Thermomechanical and Transformational Behaviour and Applications of Shape Memory Alloys and their Composites

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For my family, with love

Declaration of Originality

This thesis describes work that was carried out in the School of Aerospace, Mechanical and Mechatronic Engineering at the University of Sydney, the Aeronautical and Maritime Research Laboratory, Melbourne and at the Department of Metallurgy and Materials Engineering at the Katholieke Universiteit Leuven in Belgium. Except where otherwise acknowledged, the work presented for this degree is my own and contains no material which has been presented for a degree at this or any other university and, to the best of my knowledge and belief, contains no copy or paraphrase of work published by another person, except where duly acknowledged in the text.

Significant contributions are as follows:

Due acknowledgment is given to Dr Rudy Stalmans, Dr Jan Schrooten and Dr Yanjun Zheng for the many useful discussions that were had for the work shown in Chapters 2, 3 and 4 and Dr Xiaoming Wang for the work shown in Chapter 5. The data collection for the SMA wire experiments shown in Chapter 3 was carried out by Dr Gidnahalli Dayanunda and some of the data for the SMA-composite experiments was collected by Dr Yanjun Zheng.

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Synopsis

This thesis details an investigation into the properties and applications of shape memory alloy (SMA) composites. SMA-composites are a new material which have the possibility of having a large impact on what the structures as we know today, are constructed with. SMA-composites are adaptive materials which can be used to control the shape and frequencies of vibration of a structure. In order to determine the effectiveness of such a material, research into the functional properties of SMAs and SMA-composites was conducted.

As an initial step, the transformation behaviour of constrained SMAs was investigated in order to obtain a better understanding into the recovery stress generation of these wires when embedded into a composite material. It is known that the transformation is based on two types of martensite within the alloy; self accommodating and preferentially oriented martensite. The amounts of each type and how they vary with differing pre-strain were determined through DSC measurements and an explanation for why preferentially oriented martensite is not observed during DSC testing was made.

The next step was to investigate the effectiveness of embedding SMA wires into composites and the thermomechanical properties of the SMA wires and the SMA-composites were determined. This was completed using a specially designed tensile testing machine which was capable of having the whole specimen immersed into an oil bath and heated and cooled repeatedly. The stress-strain, strain-temperature, stress-temperature, resistance-strain and cyclic properties of various wires were obtained, giving a better understanding of the behaviour of SMA wires under different test con-

ditions. NiTiCu SMA wires were embedded into kevlar composite materials and the recovery stress generation (stress-temperature), stress-strain, and strain-temperature behaviour was determined.

If SMA-composites are to be used as new materials for structural applications, verification that the embedment of pre-strained SMA wires into the material doesn't adversely affect the impact behaviour needs to be carried out. SMA-composite specimens with varying volume fractions of superelastic SMA wires, pre-strain and position through the thickness were made up for impact damage characterisation. These specimens were impacted at three different energy levels. The results showed that by embedding SMA wires into composite materials there is a reasonably low damage accumulation after impact. There is also no adverse impact effect on the structure compared with structures without wires as well as structures with other types of wires such as steel and martensitic SMA wires. The SMA-composites showed good damping and energy absorption capabilities.

A novel application of SMA-composites is their use as a SMA patch in order to repair damage in existing cracked metallic structures. An analytical study and finite element modelling showing the closure stresses obtainable for use as patches was made.

'The most exciting phrase to hear in science, the one that heralds new discoveries, is not "Eureka!" but rather "hmmm....that's funny..." '

Isaac Asimov

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Well......

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Praise the Lord,
Give thanks to the Lord, for he is good;
his love endures forever
Psalm 106:1

List of Publications

Below is a list of publications which have been made related to the work completed in this PhD.

International Refereed Journals
First author:

1. K.A. Tsoi, R. Stalmans and J. Schrooten, "Transformation Behaviour of Constrained Shape Memory Alloys", Acta Materialia, **50**, 14, pp. 3535-3544, September 2002.

2. K.A. Tsoi, R. Stalmans, J. Schrooten and Y.-W. Mai, "Impact Damage Behaviour of Shape Memory Alloy Composites", Materials Science and Engineering: A, 342, 1-2, pp. 207-216.

Co-authored:

1. Y.J. Zheng, J. Schrooten, K. Tsoi and R. Stalmans, "Thermal Response of Glass Fiber/Epoxy Composites with Embedded TiNiCu Alloy Fibers", Materials Science and Engineering: A, **335**, 1-2, pp. 157-163, 25 September 2002.

2. Y.J. Zheng, J. Schrooten, K. Tsoi and P. Sittner, "Qualitative and Quantitative Evaluation of the Interface in Activated SMA-Composites", Experimental Mechanics, submitted 2001.

Conference Proceedings
First author:

1. K.A. Tsoi, R. Stalmans, M. Wevers, J. Schrooten and Y.-W. Mai, "Increased Impact Damage Resistance of Shape Memory Alloy Composites", Proceedings of SPIE, Smart Materials and MEMS, 13-15 December, Melbourne, Australia, Alan R. Wilson; Hiroshi Asanuma (Eds.), 4234, pp. 126-134, 2000.

2. K. A. Tsoi, X. Wang, Y.-W. Mai and S.C. Galea, "Life Enhancement and Repair of Structures using Shape Memory Alloy Composite Patches", ICCM-12 Conference, Paris, July 1999, paper 468, (CD-Rom), ISBN 2-9514526-2-4.

3. K.A. Tsoi, X.M.Wang, Y-W. Mai, and S.C. Galea, "The Use of Shape Memory Alloy Patches as a Repair Technique", Proceedings of the Aust. Fracture Group: Structural Integrity and Fracture Meeting, C.H. Wang (Ed.), pp. 33-41, 1998.

Co-authored

1. J. Schrooten, K.A. Tsoi, R. Stalmans, Y. Zheng and P. Sittner, "Comparison Between Generation of Recovery Stresses in Shape Memory Wires and Composites: Theory and Reality", Proceedings of SPIE, Smart Materials and MEMS, 13-15 December, Melbourne, Australia, Alan R. Wilson; Hiroshi Asanuma (Eds.), 4234, pp. 114-124, 2000.

2. R. Stalmans, K. Tsoi and J. Schrooten, "The Transformational Behaviour of Shape Memory Wires Embedded in a Composite Matrix", Fifth European Conference on Smart Structures and Materials, Glasgow, Scotland, May 22-24, 2000, P.F. Gobin, C.M. Friend (Eds.), Proceedings of SPIE, Vol. 4073, pp. 88-96, 2000.

3. X. Wang, K. Tsoi, L. Ye, Y.-W. Mai, S.C. Galea and L. R. Francis Rose, "SMA Composites for Aero-Structure Repairs", ICCM-12 Conference, Paris, July 1999, paper 620, (CD-Rom), ISBN 2-9514526-2-4.

Symbols and Abbreviations

Listed here are only the symbols used several times or in a global context. The symbols used locally are explained where they are used.

A_d	projected delamination area (mm^2)
A_f	austenitic finish temperature (°C)
A_m	cross sectional area of matrix (mm^2)
A_p	austenitic peak temperature (°C)
A_s	austenitic start temperature (°C)
A_{sma}	cross sectional area of SMA (mm^2)
A_T	total cross sectional area of SMA-composite patch (mm^2)
α_s	coefficient of thermal expansion of the SMA (/°C)
α_m	coefficient of thermal expansion of the matrix (/°C)
d_{min}	minimum measured displacement of impact head during impact (mm)
ΔH_a	austenitic transformation heat (J/g)
ΔH_m	martensitic transformation heat (J/g)
ΔH_r	R-phase transformation heat (J/g)
ΔH_{SAM}	measured transformation heat due to self accommodating martensite (J/g)
DSC	differential scanning calorimetry
E_a	energy absorbed (J or %)
E_m	Young's modulus of elasticity of matrix (GPa)
E_p	Young's modulus of elasticity of SMA-patch (GPa)
E_s	Young's modulus of elasticity of cracked structure (GPa)
E_{sma}	Young's modulus of elasticity of SMA (GPa)
ϵ_m	total strain of matrix
ϵ_{ma}	thermal expansion strain of matrix
ϵ_{max}	maximum shape memory strain
ϵ_{me}	elastic strain of matrix
ϵ_p	equivalent pre-strain of SMA-composite patch
ϵ_{ps}	pre-strain of SMA
ϵ_{sma}	total strain of SMA wires
ϵ_{sa}	thermal expansion strain of SMA
ϵ_{se}	elastic strain of SMA
ϵ_{sr}	recoverable shape memory strain
F_{max}	maximum force measured on impact (N)

FEM	finite element modelling
F_r	recovery force (N)
F_t	transferred force (N)
G_a	adhesive shear modulus (MPa)
h_p	thickness of SMA-composite patch (mm)
h_s	thickness of cracked structure (mm)
l_p	length of SMA-composite patch(mm)
M_f	martensitic finish temperature (°C)
M_p	martensitic peak temperature (°C)
M_s	martensitic start temperature (°C)
n_w	number of embedded wires
POM	preferentially oriented martensite
R_f	R-phase finish temperature (°C)
R_p	R-phase peak temperature (°C)
R_s	R-phase start temperature (°C)
SAM	self accommodating martensite
SIM	stress induced martensite
SMA	shape memory alloy
SME	shape memory effect
σ_c	closure stress (MPa)
σ_p	average normal stress of composite patch (MPa)
σ_r	recovery stress of SMA (MPa)
σ_s	average normal stress of cracked structure (MPa)
σ_{sma}	stress of SMA (MPa)
τ_a	shear stress in adhesive (MPa)
T_g	glass transition temperature (°C)
u_p	in-plane displacement along x-axis direction of the SMA-patch
u_s	in-plane displacement along x-axis direction of the cracked structure
V_f	volume fraction of embedded SMA wires (wires/mm)
w_p	width of SMA-composite patch (mm)
w_s	width of cracked structure (mm)

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