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1 Executive Summary

Introduction

The efficiency and service life of high value industrial components can be critically impacted by solid particle erosion and wear, particularly at high temperatures. Currently, assessment of the erosion resistance of materials and surface treatments is largely empirical, not standardised and hampered by a lack of traceable metrology. This project has created the metrological tool box to enable a step change in monitoring and control of high temperature solid particle erosion testing, thereby facilitating the accelerated development of improved materials and coatings to prevent this form of surface degradation.

The problem

High temperature solid particle erosion (HTSPE) takes many forms, for instance the particles could be volcanic ash in aero engines, fly ash in boilers, exfoliated scale in steam turbines or mineral matter in oil excavation. The impact caused can be significant. For example reduced efficiency in these industries results in additional emissions of CO_2 and wear costs the power industry an estimated 200M€ a year in lost efficiency, forced outages and repair costs. Major improvements in the efficiency of power generating plants (7% to 10%) and aero-engines would be possible by the development of new materials that have improved resistance to high temperature particulate erosion.

The solution

For many years HTSPE testing has been limited to being able to rank materials comparatively under conditions which nominally replicate in-service conditions. Better models and understanding are required, through improved and more controlled, reproducible and representative tests. The measurement of damage, the temperature of the erosive particles and the supporting gas stream, the gas stream flow rates and the size and shape of erosive particles, all influence the erosion resistance of materials. The lack of control of these parameters has been identified as the cause of a lack of reproducibility in measurements (up to 100%) by an EPRI (Electric Power Research Institute) workshop. This project addresses these issues to establish a metrological based framework for high temperature erosion testing with traceability to National Standards.

Impact

Within this project we have developed the necessary metrological tools to enable; in situ measurement of the erosion rate during the test, measurement of the particle velocity and velocity distribution, characterisation of the shape and size of erodent particles, better measurement of damage mechanisms and erosion, the determination of the relative sensitivities of test parameters which can vary with different equipment, and the creation of new generic models to predict the erosion performance of materials. In achieving these goals this project has provided a step change in the ability of industrial laboratories and research institutes to measure high temperature solid particle erosion.

The provision and uptake of this metrological framework has enhanced the capability for research laboratories to carry out HTSPE testing and will enable increased confidence in the provision of this form of data to industry. This will enable the development and use of improved material solutions to maintain plant efficiency, reduce carbon emission, reduce fuel usage in aerospace and improve productivity for advanced material systems. The project's thermal modelling techniques have also enabled room temperature data of mechanical properties to be extrapolated to give an indication of the high temperature wear resistance with greater accuracy.

2 Project context, rationale and objectives

Erosion and wear can dramatically reduce the efficiency and life of high value components across a range of industrial sectors. In the power industry this form of degradation alone costs an estimated 200 M€ a year in lost efficiency, forced outages and repair costs. This loss in efficiency has a clear environmental impact, for example reducing the erosion of the leading edge of turbine blades would result in improved efficiency, in the order of 7 %, and thus avoid, in the case of a large power plant (~800 MW), the emission of an extra 250,000 tonnes of CO_2 over the lifetime of the plant. Heavy industry such as steel processing plants also suffer from erosion to materials handling plant components such as furnaces, forges, presses, mills and dies that causes major losses in efficiency and revenue through damage to processing plant and machining tools.

In the last decade there has been increasing legislation requiring industry to cut and control carbon emissions that are believed to be linked to climate change. EC directives designed to limit CO_2 emissions, such as Directive 2010/75/EU, Directive 2003/87/EC, Directive 2006/32/EC and Directive 2001/80/EC, linked to the Kyoto Protocol and the prospects of enhanced climate change occurring as a result of man-made greenhouse gas emissions, has led the EU to commit to a 25 to 40 % reduction in CO_2 emissions by 2020. In parallel there is a predicted increase in the world energy demand. As a consequence industry is actively seeking methods to capture and control the emissions. In fact the UK Electricity Market Reform (EMR) White Paper 2011 stated that there should be “an Emissions Performance Standard (EPS) set at 450g CO_2/kWh to reinforce the requirement that no new coal-fired power stations are built without Carbon Capture and Storage (CCS)”, which not only enforces the need for CCS in new builds but also imposes stricter limits on CO_2 emission than current EC directives. Other alternatives being pursued include the retrofitting of existing plants and the conversion of coal fired plants to biomass combustion, either 100 % or co- fired with coal. Whilst this will use a more carbon neutral fuel it does not eliminate the problem of erosion, and in the case of some biomass fuel will exacerbate the problem on the fireside components in boilers.

Unfortunately capture methods impact the efficiency of high temperature plants so using this method alone is not desirable; rather increasing the efficiency of plant through higher temperatures and pressures with improved materials and process control coupled with capture technologies is the route being pursued. Whilst increasing operating temperatures does increase the efficiency of the plant, current materials are at the limits of their performance. Higher temperatures are likely to lead to increased oxidation rates and exfoliation, thereby exacerbating the occurrences of high temperature solid particle erosion of components. In an industry that considers an increase of 5 % in the plant efficiency as a major step forward, losses of 7 % efficiency due to erosion (e.g. of the steam turbine blades) are a major concern. It is critically important therefore to not only consider designed efficiency, but also running efficiency, to which HTSPE impacts.

For many years HTSPE testing has been limited to purely being able to rank materials comparatively under conditions which were believed to nominally replicate service conditions. Assessment of the erosion resistance of candidate materials and surface engineering solutions has therefore been hampered by a lack of metrology for issues such as the measurement of damage, the velocity of the erosive particles and the supporting gas stream and the erosive particle size and shape. The lack of control of these parameters has been identified as the cause of a lack of reproducibility in measurements (up to 100 %) by an EPRI (Electric Power Research Institute) workshop. There is also a requirement to understand the variability in erosion measurements between different laboratories. Once this is clearly defined there will be sufficient understanding to develop a standard test procedure for HTSPE testing, which at the inception of this project was not available, and enable advanced modelling for improved design routes and more accurate predictions of performance. Improved measurements and control of tests will facilitate exchange of data between laboratories, lead to more collaborative work (for example through activities like COST and KMM-VIN) and accelerate the rate of material development.

Without this necessary metrological framework, the development of new materials will still be based on a largely empirical approach that will significantly delay the improvements that are needed to meet the challenges of reducing environmental impact, and meeting the EU targets for CO_2 emissions, the target date for which grows ever closer.

There are currently few facilities available worldwide for the measurement of high temperature particulate erosion. Those that are available have been limited in terms of the measurement and control of particle velocity and temperature. There are also major limitations in terms of understanding the uncertainties associated with the measurements undertaken during the test, their applicability to real industrial applications and the interoperability of different test apparatus.

With regard to measurement uncertainties, current standard practice leads to large errors in measurement that requires major improvement. For example the usual approach for measurement of the velocity of erodent particles is through a twin disc test system where rotating discs are used to give a measure of velocity. This method has measurement errors of the order of 20 to 30 % leading to much greater uncertainty in the overall measurement. Moreover, the double disk method can only provide an estimate of the maximum particle speed achieved, but does not account for the velocity distribution which is dependent on particle size distribution, thus a significant spread in particle velocity is possible but unaccounted for. To improve the control and repeatability of HTSPE testing a new *in situ* method was required to measure the particle velocity and velocity distribution. This has been developed as part of this project.

Temperature measurement is also critical in understanding and quantifying material performance. In current systems the temperature of the erodent particles is assumed to be the same as the gas stream, but even this temperature is not well defined as it is often measured in the heating system for the gas and not at the nozzle, leading to unknown uncertainties in measurement. Within METROSION a clearer understanding of the temperature distribution in the nozzle and gas stream has been obtained and methods for improved instrumentation of test apparatus explored to ensure tests are conducted at the correct temperature with the correct level of control and reliability.

The particle size and size distribution are important parameters to measure and control, as these define the mass of erodent particles, and thus, together with the particle velocity, the kinetic energy of impact for erodent particles, which relates to the severity of erosive damage. Often the poorly defined data from the materials suppliers are used and assumed to be correct when sizing powders. This is further complicated when accounting for the contribution of the powder feed system, which could alter the size distribution through use. Moreover, depending on the nozzle geometry, particles can follow different trajectories depending on their size thereby affecting the erosion rate.

Particle shape is also crucially important as this defines the local contact geometry of impacts with the test sample. Although angular particles are known to give different results to rounded particles, there has been little work exploring the detailed relationship between the shape and asperity of particles and the resultant erosion behaviour. Innovative measurements have been performed using 3D optical microscopy techniques and X-ray tomography to determine the variability in size and shape determination between different techniques and for comparison with *in situ* optical methods.

Little modelling of long term performance of the high temperature erosion process has taken place, so that prediction of material life-time is very uncertain, leading to potentially unnecessary outages, unreliable plants with unplanned closure and associated high maintenance costs and loss of production (estimated to cost ~£0.5m per day). To enable better design of materials for high temperature erosion applications it is important that the behaviour of materials is well understood and that modelling of long term performance can be carried out.

Currently, empirical models exist for predicting solid particle erosion but by their very nature, these models are heavily dependent on experimental data in the form of erosion coefficients. These models are suitable for predicting erosion rates in well-defined situations where a wealth of experimental data already exists. They are useful in comparative work e.g. material ranking. If modelling of a more general erosion process or a more complex geometry is required, the empirical models are no longer applicable.

The limitation on the applicability and development of predictive models to date has been the lack of well-defined interactions between the erodent and the surface. The metrological framework outlined in this project has facilitated the development of physical understanding of HTSPE, leading to the improvements in the applicability of modelling which are required so that advances in the prediction of material performance can be delivered and material development accelerated.

Improved metrological tools and techniques provide a paradigm shift in the application of HTSPE tests; improved *in situ* measurement of all constituent parts of the test provides reliable simulation of service conditions and greatly improves the applicability of the test. The implementation of improved *in situ* measurement and rigorous characterisation of the erodent and the erosion scar will provide greater phenomenological understanding of the erosion processes at high temperature. Using a more controlled test enables better repeatability and reproducibility of testing. The provision of an improved metrological framework for high temperature erosion testing is important for other applications in materials processing where resistance to particulate impact at high temperature is required.

To meet the requirements as detailed above, this project had the following technical and scientific objectives:

1. ***In situ* measurement of the volume of erosion** through novel techniques, *in situ* sensors, capable of measuring depth of damage to a resolution of 1 µm over an area of approximately 70 mm^2. This will enable for the first time on-line measurement of the erosion rate to be made giving significant improvements in testing.
2. ***In situ* measurement of the change in mass** of the samples: The *in situ* measurement of the mass change at high temperature will significantly increase the speed in which the tests can be conducted and removes the associated uncertainty of relocating the specimen in the gas stream. Reducing the test time also reduces the extent of oxidation of the sample thereby reducing measurement uncertainty due to oxidation gains.
3. **Measurement of the gas flow, velocity and temperature of high temperature erodent particles and its distribution**. The volume of damage in erosion is highly dependent on the velocity of the erodent particles, so improved accuracy in the measurement of this parameter will significantly reduce the uncertainty in the evaluation of erosion and subsequent modelling. The performance of materials is critically dependent on temperature because of changes in temperature dependent properties such as modulus and hardness. Accurate measurement is therefore critical in the control of the test, and understanding contact and non-contact thermometry approaches is critical to reliable testing.
4. **Measurement and characterisation of the erosive particle size and shape, and consequentially their respective speeds**. These parameters dictate the detailed damage that takes place when impacts between particles and the target materials occur.
5. **Determination of the influence of test parameters** such as the angle of incidence and the geometry of the test system on the results that are obtained and the repeatability and reproducibility of the results. Understanding this helps industry to compare results from different sources and equipment.
6. **Modelling of the high temperature erosion process to achieve a life prediction capability**. Model will be developed based of fundamental physical principles to limit the requirement to curve fit to existing data, and in doing so develop more generic modelling approaches.

3 Research results

The results of the project and how they address the technical and scientific objectives is described in the following sections.

3.1 Objective 1+2: In situ measurement of the mass change and volume change caused by erosion

The measurement of erosion rate can be achieved through calculating the rate of change of mass or volume as a function of mass of erodent particles. In conventional HTSPE testing this is realised by cooling the sample periodically during the test, say after every 5g of erodent, and measuring the mass change or the volume of the erosion scar. To do this the sample has to be removed from the apparatus and measured. The sample is then reinserted into the apparatus, heated and the test can proceed. This leads to both misalignment errors, thermal cycling and increases the time needed to conduct the test. Enabling the *in situ* measurement of the mass and volume change not only reduces the time needed to conduct the test, but also eliminates the need for thermal cycling and removes errors associated with repositioning and alignment of the sample in the gas stream. One of the major deliverables of this project was a new HTSPE test apparatus, housed at NPL, which was designed to incorporate these *in situ* measurements. The design of this rig was crucial to the success of the project and being able to demonstrate the *in situ* measurement techniques, and so it is important that the main points of the apparatus are reviewed here.

The NPL rig has been designed to allow operation at temperatures up to 900 °C with a maximum gas velocity of 300 ms^{-1}. This has been achieved through the careful design of the nozzle, balancing the gas flow, gas pressure and nozzle geometry to achieve the design goals. The main components of the apparatus are shown in Figure 1.

The NPL rig has been designed to allow *in situ* measurement of the mass change and the volume of eroded material. This has been realised through the addition of a precision balance, which is counter balanced by a pivoted armature to enable the mass change of the sample to be measured with a precision of 0.1 mg. The furnace, which is not shown in the figures, was designed without a base allowing line of sight to the surface of the sample from the bottom of the furnace. An aperture was also incorporated in the furnace at its mid-point providing visibility of the region between the nozzle exit and specimen surface to accommodate high speed optics for the measurement of particle velocity.

The design of the METROSION HTSPE apparatus is shown in Figure 1 which highlights the major innovative components of the design, namely the compact air heater (also shown in Figure 2), mixing and delivery nozzle, and the *in situ* measurement systems locations within the apparatus.

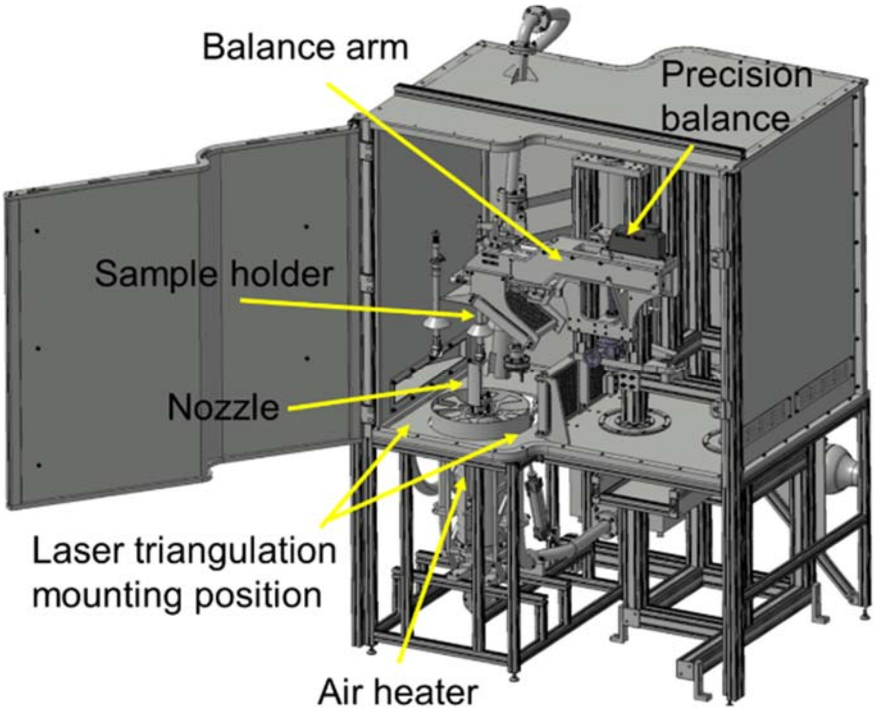


Figure 1 CAD design of the METROSION HTSPE apparatus showing the location of the major components

The carrier gas for the erosive particles is provided by an air pump operating at a maximum pressure of 1 bar, but providing a gas flow rate of 400 m^3h^{-1} (235 $cuft.min^{-1}$). This is then heated by a commercial air heater unit, approximately 20 cm in length and 9 cm in diameter housing a 17 kW heater bank (shown in Figure 2). This compact heater can heat the gas to a maximum temperature of 900 °C and allows the NPL rig to avoid the use of a high pressure heating system, such as that employed at Cranfield University, thereby simplifying the operation and avoiding the potential issues associated with high pressure systems and pressure regulations. Once heated the hot gas passes into the nozzle and the erodent particles are introduced into the gas stream either cold or from a heated hopper. The particles are accelerated down the ceramic lined nozzle and exit to impinge on the sample suspended above the nozzle at the required angle. The nozzle and the sample holder are both contained in a furnace to control and maintain the ambient and specimen temperature.

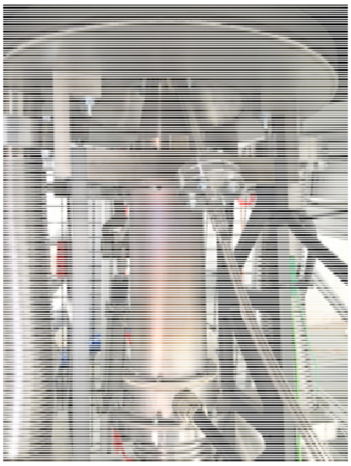


Figure 2 Air heater used to heat the erodent carrier gas

During the design process for the nozzle, extensive modelling was used to determine the appropriate dimensions to achieve the desired gas velocities of 300 ms^{-1} at 900 °C. The modelling, and subsequent experimental trials have demonstrated that the combination of air pump, heater and nozzle can achieve these velocities and temperatures. Further details regarding the nozzle design and modelling work to support the design has been reported by Smith *et al*, (2017). It should be noted that the project partners from BAM, RSE and Cranfield University all contributed to the design of the apparatus.

In situ mass

After the sample has been exposed to an aliquot of erosive powder (in the case of METROSION this was 5 g), the nozzle is moved away from the sample and the hot gas/erodent stream is diverted into an exhaust system. The sample holder is then released from a mechanical clamp thereby freely suspending the sample and holder from the balance arm shown in Figure 1 and Figure 3. Once freely hanging the precision balance (410 g capacity, 0.1 mg repeatability and 0.1 mg resolution) can be used to measure the mass of the sample with the adjustable tare weight having been previously set to counter balance the sample holder armature. In use it was found that the sample would hang with very little frictional effects from the pivot bearing and in most instances a small oscillation would start. To obtain a mass reading the data from the balance is collected over a time period and the median value used as the final mass reading. An example of the mass data and oscillation is shown in Figure 4. Once the mass is recorded the sample is once again clamped into position. With the gas/erodent stream still venting to the exhaust system it is possible to use the *in situ* laser triangulation system to scan the surface of the sample and measure the volume change.

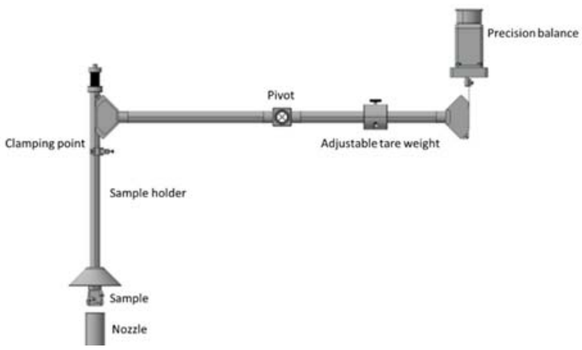


Figure 3 Schematic of the *in situ* mass measurement approach adopted in the NPL METROSION HTSPE apparatus

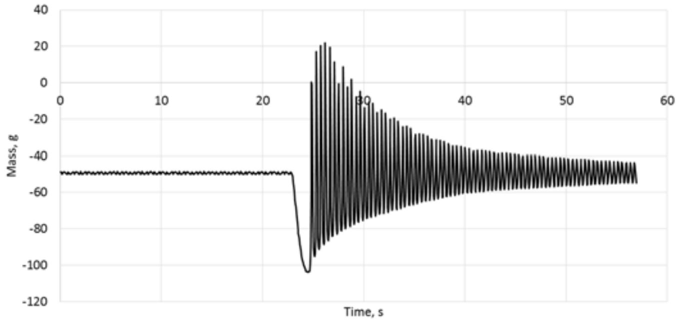


Figure 4 Example of the *in situ* mass data and standing oscillation on releasing the clamping mechanism

During use the *in situ* mass measurement approach was found to be quite sensitive to air movement and machine vibration. This is shown in Figure 4 which shows the motion of the *in situ* balance and in Figure 5 which shows the repeatability in the balance readings as a function of being clamped and unclamped. These two plots clearly illustrate that care is needed in the use of the *in situ* balance and that improvements in the repeatability of the measurements is required. However, with care it is possible to use this approach to generate erosion rate curves, an example of which is shown in Figure 6 for a test performed on Nimonic 80A coated with TiAlN, tested at 600 °C with a mean particle velocity of 117 ms^{-1} using a stand-off distance of 50 mm and an incident angle of 90°.

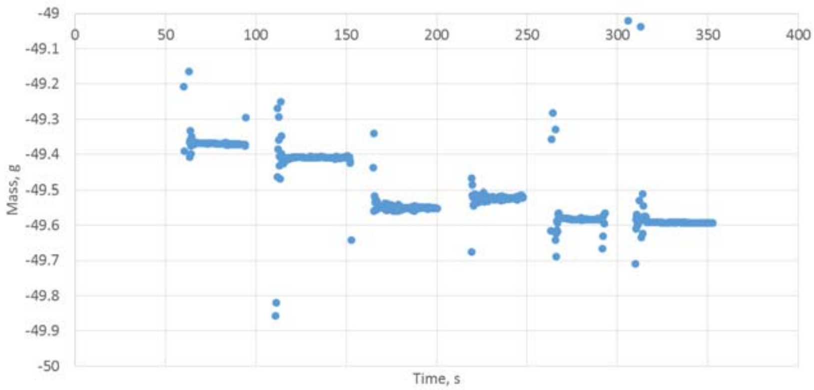


Figure 5 Repeatability of the *in situ* balance as a function of clamping and unclamping procedure

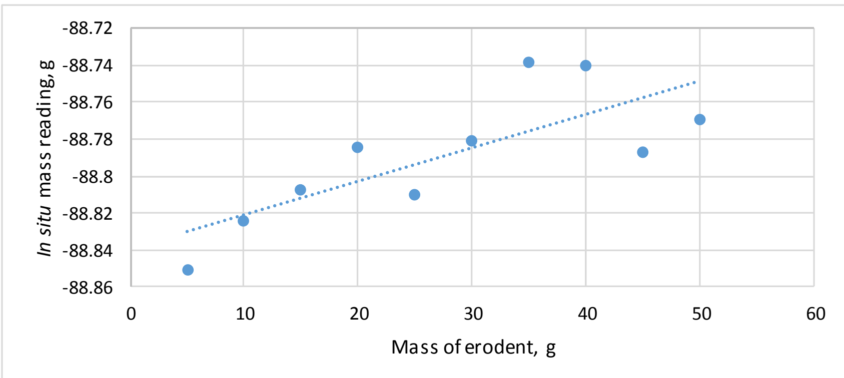


Figure 6 Example of the data generated using the *in situ* balance on TiAlN coated Nimonic 80A, tested at 600 °C with a mean particle velocity of 117 ms^{-1} using a stand-off distance of 50 mm and an incident angle of 90°

In situ volume

Due to the size and position of the furnace and sample surface the *in situ* volume measurement system must be capable of measuring erosion scars remotely from a distance of some 450 mm while the specimen is at elevated temperatures. The system must also be able to acquire its measurements without having access to a plan view of the specimen (as this is the direction from which the erodent will be injected).

There are currently no commercial solutions for this measurement and so a method had to be developed within the project. The solution devised uses a line laser (projecting a straight line instead of a spot) and a conventional digital SLR camera. When a line laser is projected perpendicularly onto a surface, the line will appear like a straight line when viewed from the same direction as the line laser source. This will be true whether the surface is flat or curved. However, if the line laser is made to shine on a surface at an angle that is significantly different from the observation angle, the line will only appear straight if the surface is perfectly flat. If the surface of the specimen has bumps or dents the laser line will appear distorted. The sensitivity of the projected line deflection to the height or depth of the surface feature is higher if the glancing angle of the laser illumination (A) is made smaller, Figure 7, although there are limits – too small an illumination angle would make it impossible to illuminate erosion scars with steep edges.

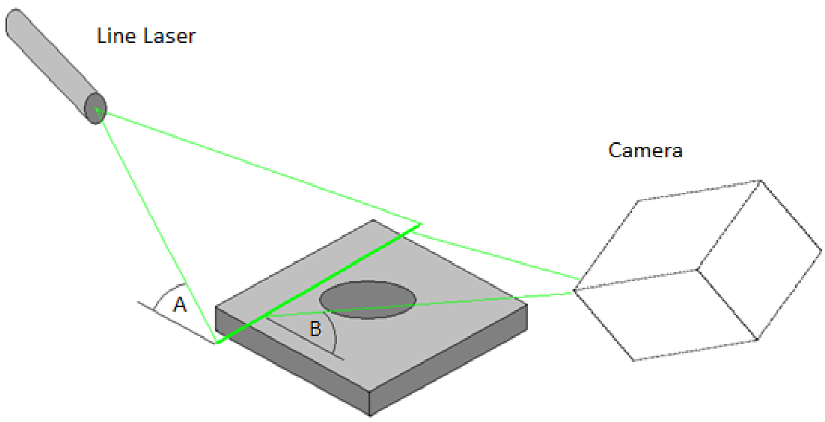


Figure 7 Principle of the wear scar measurement technique

A camera is placed on the opposite side of the laser line. Although, ideally the camera would be placed perpendicularly above the plane of the surface, this position is not available as it is needed for the erodent injection system. A compromise was reached whereby both the line laser and the camera are mounted at 45 degrees to the surface of the specimen (A =B=45 degrees in Figure 7).

In order to validate the technique, the quantitative performance of the substantial image processing algorithms developed in this project, a 'reference dimple depth standard' was produced using a 20 mm diameter ball-nose reamer to make circular dents ranging from 100 to 800 µm deep in 100 µm steps. After reaming, the surface of the entire specimen was lightly grit blasted to remove the machining marks left inside the dimples. The maximum depths relative to the average top flat surface were measured for each of the dimples using a high magnification optical microscope with a shallow depth of focus and a displacement encoder on the focus movement. The depths measured by the optical microscope are compared with the design depths in **Error! Reference source not found.**, together with measurements obtained with the technique described above.

Four separate sets of data obtained with the technique are shown. The different 'Setup Numbers' refer to total dismantling of the system followed by a new alignment and calibration. Run A and Run B were repeat measurements without re-aligning or re-calibrating, but with the reference dimple depth standard rotated by 90 degrees.

Depth of the dimples in the reference standard (um)					
		Setup 1		Setup 2	Setup 3
Design	Microscope	Run A	Run B		
100	104.3	106	107	103	100
200	203.3	212	208	196	205
300	306.5	312	304	292	290
400	402.8	413	412	386	401
500	499.5	516	511	483	504
600	602.8	620	615	578	601
700	704.3	724	719	676	709
800	801.0	826	819	792	811

Table 1 Design and measured depths of the dimples in the reference standard

The depths measured with the optical microscope have an uncertainty of around ± 5 um. The main uncertainty is due to the subjectivity of the user deciding by eye when the best focus has been achieved. The level of agreement is seen more clearly when the differences are plotted (see Figure 8).

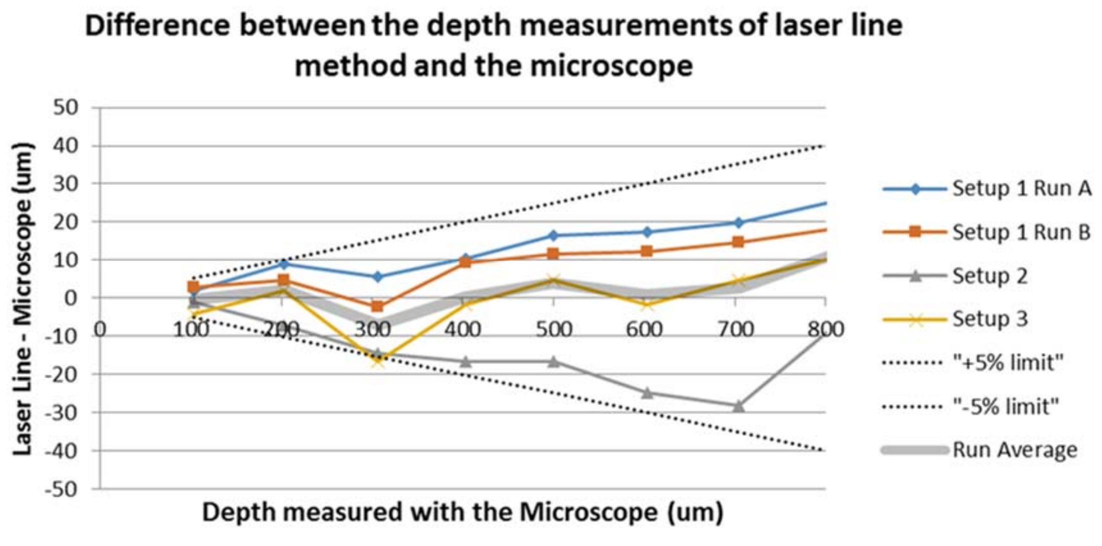


Figure 8 Differences between the Laser Line method and the optical microscope

Notice that there is reasonably good repeatability between Runs A and B in Setup 1. This shows that the image acquisition and processing steps have good repeatability. The main differences occur when the system is dismantled and realigned so that both the angles and magnifications need to be re-established. The +5 % and –5 % limits are also plotted to help visualise the level of agreement. The sensitivity of the calibration to the laser or camera angles (when these are both approximately 45 degrees) is around 2 % per degree and a combined error of 1 degree in both angles can account for around 3.4 %. In addition to this, the magnification calibration has an uncertainty of around 1 %. Bearing in mind the combination of all these potential error contributions together, the overall agreement of around 4 % is encouraging. Notice that the disagreement between the average of all runs and the microscope measurements is even better

To further validate the measurement technique five aluminium specimens were subjected to sand erosion at high velocity for different periods of time in such a way that they produced 5 erosion scars with different depths and aspect ratios. The specimens were weighed before and after to have a direct mass loss measurement from which a volume loss could be calculated independently, and the specimens were also measured with an Alicona 3D optical microscope at NPL and at PTB to obtain direct erosion scar depth and volume measurements which could then be compared with the laser line projection method.

The laser line method takes approximately 30 minutes to acquire 161 images, and a further 30 minutes to process them, producing a height map of typically 160 x 160 pixels with a square pixel size of 100 µm. Figure 9 shows a typical Alicona height map and profile on the left hand side, and corresponding laser line results on the right hand side.

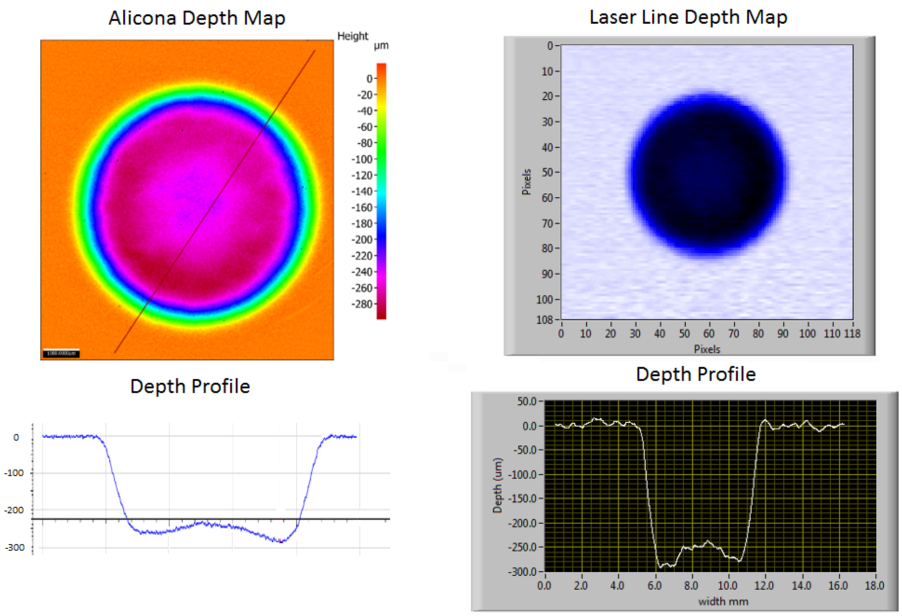


Figure 9 Typical results on the nominally 0.3mm specimen: Alicona 3D optical microscope (left) and laser line method (right)

The results for the five erosion scars were collated and a graph showing the extent of the depth measurement agreement is shown in **Error! Reference source not found.**.

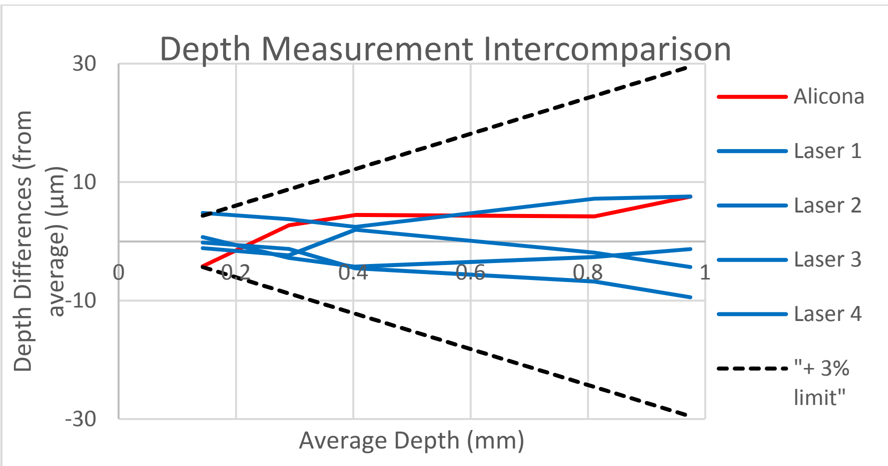


Figure 10 Depth measurement differences between the Alicona and the laser line method

The average of the Alicona measurement and the four separate laser line runs was calculated, and this was subtracted from each of the individual measurements to be able to see the differences. Notice that the ordinate axis units are micrometres. The Alicona measurements are plotted in red, and all the laser measurements are plotted in blue. The level of agreement in depth measurement is typically ± 10 µm (worst case 18 µm for a depth of 970 µm). Broken lines showing the +3% and – 3% limits are added for reference.

The results show that the *in situ* measurement of erosion scars from a distance of approximately 50 cm to an accuracy of better than 3% in depth or volume can be achieved.

Summary of objective 1+2

This work has demonstrated that it is possible to introduce *in situ* measurement technology to measure the mass and volume change during the test. Two such techniques have been developed and integrated into the NPL HTSPE apparatus and used for measurement of erosion rate. The *in situ* mass can measure the mass to an accuracy of 0.1 mg and a resolution of 0.1 mg. In addition, an *in situ* measurement method for the volume change has been shown to compare well with confocal measurements made at NPL and PTB. The technique used has shown that measurements with the resolution of 1 µm can be made and that areas greater than 70 mm^2 can be measured. Both techniques introduce a step change in measurement time and greatly reduce the uncertainties relating to specimen positioning. By removing the need to thermally cycle the sample the uncertainty and errors in the measurement caused by oxidation and spallation are also reduced if not eliminated.

3.2 Objective 3: Measurement of the Gas Flow and Particle Velocity

To be able to relate the erosion rate of a material/coating to actual operating conditions it is of great importance that the test is conducted using representative particle velocities. This is because the impact energy is proportional to the square of the velocity. It is critical therefore that the gas flow in the nozzle is controlled and that the velocity of the gas and particle can be measured to reduce errors and uncertainty in the measurement of erosion rates. Finite element (FE) modelling was used as both an aid in the design of the NPL nozzle and to determine the gas flow as a function of velocity, angle of incidence and stand-off distance. FE models of the erosion nozzle, sample and air domain have been developed for the NPL erosion nozzle. This model has been used to predict the gas flow through the nozzle, and the gas plume as it leaves the nozzle and reaches the sample enabling the design of the NPL nozzle to be optimised. To be able to validate the NPL nozzle model, the same physics was used to model an erosion nozzle used within the RSE HTSPE apparatus. The velocity predictions from this FE model have been validated using experimental data from the RSE apparatus and nozzle.

The nozzle models have both been used in parametric studies to investigate the effect of parameters such as temperature, inlet pressure, stand-off distance and impact angle on the gas flow exiting the nozzle and the velocities of the gas along the length of the sample. The results from this work have been used to make an informed decision on the optimum test set-up for the NPL HTSPE apparatus.

The parametric studies have shown that in all models, the gas velocity decreases markedly before contact with the sample surface, and that there is a region just above the sample surface where gas flow is predicted to be higher as shown in the contour plot in Figure 11. Figure 12 shows the predicted horizontal velocity for a range of different temperatures. In both figures the results are plotted for only half the sample, so that zero on the x-axis is the centre point of the sample, and in both cases a lower velocity is predicted in the central region. This gas flow pattern produces a region at the centre of the erosion scar where the erosion rate is lower than its surrounding; a phenomena that is also observed experimentally as shown in Figure 13.

The influence of inlet pressure on the gas flow was then evaluated with an inlet pressure varying between 1.3 bar and 1.1 bar in 0.05 bar increments. Contour plots of velocity magnitude showed that as the inlet pressure decreases, the outlet velocity from the nozzle decreases (from 256 ms^{-1} to 135 ms^{-1}) and the velocity magnitude at the sample surface decreases. Once again the velocity of the gas in the region of air just above the sample is higher than that at the sample surface. The vertical velocity of the gas flow exiting the nozzle decreases at a faster rate for higher inlet pressures as the gas approaches the sample surface.

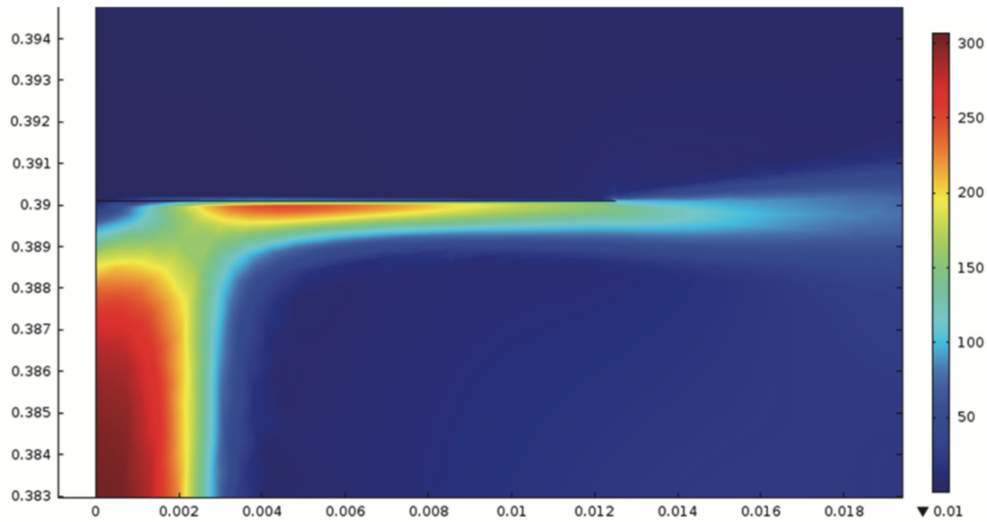


Figure 11 Contour plot of NPL nozzle, air region plus sample, showing predicted velocities (ms^{-1}) at a temperature of 500 °C

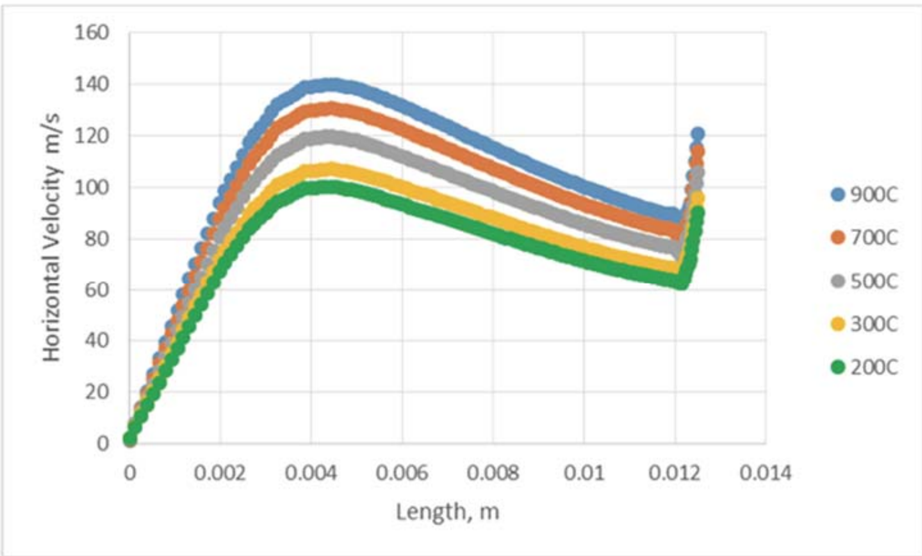


Figure 12 Horizontal velocity profile along the length of half the sample (zero is the centre point of the sample) for the 5 temperatures studied

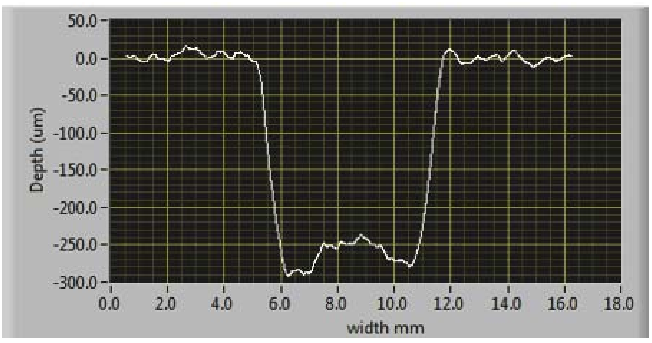


Figure 13 Laser line depth profile measured across an erosion scar

The model was later used to quantify the influence of the stand-off distance, which was varied between 16 mm to 48 mm. The results from the model show that the stand-off distance has no effect on the gas flow through the nozzle, the maximum velocity shown in the contour plots is constant (260 ms^{-1}). At larger stand-off distances, the velocity of the gas reaching the sample is lower and hence the horizontal velocity along the sample is also lower. At smaller stand-off distances, the horizontal velocity along the sample surface is higher. Once again the velocity of the gas in the region of air just above the sample is higher than that at the sample surface, but the magnitude is smaller for larger stand-off distances.

The impact angle of the gas/particles is an important parameter in determining the degree of erosion in an erosion test. Predictions from the model using the RSE nozzle show that the velocity profile along the sample changes significantly with angle. When considering the horizontal component of velocity, glancing angle impact, i.e. 30°, give the best conditions for erosion testing as a large area of stable velocity is achieved. The single particle FE model (described later in this report) also predicts that a 30° impact angle gives the smoothest velocity profile, see Figure 14. This model shows clear trends in the prediction of erosion rate with varying impact angle along with changes in the particle behaviour, from bouncing of the surface to skimming along the surface causing more erosion and possible particle embedding. Investigations into the effect of the individual velocity components suggest that the magnitude of the horizontal component of velocity cannot be used as a direct measure of likely erosion rate, but that the impact angle also needs to be considered.

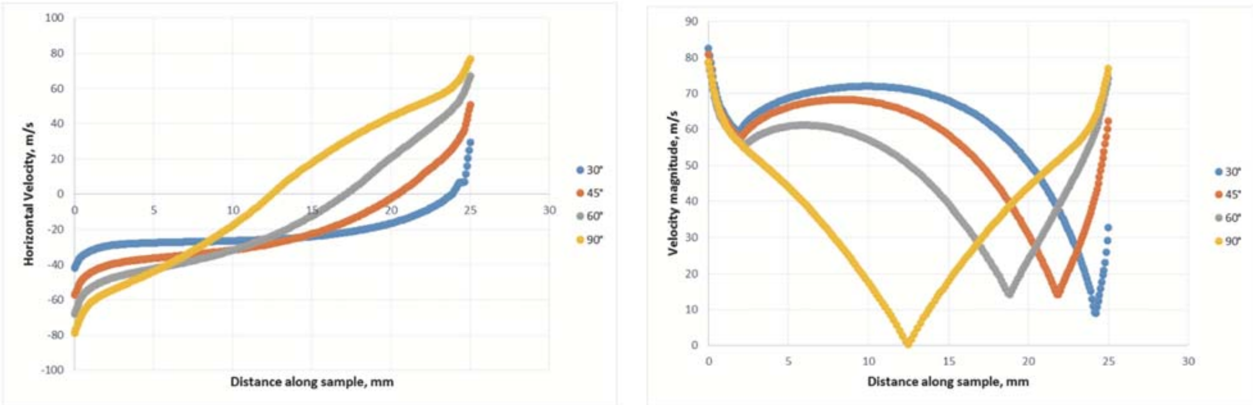


Figure 14 Horizontal and vertical velocity profile along the length of the sample for impact angles of 90°, 60°, 45° and 30°

In addition to modelling the gas flow to understand the flow as a function of test parameters, an *in situ* measurement system has been developed by DTU which enables high speed particle image velocimetry to be conducted in a cost effective manner at high temperature. The apparatus provides an improved method for velocity measurements - conventional double disc methods have uncertainties of up to 30 %. The new method uses LED background lighting of moving particles which allows imaging of fast moving particles and structures. The LED-Pulser can fire on demand (delay 50 ns from trigger signal to light pulse) two light pulses and the particle velocity and size can be found from a pair of images recorded by a CCD-camera with 1296 x 966 pixels. The measurement volume is defined by the telecentric lens and only particles inside this region appear sharp and well-focused. Resolution of the standard system is determined optically by the lens to 5.3 or 9.3 µm depending on the lens type used, whereas the camera can operate with 2 times higher resolution. A schematic of the system is provided in Figure 15.

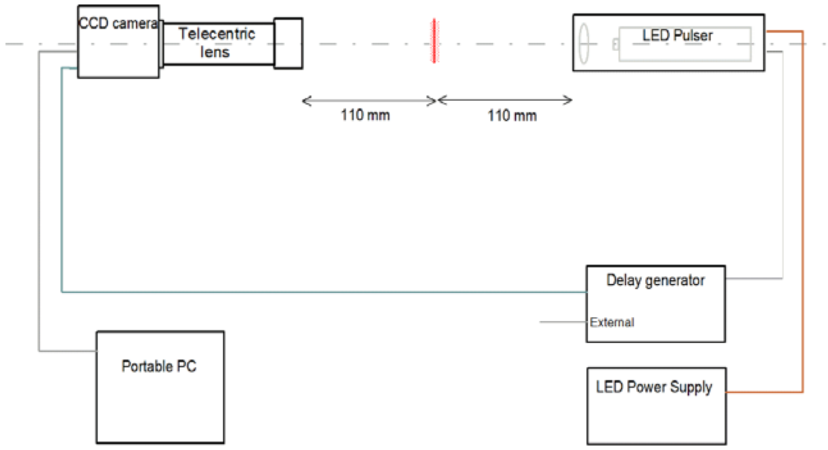
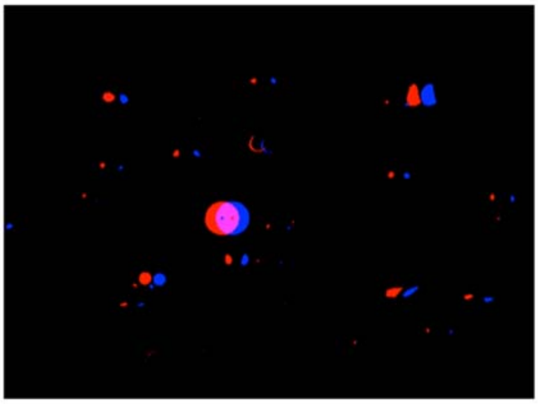


Figure 15 Overview of elements in the basic system for particle size and velocity measurement

This system has many advantages over the conventional double disc method, aside from being more accurate and providing significantly greater statistics, the apparatus has the following advantages:

- High quality pair of pictures with dual pulsed LED
- Velocity of individual particles at low and high speed
- Particle sizing of all kind of particles and droplets
- High performance, customized solutions and low costs
- Double pulsed LED light source can be synchronized with other events with only 50 ns delay
- Compact, rugged and flexible

An example of the images captured and the data generated in the erosion tests conducted at RSE are shown in Figure 16.



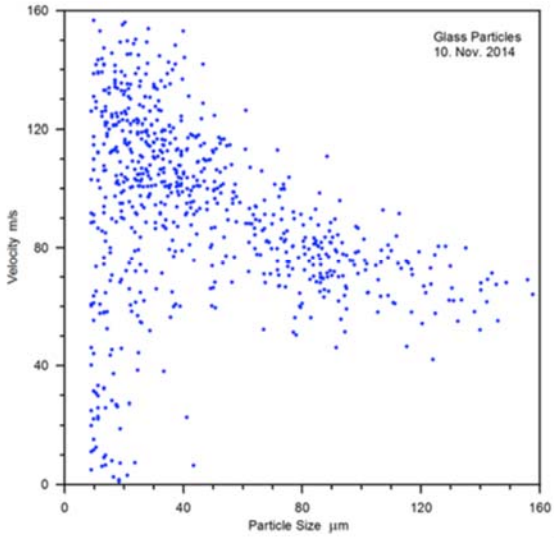


Figure 16 left: Overlay of pair of images (red and blue is first and second image, respectively) of particles. The velocity for each particle is calculated from displacement of the centre of mass. It is observed that the shadow area of an irregular particle is not necessary constant as it rotates and spin even with a short time separation of 1.0 µs between the two images. Right: Results of particle size and velocity.

The benefit of using this new optical system is evident when comparing the data to that conventionally obtained using the double disc system. Collaborative work between DTU, RSE and Cranfield University has compared the velocity distribution from the optical system with double disc data, as shown in Figure 17.

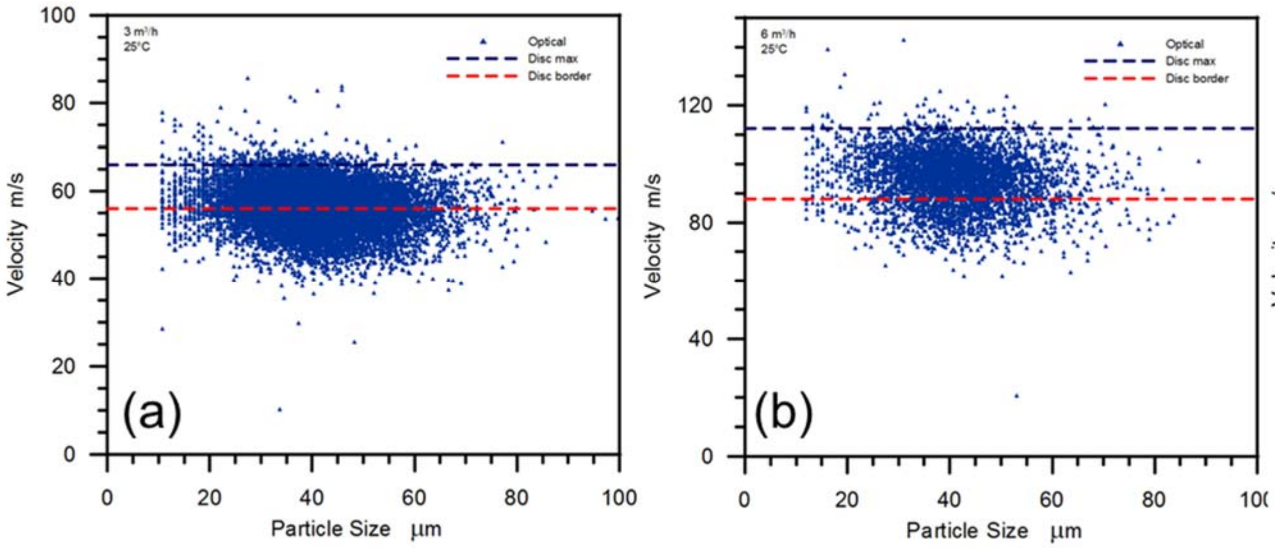


Figure 17 Particle velocity distribution compared with the maximum velocity measurement from the double disc method for erodent at flow rates of (a) 3 m^3/h and (b) 6 m^3/h

This figure shows that the double disc method agrees reasonably well with the optical data in measuring the maximum particle velocity, but it also demonstrates that it is only a small proportion of the particles which achieve this velocity and that there is quite a large velocity distribution as a function of particle size. This is further illustrated in Figure 18 which shows the velocity distribution of 150 mesh alumina particles measured at RSE. The red line in Figure 18 shows the mean value for the different particle sizes, and illustrates that within a powder sample a wide range of velocities is possible, which impacts on the amount of erosion developed in the test. Knowing this distribution and controlling it a crucial to a well-controlled experiment and reduced measurement uncertainty.

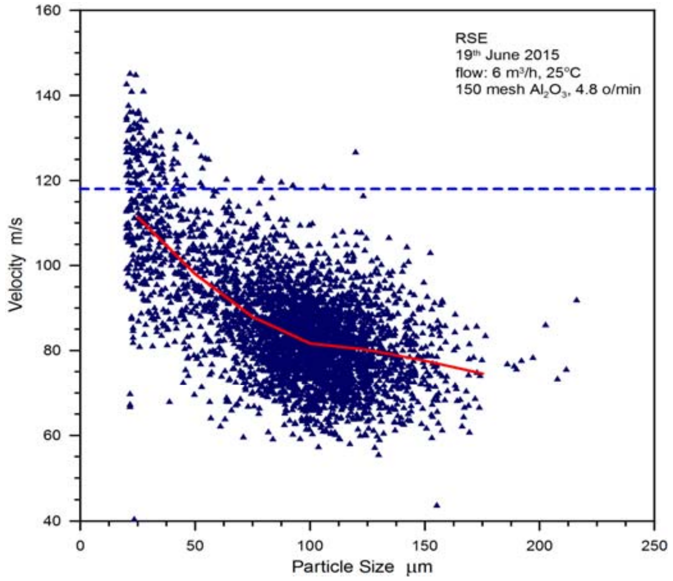


Figure 18 Velocity distribution of alumina particles, showing the double disc velocity measurement (blue line) compared to the actual distribution measured optically

Using this optical measurement approach and combining it with the work conducted at PTB to quantify the size and shape of the erodent particles (described later in the report), RSE have been able to create a model to predict the velocity profile for particles as a function of their size and shape. Figure 19 shows the prediction of the model compared to the maximum and minimum measurements of the particle velocities measured optically. This figure shows that the model predicts the mean velocity of the particles very well.

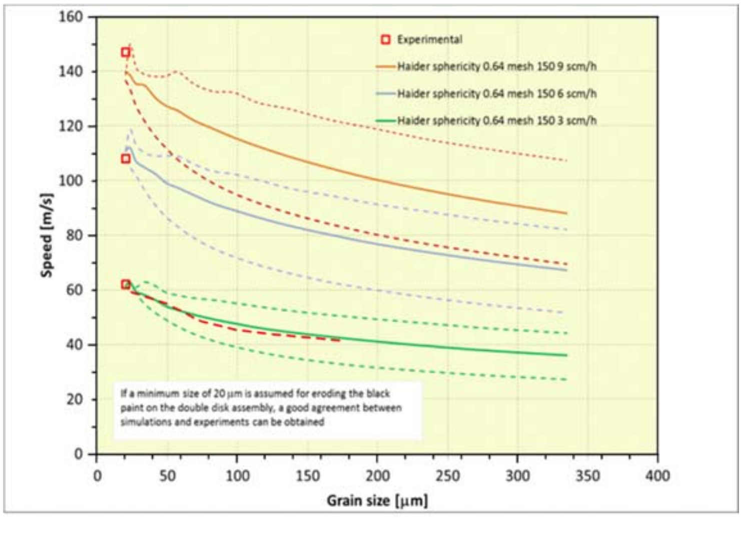


Figure 19 Predicted particle velocity for three different flow rates compared with the optically measured velocity distributions

Summary of objective 3

A series of multiphysics models have been developed to describe the gas flow through the erosion rig nozzles. These have been validated using practical pressure and gas flow data and used to optimise nozzle designs. An in situ optical method for measuring the particle velocity during the test has been developed at DTU and validated on erosion apparatus. Integration of this sensor to existing test rigs is possible and provides, for the first time, full measurement of the particle velocity distribution as a function of particle size across the gas stream. These sensors have been used to measure the speed of the erodent powders. This in situ device, which has exceeded original expectations, has been incorporated in the NPL erosion apparatus.

3.3 Objective 4: Measurement and Characterisation of the Erosive Particle Size and Shape

To be able to quantify the erosive potential of erodent particles it is crucial to be able to express their size and shape as numbers, but this is not a simple matter. PTB have, during the course of this project, been able to develop a procedure to do this using X-ray computed tomography (XCT). The particle's shape is important, as rounded particles have a different erosive behaviour to that of angular particles. Furthermore, the shape also provides information about how the particle will align when dragged along with the fluid. A better determination of these parameters, usually obtained by optical 2D or light-scattering measurements, can help to better understand erosion processes and save costs.

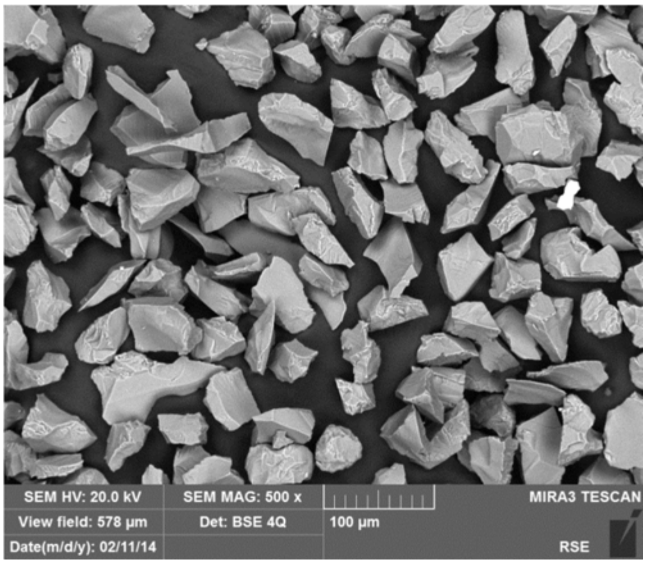


Figure 20 SEM image of a sample of alumina

Figure 20 shows a representative SEM image of the alumina particles being characterised. From the reconstructed XCT data, the surface threshold has been determined, which is illustrated in Figure 21 which shows (a) the results of the entire reconstructed volume, (b) a close-up of a sub-volume, which was investigated with a higher precision and (c) a close-up of a single particle of the same sample. Using these images and advanced surface detect methods it has been possible to generate diagrams to compare the principal component axis (PCA) as a function of the volume-equivalent diameter to classify the shape of the particles in terms of chips, spheres or fibres, as shown in Figure 22.

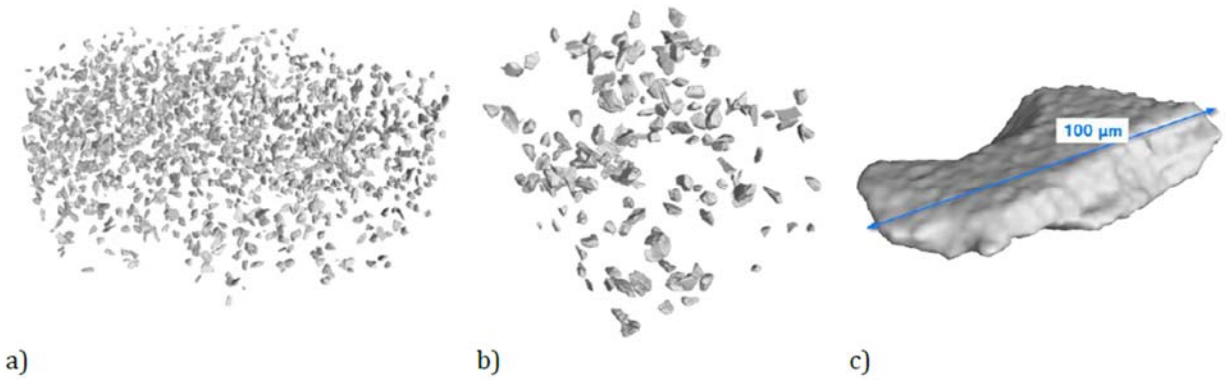


Figure 21 Reconstructed volume data of alumina mesh 320 particles. a) Total measured volume (1418 particles). b) Volume taken for comparison between Object Properties and Defect Detection. c) Close-up of single particle

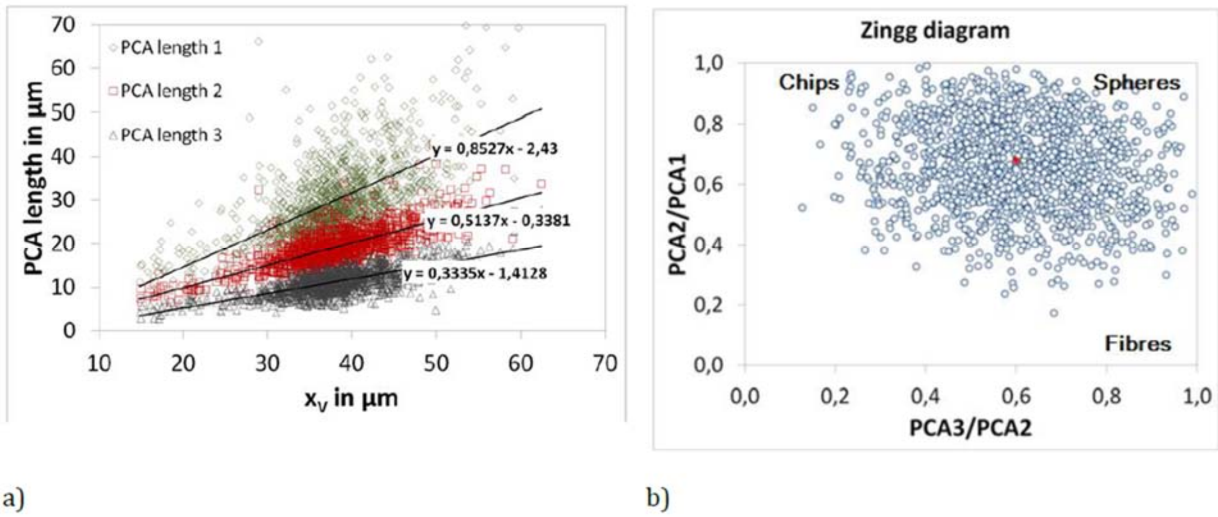


Figure 22 (a) The principal components PCA1, PCA2 and PCA3 as a function of volume-equivalent diameter xV. b) The ratios between the principal components, which can be considered as a kind of Zingg diagram (the red cross shows the centre of gravity of the distribution)

This method of particle sizing and shape determination is quite labour intensive compared to conventional methods based on light scattering techniques (LALLS). To compare these methods to the one developed in this project another sample of particles from the same powder was analysed with a Malvern Mastersizer 2000. The analysis resulted in a volume median diameter, $D_{0.5}$, of 49.0 µm. Compared to xV = 38.4 µm, the result we obtained from our analysis (which is identical to its median for this distribution), this represents an overestimation of about 28 %. This would lead to an overestimation of the kinetic energy of the particles by a factor of about 2.1. The reason for this is that LALLS assume that the measured particles have spherical shapes. The report of the analysis with the Malvern Mastersizer 2000 also tabulates the Volume Moment Mean (also called De Brouckere Mean Diameter) at 51.1 µm. Our measurement resulted in 40.9 µm for this parameter. For the Surface Area Moment Mean (also called Sauter Mean Diameter), we would get 40.0 µm, whereas from LALLS, this value is 46.9 µm. We conclude that the particle's mean diameter, whichever definition is used, is always overestimated by standard methods.

Another noteworthy principle is automated dynamic flow particle imaging. Although it is a straightforward and relatively fast method, it provides only two-dimensional information about the particles from the projection areas. This can give us a rough idea about the true particle shapes or their sizes, but for surface area determination, it is not very accurate. The analysis by XCT also allows quantities to be derived from projection areas of the particles, as was done to determine the mean surface area of the particles. The calculated mean

Surface-Equivalent Diameter was found to be 44.5 µm. This would be an overestimation of the size by about 17 %, and would thus lead to incorrect kinetic energy estimations.

As mentioned previously the measurements and shape defining approaches used here have been used to develop a model for particle velocity estimation.

Summary of objective 4

The erosive particles to be used in erosion tests were characterised in terms of their shape and size, using a range of different measurement techniques (including optical microscopy and XCT). PTB developed a method to describe the shape of the particles using mathematical descriptors. This data was then used with the *in situ* velocity measurements to develop a velocity model which enables the distribution of particle velocities to be predicted and can be used in erosion models to provide more realistic predictions of damage accumulation using velocity distributions rather than a mean value. A measurement Good Practice Guide was produced describing the methods and can be downloaded from the project website (http://projects.npl.co.uk/metrosion/publications/).

3.4 Objective 5: Determination of the Influence of Test Parameters

One of the key objectives of this project was to establish the relative sensitivity of the measured erosion rate to different test parameters dictated by apparatus type and design. To achieve this three distinct apparatus have been compared to determine the relative influences of design parameters, such as nozzle diameter, acceleration length and stand-off distance from the sample. Within the test data and the range of variables used, it was found that there was no systematic effect from the stand-off distance of the nozzle from the specimen (as shown in Figure 23), and that there was no systematic effect of the acceleration length to nozzle diameter ratio at 600 °C (as shown in Figure 24). Power law fits to the erosion rate data as a function of velocity resulted in velocity exponents of 1.9 and 2.4 for angles of 30° and 90° respectively. These values compare well with the velocity exponents reported in the literature, which were 1.9 and 2.2 for Type 410 stainless steel at 600 °C showing a similar dependence on incident angle.

It is encouraging that the erosion rates measured by the three very different erosion apparatus are comparable, and that the data fall on erosion rate curves with velocity exponents of the correct magnitude.

Tests at room temperature showed there to be a possible influence from particle embedding at higher velocities, identified from tests using different ratios of nozzle diameter to nozzle length. Further work is required to investigate this mechanism of surface modification as a function of temperature and velocity.

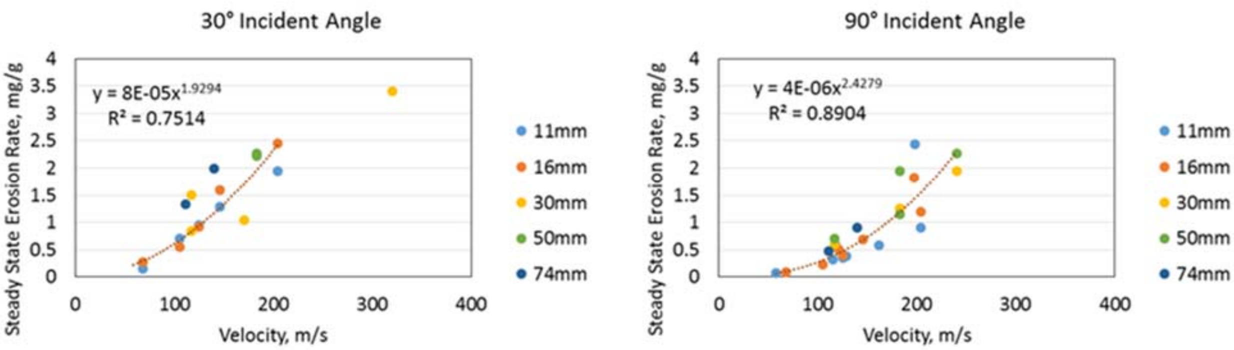


Figure 23 Steady state erosion rate for Nimonic 80A at 600 °C as a function of velocity and stand-off distance for the RSE, NPL and CU erosion apparatus

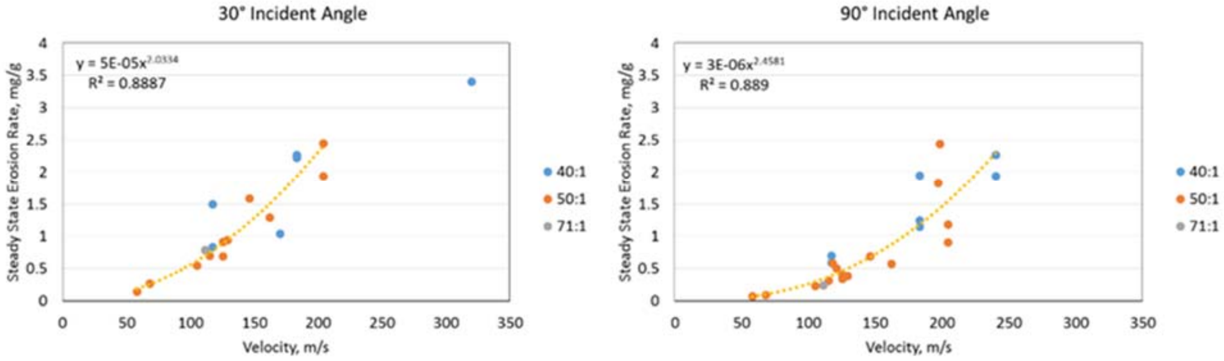


Figure 24 Steady state erosion rate for Nimonic 80A at 600 °C as a function of velocity and ratio of nozzle diameter to acceleration length for the RSE, NPL and CU erosion apparatus

Summary of objective 5

A series of HTSPE tests were conducted to allow the influence of variable test parameters to be determined. The influence of the standoff distance, the angle of incidence and ratio of the nozzle diameter to acceleration length were systematically compared for the first time. The results showed that at high temperatures (up to 650 °C) the erosion rate measured was relatively insensitive to these parameters, which is encouraging as it means that results from different apparatus are directly comparable, at least within the temperature range covered in this project. This was not the case at ambient temperatures however, and further work is needed to investigate the effects at lower temperatures.

3.5 Objective 6: Modelling of the High Temperature Erosion Process to Achieve a Life Prediction Capability

The final aspect of this project was focussed on developing mechanistic based models for the prediction of erosion rate, which did not rely on HTSPE data fitting to a curve. The ability to remove empirical fitting to experimental data enables researchers and material developers to model the erosion behaviour using physics based properties. Thus enabling design for purpose approaches to be adopted. Three distinct approaches have been adopted, the first was to use MATLAB code for the modelling of the erosion of thermal barrier coatings (TBC). This model was created to predict the erosion of brittle thermal barrier coatings. The outputs of the model have been compared to experimental data. Using the model the following main points were found:

- Erosion rates of TBC are linearly dependent on the overall kinetic energy of impacted mass.
- For tests carried out with a particle stream at an angle of incidence 90° to the surface there is an energy threshold below which the material is not damaged by the single impinging particle and its value seems to depend on the TBC morphology.
- The same results have been obtained also when the angle of incidence differs from 90°. Also plastic deformation seems to contribute to erosion of TBC especially at high temperatures.
- After a preliminary tuning activity of a proportionality constant between the erosion rate and the kinetic energy of each single impinging particle, the model has been applied to predict erosion rates for different testing conditions and TBC morphologies (shown in Figure 25); the agreement between experimental data and predictions show a reasonable agreement where differences usually do not exceed a factor of 2.

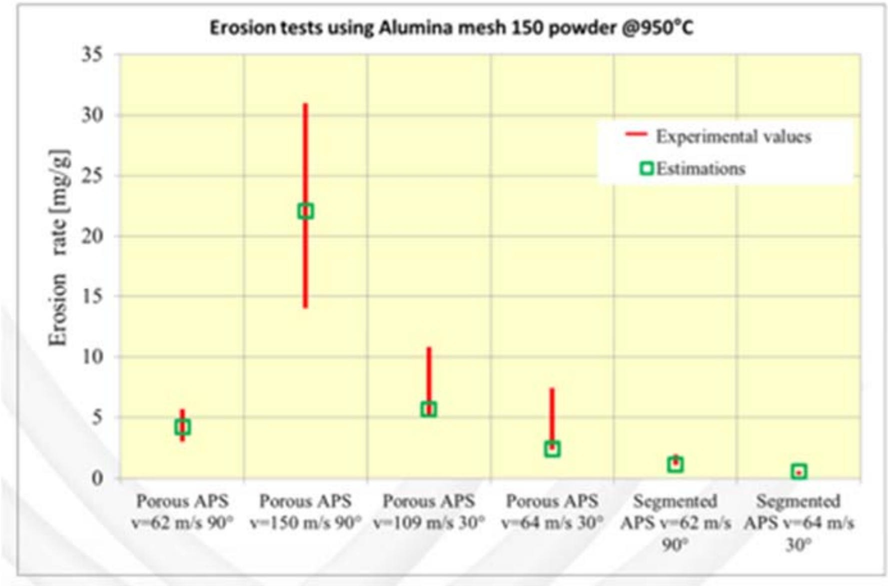


Figure 25 Effect of test parameters on the modelling of TBC erosion

The second approach to predicting erosion rates was developed at BAM. This employs fundamental physical laws to predict material and particle behaviour. The ERROW-Sim model has been shown to reproduce the correct material phenomena. Figure 26 shows a typical result from the model and the number of particle impacts used in the prediction.

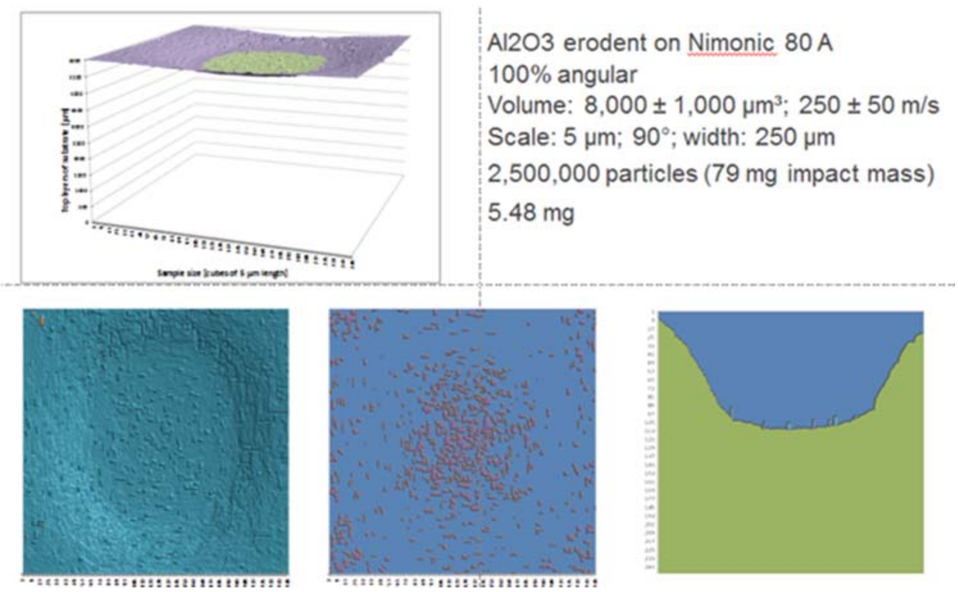


Figure 26 ERROW-Sim model prediction for erosion of Nimonic 80A after 2,500,000 impacts, showing the plan view and side projection of the erosion scar

This model is based on first principles from classical physics, and as such does not rely on parametric or empirical curve fitting to erosion data. Such an approach enables developers to rank different materials and operating conditions to gauge the performance under conditions of HTSPE. This powerful tool has been shown to replicate the physical erosion process well, without a large computational demand. It has been developed without the need for commercial software licenses and so has the potential to be readily assessable to industry, academia and SMEs.

The third approach is based on finite element modelling, and was performed at NPL. The erosion model was created using Abaqus FE software to predict the erosion caused by a particle impacting a substrate. The main features of the model are as described below:

- The model is a 3D model using element deletion to represent the erosion of material.
- The particle is modelled as either an analytical rigid particle or as a discrete meshed particle.
- The substrate's material properties are defined using Johnson-Cook models for plasticity and element deletion. There are two versions of the Johnson-Cook model for element deletion, both have been run and the results compared.
- Care has been taken with the definition of contact surfaces, so that newly exposed surfaces can still act as contact surfaces allowing subsequent particle impact to occur if desired.
- The model is run using an explicit analysis due to the high impact speeds.
- Sensitivity analyses have been carried out to investigate the effects of mesh refinement and friction between particle and substrate. A fairly refined mesh was chosen which gave the same prediction as a more refined mesh, but with a smaller cpu time. Friction had an effect on particle velocity after impact but made little difference to the erosion damage predicted.
- The number of elements deleted during the analysis can be calculated as a mass loss to compare to experimental erosion rates.
- The particle size, speed and angle of impact can be changed easily within the model.

An example of the model is provided below, whereby a cubic sample (1 mm^2, with a depth of 0.5 mm) has been modelled with a defined core region in which impact/damage occurs. This core region has a higher mesh density, Figure 27. The spherical particle has a diameter of 300 microns, with an impact angle of 45°. The particle has been defined as an analytical rigid surface with movement controlled by a reference node. At the start of the analysis, the particle is very close to the sample surface, moving with a velocity of 100 ms^{-1}. Explicit time integration has been used due to the high velocity of the particle. The plastic deformation of the sample is defined by the Johnson-Cook plasticity model. To simulate erosion, element deletion has been included by using the Johnson-Cook damage model. This material model determines whether elements have reached a critical strain level, which then leads to failure of that element. For this example, the particle is steel and the sample is a titanium alloy Ti-6Al-4V.

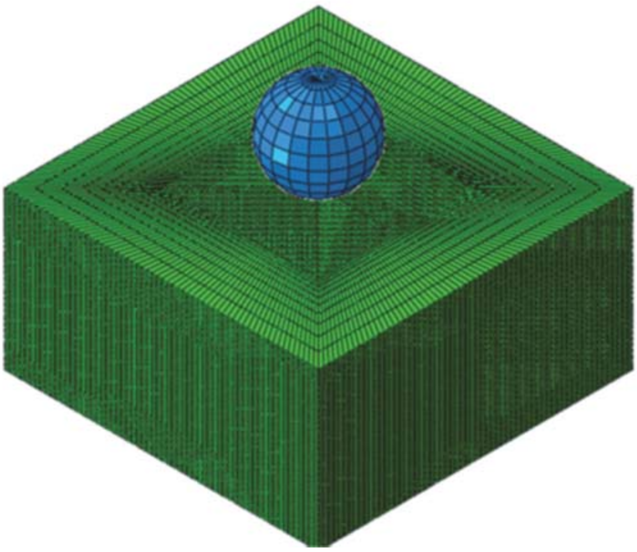


Figure 27 Abaqus mesh of sample plus single particle, with refined mesh in region of contact

Contact was set-up carefully to ensure that the interior elements of the sample were included in the contact definition, as once element deletion has occurred the interior elements can become the outer surface, see Figure 28. The mass loss due to erosion was output by comparing the total mass of the undeformed sample at the start of the analysis with the total mass of the deformed/eroded sample at the end of the analysis.

Analyses have been run with varying parameters such as particle speed and impact angle. The model has also been extended to include additional particles to investigate the effects of multiple impacts. The location of the impacts could be controlled with three options investigated: all particles impacting the same locations, particles impacting at discrete locations and particles impacting at slightly offset locations so a particle hits the edge of a previous particle's impact crater.

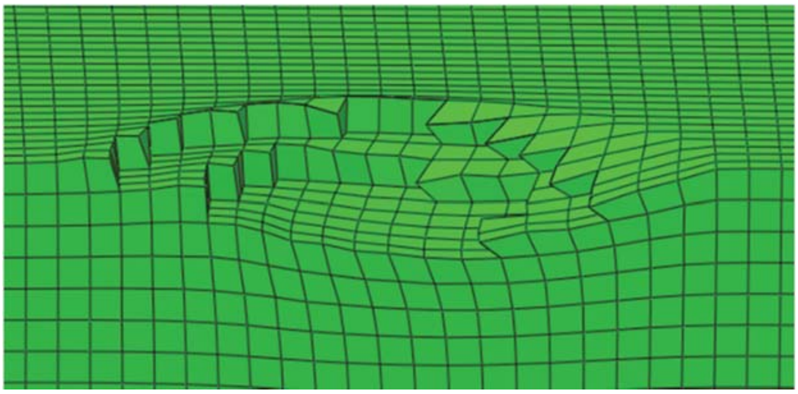


Figure 28 Abaqus deformed mesh showing area of element deletion

In all cases within the modelling activity there has been close collaboration between the modellers and practical experts. This has enabled the modellers to fully understand the phenomena taking place and ensure that they are modelling the correct physical mechanisms.

The three models discussed, use quite distinct modelling approaches. All these approaches move away from the use of empirical curve fitting to experimental data. Whilst they all have the ability to predict erosion rates there are particular benefits to each. One is specific to ceramic based thermal barrier coatings which uses kinetic energy and fracture mechanics to predict material removal of brittle phases. This has the ability to provide a quick ranking of different TBC systems. The ERROW-Sim model can be used on single and multi-phased systems and can deal with a large number of particles and include embedment of erosion particles. It provides a prediction of gross material loss in a computationally low manner. These two approaches have the ability to use the models without the requirement of costly licenses. The third approach is using FEA which has the advantage of being able to study and model fine mechanistic details, but does require additional material input parameters from mechanical tests etc. compared to the others, and does require an Abaqus licence. The advantage of the FEA approach is the ease in changing experimental parameters and the ability to conduct sensitivity analysis through parametric sweep. Access to the models can be achieved through contacting the project partners.

Summary of objective 6

A generic model (ERROW-Sim) of particle erosion was developed based on Newton's approximation, which showed good agreement with observations and practical measurement of erosion damage from erosion tests. The generic model does not need commercial software to operate. A model to predict erosion of TBCs has been formulated which allows comparison of different TBC systems and test conditions to be made. In addition a Finite Element (FE) based model has been created to model particulate erosion. This FE based model is able to apply single or multiple impacts to model the erosion damage on surfaces. A Measurement Good Practice Guide was produced on FE Erosion Modelling and is available from the publications area of the NPL website (www.npl.co.uk), although further work is needed to develop and fully validate these models.

3.6 Summary of Results

Within this three year project of the development of metrology to enable high temperature erosion testing the following key results have been achieved:

- A new design approach to HTSPE testing has been developed and built and provides NPL with a new measurement capability, extending the speed and temperature range which can be measured and incorporating *in situ* measurements, the first time this has been implemented worldwide.
- Three novel *in situ* measurement systems have been designed, built and validated to measure the *in situ* mass change of the sample during the test, the volume change of the sample during the test and the particle velocity and velocity distribution during the test. This is the first time all three measurements can be made during the test and at high temperature.
- A new measurement capability has been developed at DTU for velocity measurement of high speed particles, extending the image capture rate using a low cost LED based system.
- Two partners have modified their existing HTSPE apparatus to be able to improve control and implement *in situ* measurements.
- Improved methods for particle sizing and shape determination have been developed and demonstrated, which have a greater accuracy and lower uncertainties than existing light scattering methods.
- The measurement of erosion rate at high temperature has been shown to be relatively insensitive to changes in some test parameters, this key insight will provide greater confidence to industry and researchers when comparing results from different apparatus.
- Three models for the prediction of erosion rate have been developed that do not rely on fitting pre-existing erosion data, providing industry with greater confidence in the results and the ability to model new systems without prior experimental erosion tests.

4 Actual and potential impact

Overview

This project has provided a step change in the ability of industrial laboratories and research institutes to measure high temperature solid particle erosion (HTSPE). It has enabled this through: the development of improved metrological test systems for HTSPE, better measurement of damage mechanisms and erosion, the development of in-situ and on-line measurement of mass and erosion rates, better control and measurement of test parameters such as temperature and erodent velocity, and the development of predictive modelling for the performance of materials subject to HTSPE.

The development of this metrological framework has enhanced the capability for research laboratories to carry out HTSPE testing and provide increased confidence in the delivery of this testing to industry. There are also benefits through the provision of metrology to applications in harsh environments, and an extension of metrology into areas of direct impact and relevance to industries that are concerned with the manufacture of plants that operate in environments where conditions of mechanical loading occur at high temperatures, and in some cases within corrosive environments. Additionally this work has helped to develop an international standard, training courses and training material. Three Measurement Good Practice Guides have been written as a result of the work which will be used to disseminate the work of the project to industry and also to academia in the coming years.

Direct impact has been achieved through activities including training workshops, dissemination through web pages, technical articles, good practice guidance, symposia and direct interaction with stakeholders in industry and research establishments, as detailed below.

Dissemination of results

Within this project there have been a number of conference presentations, journal papers and trade articles aimed at disseminating the work to as wide an audience as possible. To assist in this, the project has held two industrial workshops, one in Germany and one in the UK, which were attended by academia and industry. To ensure longevity of the project findings, much of the work conducted has been incorporated into training material for training courses provided by BAM, CMI and Cranfield University. This will ensure that measurement best practice is disseminated to current and future workers in the area of particulate erosion.

To further influence policy makers, government bodies and trade associations a series of articles in Adjacent Government have been, and will continue to be written to promote best measurement practice for particulate erosion, and to highlight the measurement capabilities generated in the project.

Early impact

During the course of this project the following 'early impacts' have been achieved:

- An international standard has been published for High Temperature Solid Particle Erosion. The project partners contributed to the development of this standard both through practical contributions to inter comparison exercises to validate the proposed measurement procedures and through expert level based review and consultation during the drafting of the standard. This was published and is now available as G76 – 13: Standard Test Method for Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets.
- International standard committees have been consulted and informed of the findings and progress of the project, particular emphasis was given to ISO TC156/WG13 who have an interest in high temperature corrosion testing.
- Over the course of the project there have been twelve conference presentations to audiences in excess of 100 people per conference. The attendees of the conferences represent a good cross section of European and International industries and academia, and have been held across Europe and in the United States of America. The majority of the proceedings of these conference are peer reviewed and available to the general public.
- Three Measurement Good Practice Guides have been written, one on erosion modelling, one on the use of XCT to characterise powders and one on HTSPE Testing. Two of these (the modelling and HTSPE testing) guides are formatted in such a manner that they act as a training document and will be freely available from NPL.
- In addition to the peer reviewed conference papers, four journal papers have so far been produced from the project outputs, these have been accepted by the journals and are awaiting publication.
- Over the course of the project two workshop have been held, one at BAM and one at NPL. The audience was quite focussed with between 10-25 attendees at each workshop. The workshops were well received and follow up events requested as it was felt that Europe lacked a focus for the HTSPE testing community. The workshops were attended by major European industries including Rolls Royce, Alstom, Siemens Industrial Turbines, Wallwork and Monitor Coatings. In addition to the workshops, members of the project team have contributed to industrially focussed meetings presenting the work of the Metrosion project to representatives of the US Department of Energy and the UK Department Energy and Climate Change.

Uptake, exploitable foreground, and stakeholder engagement

In addition to the dissemination activities, measurement methodologies are being adopted, for example;

- a UK based coatings company is using the design approaches demonstrated in the manufacture of the NPL erosion rig and modifying in-house equipment to provide a more cost effective and robust testing solution to validate their coatings.
- A Danish SME is now marketing the particle velocity measurement system developed in this JRP and has sales in academia and industry. This device is being applied to other measurement issues for example imaging droplet impact in water droplet erosion studies.
- Larger companies have benefitted from improved analysis methods and algorithms in imagining software used for tomography.
- Academia has been using the HTSPE erosion apparatus developed in this project to support their research programmes, taking advantage of the high temperature and velocities attainable by the system, to extend the low speed and low temperature work performed in their own laboratories.
- Hard coating suppliers are also performing research work on the new HTSPE system to better understand the erosion process encountered by hard coatings on tool bits.

The Metrosion project also had a large stakeholder group which met every six months for updates on the project progress and to direct the work to ensure its relevancy to industrial concerns and issues. The stakeholders formed a good cross section of European industry with major sectors being represented.

In terms of the power generation community the stakeholders had representation from OEMs and end user utilities. For turbine (steam and gas) manufactures the project had representation from Alstom Power (subsequently GE Power), Siemens Industrial Gas Turbines and Rolls-Royce. There was also representation from large scale industrial boiler makers (Doosan Babcock) and from end user utilities such as RWE nPower and E.On New Build and Technology (subsequently Uniper).

The coating supplier chain was also represented by some SME organisations and larger corporations, such as Monitor Coatings, Tecvac, Laser Cladding and Praxair. Equipment manufactures were also part of the stakeholder community, and they took a particular interest in the *in situ* measurement tools and design approaches being used.

One other important community the project interacted with, and disseminated information to, was the academic and research institutes. These include The Welding Institute, CNR-ITC, Electric Power Research Institute, Southampton University, Loughborough University, Nottingham University and Sheffield University.

Collaboration and interaction with the wide ranging stakeholder group has helped to ensure the relevancy of the work and to disseminate the findings to as wide an audience as possible to maximise the future impact of the project. Development of new material systems is a drawn out process, particularly in safety critical applications, so direct impact through new materials is not demonstrable at this point. However, there have been some examples of early impact from this work which are detailed below.

- The *in situ* velocity profiler has been developed and is now being commercially marketed and is seeing sales in Germany, Italy and the UK. The apparatus can be marketed as a very cost effective alternative to Laser Doppler Anemometry instruments which are much more expensive and do not offer the same level of flexible operation or application to different measurement issues. This unit provides a great advantage over conventional velocity measurement approaches in HTSPE testing and will greatly reduce the measurement uncertainty in testing. It has the ability not only to improve the test methods used but also to provide better understanding of the erosion mechanisms, material performance and better modelling.
- The modelling approach developed at BAM has been successful at reproducing the erosion mechanism in a very simple and straight forward manner. The standalone system can run on a basic PC and can be adapted to different material systems by changing some material based input parameters. This software has the potential to be a very powerful research and measurement tool for academia and industry.
- Measurement and the improvement of testing approaches has been at the heart of this project. The measurement good practice guides developed, and made freely available will form the basis of HTSPE testing and modelling by FEA. The guides will provide the underlying training and understanding to conduct robust and accurate measurements of particulate erosion and the modelling of such processes. In conjunction some of the project partners had embedded the results and work of this project into their bespoke training courses for students and industrial participants. Thereby ensuring the future dissemination of best practice to researchers and operators for many years.
- The development and validation of the *in situ* measurement tools provides a step change in the speed and potential for knowledge generation from HTSPE tests. It has been demonstrated in the project that erosion rates can be measured in 90 minutes using these tools, instead of periods of days using conventional testing approaches. This has the potential to save industry ~90% on the cost of each HTSPE test based on average costs for one test.

Economic Impact

The research and development conducted in this project will have future impact through improved materials which would lead to major improvements in the competitiveness of European industry, particularly in industries which rely on or develop engineered surfaces for harsh environments or high value added applications, such as aerospace, energy, mining and oil and gas. The improved measurement procedures and better understanding of uncertainties in test methods will help to achieve this through increased confidence in experimental data. This enables the development of accurate models based on an improved understanding of erosion and wear, resulting in better assessment of in-service components and improved design of novel materials. This will lead to cost savings in industry through improved efficiency, more resilient surfaces, reduced down time, improved design and as a consequence increased lifetime and performance of components. For example reducing the erosion of the leading edge of turbine blades would result in improved efficiency and thus avoid, in the case of a large power plant (~800 MW), the emission of an extra 250,000 tonnes of CO_2 over the lifetime of the plant.

There is further benefit from improved metrological capabilities in 3D particle characterisation. Particle size, shape, temperature and velocity are also of interest in other fields of engineering such as the chemical industry, seed production and in the food industry. The better knowledge of these process parameters has an impact on the quality of products and on production costs and risks.

The improved competitiveness of EU industry will help to secure employment in this important area of European industry.

Environmental Impact

The results of this project will help to enable European manufacturers to provide energy generation solutions, land and aero, with reduced impact on the environment. There are two ways that this will occur. The first is by enabling higher operating temperatures to be used in power generation plants through improved materials that can withstand HTSPE at higher temperatures than before. The second is through the use of environmentally friendly fuels such as biofuels which would allow the operation of power plants with little or no overall impact on carbon dioxide generation. In power generation these fuels often lead to hard particulate material in the flue gases which can cause considerable erosion damage, so the validation of new material protection systems is critical in delivering major reductions in environmental impact.

5 Website address and contact details

The project website can be viewed using the following link:

http//projects.npl.co.uk/metrosion/

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6 List of publications

- A T Fry, M G Gee, S Clausen, U. Neuschaefer-Rube, M Bartscher, D Spaltmann, M Woydt , S Radek, F. Cernuschi, J R Nicholls and T W Rose, Metrology to Enable High Temperature Erosion Testing–A New European Initiative, Advances in Materials Technology for Fossil Power Plants, Proceedings from the Seventh International Conference, October 22-25, 2013, Waikola, Hawaii, USA
- F. Cernuschi, L. Augello, Solid particle erosion of TBCs: jet tester modelling and erosion forecasts, Developments in Strategic Materials and Computational Design V: Ceramic Engineering and Science Proceedings, Volume 35 Issue 8. ISBN: 978-1-119-04028-6. pp 139 – 149

- N. Smith, A. T. Fry, L. E. Crocker, F. Cernuschi, Design and Optimisation of the Nozzle of an Innovative High Temperature Solid Particulate Erosion Testing System using Finite Element Modelling, Applied Mathematics and Computation, Volume 301, 15 May 2017, Pages 60–69
- A.T.Fry, D.Gorman, L.E.Crocker, M.G.Gee, A.Gant, J.Nicholls, T.Rose, F.Cernuschi, L.Lorenzoni and C.Guardamagna, Influence of apparatus design and test method on the high temperature solid particle erosion of Nimonic 80A, Advances in Materials Technology for Fossil Power Plants, Proceedings from the Eighth International Conference, October 11-14, 2016, Albufera, Portugal
- Ch. Rothleitner, U. Neuschaefer-Rube, J. Illemann, Size and shape determination of sub-millimeter sized abrasive particles with X-ray computed tomography, 6th Conference on Industrial Computed Tomography (ICT 2016), Wels, Austria, Feb 2016
- Ch. Rothleitner, U. Neuschaefer-Rube, J. Illemann, Dreidimensionale Form- und Größencharaketrisierung von Erosionspartikeln mittels Röntgen-Computertomographie, Sensoren und Messsysteme 2016, ISBN 978-3-9816876-0-6
- John Nunn, In Situ Remote Hot Erosion Scar Measurement, Wear, volumes 380-381, 15 06 2017; p217-227
- A.T. Fry, P. Lovelock, N. Smith, M. Gee, A.J. Gant, An Innovative High Temperature Solid Particulate Erosion Testing System, Wear, Volumes 376–377, Part A, 15 April 2017, Pages 458-467
- Federico Cernuschi , Christian Rothleitner, Ulrich Neuschaefer-Rube, Jens Illemann, Lorenzo Lorenzoni, Cristina Guardamagna, Sønnik Clausen, Henning Engelbrecht Larsen, Accurate Particle Speed Prediction by Improved Particle Speed Measurement and 3 Dimensional Particle Size and Shape Characterisation Technique, Powder Technology
- A.B. Schubert, R. Wellman, j. Nicholls and M.M. Gentleman, Direct observations of erosion-induced ferroelasticity in EB-PVD thermal barrier coatings, J. Material Science, DOI: 10.1007/s10853-015-9623-7
- J. Rao, T. Rose, M. Craig and J.R. Nicholls, Wear coatings for high load applications, Procedia CIRP, https://doi.org/10.1016/j.procir.2014.07.005
- High temperature particulate erosion: Setting limits with confidence, http://www.adjacentgovernment.co.uk/research-science-innovation-news/high-temperature-particulate-erosion-setting-limits-confidence/28035/
- Modelling particulate erosion, improving material performance, http://www.adjacentgovernment.co.uk/research-science-innovation-news/modelling-particulate-erosion-improving-material-performance/29246/
- In situ measurements to accelerate the development of material solutions to particulate erosion, http://www.adjacentopenaccess.org/research-science-innovation-news/situ-measurements-can-offer-insight-particulate-erosion/33932/