UNIVERSITI PUTRA MALAYSIA

CONCURRENT CONCEPTUAL DESIGN OF HYBRID NATURAL/GLASS FIBER REINFORCED THERMOPLASTIC COMPOSITES FOR AUTOMOTIVE PARKING BRAKE LEVER

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By

MUHD RIDZUAN BIN MANSOR

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November 2014

Chair: Professor Mohd Sapuan Salit, PhD, P.Eng

Faculty: Engineering

This thesis presents the potential of hybrid polymer composites application made from short natural fiber/glass fiber reinforced thermoplastic composites for the development of automotive parking brake lever component. Concurrent engineering approach was implemented in the overall product development process which covers materials selection, concept design development, theoretical performance analysis and environmental impact assessment to achieve the required component structural strength for safe and operational performances. Analytic Hierarchy Process (AHP) method was first applied in the material selection process where kenaf natural fiber was confirmed as the most suitable candidate material for the hybrid polymer composites formulation. The materials selection process was continued using integrated Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods whereby polypropylene was found as the most suitable type of thermoplastic matrix to be used for the hybrid polymer composites formulation. For the concept design development process, a new integrated TRIZ-Morphological Chart-AHP method was used during the conceptual design stage of the hybrid polymer composites automotive parking brake lever component and concept design 2 was selected as the final design concept based on the product design specifications. Rule of Mixtures (ROM) and Rule of Hybrid Mixtures (ROHM) micromechanical models were later employed to predict the Young's modulus of the short kenaf/glass fiber reinforced polypropylene composites where results show that positive hybridization effect was able to be achieved at minimum relative glass fiber content of approximately 87.5 volume percentage compared to kenaf/polypropylene single system for all

varying total fiber contents cases. Finally, the use of hybrid kenaf/glass fiber reinforced polypropylene composites also revealed better environmental performance through life cycle assessment analysis carried out using Eco-indicator 99 method at the end of the product development process. Results showed that approximately 20 percentage reduction of overall environmental impact is achieved by using hybrid kenaf/glass fiber reinforced polypropylene composites compared to glass fiber/polypropylene composites which further strengthened its potential for automotive parking brake lever application.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

REKABENTUK KONSEP SERENTAK KOMPOSIT HIBRID GENTIAN SEMULA JADI/KACA DIPERKUAT TERMOPLASTIK UNTUK TUIL BREK LETAK KENDERAAN AUTOMOTIF

Oleh

MUHD RIDZUAN BIN MANSOR

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Tesis ini membentangkan potensi aplikasi komposit polimer hibrid yang diperbuat daripada komposit gentian pendek semula jadi/kaca diperkuat termoplastik untuk membangunkan komponen tuil brek letak kenderaan automotif. Pendekatan kejuruteraan serentak telah digunapakai dalam keseluruhan proses pembangunan produk bagi meliputi pemilihan bahan, pembangunan rekabentuk konsep, analisis prestasi secara teori dan penilaian impak alam sekitar dalam memperoleh kekuatan struktur komponen yang diperlukan ke arah mencapai prestasi keselamatan dan pengoperasian. Kaedah Proses Hirarki Beranalitis (AHP) telah diaplikasikan pada peringkat permulaan dalam proses pemilihan bahan di mana gentian semula jadi kenaf disahkan sebagai calon bahan yang paling sesuai untuk formulasi komposit polimer hibrid tersebut. Proses pemilihan bahan seterusnya disambung menggunakan kaedah integrasi Proses Hirarki Beranalitis (AHP) dan Teknik untuk Susunan Berkeutamaan menurut Persamaan kepada Penyelesaian Ideal (TOPSIS) di mana polipropilena telah didapati merupakan jenis matrik termoplastik yang paling sesuai digunakan untuk formulasi komposit polimer hibrid tersebut. Untuk proses pembangunan rekabentuk, suatu kaedah baru bersepadu TRIZ-Carta Morfologi-AHP telah digunakan semasa peringkat rekabentuk konsep bagi komponen tuil brek letak kenderaan automotif komposit polimer hibrid dan rekabentuk konsep 2 telah dipilih sebagai rekabentuk konsep akhir berdasarkan spesifikasi rekabentuk produk. Model mikromekanikal Hukum Campuran (ROM) dan Hukum Campuran Hibrid (ROHM) seterusnya telah digunakan bagi meramalkan modulus Young komposit gentian pendek kenaf/kaca diperkuat polipropilena yang mana

keputusan menunjukkan kesan penghibridan yang positif mampu diperoleh pada kandungan relatif gentian kaca minima sebanyak kira-kira 87.5 peratus isipadu berbanding sistem tunggal kenaf/polipropilena untuk semua kes kandungan keseluruhan gentian yang berbeza. Akhir sekali, penggunaan komposit gentian kenaf/kaca diperkuat polipropilena juga menunjukkan prestasi alam sekitar yang lebih baik melalui analisis penilaian alam sekitar yang dijalankan menggunakan kaedah Petunjuk-Eko 99 di akhir proses pembangunan produk. Keputusan menunjukkan kira-kira 20 peratus penurunan keseluruhan impak alam sekitar diperoleh dengan menggunakan komposit hibrid gentian kenaf/kaca diperkuat polipropilena berbanding komposit gentian kaca/polipropilena yang mana mengukuhkan lagi potensinya bagi aplikasi tuil brek letak kenderaan automotif.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

3D	Three Dimensional
ABS	Acrylonitrile Butadiene Styrene
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
ARIZ	Algorithms Of Inventive Problem Solving
EPB	Electric Parking Brake
CAD	Computer-Aided Design
CDCSMS	Concurrent Design Concept Selection And Materials Selection
CE	Concurrent Engineering
CI	Consistency Index
CLT	Classical Laminate Theory
CMVSS	Canadian Motor Vehicle Safety Regulations
CO_2	Carbon Dioxide
CR	Consistency Ratio
CS	Customer Satisfaction
CTQ	Cost, Time And Quality
DFA	Design For Assembly
EFB	Empty Fruit Bunch
ELECTRE	Elimination And Et Choice Translating Reality
EU	European Union
FMEA	Failure Mode And Effect Analysis
FMVSS	Federal Motor Vehicle Safety Standards
HDPE	High Density Polyethylene
IPCC	Intergovernmental Panel On Climate Change
IROM	Inverse Rule Of Mixtures
ISO	International Standard Organization
LCA	Life Cycle Assessment
LDPE	Low Density Polyethylene
LKTN	Lembaga Kenaf Dan Tembakau Negara
MADM	Multiple Attribute Decision Making
MCDM	Multi-Criteria Decision Making
MMC	Metal Matrix Composites
MODM	Multiple Objective Decision Making
MoM	Meaning Of Material
NFC	Natural Fiber Composites
NFRP	Natural Fiber Reinforced Polymer
NHTSA	National Highway Traffic Safety Administration
NVH	Noise, Vibration And Harshness
PA 6	Polyamide 6
PDS	Product Design Specifications
PGP	Pre-Emptive Goal Programming
PLLA	Poly-L-Lactide
PP	Polypropylene
PS	Polystyrene

PSI	Preference Selection Index
QFD	Quality Function Deployment
RI	Random Consistency Index
RMS	Reconfigurable Manufacturing System
ROHM	Rule Of Hybrid Mixtures
ROM	Rule Of Mixtures
SME	Small And Medium Enterprise
TOPSIS	Technique For Order Preference By Similarity To Ideal Solution
TPNR	Thermoplastic-Natural Rubber
TRIZ	Theory Of Inventive Problem Solving
UCPTE	European Union For The Co-Ordination Of Production And Transmission Of Electricity
UNECE	United Nations Economic Commissions For Europe
VIKOR	Vise Kriterijumska Optimizacija Kompromisno Resenje
WBCSD	World Business Council For Sustainable Development
WPIM	Weighted Property Index Method

CHAPTER 1

INTRODUCTION

1.1 Background

Traditionally, the design of automotive related products or components is focused on achieving operational performance and meeting safety regulations. For automotive brake component design, various performance and safety regulations must be complied such as the US Federal Motor Vehicle Safety Standards (FMVSS) 571.135 and United Nations Economic Commissions for Europe (UNECE) R13-H (DOT, n.d.; UNECE, n.d.). However, due to the current increasing awareness on environmental impact and subsequently the need towards sustainability, new automotive product designs must also adhere to environmental related requirements imposed by government bodies such as vehicle end-of-life regulation and hazardous substance as well as CO_2 emission performance standard for new passenger vehicles which includes vehicle weight reduction criteria (2000/53/EC, 2000; 2009/443/EC, 2009). Thus, the change has driven new trend in automotive product design and its whole product development process in order to meet the performance, safety and sustainability requirements (Fontaras & Samaras, 2010).

In conjunction to that, many efforts have been made to comply with the legislations by automakers to sustain their product competitiveness in the targeted market. Among the most promising solution towards achieving in both weight reduction and recyclability targets is by using natural fiber composites (NFC) as the substitute material for making car components such as door panel, door trims, dashboards, rear trays etc. (dos Santos et al., 2008; Holbery & Houston, 2006). However, the use of similar material in higher load bearing automotive applications is still limited due to their lower mechanical properties compared to synthetic polymer composites as well as metal alloys. Nevertheless, NFC offers lower density, higher specific strength and Young's modulus as well as good impact properties compared to synthetic polymers (El-Shekeil et al., 2012; Monteiro et al., 2009) and most notably, they are renewable, recyclable and biodegradable source of materials which makes them able to be produced at lower cost (Koronis et al., 2013; Qatu, 2011).

Looking at national perspective, there are many economically available natural fiber resources in Malaysia that can be processed into NFC. The most promising is kenaf fiber which is currently gaining higher focus to become among the top national commodity crop under the supervision of

the Malaysian Lembaga Kenaf dan Tembakau Negara (LKTN) (Anonymous, 2014c). According to the Malaysia LKTN statistics, kenaf plants are currently being planted across Perak, Kelantan, Terengganu, Pahang and Selangor which covers total cultivation area of approximately 2,000 hectares in 2013 and is expected to grow to 10,000 hectares by 2020, showing the vast availability of the resource to be exploited to support mass production activities. Apart from that, kenaf fibers are also currently priced between 1,700 to 2,200/tonne in 2014 compared to jute fiber (price between Ringgit Malaysia 1,590-1,321/tonne) and meshta fiber (price between Ringgit Malaysia 2,205-2,102/tonne), indicating its price competitiveness with other major fibers resources in Asia. The statistics highlight the potential of gaining economical advantage of utilizing kenaf fibers for composites product development especially for the country.

In addition to economic advantage, kenaf fibers also have comparable mechanical properties with many commercially available natural fibers in the market such as jute, flax and hemp which makes them suitable for structural applications. Akil et al. (2011) pointed that kenaf fibers have high tensile strength ranging between 295 to 930 MPa which is comparable to jute (400-800 MPa), flax (800-1500 MPa) and hemp (550-900 MPa). In addition, kenaf fibers also have high Young modulus property approximately 53 GPa which is comparable to jute (10-30 GPa), flax (60-80 GPa) and hemp (70 GPa). They also reported that kenaf fibers inherent superior toughness and high aspect ratio compared to other natural fibers which makes it very suitable to be used as reinforcing fiber especially in thermoplastic composites. Another distinctive advantage of kenaf fibers compared to other natural fibers is in term of lightweight property, whereby kenaf fiber density is reported to be ranging from 1.2 to 1.4 g/cm^3 which is comparable to jute (1.46 g/cm^3), hemp (1.48 g/cm^3) and flax (1.4 g/cm^3) (Akil et al., 2011). In addition, kenaf fibers has high cellulose content (72 wt%) which contribute to higher tensile properties due to its crystalline structure comparable with other establish natural fiber used in production cars such as hemp (68 wt%), sisal (65 wt%), jute (61-71 wt%) and flax (71 wt%) (Faruk, Bledzki, Fink, & Sain, 2012).

On the other hand, the application of kenaf fibers for product development may also provide additional benefits apart from renewability and biodegradability for the environment. One notable benefit is by helping to reduce the carbon dioxide level in the atmosphere through kenaf plant cultivation. The photosynthesis process during kenaf cultivation was reported able to produce higher rate of carbon dioxide to oxygen conversion (23.4 mg CO_2/dm^2/h) compared to conventional trees (8.7 mg CO^2/dm^2/h) under 1000 µmol/cm^2/s (Lee et al., 2014).

Kenaf based polymer composites can be produced either using thermosetting matrix such as epoxy and polyester or using thermoplastic matrix such as polypropylene (PP) and high density polyethylene (HDPE).

However, the use of thermoplastic matrix is of more interest due to its eco-friendly property which are able to be completely recycled as well as low cost and low processing temperature. The low processing temperature is also an advantage considering that natural fiber's mechanical and physical properties will deteriorate when exposed to high temperature of more than 300^{o}C (Mohanty et al., 2004). Kenaf based thermoplastic composites are also able to be manufactured economically in variety of processes such as resin transfer molding, compression molding, injection molding as well as hand lay-up technique. Apart from that, the mechanical properties of the kenaf based thermoplastic composites can also be economically improved using chemical modifications such as fiber treatment and coupling agents (Li et al., 2007). Due to advantages, kenaf composites have been applied for automotive application primarily for trim components such as seatbacks, package trays, door panels and headliners. It is reported that kenaf composites have been applied for developing automotive interiors since the mid-1990s by Toyota Boshoku Corporation. The Japanese carmaker first started using kenaf composites to produce vehicle door trim component, and currently applying similar material to produce other components in its high-end vehicle models (Dungani et al., 2014; Loh et al., 2015). Other application on related NFRP composites by car makers for vehicle weight reduction while complying with the environmental criteria are in the case of Mercedes Benz A-class and Ford Model U hybrid-electric car (Marsh, 2003).

Despite the advantages that NFC able to offer, their hydrophilic and lower mechanical strength nature has limited their application especially to aesthetically related automotive components such as dashboard, floor pan and interior accessories (Akil et al., 2011; Faruk et al., 2012; Friedrich & Almajid, 2013). To address the issue, researchers has also developed hybrid polymer composites where the natural based fiber is combined with synthetic based fiber such as glass fiber using the same matrix (Davoodi et al., 2010; Kumar et al., 2010; Rao et al., 2011).

In general, hybrid composites are made from the combination of pure synthetic fibers (glass/carbon), combination of synthetic fiber with natural fiber (glass/kenaf) or combination of pure natural fibers (oil palm empty fruit bunch/jute) either in unidirectional, woven and randomly fiber orientation (Davoodi et al., 2012; Dong & Davies, 2012; Jawaid et al., 2012). In the hybridization method, usually two different types of fiber are combined together to form either interply or laminate hybrid, intraply or tow-by-tow hybrid, intimacy mixed hybrid and of type of mixtures (Zhang et al., 2012). The properties of a hybrid composite depend on the fiber content, fiber length, orientation of fibers, extent of intermingling of fibers, fiber to matrix interface, layering pattern of both fibers and also dependent on the failure strain of individual fibers (Jawaid et al., 2010). The hybrid technique main advantage is giving balance to the performance between the combined fibers such as improving the tensile and flexural properties and improving the chemical resistance of the initial single fiber composites system (Aji et al., 2011). In another report, Burgueno et al. suggested that

through hybridization, the natural fiber based reinforced polymer composites mechanical properties such as strength and Young's modulus are enhanced due to the direct contribution of the stiffer and stronger synthetic fiber, as well as gaining higher dimensional stability with respect to moisture absorption due to the barrier provided by the more impermeable synthetic fibers (Burgueño et al., 2005). Apart from that, a balance of cost are also achieved by utilizing a combination of cheaper type of fiber to reduce the amount of more expensive type of fiber (such as combining low cost natural fiber with higher cost synthetic fiber) in making up the hybrid laminates in order to gain comparable mechanical strength and chemical property as the laminates made from the expensive fibers alone (Jarukumjorn & Suppakarn, 2009).

In this research, the potential of introducing hybrid natural fiber reinforced thermoplastic composites; more specifically using hybrid kenaf/glass fiber reinforced polypropylene composites is explored towards the development of automotive parking brake lever component. The main research is concentrated within the concurrent conceptual design and materials selection framework in the product development process which covers aspects in conceptual design development and selection, modeling of natural fiber composites, product environmental performance assessment and hybrid natural fiber composites materials selection. Among the concurrent engineering design tools applied in this research are Theory of Inventive Problem Solving (TRIZ), Morphological Chart, Analytic Hierarchy Process (AHP) and Life Cycle Assessment (LCA) method. In the end of this research, a new conceptual design of automotive parking brake lever utilizing hybrid kenaf/glass fiber reinforced polypropylene composites is developed which successfully concur with the product design specifications.

1.2 Problem Statements

Conceptual design is regarded as the most important aspects in concurrent engineering (CE) approach as significant total product development cost and product quality is decided during the design stage (Chiu & Okudan, 2014; Ghazilla et al., 2013). The cost is often associated with the higher amount of resources and time in developing the final concept design of the product and identifying the materials to best suit the intended application based on the product design specifications. Apart from that, extra efforts are also embedded within the conceptual design scope in providing useful early insights to product designers on the final product performance such as structural and environmental aspects in order to minimize the risks and possible errors during later product development process. Henceforth, faster and cheaper new product may be developed with higher quality to achieve the cost, time and quality (CTQ) improvement and consequently increasing the probability of achieving successful product launch to the market (Sapuan et al., 2006).

In spite of the successful adoption of CE approach in product development as conventional materials such as metal, its implementation in composites design is still limited (Liu et al., 2004; Yang & Nezu, 1998). Moreover, implementation of CE in composites design related to the application of semi-structural and structural components using NFC are far scarcer compared to using synthetic composites and metal-based materials due to lower structural properties and reduce dimensional stability when exposed to high moisture especially for automotive applications (Duflou et al., 2009; Imihezri et al., 2005; Sapuan, 2005b). Hybridization method has been regarded as the potential solution in boosting NFC application in automotive structural design. One example is for automotive bumper beam component using hybrid kenaf/glass fiber reinforced epoxy composites (Davoodi et al., 2011). However, for other automotive structural components especially for automotive parking brake lever application, the implementation of similar hybrid composites is still limited despite the balance in performance, cost and sustainability advantages they offer compared to synthetic composites thus making it a winning candidate to reduce the use of synthetic composites for semi-structural and structural automotive applications if the design barrier can be demolished.

One of the possible solutions to break the design barrier using hybrid NFC towards automotive parking brake lever application automotive applications is by applying innovative concurrent engineering tools for the development of natural fiber composites product. Among them is through implementing innovative idea generation-concept development-concept selection method during the product conceptual design stage to obtain NFC-friendly component geometry which satisfy the product design specifications. Apart from that, multi-criteria decision making (MCDM) method may also be applied for the materials selection of NFC during the conceptual design stage of the product. The MCDM method capability of incorporating multiple and often conflicting design requirements with varying material properties in the analysis all at the same time will enable systematic and justified decision making process to be performed. Thus, optimum decision on the best natural fiber candidate materials to satisfy the designated product function may be obtained within shorter time.

Other related tools that may be implemented during the component conceptual design process to aid the design process are modeling of the final hybrid NFC to determine the material structural performance as well as environmental performance assessment to determine the potential impact of the new component throughout its entire life cycle. The information obtained from both tools is very useful to composite designers in conducting more thorough decision making process during the conceptual design of the product.

1.3 Research Objectives

The research objectives are as follows:-

i) To select the best type of natural fiber and thermoplastic matrix materials for hybrid natural fiber composites formulation based on the parking brake lever product design specifications

ii) To develop conceptual design of new automotive center lever type parking brake lever using hybrid natural fiber composites and determine the final design concept using TRIZ-Morphological Chart-AHP method

iii) To determine the Young's modulus mechanical property of the final natural fiber composites and hybrid natural fiber composites using theoretical modeling method

iv) To evaluate the potential environmental impact effect of the new automotive center lever type parking brake lever design using hybrid natural fiber composites and synthetic composites.

1.4 Significance of Study

It is expected that the findings of this study may add to the effort to realize the potential of using hybrid kenaf/glass fiber reinforced NFC in development of new automotive center lever type parking brake lever component. Consequently, the new hybrid NFC can provide the sought after alternative towards improving the lightweight property of the current product while able to adhere successfully to the intended design requirements and better overall sustainable performance. In addition, findings of this study may also help to enhance the knowledge in the implementation of CE approach for NFC product design.

1.5 Scopes and Limitation of Study

The scopes of the present research is limited to the conceptual design stage of natural fiber composite for automotive center lever type parking brake lever application which includes market investigation, development of the product design specification, development of new product conceptual design and final conceptual design selection, materials selection, modeling of NFC and product environmental life cycle assessment. In addition, focus of the research is also given to the utilization of kenaf natural fiber, glass fiber and polypropylene thermoplastic matrix in the formulation of the hybrid natural/synthetic thermoplastic composites for the parking brake lever application.

1.6 Structure of the Thesis

This thesis is structured into 5 chapters. The first chapter is an introduction followed by Chapter 2 which presents comprehensive literature review on relevant areas associated with the topics in this research. Next is Chapter 3 which presents the overall research methodology applied in this research. The research methodology chapter composed of the overall structure of the research works, conceptual design and materials selection for the new automotive parking brake lever using hybrid NFC, modeling of NFC and environmental life cycle assessment for the new parking brake lever design.

The following Chapter 4 presents the results and discussion of the research works. Chapter 4 is divided into four main sections, which covers materials selection for the best type of natural fiber and thermoplastic matrix for the hybrid composites formulation, development of new conceptual design and final concept design selection for the automotive parking brake lever, modeling of the final single system composites and hybrid natural/glass fiber reinforced thermoplastic composites Young modulus performance as well as evaluation of the potential environmental impact of the new automotive parking brake lever design using hybrid natural/glass fiber reinforced thermoplastic composites and synthetic composites.

Finally, in Chapter 5, the overall conclusion and recommendation for future works are presented.

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