Mechanical Recycling of Automotive Composites for Use as Reinforcement in Thermoset Composites

Submitted by James Alexander Thomas Palmer,

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

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Abstract

The aim of this research was to investigate the potential use of recycled glass fibre composite materials as a replacement for virgin reinforcing materials in new thermoset composites. Specifically the closed-loop mechanical recycling of composites used heavily in the automotive sector known as dough and sheet moulding composites, DMC and SMC respectively, are investigated. The recycling of glass reinforced thermoset polymer composite materials has been an area of investigation for many years and composites used in the automotive industry are of particular interest due to legislative and social pressures on the industry.

The mechanical recycling process and then collection of useful fibrous grades of recycled materials, recyclate, by a novel air separation technique were investigated first. The properties of these recyclate fibres were characterised and compared directly with the properties of virgin glass fibres they were to be used to replace. Single fibre tensile tests were employed to compare the strengths of the fibres and single fibre pull-out tests were used to investigate the strength of the interface between the fibres and a polyester matrix. These tests showed the recyclate fibres to be weaker and have a poorer interface with the polyester matrix than the virgin glass fibres. Understanding the properties of the recyclate materials meant their reformulation into new composites could be carefully considered for the production of new high performance materials.

Two grades of the collected recyclate materials were then reformulated in to new DMC and SMC composites, replacing percentages of the virgin glass fibre reinforcement. The mechanical properties of the resulting manufactured composites were characterised throughout for direct comparison against one another and an unmodified control material, using both three-point flexural tests and Charpy impact tests. Through the modification of existing manufacturing techniques and the development of novel production equipment it has been possible to successfully manufacture both DMC and SMC composites with the recyclate materials used to replace virgin glass fibres. Virgin glass fibres have successfully been replaced by recyclate materials without disrupting standard production techniques and with minimal reduction of the mechanical properties of the resulting composites. As the loadings of recyclate materials used were greatly increased both the flexural and impact strengths were significantly degraded and it was found that chemical modification of the composite could be used to improve these formulations. It has been shown that the recyclate materials should be considered and treated as a distinct reinforcing ingredient, separately from the remaining virgin glass fibres.

Publications

Some of the content of this thesis has been published during the course of the research:

J. Palmer, O.R. Ghita, L. Savage, K.E. Evans. *Successful closed-loop recycling of thermoset composites*. Composites Part A: Applied science and manufacturing, 2009. 40(4) p. 490-498.

J. Palmer, O.R. Ghita, L. Savage, K.E. Evans. *Recyclate fibres – matrix interface analysis for reuse in sheet moulding compounds (SMC).* Proceedings of European Conference on Composite Materials (ECCM 13). 2008. Stockholm, Sweden.

J. Palmer, O.R. Ghita, L. Savage, K.E. Evans. *New automotive composites based on glass and carbon fibre recyclate.* Proceeding of International Conference for Composite Materials (ICCM 17). 2009. Edinburgh, UK.

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Nomenclature

Symbol	Dimension	Description
V	(mm s^{-1})	Cross head speed
ε'	(s^{-1})	Rate of applied strain
l_s	(m)	Sample span
h	(m)	Specimen thickness
σ_F	(Pa)	Flexural stress
$F_{\max}$	(N)	Maximum force
b	(m)	Specimen width
s	(m)	Deflection
E_F	(N m^{-2})	Flexural modulus
a_{cU}	(kJ m^{-2})	Charpy impact strength
W_b	J	Energy at break
W_f	J	Frictional energy losses
F_D	(N)	Drag force
F_L	(N)	Lift force
F_B	(N)	Buoyancy force
C_D	-	Drag coefficient
u	(m s^{-1})	Velocity of particle relative to fluid
A_p	(m^2)	Cross-sectional area of particle normal to the direction of the drag force
ρ	(Kg m^{-3})	Fluid density
L_c	(N)	Load applied to composite
L_m	(N)	Load applied to matrix
L_f	(N)	Load applied to fibre
A_f	(m^2)	Fibre surface area
σ_c	(Pa)	Stress on composite
σ_f	(Pa)	Stress on fibre
σ_m	(Pa)	Stress on matrix

σ^*	(Pa)	Failure Stress
V_f	-	Fibre volume fraction
E_c	(N m^{-2})	Composite Young's Modulus
E_f	(N m^{-2})	Fibre Young's modulus
E_m	(N m^{-2})	Matrix Young's modulus
ε_f^*	-	Fibre failure strain
σ_f^*	(Pa)	Fibre failure strength
ε	-	Strain
l	(m)	Fibre length
x	(m)	Distance from fibre end
r	(m)	Fibre radius
τ_{IF}	(Pa)	Interfacial shear stress
R	(m)	Radius of matrix
l_c	(m)	Critical fibre length
$P_f(\sigma_f)$	-	Probability of fibre failure
m	-	Weibull modulus or shape parameter
σ	(Pa)	Stress
σ_0	(Pa)	Weibull scale parameter
l_0	(m)	Largest fibre length that contains only one flaw
n	-	Number of data points
i	-	Rank of a data point
P_i	-	Probability of failure of *i*'th data point
$\langle\sigma\rangle$	(Pa)	Average fracture stress
Γ	-	The gamma function
τ_d	(Pa)	Critical value of interfacial shear stress above which debonding occurs
L_d	(N)	Load at debonding
l_e	(m)	Embedded fibre length
μ_m	(Pa)	Matrix shear modulus

G_i	(J m^{-2})	Interfacial fracture toughness
ν_m	-	Matrix Poission's ratio
ν_f	-	Fibre Poission's ratio
z	(m)	Debonded fibre length
q_o	(Pa)	Residual clamping stress
μ	-	Friction at interface
σ_d	(Pa)	Maximum debond stress
σ_i	(Pa)	Initiation of debonding stress
σ_{fr}	(Pa)	Frictional pull-out stress
l_{free}	(m)	Free fibre length
X	(m)	Extension
C	(m N^{-1})	True fibre compliance
C_a	(m N^{-1})	Recorded fibre compliance
C_s	(m N^{-1})	System compliance
d_f	(m)	Diameter of fibre