Stress-wave monitoring of erosive particle impacts

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Statement of Sources

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution

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Abstract

The impact of a small particle with a wear surface can lead to very high strain-rates in the material being encountered. Often predictive erosion models are based on material property parameters taken from quasistatic test conditions. However, the material properties of the impacted wear surface can change dramatically with strain and strain-rate, leaving some doubt as to the validity of an erosion model based on quasistatic parameter values. In this study, a new stress-wave monitoring process is developed for the study of material characteristics and erosion phenomena, at strain-rates approaching $10^6 s^{-1}$. For this study a newly designed piezo-electric transducer was used to monitor the stress-waves produced by small erosive particle impact events. A computational study was also conducted to aid in the transducer design and location distance from the impact source by considering the effects caused by spatial averaging. Spatial averaging affects the recorded stress-wave signal and is caused by the curvature of the stress-wave as the wave passes through the flat piezo-electric sensing element.

This study was conducted using a computational and experimental approach. The joint study allowed significant knowledge to be gained for the study of elasto-plastic impact and stress-wave motion. Finite element analysis (FEA) was used to model the experimental system in detail. The stress-waves produced by the experimental process were directly compared to the FEA model. Once the FEA model was validated, detailed information from the impact event at the surface could be obtained from the model, which would otherwise be difficult if not impossible to obtain experimentally.

The issues of wave dispersion have been an underlying problem in the correct interpretation of stress-wave phenomena for many years. The impact of the wear surface causes stress-waves with many frequency components, each component propagating through the wear material at distinct wave velocities. Wave dispersion causes the initial stress-wave pulse to be dispersed into many waveforms. In this study the longitudinal stress-wave was the main waveform studied. FEA simulations were conducted for a purely elastic impact and an impact causing significant plastic deformation of the surface. A comparison between these waveforms showed that in the case of impacts causing plastic deformation, the initial part of the stress-wave, measured from the time

of arrival to the first peak, corresponded to the elastic stress component of the impact event at the surface. The characterisation of the waveform in regards to elastic and plastic stress components at the surface was significant for validating model parameters of the Johnson-Cook material model.

The stress-wave monitoring process was applied in the first instance to erosive particle impacts to AISI 1020 steel at impact velocities up to 104m/s. A specially designed erosion apparatus, fitted with a modified double disc system was used to impact the 10mm thick steel plate. The piezo-electric transducer was firmly clamped to the rear surface, directly behind the point of impact to obtain the stress-wave signals produced by impacts of 0.4mm zirconia spheres. The study showed that the contact interface of the wear material and the piezo-electric transducer could cause a phase change and amplitude reduction of the stress-wave transmitted to the transducer at wave frequencies above 0.9MHz. The results showed that the most likely cause for the phase shift to occur was the restriction of tensile stresses across the contact interface. For wave frequencies below 0.9MHz, no phase shift or amplitude reduction was apparent in the experimental stress-wave recordings.

The combined experimental / FEA study was shown to be able to validate the strain-rate parameter of the Johnson-Cook model. The parameters, which could not be validated by the stress-wave monitoring process, were the parameters relating to plastic deformation of the surface, which were the strain-hardening terms of the Johnson-Cook model. These terms were later validated by studying the extent of plastic deformation at the surface, which occurred in the form of impact craters. By comparing the predicted impact crater depths from the FEA model with the experimental results, the strain-hardening parameters of the Johnson-Cook model could be validated.

The robustness of the stress-wave monitoring process was proven for the impact study of ultra high molecular weight polyethylene (UHMWPE) and vinyl ester resin (VER). Unlike AISI 1020 steel, little is know about the high strain-rate response of these polymers. Initial estimates of material property parameters were made by applying computational *curve fitting* techniques to the stress-strain curves of similar polymers, which were from published results obtained from split Hopkinson's pressure bar method. The impact and stress-wave study showed UHMWPE and VER to be highly sensitive to strain-rate effects. The main effect was a substantial increase in hardness with increasing strain-rate and it was considered that the hydrostatic stress component contributed to the strain hardening of the polymers.

The stress-wave monitoring and FEA computational techniques developed in this study were implemented in the development of an improved erosion model. The model form is similar to that of the well-known Ratner-Lancaster model. The Ratner-Lancaster model assumes wear rate to be proportional to the inverse of deformation energy, where deformation energy is approximated as the product of the ultimate stress and ultimate strain. The improved Ratner-Lancaster model uses the Johnson-Cook model to obtain the von-Mises stress as a function of strain. The area integral of the stress-strain curve is used to derive the deformation energy capacity of the material in the deformed zone close to the surface. The model accounts for strain, strain-rate and thermal effects and is therefore more soundly based on material deformation characteristics valid for erosion events than the Ratner-Lancaster model assumptions. The model developed in this work was applied to the erosion study of 1020 steel, UHMWPE and VER, with good correlation being obtained between experimental erosion rates and model predictions.

Nomenclature

Quantity symbol	Term	Unit symbol	First text reference
a	The angle of the particle trajectory relative to the wear surface	Degrees	2.1.1
H	Material hardness	Pa	2.1.1
m	Mass	kg	2.1.1
W	Wear or erosion rate	$mm^3 g^{-1}$	2.1.1
r	Density	$Kg\ m^{-3}$	2.1.1
V	Velocity	$m\ s^{-1}$	2.1.1
E	Energy	N m	2.1.1
s_u	Ultimate stress, defined by the stress at the point of failure	Pa	2.1.2
e_u	Ultimate strain, defined by the strain at the point of failure	Dimensionless	2.1.2
m	Coefficient of friction	Dimensionless	2.1.2
s_{yield}	Yield stress	Pa	2.1.2
e_{yield}	Yield strain	Dimensionless	2.1.2
e_p	Plastic strain	Dimensionless	2.2.1
$\dot{e}$	Plastic strain-rate	s^{-1}	2.2.1
T	Temperature	Degrees C	2.2.1
s_f	Flow stress	Pa	2.2.2
n	Poisson's ratio	Dimensionless	3.1.1
c_{el}	Bulk elastic wave speed	$m\ s^{-1}$	3.1.1
E_T	Plastic or tangent modulus	Pa	3.1.1
V_{out}	Output voltage	Volts	3.2.2
X	Electrical impedance	Ohms	3.2.5
s_y	Stress in the *y* direction	Pa	3.2.8
B_m	Elastic bulk modulus	Pa	5.2.1
G	Shear modulus	Pa	5.2.1
C_p	Specific Heat	J/kg K	5.4.1

Published Works

Journal Papers

Cenna A. A, Allen S. P, Dastoor P, Page N. W, (2002) “Modelling the three-body wear of UHMWPE particle reinforced composites” Wear Vol 254, pages 581-588

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