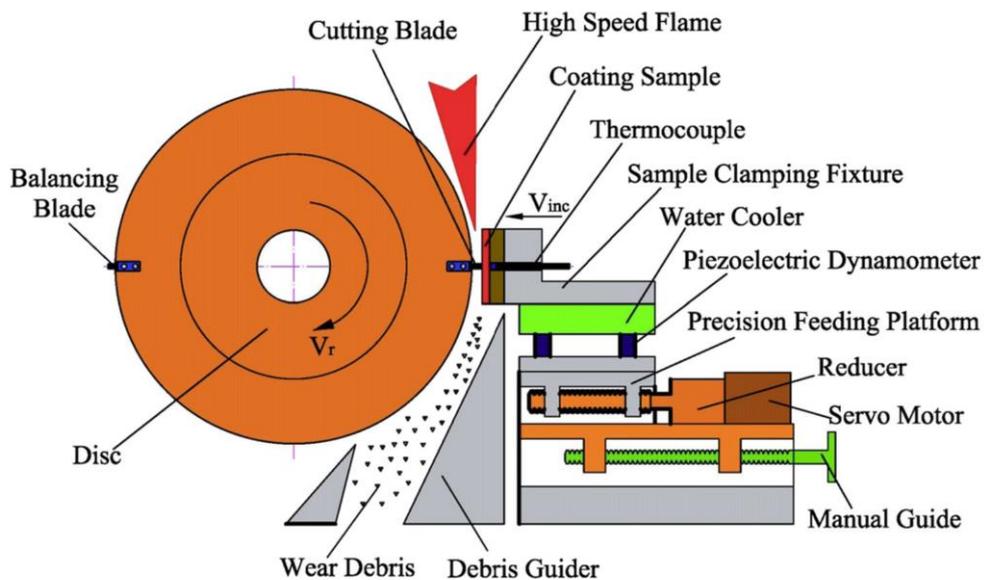


Figure 6. Schematic of the abradable test rig developed by BGRIMM (Liu et al., 2017).

The disc's theoretical maximum rotation velocity is 15,000 RPM, and the linear velocity reaches up to 350 m/s. The system's operation involves programming the feed rate and displacement to regulate the lateral position of samples through the rotor. The feed rate is adjustable within a range of 5 $\mu\text{m/s}$ to 500 $\mu\text{m/s}$ with an accuracy of less than 5%. Precise feed displacement matching the set values is achieved through feed zero-calibration (Liu et al., 2017; Lu et al., 2013).

In order to subject the testing pieces to high temperatures, a rapid and intense flame with the potential to reach temperatures as high as 850°C is utilized. This heating process is initiated by an oxygen-acetylene gas flame spray gun (Liu et al., 2017; Lu et al., 2013).

2.2 Cost-Effective Abradable Test Rig developed at Concordia University

Despite using the high-velocity abradable test rig, conducting tribological evaluations on abradable coatings remains a costly endeavor. Thus, the following topic describes the design of a cost-effective test rig methodology to assess different abradable coatings and their interactions with blade tips, simulating an application-relevant environment that can be very helpful for the tribological pre-screening of abradable materials.

The cost-effective abradable test rig offers a swift and economical solution for assessing abradable coatings across various conditions and securing reliable outcomes. In contrast to alternative testing setups such as high-speed abradable test rigs, test cells, on-wing evaluations, or in-situ testing on operational turbine engines, the abradable test rig stands out for its efficient, low-risk, and highly budget-friendly approach.

However, it's important to acknowledge that the primary limitation of this cost-effective abradable rig lies in its constrained blade tip speed, for example 60 m/s. This stands in contrast to high-speed abradable rigs which can achieve speeds of up to 300 m/s or even 500 m/s in some instances (Dadouche et al., 2008; Irissou et al., 2014; Oerlikon Metco, 2020; Stringer and Marshall, 2012; Xue et al., 2018). Nevertheless, this testing facility serves well for the preliminary screening of material compositions and practical testing of abradable coatings. Such low-speed abradable tests can also be found in literature references (Baiz et al., 2013; Cuny et al., 2014; Ma et al., 2015; Mandard et al., 2015; Rahimov et al., 2022).

The validation of abradable systems hinges on the identification of wear mechanisms, blade wear under various operating conditions, and the determination of frictional heating temperature and rubbing forces (Irissou et al., 2014; Zhang et al., 2022). To this end, the developed abradable test rig showcases an extensive array of inputs and outputs.

The main inputs of the abradable test apparatus, along with the outputs are outlined in Table 1.

Table 1. Main inputs and outputs of the abradable test apparatus.

Input Parameters	Output Parameters
Blade Tip Velocity	Reaction Forces
Incursion Rates	Rubbing Temperature
Incursion Depths	Blade Wear and Transfer
Operating Temperature	Acoustic Inspection

The assortment of inputs, coupled with the rig's adaptability, enables testing across a diverse spectrum of conditions. Furthermore, the outputs hold substantial importance in comprehending and enhancing the efficiency of turbine blade systems. In Figure 7, an image of the cost-effective abradable test rig's functionality is presented, showcasing the assessment process of an abradable material.



Figure 7. Cost-effective abradable test rig in operation.

Figure 7 shows a crucial moment where the abrasible test rig is in operation, providing a dynamic insight into the elaborate mechanics and processes involved in the evaluation. This image summarizes the culmination of the rig's meticulous design and development phases, where a comprehensive approach to assessing abrasible materials has been successfully created.

3. CONCLUSION

In summary, abrasible test rigs presented as valuable tools for evaluating turbine blade systems, offering insights into abrasible-blade tip interaction and wear behaviour. Its capabilities in simulating operational conditions, gathering diverse output data, and facilitating comparative studies are vital for improving turbine efficiency and reliability.

The cost-effective abrasible test rig offers a quick and affordable way to pre-screen abrasible coatings under various conditions and obtain reliable results. However, acknowledging its limitations, such as the lower blade speed, the abrasible test rig stands out for its efficiency, low-risk, and highly budget-friendly approach.

Overall, the development process of the cost-effective abrasible test rig was well-structured and may create an effective, versatile, and affordable tribological methodology. Looking ahead in time, it can contribute to the development of wear-resistant coatings, particularly when implementing a pre-screening approach.

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