



Good Practice Guide No. 146

Good Practice Guide to the Application of Finite Element Analysis to Erosion Modelling



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Guide Information

What is it about?

This Guide describes the application of Finite Element (FE) analysis for predicting the erosion of ductile materials. The basics of setting up an FE analysis for modelling erosion are discussed, covering such topics as element selection, analysis type, contact definitions, selection of material model, model parameter sensitivity, erosion predictions, additional outputs and modelling multiple particle impacts. Examples, mainly from erosion analyses of a Ti-6Al-4V sample impacted by a steel ball, are used to illustrate the pertinent points. The finite element package Abaqus has been used to produce the examples shown in this guide.

Who is it for?

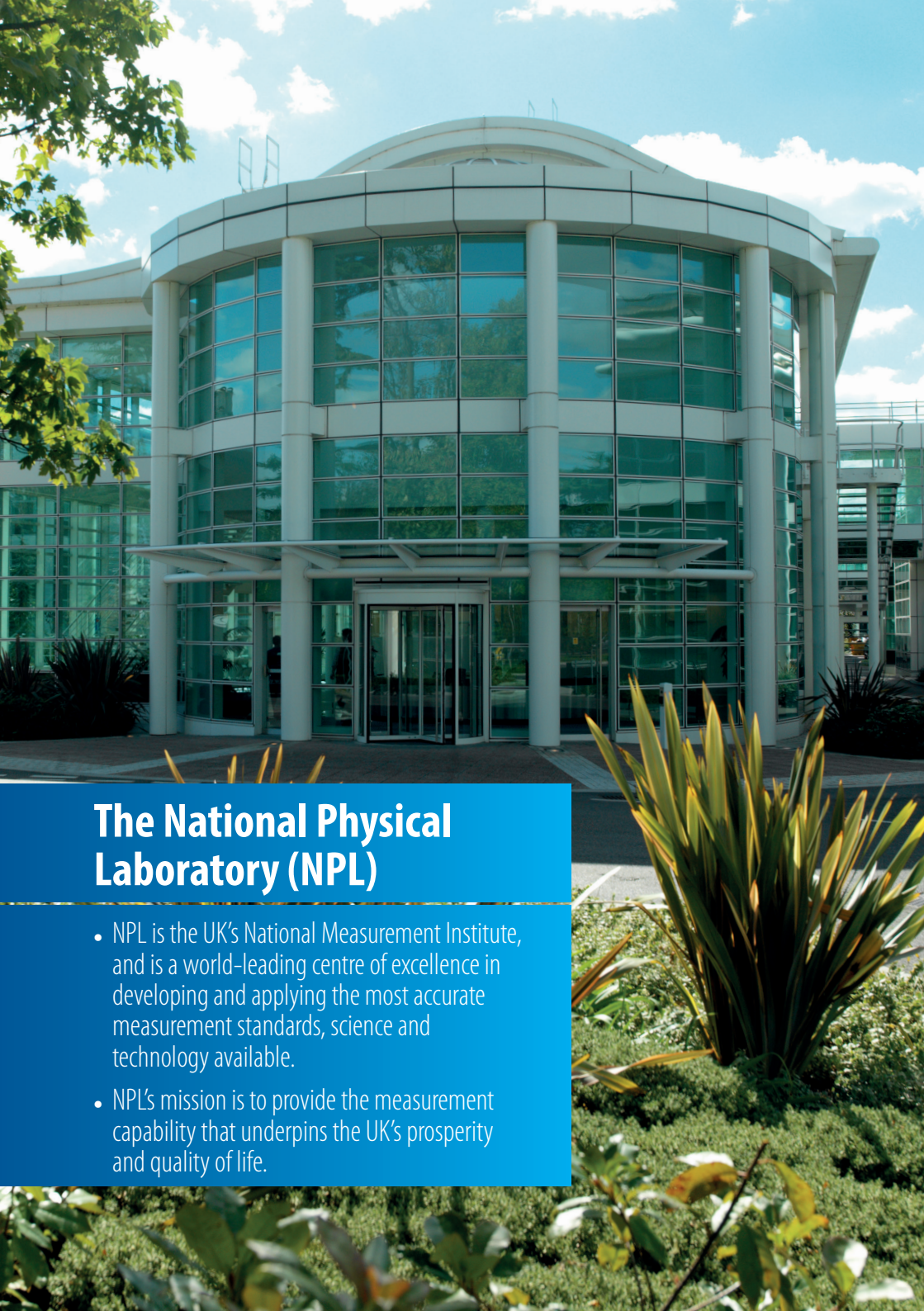
This guide is for users who have previous experience of using finite element packages such as Abaqus, and that are interested in simulating an erosion process. The basic principles of impact and element removal can also be applied to other situations.

What is its purpose?

In industrial environments, wear is a common problem. Within complex systems the in-service conditions are often demanding and various factors can influence the service life of components, potentially causing serious problems and economic loss. This Good Practice Guide has been developed as part of the MetroErosion project. The aim was to develop significantly improved test protocols and implement state of the art *in-situ* metrology for the measurement of high temperature solid particle erosion, through traceable measurement of mass, shape, volume, flow, velocity and temperature. The development of models for the prediction of materials behaviour under high temperature erosion conditions was part of the remit of the project. The purpose of the guide is to give a step-by-step approach to developing an erosion model within a finite element package, such as Abaqus.

What is the knowledge prerequisite?

The guide is at expert level, it requires a working knowledge of finite element analyses. Some background in materials degradation would be useful.



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Foreword

This Good Practice Guide has been developed as part of the MetroSION project. The aim of this project was to develop significantly improved test protocols and implement state of the art *in-situ* metrology for the measurement of high temperature solid particle erosion, through traceable measurement of mass, shape, volume, flow, velocity and temperature. The development of models for the prediction of materials behaviour under high temperature erosion conditions was part of the remit of the project.

This work was funded through the European Metrology Research Programme (EMRP) project IND61 MetroSION. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

A finite element (FE) analysis is a very powerful method for predicting the erosion of material. Element deletion techniques available in finite element packages enable the direct prediction of erosion rates, as well as other outputs such as residual stresses, crater depths, plastic strains and particle velocity and displacement. When high-rate impact is involved, it is necessary to take proper account of the high particle velocities and the effect on the sample i.e. possible large deformations. Material models suitable for highly dynamic events must be used.

In this Good Practice Guide, guidance on the use of finite element analysis for predictive erosion modelling is provided. This includes the basics of setting up an analysis, such as element selection, analysis type and choice of solver. A procedure is described for setting up the contact algorithms correctly, so that the elements within the interior of the sample are defined as contact surfaces. This ensures that when element deletion occurs, the newly exposed elements are still defined as contact surfaces. The effect of friction is also considered. The selection of a material model suitable for high-impact analysis is discussed, with detail of the Johnson-Cook model provided and the effect of parameter sensitivity highlighted. A method for obtaining mass/volume loss and hence erosion rate is detailed, along with additional outputs that are available. Finally, an overview of models with multiple particles is given. Relevant Abaqus FE analyses are provided as examples to illustrate the pertinent points.

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Chapter I

Introduction

Introduction

In industrial environments, wear is a common problem. Within complex systems the in-service conditions are often demanding and various factors can influence the service life of components, potentially causing serious problems and economic loss. Bitter^[1] described erosive wear as “Material damage caused by the attack of particles entrained in a fluid system impacting the surface at high speed”. Impacting solid or liquid particles carried within gas or fluid gradually remove material from the surface through repeated contact with the surface. Material removal due to repeated impacts can be concentrated at particular locations due to geometry design and flow patterns within the system.

The presence of water droplets in the flow of a steam turbine, for example, leads to erosion of the moving blade. Similarly, sand within oil/gas pipelines can lead to pipe thinning. Erosion is a complex surface damage process, strongly affected by mechanical and metallurgical factors such as shape, size, density, hardness and quantity of erosive particles, particle velocity and angle of impact. The degree of degradation will also generally depend on the system characteristics e.g. pressure, temperature and type of erosive particles, and will also be strongly dependent on the materials used in the system.

The behaviour of materials when impacted by particles is very complex and depends on the material properties. When the material surface behaves in a ductile manner, the impact of solid particles causes local plastic deformation at the impact site. Repeated impacts cause material loss as a result of a cutting or gouging action. If the surface behaves in a brittle manner, the impact of the particles cause elastic deformation and crack formation. These cracks eventually link together and the material detaches from the surface. The erosion rate is defined as the ratio of material mass loss to impacting particle mass. Material degradation often cannot be avoided, but a good understanding of the fundamental aspects of the particle impact erosion process, and the ability to predict erosion, is of key importance for selection of appropriate materials and improved design of complex systems. While some of this understanding comes from studying plant data, much research has concentrated on lab-based studies using erosion rigs of various designs. With lab-based experiments, the factors influencing erosion are easier to control and measure, although it can be difficult to replicate real-world situations.

The main problems in obtaining meaningful explanations of erosion data lie in the fact that variables are often inseparable and that a number of different mechanisms may be operating at the same time. In 1987, Bell and Rogers^[2] suggested that a more detailed knowledge of particle interactions was required and that the most promising approach would be to use mathematical modelling. Modelling of the erosion process can be used to interpret existing experimental data, or to extend experimental data to

conditions that cannot be tested with current facilities. Most significantly, modelling erosive wear can assist design engineers both in the design of better experimental test facilities for material characterisation and in the design of improved industrial components/systems. The long-term industrial aim is to develop a system where the components are manufactured from appropriate materials, the materials degradation modes are identified and models are used to predict material performance^[3].

Computational fluid dynamics (CFD) is often the modelling technique used to study flow behaviour e.g. movement of particles within a gas or liquid, while finite element analysis (FEA) is used to predict erosion directly using element deletion techniques.

Finite element (FE) modelling has become widely used and accepted in many industrial sectors, primarily for improving design processes and predicting performance. In recent years, advances in the capabilities of commercial FE packages have enabled this approach to be extended into other areas such as failure analysis. The availability of techniques such as element failure and element deletion have made it much more feasible to use finite element analysis for erosion modelling. A finite element analysis can be used to calculate particle velocity, displacement and force, along with displacements, stresses and strains throughout the components involved in an erosion situation. An array of 2- or 3-dimensional elements is used to define the shape and size of the components, with elastic-plastic models needed to describe the deformation behaviour of materials. The finite element model can also predict material removal i.e. predict erosion directly. FEA has also been used to simulate other complex wear processes such as the effect of wear generated debris on fretting wear^[4]. In terms of erosion modelling FEA has generally been used to model the single or multiple impact of solid particles onto a substrate^[5-11]. The number of particles that can be simulated in an analysis is much lower than in CFD modelling, but it allows the finer detail of the erosion process to be captured such as material pile-up^[12,13], pit depth^[9-11,13] and subsurface residual stresses^[10,11,13]. FE modelling may also enable estimation of constants required for existing analytical models.

This Good Practice Guide provides detailed information on setting up an FE erosion model, using the FE package Abaqus, covering a range of aspects that need to be considered, with examples illustrating the key points. A rich array of further experimental possibility that can be brought to bear in order to investigate, for instance, the connectivity of the porosity^[6] or the transport of water within it^[7].

Chapter II

Finite element basics

- Element type
- Mesh density
- Example 1: Effect of mesh density

Element type

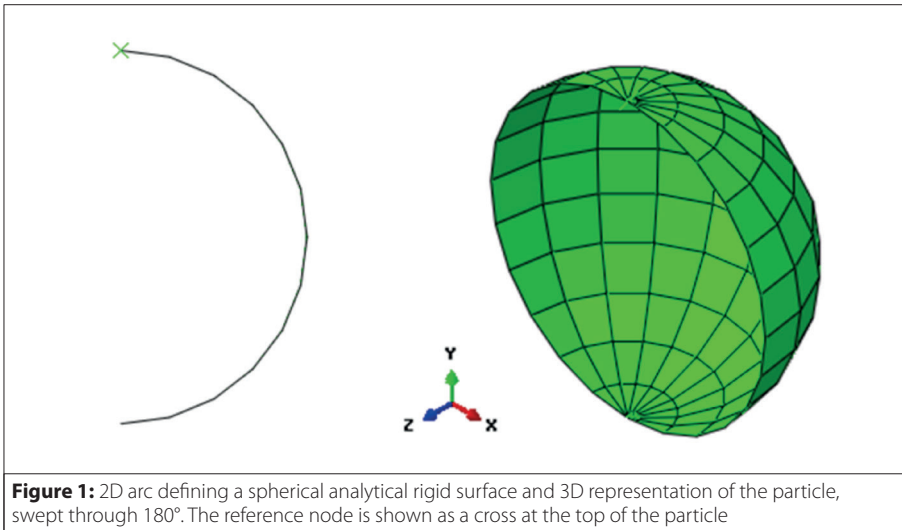
In a finite element model an element mesh is used to represent the component geometry. The key features of the geometry need to be modelled accurately, taking account of any symmetry that would reduce the size of the model. In many models, a pre-processor (such as Abaqus/CAE^[14]) is used to generate the geometry, before the FE mesh is applied to it. There are several factors to consider when meshing a geometry, such as element type, mesh density etc. The choice of elements can greatly influence results obtained from an analysis. In some cases the difference in results between element types may not be visible in force/extension plots, but maybe observed in the values obtained for stress or strain contours, or deformed shape. There is a wide range of element families available in FE packages such as Abaqus^[14], ranging from simple beam elements to solid (continuum) elements. There are also a variety of elements within each element family, each with their own advantages and disadvantages.

The elements used to model a substrate in an erosion analysis will be solid (continuum) elements; either 2D^[4,12], 2D axisymmetric^[8,13] or 3D^[9-11,13], depending on the size of the component to be modelled. Stress/displacement elements are used in the modelling of linear or complex nonlinear mechanical analyses that possibly involve contact, plasticity and/or large deformations. The vast majority of stress/displacement elements in commercial FE packages are based on the Lagrangian or material description of behaviour, where the element deforms with the material. 3D elements are generally used to model more complex three-dimensional structures and material responses, such as erosion, and these models will give the most representative predictions. However, 3D elements normally lead to larger computational problems and, hence, longer run times.

There are a number of continuum elements available within FE element libraries. The elements selected need to be appropriate for each particular analysis. When modelling high loading rates or problems that involve complex contact conditions, the first order form of the hexahedral (linear brick) continuum elements is recommended. First-order brick elements perform best if their initial shape is approximately cubic, becoming much less accurate when they are initially distorted. The chosen FE solver controls some element selections; for instance, in Abaqus Explicit the only continuum elements available are the reduced-integration first-order quadrilateral and hexahedral elements.

In finite element analyses the stiffness and mass of elements are calculated by numerical integration. Abaqus uses Gaussian quadrature for most of the elements. Reduced integration uses a lower order integration (only one Gauss-point for linear elements, or more dependent on the geometry of element and order of interpolation) to calculate the element matrices. For example C3D8R only uses 1

integration point compared to C3D8 which uses 8 integration points therefore allowing for fast and cheap calculation of the element matrices. For first-order elements the accuracy achieved with full versus reduced integration is largely dependent on the nature of the problem.



In an erosive situation, the impacting particles tend to be much harder than the material being eroded. This fact can be made use of in setting up the FE model by representing the particle as a rigid body, where its deformation is negligible. This can be defined in one of two ways. One option is to create the geometry representing the particle, mesh the particle, then define the part as a rigid body. This is useful for parts with complex shapes^[4,13]. In erosion modelling, the particles are often represented by simple shapes, such as spheres. In this case, a cost effective solution for defining the particle is to use an analytical rigid surface with an associated mass^[8,9]. The benefit of analytical rigid surfaces is that they are defined by only a small number of geometric points and are computationally efficient. However, in three dimensions the range of shapes that can be created with them is limited, although this is not an issue when modelling a simple particle. In the Abaqus package the specific form of an analytical rigid surface is a two-dimensional, segmented rigid surface, using straight lines, circular arcs, and parabolic arcs. Then, this cross-section is swept around an axis to form a surface of revolution, see Figure 1, or extruded along a vector to form a long three dimensional surface. An analytical rigid surface is associated with a rigid body reference node, whose motion governs the motion of the surface. By applying predefined field conditions to the reference node, the initial velocity field condition can be controlled i.e. the particle's initial velocity. The angle of impact is determined

by the individual magnitudes of the velocity components e.g. using the co-ordinate system shown in Figure 1, equal velocity components in the $-y$ and x directions produce a 45° impact angle, with the total velocity magnitude being the initial velocity.

Mesh density

Mesh density is the distribution (number and size) of elements used within the mesh. Adding more elements, if they are chosen sensibly, leads to better accuracy but a higher computational cost. It is standard practice with finite element models to run an initial analysis with a coarse mesh, but in situations where contact is occurring there are limits to how coarse the mesh can be, see section on Contact surfaces and boundary conditions. The mesh density should then be increased until there is no change in the predictions (mesh convergence).

A highly refined mesh with high element density can lead to long analysis process times, especially in explicit analyses, see section on Choice of solver. It is unnecessary to refine the whole mesh, but areas of high stress gradient will need refinement along with areas where quantitative predictions are required. By using a refined mesh in the region of interest and a coarse mesh for the remainder of the model, see Figure 2, the computational costs can be kept lower, without sacrificing the accuracy of the predictions.

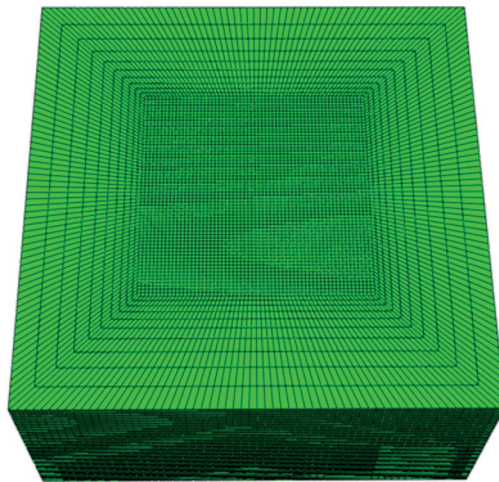


Figure 2: Meshed sample showing refined region in the centre of the sample, and a coarser mesh in the outer region

Example 1: Effect of mesh density

Three erosion analyses were run with differing mesh densities in the refined central region of the sample. The first mesh (mesh 1) had an element dimension of $4\text{ }\mu\text{m}$, the second mesh (mesh 2) has an element dimension of $8\text{ }\mu\text{m}$, while mesh 3 had the largest element size ($12\text{ }\mu\text{m}$). The sample was impacted by a particle with a diameter of $300\text{ }\mu\text{m}$. The deformed surface plots are shown in Figure 3. The coarsest mesh gives a slightly less accurate prediction of surface definition, while the other 2 mesh densities give similar results. However, there is a marked difference in computational time between the models. The model with the finest mesh took 1 hour and 36 minutes to solve, whereas the analysis time for the model with mesh 2 was only 16 minutes, and for mesh 3 it was 9 minutes. Hence mesh 2 has a good balance between predictive accuracy and computational cost.

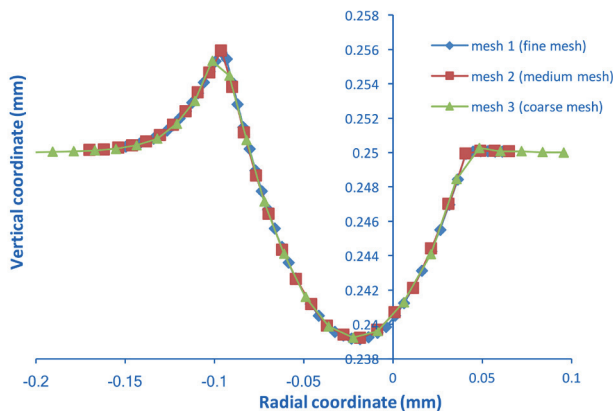


Figure 3: Plots of surface deformation from analyses with three different mesh densities after the impact of a spherical particle at 45°

Choice of solver

During an FE simulation, the numerical problem defined in an input file is solved using a mathematical code. The FE package Abaqus has a choice of solver codes. The standard (implicit) code can solve a wide range of linear and nonlinear problems by treating the problem as a sequence of quasi-static steps. The explicit code is suitable for short, transient dynamic events where inertial effects are significant, such as impact, and is also very efficient for highly nonlinear problems.

In nonlinear analyses the term “convergence” is used to indicate that the solution process for the nonlinear equation system converges. FE codes solve transient problems by calculating the changes in variables (such as displacement) over a short time step. For nonlinear problems, the change in variables cannot be calculated directly, so the codes estimate the likely change, put the estimated new variable values into the equations and calculate how incorrect the estimated values are, and use the incorrectness (the residuals) to produce a new estimate of the variable values. This process happens repeatedly until the residuals are sufficiently small that the variable values are regarded as satisfying the equations. When this has been achieved, the solution is regarded as having converged. If this is not achieved, the solver terminates the analysis – the model has failed to converge.

The erosion process is dynamic, with fast moving particles and large deformation of the substrate. For this scenario, the use of an explicit solver is recommended. The explicit dynamics procedure performs a large number of small time increments efficiently and is therefore computationally efficient for the analysis of large models with relatively short dynamic response times and for the analysis of extremely discontinuous events or processes. One limitation of using the explicit solver is that the time step is proportional to the time for a stress wave to cross the smallest element dimension. The result is that processing times can be excessive, especially when a refined mesh is being used. Therefore, care must be taken to avoid meshes with a few very small elements. For erosion modelling, a uniform mesh in the region of interest is desirable.

Contact surfaces and boundary conditions

- Overview
- Example 2: Effect of incorrect contact definitions
- Friction
- Example 3: Effect of friction

Overview

Contact surfaces and boundary conditions can be applied to the geometry of the component to be modelled or to the mesh itself. If the component is likely to be remeshed (for instance when changing mesh density, or altering component dimensions), then it is useful to apply constraints to the geometry, as this will then automatically apply to the new mesh.

Boundary conditions should be applied such that they represent the physical constraints of the modelled component as closely as possible. Constraints can be applied to the three displacement degrees of freedom and the three rotational degrees of freedom. Boundary conditions can also be used to set up symmetry conditions. Symmetry within the component can be used to decrease the size of the geometry modelled as this in turn reduces the computational cost of the analysis.

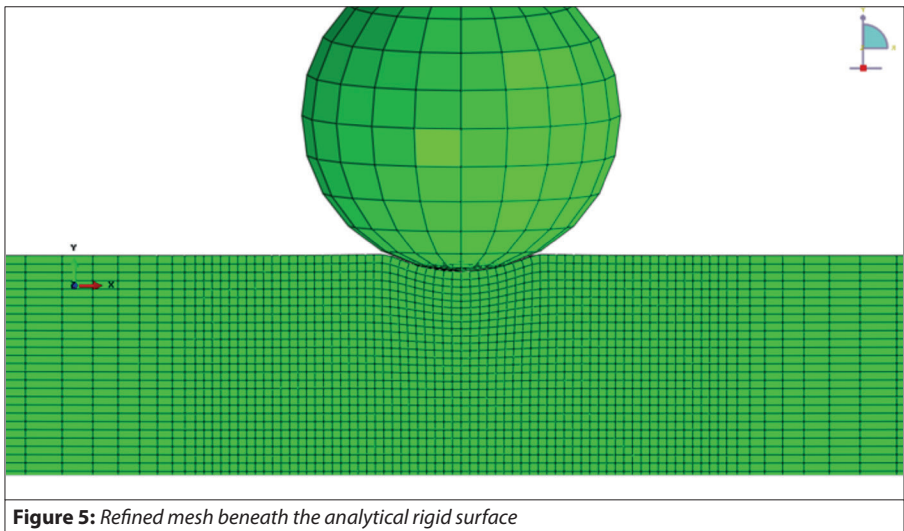
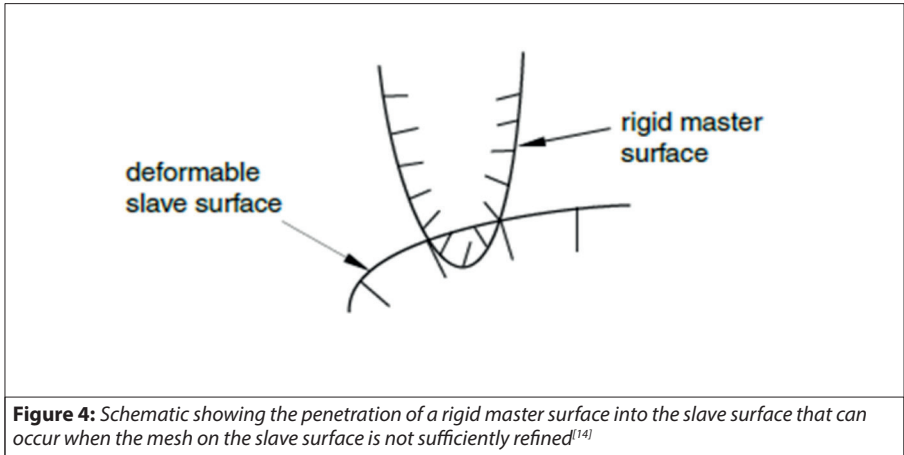
In impact analyses, contact surfaces need to be included. Abaqus/Explicit provides two algorithms for modelling contact interactions. The general contact algorithm allows very simple definitions of contact with very few restrictions on the types of surfaces involved. The contact pair algorithm has more restrictions on the types of surfaces involved and often requires more careful definition of contact, but it allows for some interaction behaviours that currently are not available with the general contact algorithm. For erosion modelling, the general contact algorithm can be used.

There are a number of issues that you should consider when modelling contact problems. The rigid surface is always the master surface in a contact interaction, with the deformable surface designated the slave surface. For contact, as with other types of analyses, the solution improves as the mesh is refined. For contact analyses using a pure master-slave approach, it is especially important that the slave surface is refined adequately so that the master surface facets do not overly penetrate the slave surface, see Figure 4, which shows an example of the penetration that can occur if the discretization of the slave surface is poor compared to the dimensions of the features on the master surface. A sufficiently refined mesh on the deformable surface will prevent the rigid surface from penetrating the slave surface, see Figure 5.

The rigid surface normal must always point toward the deformable surface with which it will interact. If it does not, the surface is effectively “inside out” and Abaqus will detect severe overclosures at all of the nodes on the deformable surface and the simulation will terminate due to convergence difficulties. The normals for an analytical rigid surface are defined as the directions obtained by the 90° counterclockwise rotation of the vectors from the beginning to the end of each line and circular segment forming the surface.

General contact interactions typically are defined by specifying self-contact for a

default, element-based surface that includes the outer surfaces of all bodies in the model. For an erosion model including element deletion, the default exterior surface definition is not sufficient. If, for example, a second particle hit a damaged interior region with no contact definition, the particle would not know it was in contact with any substrate and would pass through the body of the sample. Hence, contact must occur on both exterior and interior faces of regions that can erode due to material failure. Consequently, a non-default contact domain needs to be defined, whereby interior surfaces are also defined.



Example 2: Effect of incorrect contact definitions

Two erosion analyses were run, each with a 300 μm diameter steel particle impacting a Ti-6Al-4V sample at an angle of 45° and an impact speed of 100 m/s. In the first analysis, the contact definition was set-up using the default general contact option in Abaqus/Explicit. This defines contact between the surface of the analytical rigid surface of the particle and the surface of the sample. In the second analysis, the contact definition was manually altered within the input file, such that contact is defined between particle surface and all surfaces (exterior and interior) within element set Centre. This is achieved by replacing the default surface definition of the sample (called erode in this example) with a description of the element set Centre which includes the interior surface of the element set i.e. in this case replacing:

```
*Surface, type=ELEMENT, name=erode  
  
_erode_S2, S2  
  
_erode_S5, S5  
  
_erode_S4, S4  
  
_erode_S6, S6
```

with

```
*Surface, type=ELEMENT, name=erode  
  
Centre  
  
Centre, interior
```

The predictions from the first analysis are shown in Figure 6, which is a contour plot of contact pressure (CPRESS) on the defined contact surface. Here a particle has bounced off the sample surface causing some element deletion. As there is no contact pressure at this increment in the analysis, the contact pressure is shown as zero (blue contour) on all available contact surfaces. The elements that are coloured white only, do not have a contact surface defined on them. This plot highlights that the newly visible surface is not included in the contact definition.

The predictions from the second analysis are shown in Figure 7. By changing the contact definition to include all interior surfaces in this analysis, it can be seen that the newly exposed surface is defined as a contact surface. In this case, with a single particle bouncing off the surface, the wrong contact definition has not affected the shape of the crater, but this incorrect definition would cause a problem if more impacts were going to happen.

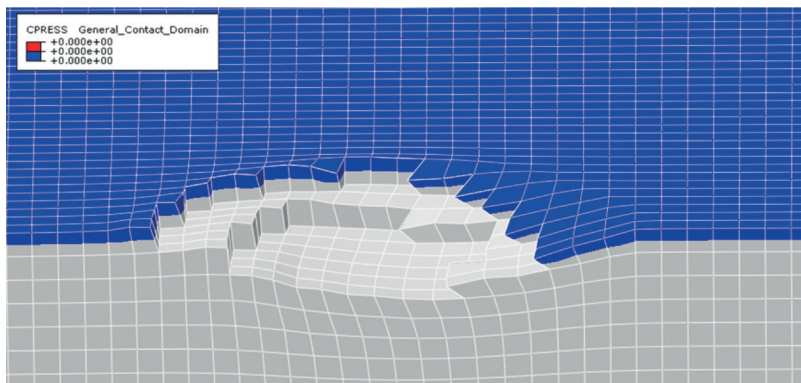


Figure 6: Contour plot of an eroded surface showing the output CPRESS, or contact pressure on the defined contact surface, for analysis with contact set as the default general contact

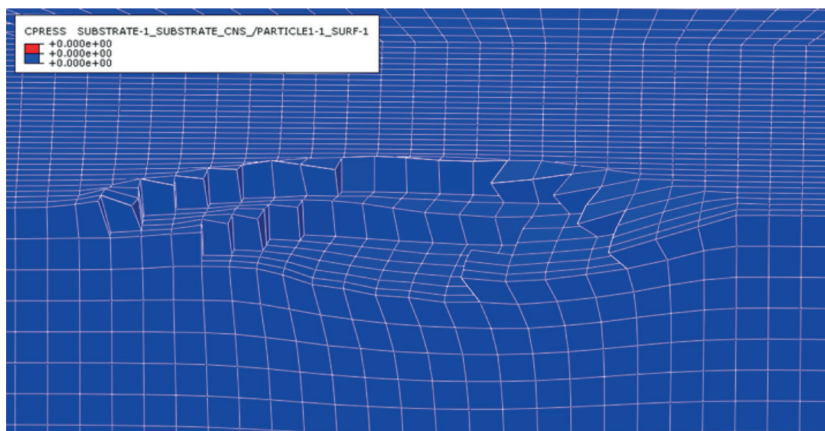


Figure 7: Contour plot of an eroded surface showing the output CPRESS, or contact pressure on the defined contact surface, for analysis with contact set to include all interior elements

Friction

When modelling contact, it is also important to consider that friction could be significant between the surfaces in contact. When surfaces are in contact they usually transmit shear as well as normal forces across their interface. The relationship between these two force components is referred to as friction. In many FE packages, the default assumption is that the interaction between two surfaces is frictionless. Friction can be specified between two surfaces by defining friction properties as part of the contact property definition.

Example 3: Effect of friction

A series of 5 analyses were run, with a range of friction coefficients. The model consisted of a 300 μm diameter steel particle impacting a Ti-6Al-4V sample at an angle of 45° and an impact speed of 100 m/s. The model geometry is shown in Figure 8. The predicted deformed surfaces are shown in Figure 9 and highlight the effect that choice of friction parameter can have on the deformation. With the higher levels of friction, greater deformation of the surface is observed, leading to greater material pile-up on one side of the impact crater (one side only due to the 45° angle of impact). For the analyses run as part of the MetroSION project, a friction coefficient of 0.2 was selected.

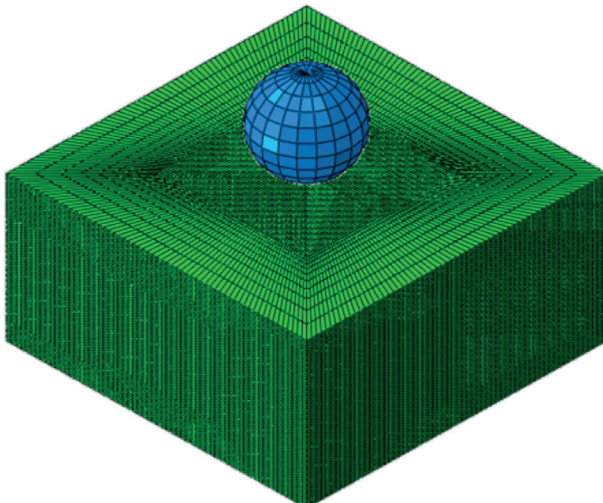


Figure 8: Meshed sample and analytical particle used for erosion modelling

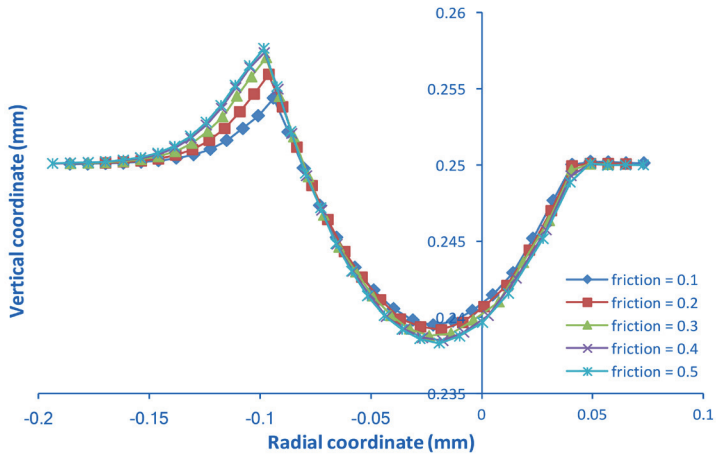


Figure 9: Plots of surface deformation from analyses with five different friction coefficients after the impact of a spherical particle at 45°

Material models

- Overview
- Johnson-Cook models
- Example 4: Comparison of Johnson-Cook Dynamic Failure Model and Johnson-Cook Progressive Damage and Failure model
- Johnson-Cook parameters
- Example 5: Parameter sensitivity

Overview

The choice of material model will have a large effect on the predictions obtained from an analysis. There are a range of material models available within FE packages which are suitable for high-impact, large deformation analyses, such as erosion modelling. Different material models are required for modelling brittle and ductile behaviour, for example, the Johnson-Cook model for ductile materials^[10-13] and the Johnson-Holmquist model for brittle materials^[11]. For all models it is necessary to input material properties to properly describe the material behaviour. With the more complex 3D models element failure and deletion can be used to simulate actual material loss. There is a range of failure criteria available for predicting element failure with additional parameters needed to describe the failure process. These parameters can be measured experimentally. For ductile materials, a shear failure model is often selected^[9,10,13], which uses the value of the equivalent plastic strain at element integration points as its failure criterion. Weight loss due to erosion can be calculated directly from failed elements to give the erosion rate, removing the need for an erosion equation.

When setting up the material properties for the sample there are three components to consider:

- The elasticity model i.e. Young's modulus and Poisson's ratio,
- the plasticity model to account for plastic deformation of the sample, and
- the damage model to calculate whether any elements will fail and be removed from the model.

Johnson-Cook models

A commonly used model for the dynamic plasticity and damage of ductile materials is that of Johnson and Cook^[15]. The Johnson-Cook model has two principal elements: plasticity and damage initiation. The Johnson-Cook plasticity model is applied to the deformable sample and a Johnson-Cook damage model determines whether elements have reached a critical strain level, which causes failure of that element, with the element then being deleted from the mesh.

The plasticity model prescribes the dependency of plastic flow stress on equivalent plastic strain, $\bar{\epsilon}^{pl}$, equivalent plastic strain rate, $\bar{\dot{\epsilon}}^{pl}$, and temperature:

$$\bar{\sigma} = (A + B \bar{\epsilon}^{pl^n}) [1 + C \ln \bar{\dot{\epsilon}}^{pl*}] (1 - T^{*m}), \quad (1)$$

where $\bar{\sigma}$ is the yield stress at non zero strain, A, B, C and m are constants, n is the strain hardening exponent, $\bar{\dot{\epsilon}}^{pl*} = \bar{\dot{\epsilon}}^{pl}/\dot{\epsilon}_0$ is the normalised equivalent plastic strain rate, $\dot{\epsilon}_0$ is a material parameter and T^* is the homologous temperature as shown here.

$$T^* = \frac{T - T_{\text{room}}}{T_{\text{melt}} - T_{\text{room}}}, \quad (2)$$

where T is the current temperature, T_{melt} is the melting temperature of the material and T_{room} is room temperature. The model assumes that the strength is isotropic and independent of mean stress.

A major mechanism in the erosion of ductile materials is plastic deformation. As plastic strain accumulates and reaches a failure strain, $\bar{\epsilon}_f^{\text{pl}}$, material removal takes place. The accumulation of plastic strain is accounted for in the Johnson-Cook damage model, and is defined as shown:

$$\bar{\epsilon}_f^{\text{pl}} = \left[d_1 + d_2 \exp \left(d_3 \frac{p}{\bar{\sigma}} \right) \right] \left[1 + d_4 \ln \dot{\epsilon}^{\text{pl}*} \right] (1 + d_5 T^*), \quad (3)$$

where d_1 to d_5 are constants, and $p/\bar{\sigma}$ is the ratio of pressure to the von Mises stress.

There are two versions of the Johnson-Cook damage model available within Abaqus/Explicit. One is the dynamic failure model based on shear failure, suitable for high strain rate, dynamic deformation of metals. The second is a progressive damage and failure model, a more general implementation of the failure model which can also be used for quasi-static problems.

The Johnson-Cook dynamic failure model is based on effective plastic strain at element integration points. Failure is assumed to occur when the damage parameter exceeds 1. The damage parameter, ω , is defined as:

$$\omega = \sum \left(\frac{\Delta \bar{\epsilon}^{\text{pl}}}{\bar{\epsilon}_f^{\text{pl}}} \right), \quad (4)$$

where $\Delta \bar{\epsilon}^{\text{pl}}$ is an increment of equivalent plastic strain and $\bar{\epsilon}_f^{\text{pl}}$ is the equivalent plastic strain at failure.

With the progressive damage and failure model a damage initiation criterion based on the Johnson-Cook failure strain is used along with a damage evolution option which defines the evolution of damage leading to eventual failure. The damage evolution is controlled using the effective plastic displacement, $\bar{u}^{\text{pl}}$. The user specifies a maximum value for the effective plastic displacement, $\bar{u}^{\text{pl}}_{\text{cr}}$, and once the calculated value within an element exceeds the critical value, that element is deleted. The effective plastic displacement rate is calculated from equation (5) where L is equal to the characteristic element length, to avoid problems with strain localisation.

$$\dot{\bar{u}}^{\text{pl}} = L \dot{\bar{\epsilon}}^{\text{pl}}, \quad (5)$$

The progressive failure model allows the mechanical behaviour of the material to vary with the ratio of calculated effective plastic displacement to critical effective plastic displacement, with the simplest option being a linear dependence of properties on the ratio, where the damage variable d increases according to

$$\dot{d} = \frac{L \dot{\epsilon}^{pl}}{\bar{u}^{pl}_f} = \frac{\ddot{u}^{pl}}{\bar{u}^{pl}_f}, \quad (6)$$

Both these models have been used within the Metrosion project. It should be noted that the Johnson-Cook ductile failure criterion is not available within the pre-processor Abaqus/CAE.

Example 4: Comparison of Johnson-Cook Dynamic Failure Model and Johnson-Cook Progressive Damage and Failure model

The erosion of a Ti-6Al-4V sample (Figure 8) by a 300 μm diameter steel particle impacting at a range of impact angles and an impact speed of 100 m/s has been predicted using both the Johnson-Cook Dynamic Failure Model (DFM) and Johnson-Cook Progressive Damage and Failure model (PDFM). The predicted erosion rates are shown in Figure 10. Different damage evolution parameters have been defined for the Progressive Damage and Failure model (PDFM). These parameters were $\bar{u}^{pl} = 0.001$ (U1) and $\bar{u}^{pl} = 0.002$ (U2). At an impact angle of 45°, two further analyses were run with $\bar{u}^{pl} = 0.0005$ (U05) and $\bar{u}^{pl} = 0.0003$ (U03). The effect of varying the evolution parameter can be seen clearly. As the value of the evolution parameter decreases, the predicted erosion rates approach those predicted by the dynamic failure model.

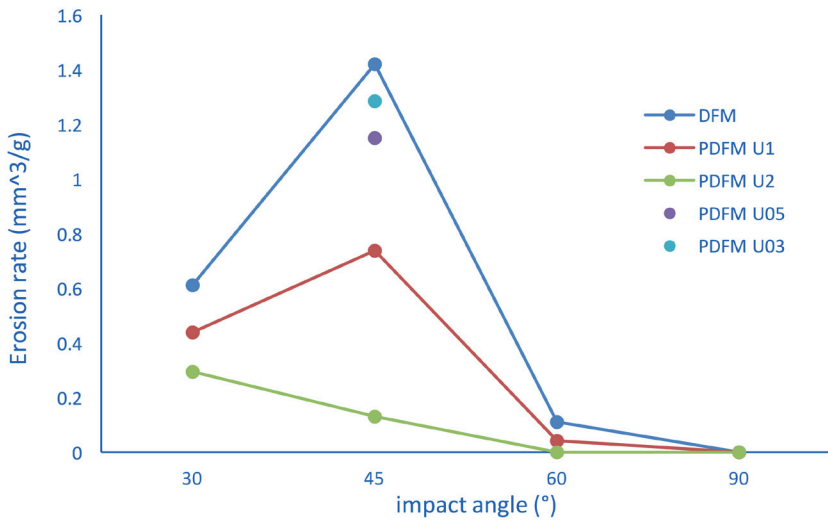


Figure 10: Predicted erosion rates for a Ti-6Al-4V sample impacted by a 300 μm diameter steel particle, at a range of impact angles and an impact speed of 100 m/s using the Johnson-Cook Dynamic Failure Model (DFM) and Johnson-Cook Progressive Damage and Failure model (PDFM)

Johnson-Cook parameters

The parameters required for these models are generally determined experimentally using tests such as the split Hopkinson torsion bar test^[16,17], although computational methods involving complex algorithms have also been developed to predict the parameters^[17,18]. Johnson-Cook parameters can be found within the literature for a wide range of materials, examples are provided in Table 1.

The Johnson-Cook parameters will vary depending on the temperature and strain rate of the underlying experimental tests, as can be seen in Table 1, where two sets of data for Ti-6Al-4V are presented. The data sets differ in the values for plasticity parameters A, B, C and n. A is sometimes referred to as the yield stress constant, and B as the strain hardening constant. The plasticity parameters of the second set of Ti-6Al-4V data are lower than that of the first set. The parameters in Table 1 have been used to predict erosion rates in the following example.

Johnson-Cook parameters for a range of materials							
J-C parameters		4340 Steel	A36 hot rolled steel	A36 hot rolled steel	6065-T6 Aluminium	Ti-6Al-4V	
A	MPa	792	286	429	261	1098	862
B	MPa	510	500	243	126.8	1092	331
C		0.014	0.022	0.021	0.0125	0.014	0.012
n		0.26	0.2282	0.0868	0.3008	0.93	0.34
$\dot{\epsilon}_0$	1/s	0.001	0.001	0.001	0.001	0.001	0.001
M		1.03	0.9168	0.8741	1.1	1.1	0.8
d ₁		0.05	0.4025	0.2431	0.2632	-0.09	-0.09
d ₂		3.44	1.107	1.242	1.042	0.27	0.27
d ₃		-2.12	-1.899	-2.525	-2.312	0.48	0.48
d ₄		0.002	0.009607	0.003551	0.04424	0.014	0.014
d ₅		0.61	0.3	0.25	2.6	3.87	3.87
reference		(19)	(16)	(16)	(16)	(10)	(11)

Table 1: Johnson-Cook parameters for a range of materials.

Example 5: Parameter sensitivity

A series of erosion analyses were run using the material parameters provided in Table 1. In all cases the sample was impacted at 45° by a 300 µm diameter steel particle with a velocity of 100 m/s. The erosion rates have been predicted using the Johnson-Cook Dynamic Failure Model (DFM) and are shown in Figure 11.

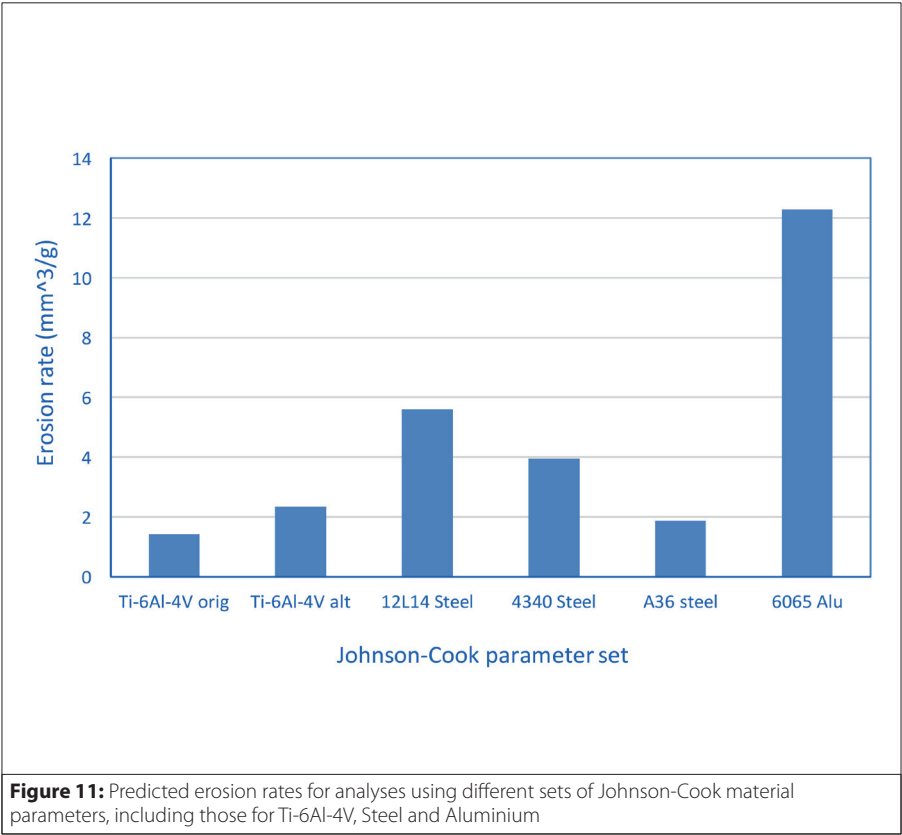


Figure 11 shows a large variation in predicted erosion rate for the three sets of steel data. There is also a noticeable difference in predictions from the Ti-6Al-4V data set with the smaller values for A, B, C and n (lower yield stress leads to greater erosion). Aluminium is a much softer material (lower Young’s modulus and smaller plasticity parameters) than the steels or Ti-6Al-4V and therefore has a significantly higher erosion rate.

Calculation of erosion rate

- Calculation of erosion rate
- Example 6: Erosion data output from a parametric study of particle size

Calculation of erosion rate

An erosion equation is not required to calculate the erosion rate for the finite element predictions. As elements are removed during the analysis, the mass loss or volume loss, can be output directly from the analysis. The mass loss due to erosion is 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. Volume change can also be output in a similar manner. If the element size in the region of interest is known and is uniform, then the number of elements deleted can also be calculated. By knowing the mass and volume loss during the analysis, and the mass of the impacting particle, the erosion rate can be calculated directly as:

$$\text{Erosion rate} = \frac{\text{cumulative mass (or volume) loss of sample}}{\text{total mass of impact particles}} \tag{7}$$

giving erosion rates with units of mg/g or mm³/g. One point to note: in some cases, once elements are removed from the sample mesh, they appear as floating elements. These elements will need to be removed from the deformed plot before any volume or mass data are output.

The erosion rate can be obtained over a range of particle speeds, for example, as shown in Figure 12.

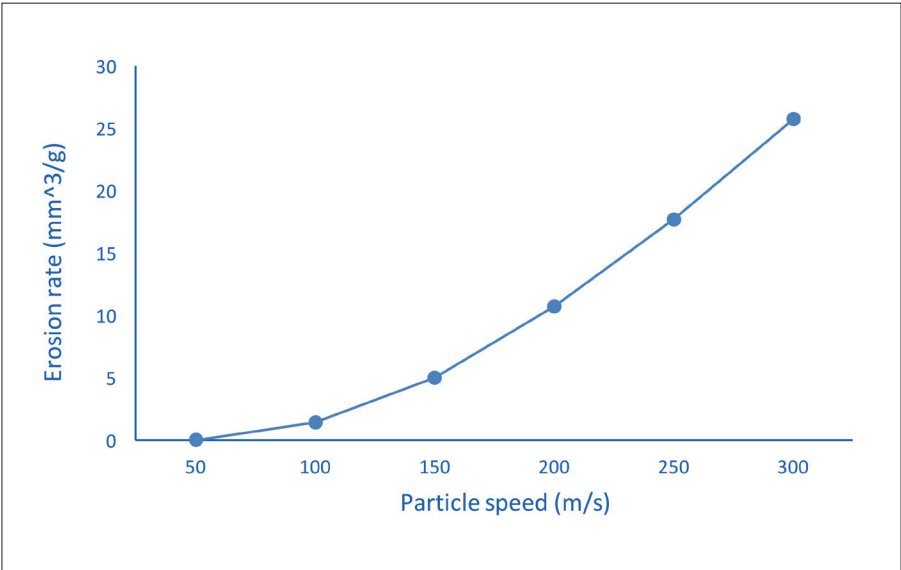
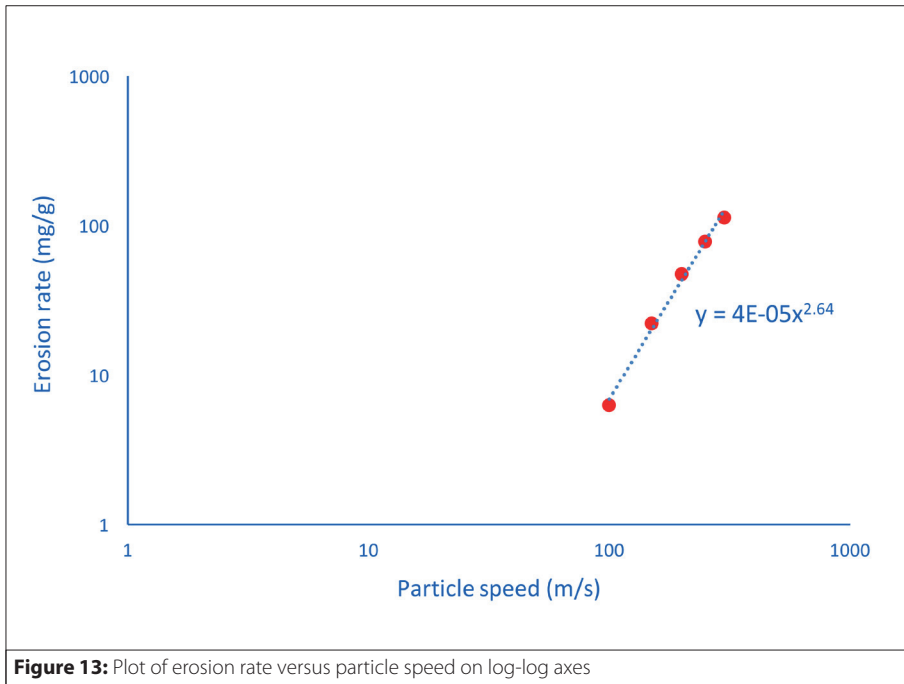


Figure 12: Plot of erosion rate against particle speed

It is known that the erosion rate is related to the impact velocity by the following relationship:

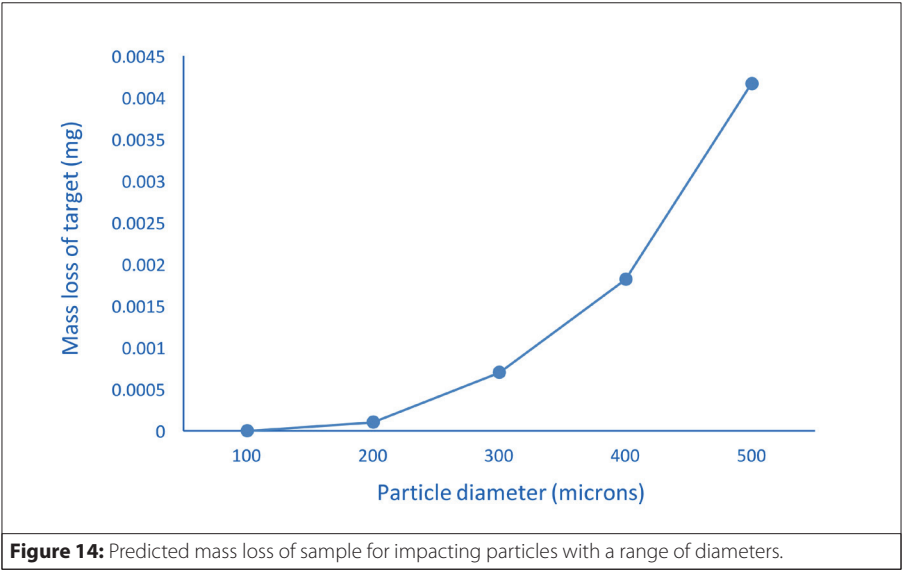
$$\text{Erosion rate} \propto V^n, \quad (8)$$

Finnie^[20] proposed an exponent, n , of 2, while Sheldon and Kanhere^[21] suggested the exponent was closer to 3, based on experimental and predicted data. The exponent can be obtained by plotting the erosion rate versus impact velocity on a log-log plot. The data presented in Figure 12 are plotted in this manner in Figure 13, the slope of a straight line fitted through the data provides the exponent n , in this case $n = 2.64$.



Example 6: Erosion data output from a parametric study of particle size

A series of 5 analyses were run to investigate the effect of particle size on erosion rates. In all cases the sample was impacted at 45° by a steel particle with a velocity of 100 m/s. The diameter of this particle varied from 100 µm to 500 µm with the associated particle mass changed accordingly. Erosion has been predicted using the Johnson-Cook Dynamic Failure Model (DFM). The number of elements deleted, mass loss and volume eroded were output from the analyses. Figure 14 shows a graph of mass loss versus particle diameter and highlights that a higher mass loss occurs when larger particles are used as the erodent. These output data along with the mass of the impacting particle were used to calculate erosion rates. Erosion rates are commonly quoted as either mass loss per gram of erodent or volume loss per gram of erodent. Both rates have been calculated. All data are provided in Table 2. Although there is a greater element deletion and hence greater mass and volume loss as particle size increases, when this is converted into erosion rates the heavier mass of the larger particles is taken into account. It can then be seen that the effect of particle size on erosion rate is smaller once the particle diameter exceeds 300 µm, than it is at smaller particle diameters, Figure 15.



Predicted erosion data for a range of impacting particle diameters

particle size	Number of elements deleted	Mass loss (mg)	Volume eroded (mm ³)	Erosion rate (mg/g)	Erosion rate (mm ³ /g)
100	0	0	0	0	0
200	44	0.000101	2.29E-05	3.075	0.694
300	304	0.0007	0.000158	6.295	1.422
400	789	0.001818	0.000411	6.890	1.556
500	1810	0.00417	0.000942	8.092	1.827

Table 2: Predicted erosion data for a range of impacting particle diameters

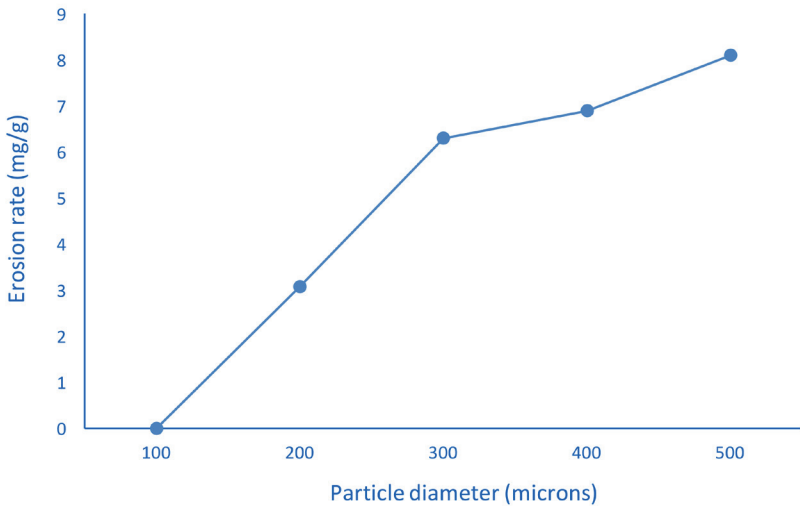


Figure 15: Predicted erosion rates (mg/g) caused by particles with a range of diameters.

Additional outputs

- Additional outputs
- Example 7: Residual stresses and crater depth predictions

Additional outputs

The benefit of using finite element analyses to predict erosion is that additional information, which can be difficult to acquire experimentally, can be obtained from the predictions. These outputs can include data such as contact time, velocity and displacement of particles, plastic strains, residual stresses and changes in temperature (if temperature is included in the analysis). Alternatively, outputs such as crater depth can be used as a further comparison against experimental data.

Example 7: Residual stresses and crater depth predictions

Residual stress predictions were obtained from an analysis of a 300 μm diameter steel particle impacting a Ti-6Al-4V sample at an angle of 90° and an impact speed of 100 m/s. The residual stress predictions were obtained from three paths defined within the sample, shown in Figure 16. Path 2 is directly below the point of particle impact, while paths 1 and 3 are out the outer edges of the crater formed during impact. The residual stress predictions obtained along these three paths are given in Figure 17. The residual stresses shown are S11 (x direction) stresses, the stresses in the z direction (S33 stresses) are very similar. The graph shows a compressive residual stresses at the surface, with the magnitude increasing below the surface. The maximum residual stresses occur at a depth of approximately 50 μm before decreasing. The residual stresses become slightly tensile at about 150 μm before reducing to zero. These trends are similar to those published by ElTobgy *et al*^[10] and Wang and Yang^[11].

The crater depth predictions shown in Figure 18 were obtained from an analysis run with a 30 μm diameter alumina particle impacting a sample with an impact angle of 90° and varying impact speeds. The eroded sample is steel, modelled with the Johnson-Cook dynamic failure model. The figure illustrates that the crater depth increases as the particle speed increases.

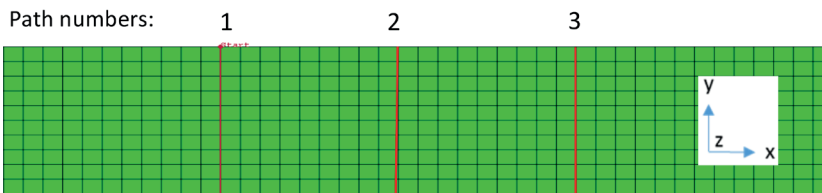


Figure 16: The locations of three paths used to output residual stress data. Path 2 is directly below the point of particle impact

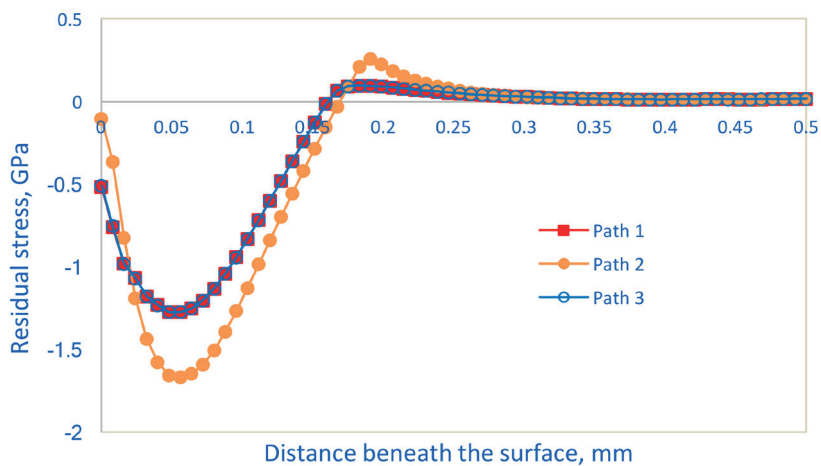


Figure 17: Residual stress (S11) profiles along three paths below the impact site

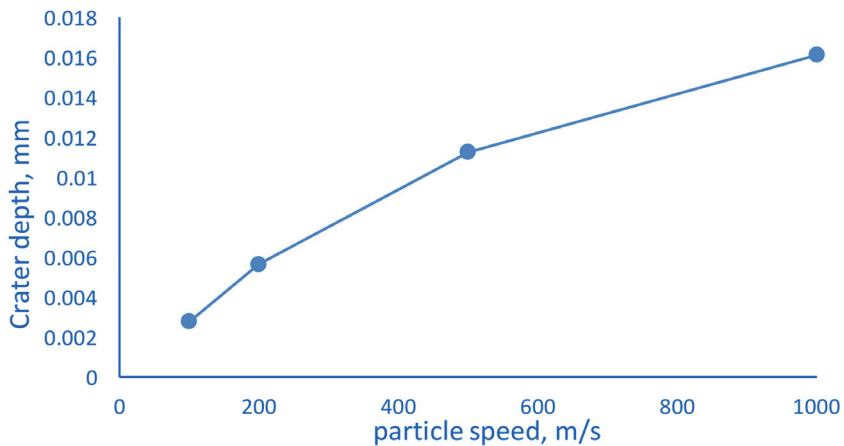


Figure 18: Predicted crater depth for a range of particle speeds

Multiple particles

- Overview
- Example 8: Multiple particle analyses

Overview

The single particle erosion model can be extended to include additional particles. In experimental erosion tests, large numbers of particles are used. Some of these particles will hit the surface, resulting in some plastic deformation but with no material removal, causing the substrate material to strain-harden. The following particles will then remove this strain-hardened region. To take account of this effect within an FE model, a number of particles need to impact the surface.

It is straightforward to add additional particles to the model. One point to consider is whether you want interactions between particles. If you are only concerned with multiple impacts on the sample surface, the most efficient way of modelling multiple particles is to define contact interactions between the additional particles and the sample surface but not set up any contact definitions between the particles. This means that no particle knows the others are there, and hence they do not interact with each other e.g they will not collide and rebound. Hence, the particles can start the analysis occupying nearly the same space, see Figure 19, and so the time between impacts is reduced. This reduces the computing time for the analysis. The impact location for each particle can be controlled, for instance: hitting at separate locations i.e. random impacts; the same location as previous particles; or at slightly offset locations where for instance a second particle may impact on the edge of the crater caused by an initial impact. From a multiple particle analysis, data can be output after all impacts have taken place, but also after each individual impact. When calculating the erosion rates, the mass of the additional particles must be taken into account.

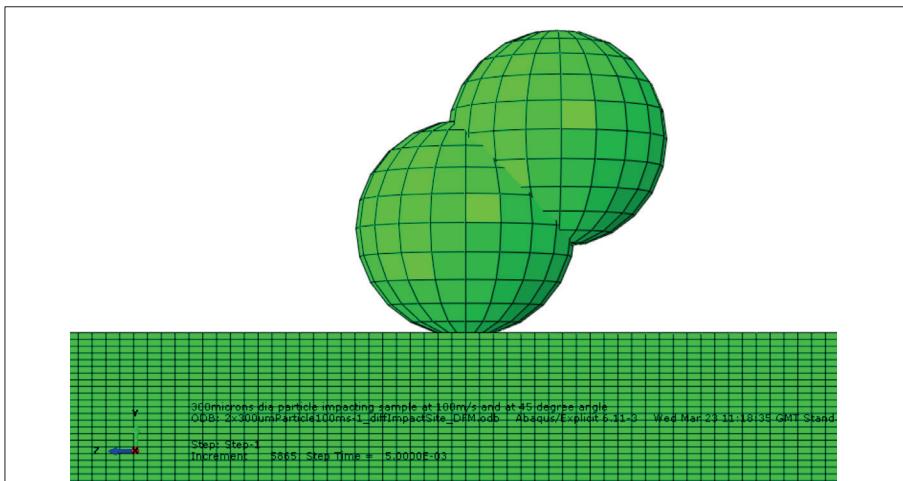


Figure 19: Starting locations of two particles in a multiple particle analysis.

Example 8: Multiple particle analyses

A series of multiple particle analyses were run. Three models were set up with two particles, and two models had five particles. The difference between the two particle models was impact location. In one case the two particles hit the surface at different locations, Figure 20. A second analysis was run with the particles impacting at the same point on the surface, Figure 21. In the third case, the second particle was slightly offset from the first so that it hit the surface on the edge of the crater caused by the first impact, see Figure 22. In Figure 20 some floating elements are visible that have detached from the sample surface, but haven't been completely deleted from the analysis yet.

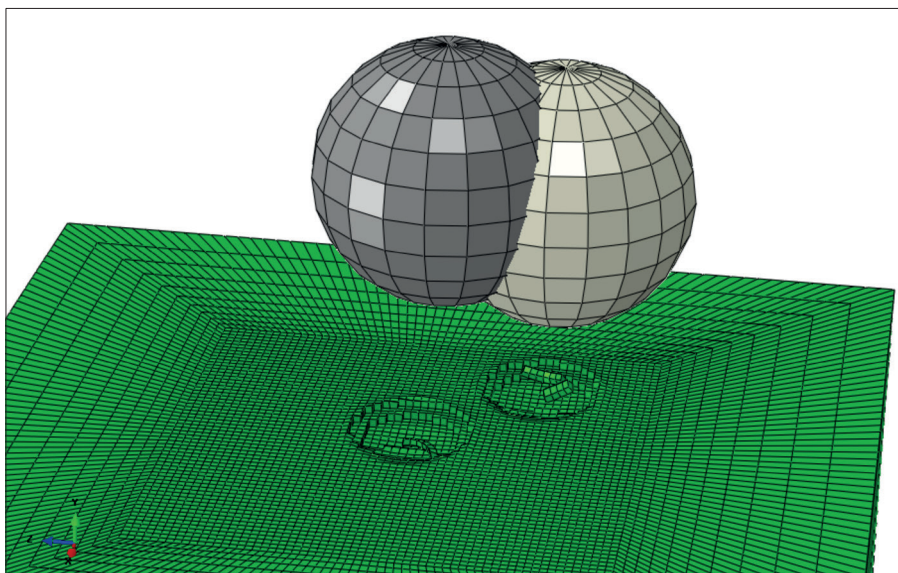


Figure 20: Two particles impacting at different locations

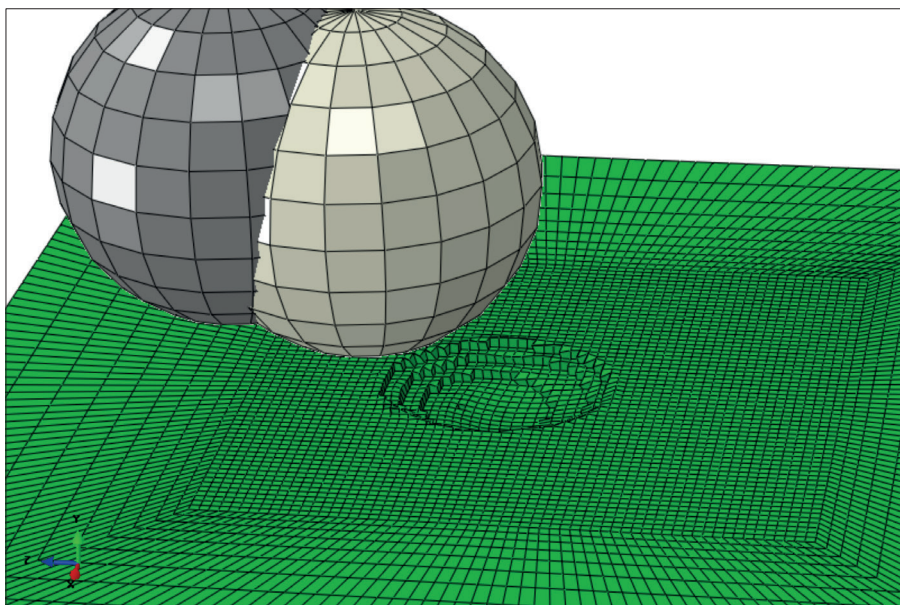


Figure 21: Two particle impacting at the same location

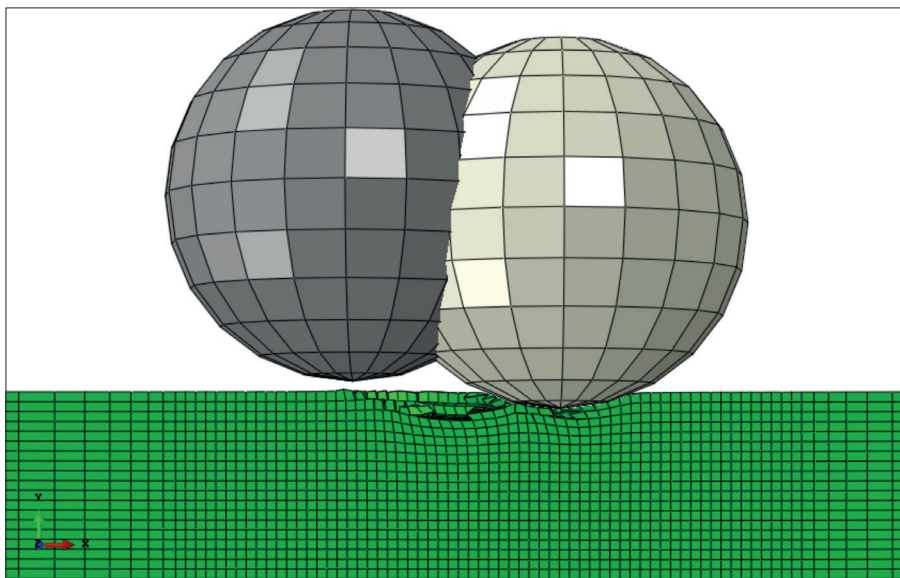


Figure 22: Cutaway view of sample showing the second particle impacting at the edge of the crater created by the first particle impact

The two five particle analyses also had different impact locations. The first had all particles impacting at different locations, see Figure 23. The second case had all five particles hitting the sample at the same location, see Figure 24.

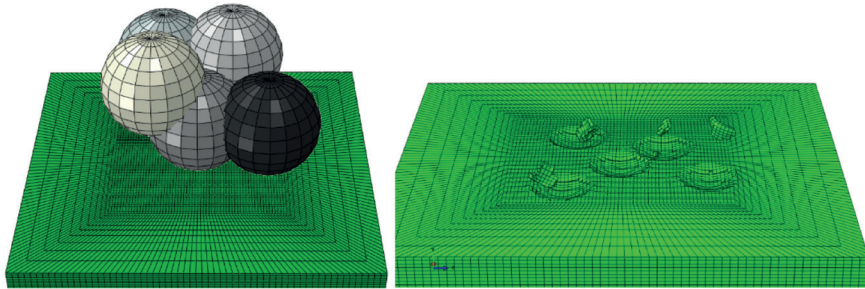


Figure 23: Initial particle locations and resulting impact craters for case with 5 particles impacting in different locations

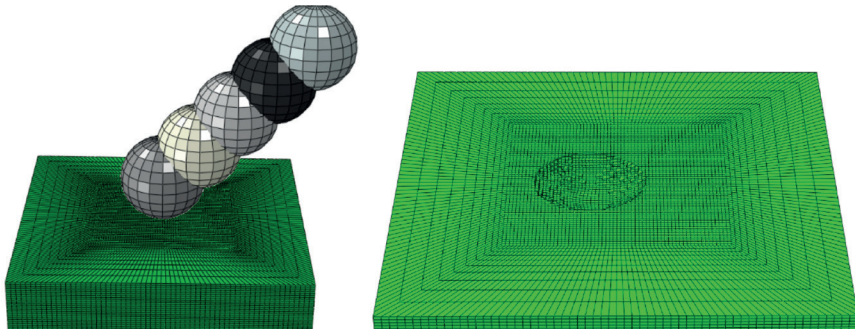


Figure 24: Initial particle locations and resulting impact crater for case with 5 particles impacting at the same location

Predicted erosion data and erosion rates for multiple particle analyses					
No of particles and impact locations	Number of elements deleted	Mass loss (mg)	Volume eroded (mm ³)	Erosion rate (mg/g)	Erosion rate (mm ³ /g)
1	304	7.00E-04	1.58E-04	6.295	1.422
2 (different impact)	610	1.41E-03	3.17E-04	6.316	1.426
2 (same impact)	846	1.95E-03	4.40E-04	8.760	1.978
2 (offset impact)	768	1.77E-03	4.00E-04	7.952	1.796
5 (different impact)	1522	3.51E-03	7.92E-04	6.303	1.424
5 (same impact)	2704	6.23E-03	1.41E-03	11.198	2.529

Table 3: Predicted erosion data and erosion rates for multiple particle analyses

Table 3 gives the data obtained from the series of multiple particle analyses, and the mass loss and erosion rate data are presented graphically in Figure 25 and Figure 26.

The results from the impacts that hit at different locations scale linearly with number of particles. If we look at the number of elements deleted, which is the easiest number to focus on, a single impact causes 304 elements to be deleted. Doubling the number of particles roughly doubles the number of elements deleted to 610 elements, and this also scales for 5 particles. But in the case where two particles hit at the same location, the number of elements deleted is increased to 846 elements and similarly for 5 particles, the number of elements deleted is 2704 elements, much greater than the number deleted when the particles hit at different locations. This is because in this instance the particle is not hitting a flat area of the sample, but landing in an existing crater where there is more surface area and more opportunity for extra element deletion. In the 2 particle analysis, when the second particle is only slightly offset from the first, the number of elements deleted falls partway between the data from the other two analyses, and the particle is seen to slide along the original crater creating an extended impact crater. These trends are seen in the predictions of mass loss in Figure 25. When the erosion rates are calculated, the total mass of the impacting particles is taken into account. Figure 26 highlights that the erosion rate is constant in the situation where the particle impact at discrete locations, regardless of the number of impacting particles. But once the particle impact sites start overlapping, the erosion rate increases significantly.

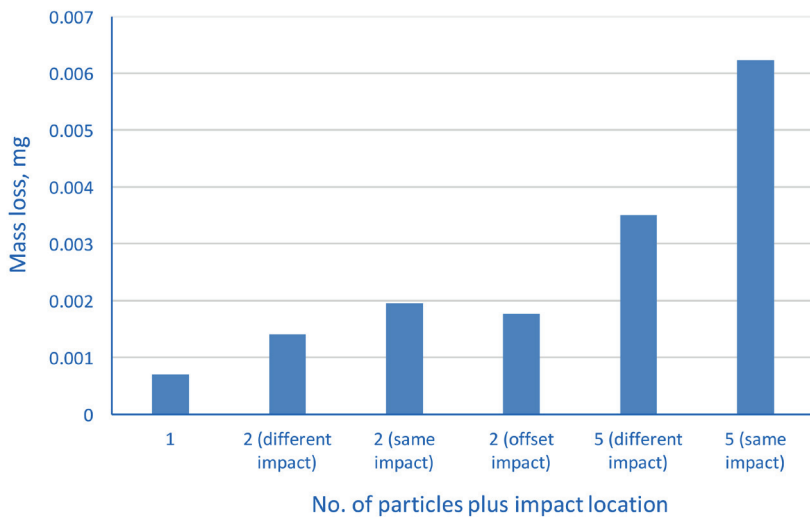


Figure 25: Bar chart showing the predicted mass loss from multiple particle erosion analyses

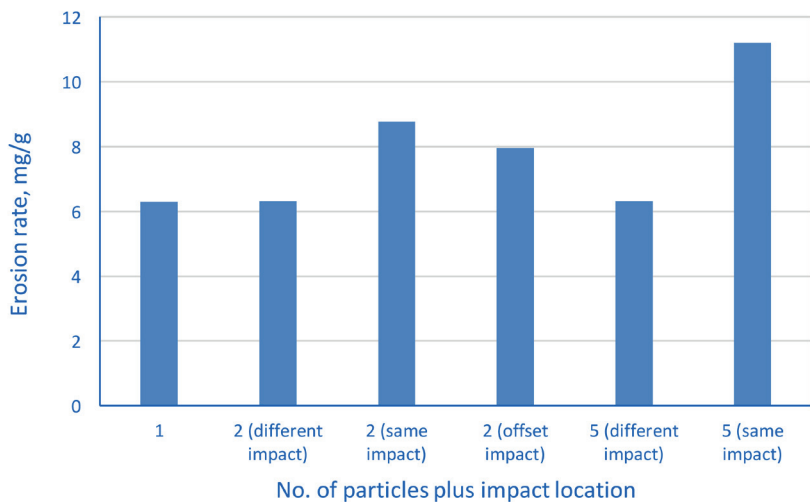


Figure 26: Bar chart showing the erosion rates predicted by multiple particle erosion analyses

Conclusions

Conclusions

Erosion is known to be a complex process that can be detrimental to industrial components with demanding in-service conditions. Experimental research carried out over many years has led to greater understanding of the erosion mechanisms. In recent years this knowledge has been applied to the development of models with the aim of predicting erosive wear.

Due to the complexity of the erosion process, no universally accepted predictive model exists. Empirical 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. For erosion of complex geometry, CFD has proven a useful tool, although this method is still reliant on erosion equations and in some cases, experimentally determined erosion coefficients. As well as dealing with complex geometries this method can also account for the effects of different types of flow.

In terms of a more general approach for modelling solid particle erosion of a substrate, FEA is an appropriate choice. An advantage of FEA modelling is its flexibility. Models can be simple 2D analyses, useful for comparative work, or complex 3D dynamic analyses when greater predictive accuracy is required. The substrate material type can be changed easily, although care needs to be taken over the material model used to represent the substrate. In setting up the model, no experimentally determined erosion rate constants are required, only the material properties needed for the material model are used. FE models have the ability to predict material loss (erosion) and cracking through the use of advanced tools such as element failure and deletion. The method can model multiple impacts, though the number of particles is usually small e.g. 5-10, due to computational constraints. The main issue with FEA modelling is the balance between mesh density and computational cost. A finer mesh yields greater accuracy, but the degree of mesh refinement is limited due to the use of the explicit algorithm and the corresponding increase in computational cost for smaller elements. Due to the high impact nature of the erosion process, FE meshes can be prone to excessive element distortion. There are meshing techniques such as adaptive meshing that can be used to help alleviate this problem. One of the main advantages in using FEA to simulate the erosion process is the ability to obtain difficult to measure data such as residual stress, contact time and penetration depth.

There are many decisions to be made when setting up an FE model, this Good Practice Guide has discussed some of the options available such as the use of different element types, mesh density, modelling contact and the influence of

friction, choice of solver, material models and parameter sensitivity. Information regarding the use of predictions to obtain erosion rates is provided as well as an overview of additional output. Scaling up models from a single particle impact to multiple particle impacts is also described.

Examples have been provided where necessary to illustrate pertinent points. These examples are generally from erosion analyses of a single steel particle impacting a Ti-6Al-4V substrate, using the Abaqus FE package. The substrate is modelled using the Johnson-Cook dynamic failure model. The particle is nominally 300 μm in diameter, travelling at a velocity of 100 m/s, and impacting the sample at 45°, although parametric studies have also been presented where variables such as impact angle, particle velocity and particle size have been varied.

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Good Practice Guide to the Application of Finite Element Analysis to Erosion Modelling

Good Practice Guide No. 146

What is it about?

This Guide describes the application of Finite Element (FE) analysis for predicting the erosion of ductile materials. The basics of setting up an FE analysis for modelling erosion are discussed, covering such topics as element selection, analysis type, contact definitions, selection of material model, model parameter sensitivity, erosion predictions, additional outputs and modelling multiple particle impacts. Examples, mainly from erosion analyses of a Ti-6Al-4V sample impacted by a steel ball, are used to illustrate the pertinent points. The finite element package Abaqus has been used to produce the examples shown in this guide.

Who is it for?

This guide is for users who have previous experience of using finite element packages such as Abaqus, and that are interested in simulating an erosion process. The basic principles of impact and element removal can also be applied to other situations.

What is its purpose?

In industrial environments, wear is a common problem. Within complex systems the in-service conditions are often demanding and various factors can influence the service life of components, potentially causing serious problems and economic loss. This Good Practice Guide has been developed as part of the MetroErosion project. The aim was to develop significantly improved test protocols and implement state of the art *in-situ* metrology for the measurement of high temperature solid particle erosion, through traceable measurement of mass, shape, volume, flow, velocity and temperature. The development of models for the prediction of materials behaviour under high temperature erosion conditions was part of the remit of the project. The purpose of the guide is to give a step-by-step approach to developing an erosion model within a finite element package, such as Abaqus.

What is the knowledge prerequisite?

The guide is at expert level, it requires a working knowledge of finite element analyses. Some background in materials degradation would be useful.

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