STIFFNESS AND VIBRATIONAL CHARACTERISTICS OF SMA/DER331 COMPOSITES WITH SHAPE MEMORY ALLOY LONG FIBERS

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To my loving wife, Zulaika A. G. Khan,M.Naseem Khan and M. Zarif Khan(sons), Ainaa Syahirah(daughter), my mother and my father, my family and my supporting friends ...

"THANK YOU for your support"

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In the name of Allah, The Most Gracious and The Most Merciful

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ABSTRACT

SMA-composites are an adaptive composite in which SMA elements are incorporated into fiber reinforced epoxy composites. Many researches have been done on investigating the properties of shape memory effect and superelastic influence in SMA composites. However, little information available on the effect of different fiber volume fraction with continuous flexinol long wire to mechanical strength and vibrational characteristics. This study is mainly focused on the integration of shape memory alloy (SMA) elements with epoxy composites based on different fiber volume fraction. The aim is to analyze and investigate static and dynamic mechanical properties of SMA/DER331 by measuring the first vibration mode of clamped cantilever beams, elastic strength and hysteresis behavior of SMA-composites through monotonic tensile, cyclic and vibration analysis. This observation indicates that the Young's modulus increases (1667.083MPa) at 2.4% fiber volume fraction of flexinol wire of SMA/DER331 compared to matrix Young's modulus (904.495MPa). The increase of temperature up to 75°C and 90°C lead to the recovery of stress and strain and therefore closed hysteresis achieved. The temperature dependency of vibration property is affected largely due to the addition of SMA Flexinol long fibers. The vibrational characteristics of SMA composites can be improved by the addition of certain amount of flexinol wire. The addition of 2.4% fiber volume fraction of flexinol long fibers resulted in the highest natural frequency with the value of 171Hz at the temperature of 70° C.

ABSTRAK

Komposit aloi memori bentuk merupakan gabungan dimana elemen-elemen aloi memori bentuk disatukan ke dalam bahan komposit. Terdapat banyak kajian dijalankan berkenaan sifat dan kesan aloi memori bentuk dan sifat *superelasticity*. Bagaimanapun, terdapat sedikit maklumat berhubung kesan kekuatan mekanikal dan getaran. Kajian ini memberi tumpuan kepada pendekatan terhadap integrasi aloi memori bentuk dengan komposit *epoxy* berasaskan kepada perbezaan pecahan isipadu serat. Objektif kajian ini adalah untuk menganalisa dan menyiasat ciri-ciri mekanikal secara statik dan dinamik bagi integrasi (SMA/DER331) dengan mengukur mod getaran asas bagi rasuk, kekuatan elastik dan sifat histerisis bagi komposit aloi memori bentuk menerusi tegangan monotonik, kitaran dan analisis getaran. Hasil kajian menunjukkan bahawa *Young's modulus* meningkat sebanyak 1667.083MPa pada 2.4% isipadu serat komposisi dawai flexinol bagi integrasi (SMA/DER331) berbanding 904.495MPa bagi matrik. Peningkatan suhu sehingga 75°C dan 90°C pula menyebabkan kewujudan pengembalian terikan dan tegasan pada struktur dan histerisis lengkap juga dicapai. Sifat-sifat getaran dipengaruhi secara nyata oleh peningkatan serat panjang aloi memori bentuk dan suhu. Ciri-ciri getaran bagi komposit aloi memori bentuk boleh diperbaiki dengan penambahan jumlah dawai flexinol pada kadar yang tertentu. Penambahan sebanyak 2.4% pecahan isipadu serat bagi dawai flexinol menghasilkan frekuensi semulajadi yang tertinggi sebanyak 171Hz pada suhu 70° C.

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LIST OF SYMBOLS & ABBREVIATIONS

A	Cross-sectional area
A_s	Austenite start temperature
A_s^0	Austenite start temperature (stress –free value)
A_f	Austenite finish temperature
A_f^0	Austenite finish temperature (stress –free value)
A-phase	Austenite phase
Al	Aluminium
a_M, a_A, b_M, b_A	Material constant in terms of transition temperature A_s, A_f, M_s, M_f
Cu	Copper
C_A, C_M	SMA material constant related to stress-induced phase transformation
$D(\xi)$	Young's modulus
D_m	Young's modulus for the SMA 100% martensite
D_a	Young's modulus for the SMA 100% austenite
E	Modulus of elasticity/Young's modulus
E_1	Young's modulus in 1/or x direction
E_f	Young's modulus for an isotropic fiber.
E_m	Young's modulus for an isotropic matrix
E^{Ω}	Fourth order elastic tensor of SMA
E^{M}	Fourth order elastic tensor of matrix
G	Shear modulus of the material
I	Second order identity tensor

I	Area moment of inertia
J_2	Second invariant of the deviatoric tensor
J_3	Third invariant of the deviatoric tensor
M_s	Martensite start temperature
M_s^0	Martensite start temperature(stress –free value)
M_f	Martensite finish temperature
M_f^0	Martensite finish temperature(stress –free value)
M-phase	Martensite phase
NiTi	Nickel-Titanium
T	Temperature
T_0	Reference temperature
T_c	Temperature above which yield strength of A-phase lower than stress required to induce A –M transformation
V	Volume
V_f	Volume of fibers / Total volume of composite material
V_m	Volume of matrix / Total volume of composite material
X	Thermodynamic force
X	Inclusion volume
c	Damping
c_c	Critical damping
d	Deviatoric strain
d'	Transformation strain
f	Natural frequency
h	Material parameter indicate the slope of the linear stress transformation
k	Stiffness
k	Bulk modulus of the material
k^3	Versor in the direction of fiber
k^3	Versor in the direction of fiber
kl	Standard $k_i l$ value based on common beam boundary condition

	(fixed –free)
l	Length
p	Volumetric stress
s	Deviatoric stress
vs	Versus
wt	Weight
x	Displacement
σ	Stress
σ_{eq}	Equivalent stress
σ^{M}	Stress tensor of matrix
σ^{Ω}	Stress tensor of SMA
σ_{t}	Uniaxial critical stress in tension
σ_{c}	Uniaxial critical stress in compression
ε	Strain
ε_{L}	Recovery strain limit/Maximum recoverable strain
ε^{M}	Total strain of matrix
ε^{Ω}	Total strain of SMA
ξ	Martensite fraction
Θ	Thermoelastic tensor
$\Omega(\xi)$	Transformation tensor
η^{M}	Elastic strain of matrix
τ	Inelastic strain of matrix
α^{M}	Expansion coefficient
η^{Ω}	Elastic strain of SMA
π	Inelastic strain of SMA
x_1, x_2, x_3	Coordinate system
α^{Ω}	Expansion coefficient of SMA
δ	Possible pre-strain
ε_{L}	Material parameter of the maximum transformation strain
∂	Volumetric strain
$(\bullet)$	Scalar product

α	Back stress
β	Material parameter linked to the dependence of the critical stress on the temperature
$\dot{\zeta}$	Plastic multiplier
ω_n	Natural frequency for free oscillation
ζ	Damping ratio/ damping factor
ρ	Density
$>$	Greater than
$<$	Lower than

$°C$	Degree Celsius
$°C$ / min	Degree Celsius per minute
GPa	Giga Pascal
Hz	Hertz
K	Kelvin
kg / m^3	Kilogram per cubic meter
mg	Milligram
mm	Millimeter
MPa	Mega Pascal
$mPa.s$	Milli pascal second
N	Newton
%	Percentage

ASTM	American Society for Testing and Materials
CNC	Computer numerical control
DER	Liquid epoxy resin by DOW
D-MX-90	Pseudoelasticity test for MX at temperature of 90°C
D-RC1-90	Pseudoelasticity test for RC1 at temperature of 90°C
D-RC2-90	Pseudoelasticity test for RC2 at temperature of 90°C
D-RC3-90	Pseudoelasticity test for RC3 at temperature of 90°C

DSC	Differential Scanning Calorimetry
M	Matrix material
MX	Matrix
RC1	Reinforced composites with fiber volume fraction of 0.8% (3 wires)
RC2	Reinforced composites with fiber volume fraction of 1.6% (6 wires)
RC3	Reinforced composites with fiber volume fraction of 2.4% (9 wires)
MX-30C,45C, 60C, etc	Matrix specimen tested at temperature of 30°C,45°C, 60°C, etc.
RC1-30C,45C, 60C, etc	RC1 specimen tested at temperature of 30°C,45°C, 60°C, etc.
RC2-30C,45C, 60C, etc	RC2 specimen tested at temperature of 30°C,45°C, 60°C, etc.
RC3-30C,45C, 60C, etc	RC3 specimen tested at temperature of 30°C,45°C, 60°C, etc.
ROM	Rules of mixtures
RVE	Representative volume element
SMA	Shape memory alloy
SME	Shape memory effect

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CHAPTER I

INTRODUCTION

1.1 Introduction to Shape Memory Alloy (SMA)

Shape memory alloys are unique alloys that have the ability to undergo large deformations, but can return to their undeformed shape by heating known as the shape memory effect or through removal of the stress known as the superelastic effect. Although first discovered in the 1960s, shape memory alloys (SMAs) have found functional applications only in the past 15–20 years. The high cost, lack of clear understanding of the thermo-mechanical processing, and the inability to reliably predict the behavior of shape memory alloys were the reasons for the slow introduction of the material into application. Higher quality and reliability, coupled with a significant reduction in price has recently led to numerous applications of shape memory alloys in the biomedical, commercial, and aerospace industries (Reginald *et al.*, 2004).

Driven by a search for devices that could result in less invasive medical procedures, researchers have found numerous applications for shape memory alloys in the medical field. Arterial stents, medical guidewires, catheters, orthodontic braces, and orthopaedic prostheses have all taken advantage of the unique properties of

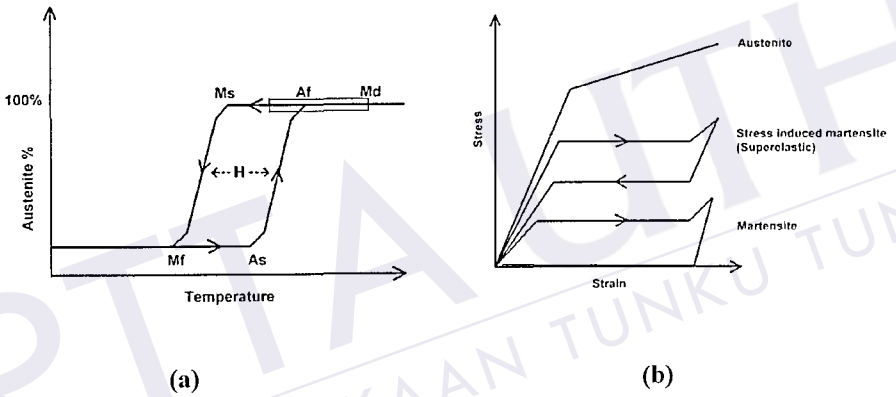
superelastic shape memory alloys (Duerig *et al.,* 1990). In the aerospace industry, shape memory alloys have been used in adaptive aircraft wings and smart helicopter blades for increased efficiency and reduced noise and vibration (Beauchamp, 1992; Chandra, 2001). Recent years have seen numerous commercial and consumer applications of shape memory alloys. Eye glass frames, cellular telephone antennas, frames for brassiers, and golf clubs all take advantage of the superelastic properties of SMAs (Asai and Suzuk, 2000; Hsu *et al.,* 2000)

New opportunities for expanding the use of SMAs in the design of smart structure is being realized by embedding NiTi wires into polymers, elastomers, and fiber-reinforced/epoxy composites (Hugh and Charles, 1999). The embedded wires can be used to activate flexible materials, like polymers and elastomers, or improve the toughness and buckling resistance of brittle materials, like fiber-reinforced/epoxy composites . In developing these materials, research efforts are focussing on overcoming technical barriers such as: increasing actuator stroke, building reliable smart material data bases, developing robust distributed parameter control strategies, and mathematically modeling smart systems.

1.1.1 General Principles of SMA

When martensite NiTi is heated, it begins to change into austenite (Figure 1.1a). The temperature at which this phenomenon starts is called austenite start temperature (A_s). The temperature at which this phenomenon is complete is called austenite finish temperature (A_f). When austenite NiTi is cooled, it begins to change onto martensite. The temperature at which this phenomenon starts is called martensite start temperature (M_s). The temperature at which martensite is again completely reverted is called martensite finish temperature (M_f), (Istvan, 2001).

Composition and metallurgical treatments have dramatic impacts on the above transition temperatures. From the point of view of practical applications, NiTi can have three different forms: martensite, stress-induced martensite (superelastic), and austenite. When the material is in its martensite form, it is soft and ductile and can be easily deformed (somewhat like soft pewter). Superelastic NiTi is highly elastic (rubber-like), while austenitic NiTi is quite strong and hard (similar to titanium) (Figure 1.1b). The NiTi material has all these properties, their specific expression depending on the temperature in which it is used.



(a) (b)

Figure 1.1. (a) Martensitic transformation and hysteresis,H upon a change of temperature.(b) Stress-strain behavior of different phases of NiTi at constant temperature.(Istvan, 2001).

1.1.2 Hysteresis

The temperature range for the martensite to austenite transformation, i.e. soft to hard transition, that takes place upon heating is somewhat higher than that for the reverse transformation upon cooling (Figure 1.1a). The difference between the transition temperatures upon heating and cooling is called *hysteresis*. Hysteresis is

generally defined as the difference between the temperatures at which the material is 50 % transformed to austenite upon heating and 50 % transformed to martensite upon cooling. This difference can be up to 20-30 °C In practice, this means that an alloy designed to be completely transformed by body temperature upon heating ($A_f < 37$ °C) would require cooling to about +5 °C to fully retransform into martensite (M_f).

1.1.3 Thermoelastic Martensitic Transformation

The unique behavior of NiTi is based on the temperature dependent austenite to martensite phase transformation on an atomic scale, which is also called *thermoelastic martensitic transformation*. The thermoelastic martensitic transformation causing the shape recovery is a result of the need of the crystal lattice structure to accommodate to the minimum energy state for a given temperature. In NiTi, the relative symmetries between the two phases lead to a highly ordered transformation, where the displacements of individual atoms can be accurately predicted and eventually lead to a shape change on a macroscopic scale. The crystal structure of martensite is relatively less symmetric compared to that of the parent phase.

If a single crystal of the parent phase is cooled below M_f, then martensite variants with a total of 24 crystallographically equivalent habit planes are generally created. There is, however, only one possible parent phase (austenite) orientation, and all martensitic configurations revert to that single defined structure and shape upon heating above A_f. The mechanism by which single martensite variants deform is called *twinning,* and it can be described as a mirror symmetry displacement of atoms across a particular atom plane, the twinning plane (Buehler *et al.,* 1967). While most metals deform by slip or dislocation, NiTi responds to stress by simply

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