

Stress-wave monitoring of erosive particle impacts

By

Stephen Phillip Allen, Bachelor of Engineering (Mechanical)

Submitted to

The University of Newcastle

For the degree of

DOCTOR OF PHILOSOPHY

November 2004

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

Stephen Phillip Allen

Acknowledgements

I would like to give special thanks to the Cooperative Research Centre for Advanced Composite Structures (CRC-ACS) who provided funding for this project. The staff at CRC-ACS were friendly and offered many words of encouragement, in particular I would like to thank Stuart Dutton, Murray Scott, Ian Crouch and Rodney Thompson for advice and constructive comments. I was also privileged to work closely with Bruce Cartwright of CRC-ACS and Bruce provided many hours of technical advice and words of encouragement.

I would like to thank the technical staff at the University of Newcastle. The workshop staff led by Phillip Reddy provided materials and expertise. I would like to thank Ian Miller who provided many hours of expertise in the design, construction and implementation of electrical instrumentation.

I would like to thank my supervisor Dr Paul Dastoor of the Physics department for motivation and guidance. I would like to give a special thanks to my supervisor Professor Neil Page who I regard in the highest esteem. I met regularly with Professor Page and he gave me the guidance and encouragement to pursue the task, typical of his own professional manner.

I would like to thank my parents Bob and Jean and my sisters Janette and Vicki for their support and words of encouragement. Lastly, I would like to thank my wife Corinna, who supported me in times of need and who encouraged me all the way to complete the task.

Table of Contents

Statement of Sources	ii
Acknowledgements	iii
Table of Contents	iv
Abstract	viii
Nomenclature	xi
Published Works	xii
CHAPTER 1	1
INTRODUCTION	1
1.1 Introduction to Erosion	1
1.1.1 Erosion mechanisms	2
1.1.2 The physics of the erosion process	6
1.1 Stress-waves and the study of erosion	9
1.3 FEA and the study of erosion	10
1.4 Thesis Objective	15
1.5 Thesis Outline	15
CHAPTER 2	17
LITERATURE REVIEW	17
2.1 Introduction	17
2.2 Erosion models	18
2.1.1 Erosion models for ductile metals	18
2.1.2 Erosion models for polymers	22
2.2 FEA Material Models	26
2.2.1 FEA material model for AISI 1020 steel	27
2.2.2 Review of mild steel at high strain-rates	28
2.2.3 FEA material models for polymers	29
2.2.4 Review of ductile polymer at high strain-rates	32
2.3 Past erosion studies involving stress-wave monitoring processes	34
2.3.1 Literature review of stress-waves produced by small particle impacts	34
2.4 Chapter summary	36

CHAPTER 3	39
EXPERIMENTAL METHODS	39
3.1 Introduction	39
3.2 Considerations for stress-wave monitoring process	40
3.2.1 Stress-waves and wave dispersion	40
3.2.2 Study of stress-time profiles for an elastic and elasto-plastic impact	45
3.3 Piezo-electric transducer design	47
3.3.1 Considerations for the design of a piezo-electric transducer	47
3.3.2 Matlab computer program for the design of piezo-electric transducer	48
3.3.3 Results of Matlab simulations	49
3.3.4 Piezo-electric transducer design	50
3.3.5 Piezo-electric materials	53
3.3.6 Natural frequency response of the piezo-electric transducer	60
3.3.7 Electrical coupling considerations for the piezo-electric transducer	61
3.3.8 Application of piezo-electric materials to stress-wave monitoring	62
3.3.9 Consideration of a three-dimensional stress state at the wear material sensing element interface	64
3.3.10 Recording device considerations	65
3.3.11 Rise-time consideration of piezo-electric transducer response	65
3.4 Apparatus	67
3.4.1 Stress-wave monitoring apparatus	67
3.4.2 Particle velocity calculations	73
3.4.3 Clamping of the wear material to the piezo-electric transducer	73
3.4.4 Stress-wave monitoring chamber and gas-blast apparatus	74
3.4.5 Particle characterisation	76
3.4.6 Erosion testing	79
3.4.7 Mass loss measurements	85
3.5 Chapter summary	87
CHAPTER 4	89
FEA MODELLING OF STRESS-WAVES	89
4.1 Introduction	89
4.2 Impact modelling by the FEA method	91
4.2.1 Implicit and explicit FEA modelling	91
4.2.2 The LS DYNA FEA code	92
4.2.3 Axisymmetric modelling techniques	93
4.2.3 Mesh size considerations	94
4.2.4 Numerical stability of the FEA model	97
4.2.5 Mesh size consideration for elastic stress-wave motion	99
4.2.6 FEA modelling of contact	101
4.2.7 Equation of State	106
4.2.8 Spatial averaging considerations of FEA model	107
4.3 Chapter summary	110

CHAPTER 5	113
STRESS-WAVE MONITORING RESULTS	113
5.1 Introduction	113
5.2 Experimental and FEA study of impacts and stress-wave motion of AISI 1020 steel	114
5.2.1 Implementing the Johnson-Cook FEA material model	114
5.2.2 Experimental and FEA stress-wave monitoring study of AISI 1020 steel under low velocity impact conditions	116
5.2.3 Experimental impacts to AISI 1020 steel at higher impact velocities	122
5.2.4 Comparison of experimental and FEA stress-wave recordings of AISI 1020 steel under higher velocity impact conditions	124
5.2.5 Sensitivity study of FEA model parameters due to strain-rate effects	128
5.2.6 Validation of Johnson-Cook model by impact crater study	131
5.2.7 Sensitivity of strain-hardening terms under high strain impact conditions	134
5.2.8 Strain-rate of impacts extracted from FEA model	135
5.2.9 Stress-strain curves related to stress-wave monitoring	135
5.3 Experimental and FEA study of impacts and stress-wave motion to polymer wear surfaces	137
5.3.1 Introduction	137
5.3.2 Implementation of the FEA material model	138
5.3.3 Specimen manufacture	142
5.3.4 High velocity impact and FEA modelling of polymer materials	142
5.3.5 Impact crater study	145
5.3.6 Stress-strain curve obtained from FEA model	150
5.4 Chapter summary	152
CHAPTER 6	157
EROSION MODELLING	157
6.1 Introduction	157
6.2 Stress-wave monitoring results applied for the study of erosion	158
6.2.1 Energy based approach to erosion	158
6.2.2 Development of FEA solid model for the study of erosive impacts	161
6.2.3 Erosion testing procedure	165
6.2.4 Specimen manufacture and material properties	165
6.2.5 Temperature and strain-rate values obtained from FEA simulations	167
6.2.6 Erosion results compared with erosion model prediction	170
6.3 Chapter Summary	173

CHAPTER 7	175
DISCUSSION AND CONCLUSION	175
7.1 Important findings	175
7.1.1 Introduction	175
7.1.2 Piezo-electric transducer design	175
7.1.3 Stress-wave interpretation	176
7.1.4 Effects of stress-wave recording from piezo-electric transducer coupling	177
7.1.5 Stress-wave monitoring of erosive particle impacts	178
7.1.6 Implementation of stress-wave monitoring process for the study of erosion	179
BIBLIOGRAPHY	181
APPENDIX A	185
MATLAB PROGRAMS	185
A.1 Matlab programs	185
A.1.1 Matlab program for the design of the piezo-electric transducer	185
A.1.2 Matlab program to measure volume loss of wear specimens	188
A.1.3 Matlab program to compare experimental stress-wave recordings with FEA model prediction	190
APPENDIX B	193
LS DYNA FEA PROGRAMS	193
B.1 LS DYNA programs	193
B.1.1 LS DYNA input code for stress-wave monitoring FEA model	193
B.1.2 LS DYNA input code for FEA erosion modelling	195
APPENDIX C	199
MATERIAL PROPERTIES	199
C.1 Material property specifications	199
C.1.1 Material property data sheets for AISI 1020 steel	199
C.1.2 Material property data sheets for AISI 1006 steel	200
C.1.3 Material property data sheets for UHMWPE	201
C.1.4 Material property data sheets for VER	202
C.1.5 Material property data sheets for piezo-electric material	203

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 10^6s^{-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 known 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
α	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	$\text{mm}^3 \text{g}^{-1}$	2.1.1
ρ	Density	Kg m^3	2.1.1
V	Velocity	m s^{-1}	2.1.1
E	Energy	N m	2.1.1
σ_u	Ultimate stress, defined by the stress at the point of failure	Pa	2.1.2
ϵ_u	Ultimate strain, defined by the strain at the point of failure	Dimensionless	2.1.2
μ	Coefficient of friction	Dimensionless	2.1.2
σ_{yield}	Yield stress	Pa	2.1.2
ϵ_{yield}	Yield strain	Dimensionless	2.1.2
ϵ_p	Plastic strain	Dimensionless	2.2.1
$\dot{\epsilon}$	Plastic strain-rate	s^{-1}	2.2.1
T	Temperature	Degrees C	2.2.1
σ_f	Flow stress	Pa	2.2.2
ν	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
σ_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

Cenna A.A, Allen S.P, Page N.W, Dastoor P, (2001) “A polyethylene-reinforced polymer composite abraded by bulk solids.” Wear Vol 249 Pages 663-671
Refereed Conference Papers

Allen S. P, Page N. W, Dastoor P, (2002) “Stress-wave monitoring of individual particle impacts during erosion tests.” Proceedings of the 6th International Tribology Conference. Published by Fineline, Perth WA. Volume 1 Pages 235-239

Allen S.P, Cenna A.A, Page N.W, Dastoor P, (2001) “Abrasive wear of PTFE and PTFE/UHMWPE particle reinforced vinyl ester resin by bulk solid material”. Presented at the 7th International Conference on Bulk Materials Storage and Handling and Transportation. Vol 2 pages 50