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MASTER OF SCIENCE IN ENGINEERING
(AERONAUTICS)

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AN IMPACT LOADING SIMULATION OF RUBBER TOUGHENED POLYMETHYL METHACRYLATE (PMMA) USING ABAQUS EXPLICIT

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SITI MUNIRAH BINTI MOHD TAHIR

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ABSTRACT

Polymethyl methacrylate (PMMA) is a glass replacement product due to lightweight, transparent thermoplastic and better impact resistance. Despite the advantages, it is brittle or has low ductility. During crashes, impact load can produce the fragmentation of small glass which is hazardous to person. Thus, the improved PMMA incorporates rubber nano-particles in the PMMA matrix called rubber toughened PMMA (RT-PMMA) was introduced. Rubber particles affect the toughening mechanism in energy dissipation during the initial crack and hence it's improve the ductility of the PMMA. However, limited number of research for numerical simulation studies for RT-PMMA under impact loading were conducted. Thus, this study aims to visualise and validate the impact properties for RT-PMMA 45, RT-PMMA 65 and RT-PMMA 100 under different impact velocity by numerical simulation approach. This study was conducted using The Extended Drucker-Prager and Ductile Damage Model in Abaqus Explicit 2021 software. The impact visualisation was then validated qualitatively with the experimental from published manuscript. From the results, it was found that the highest content of rubber particle fraction has better ductility and the lower the Von Mises stress in the material during impact. The higher the impact velocity, the greater the stress propagation. The outcome of this study is to identify the simulation damage model to simulate the impact on RT-PMMA thus it is able to reduce experiment research costs for other grades of RT-PMMA and impact velocities.

ABSTRAK

Polymethyl methacrylate (PMMA) ialah produk pengganti kaca kerana bersifat ringan, lutsinar dan mempunyai rintangan hentaman yang lebih baik. Walau bagaimanapun, ianya rapuh dan mempunyai kemuluran rendah. Semasa terhempas, hentaman boleh menghasilkan pecahan kaca kecil yang berbahaya kepada pengguna. Justeru, PMMA yang dipertingkatkan dengan zarah-nano getah dalam matriks PMMA yang dipanggil PMMA yang dikeraskan (RT-PMMA) telah diperkenalkan. Kehadiran zarah getah menjejaskan mekanisme peneguhan dalam pelesapan tenaga semasa retakan awal dan oleh itu ia meningkatkan kemuluran PMMA. Walau bagaimanapun, bilangan penyelidikan untuk kajian simulasi berangka untuk RT-PMMA di bawah pemuatan impak adalah terhad. Oleh itu, kajian ini bertujuan untuk menggambarkan dan mengesahkan sifat impak untuk RT-PMMA 45, RT-PMMA 65 dan RT-PMMA 100 di bawah halaju impak yang berbeza melalui pendekatan simulasi berangka. Kajian ini dijalankan dengan menggunakan model *'Extended Drucker-Prager'* dan *'Ductile Damage'* dalam perisian Abaqus Explicit 2021. Visualisasi impak kemudiannya disahkan secara kualitatif dengan eksperimen daripada manuskrip yang telah diterbitkan. Berdasarkan keputusan simulasi yang dijalankan, didapati bahawa PMMA dengan kandungan partikel getah yang tinggi mempunyai kemuluran yang lebih baik dan tekanan Von Mises yang lebih rendah semasa impak. Semakin tinggi halaju impak, semakin besar perambatan tekanan. Hasil kajian ini adalah untuk mengenal pasti model kerosakan simulasi untuk mensimulasikan kesan ke atas RT-PMMA sekali gus dapat mengurangkan kos penyelidikan eksperimen untuk gred RT-PMMA yang lain dan halaju impak yang berlainan.

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APPROVAL

The Examination Committee has met on **17th March 2022** to conduct the final examination of **Siti Munirah binti Mohd Tahir** on her degree thesis entitled **'An Impact Loading Simulation of Rubber Toughened Polymethyl Methacrylate (RT-PMMA) Using Abaqus Expilcit'**

The committee recommends that the student be awarded the Master of Science in Engineering (Aeronautics)

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UNIVERSITI PERTAHANAN NASIONAL MALAYSIA

DECLARATION OF THESIS

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Date of birth : 24 May 1986

Title :An Impact Loading Simulation of Rubber Toughened Polymethyl Methacrylate (RT-PMMA) Using Abaqus Explicit

Academic session : 2021/2022

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LIST OF ABBREVIATIONS

AEO	Air Engineer Officer
CAD	Computer Aided Design
EDP	Extended Drucker-Prager
ISO	International Organization for Standardization
KW	Kalthoff-Winkler
MINDEF	Ministry of Defence
MSTA	Malaysian State Technical Airworthiness
PC	Polycarbonate
PMMA	Poly Methyl Methacrylate
PS	Polystyrene
PVC	Polyvinyl chloride
PVDF	Poly (vinylidene fluoride)
RMN	Royal Malaysian Navy
RT-PMMA	Rubber Toughened Poly Methyl Methacrylate
UPNM	Universiti Pertahanan Nasional Malaysia
UTM	Universiti Teknologi Malaysia
3D	Three Dimension

CHAPTER 1

INTRODUCTION

Plastic was invented more than a century ago due to its lightweight and easily shaped advantages. In the aviation industry, plastic has huge benefits in application due to its advantages such as lightweight density, heavy-duty strength, durability, thermal stability and easier to mould, which will give freedom in design. It is used in the interior compartment, windscreen, or even smaller components such as bushing.

1.1 Background of Research

There are two kinds of plastics which are synthetic and semi-synthetic plastic. Plastic is comprised of chains of monomer molecules known as a polymer. Two categories of plastic are thermoplastic and thermosetting. The advantage of thermoplastic is the ease of shape, which can be melted, recycled, and moulded. On the other hand, thermosetting plastic cannot be melted, reshaped or moulded.

Polymethyl methacrylate (PMMA) is one of the thermoplastic groups. The chemical formula for its monomer methyl methacrylate is $C_5O_2H_8$. Thus the polymer chemical formula is the long chain of the monomer molecules; $(C_5O_2H_8)$-n [1], [2]. PMMA is lightweight, easy to shape, and transparent, widely used in various industries as a glass replacement. It also has better weather-resistant, high impact strength, shatter-resistant and non-toxic.

Its excellent properties make it widely used in various industries, such as bone substitute material [3] and cavity fillings in clinical dentistry, car windows, headlamps, aquariums, marine centres, aircraft windows, and cockpits. PMMA was used during World War II as an aircraft window and canopies [2]. However, one of the significant disadvantage properties is low ductility, which is easy to break or crack. Thus, many researchers have come out with the blended PMMA with materials such as polycarbonate (PC), polyvinyl chloride (PVC), polystyrene (PS) or poly(vinylidene fluoride) (PVDF) to improve the mechanical properties of the PMMA.

In this study, only rubber nano-particle blended in the PMMA matrix, later known as rubber toughened PMMA (RT-PMMA), is considered to investigate the impact properties. The rubber nano-particle acted as the toughening mechanism of the matrix PMMA by dissipating the load exerted on the material.

Most mechanical properties tests were conducted under certain loads, such as static or dynamic loads. The prominent load was impacted during accidents, which occurred at a high strain rate. Impact load is usually subjected to loading in projectile motion, or hammer struck in a short period. The impact speed is higher than strain rates tested in the static loading test, and the impact load is categorised as dynamic load. Impact loading test can be conducted by Charpy test, Izod test, *Kaltholf and Winkler*-impact test, falling weight test or can be determined via fracture mechanics approach. For the first two tests, based on standard ISO 8256:2004 and ASTM D1822M-93, impact energy is calculated by dividing impact energy in J with the thickness of the specimen (i.e., the notch width in m) [4]. While *Kalthoff and Winkler*-impact test (KW) was conducted using gas launcher impact on the pre-cracked area with high impact velocity [5].

1.2 Problem Statement

Many researchers proved the mechanical properties of RT-PMMA by experimental under static loading such as uniaxial tensile or compression load. Some experiments were studied under dynamic loadings, such as impact load.

Nevertheless, for numerical simulation approaches that covered most static loading, less study was conducted for impact load tests on RT-PMMA. Therefore, this study investigates the mechanical properties for different grades of RT-PMMA under various impact velocities using Abaqus Explicit 2021 software.

1.3 Research Objectives

This study will embark on the following objectives:

i. To conduct simulation using the Extended Drucker-Prager model for RT-PMMA and validate with the published experiment manuscript.
ii. To study the effect of different grades of RT-PMMA under impact loading.
iii. To investigate the effect of different impact velocities on RT-PMMA.

1.4 Scopes of Work and Limitation

i. This project is conducted only for a numerical simulation approach using Abaqus/Explicit 2021 software.
ii. Three different grades of RT-PMMA, which are RT-PMMA 45, RT-PMMA 65 and RT-PMMA 100 are selected as the material of specimens.
iii. The impact velocity exerted on the specimen is 50 m/s, 80 m/s and 100 m/s.
iv. The simulation is conducted without considering the effect of temperature.
v. The simulation findings are validated only with a qualitative result from the *Kalthoff-Winkler* impact test manuscript.

1.5 Significance or Research

This numerical simulation study will reduce experiment research costs that involve the destruction of the specimens. Based on the results, the Extended Drucker-Prager and Ductile Damage Model can study the impact properties for other grades of RT-PMMA.

1.6 Thesis Outline

The chapters that are included in this research are as follows:

i. **Chapter One** provides the study's introduction, which covers the problem statement, research objectives, scope and limitation, the significance of the study, and the chapter's organization.
ii. **Chapter Two** generally explains the mechanism of rubber toughening and the mechanical properties proved through experiments. It also describes the numerical analysis for RT-PMMA.

iii. **Chapter Three** will discuss the methodology of the research conducted. It also explains the detailed simulation materials using the Abaqus/Explicit 2021 software to perform the research.

iv. **Chapter Four** explains the result obtained from the simulation and its detailed analysis. The validation of the experiment manuscript is performed.

v. **Chapter Five** is the concluding chapter that will deliberate and summarize the content of the previous chapters of this research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Plastic development was started at the end of the 19th century to replace natural ivory. The plastic revolution has benefitted humans from the advantages of plastic, such as ease of shape, lightweight, and preserved nature and environment. Then, during World War II, the development of plastic had contributed to technology such as aircraft windscreens, helmets, nylon rope, parachutes and more.

Plastic consists of the long polymer chains from the process of polymerisation. There are two classes of plastic; thermoplastic and thermosetting plastic. Thermoplastic can be melted, moulded and shaped, while thermosetting plastic cannot be melted and has less shape variation. Polymethyl methacrylate is one example of thermoplastic.

2.2 Polymethyl Methacrylate

Polymethyl methacrylate (PMMA) is familiar as an amorphous thermoplastic that is lightweight, transparent and can replace glass in an application. PMMA can transmit up to 92% of visible light [6]. It also has high impact strength and is shatter-resistant [2]. Moreover, it is better weather resistant than polystyrene [7]. Despite its advantages, PMMA is very brittle or has low ductility [1 - [4], [7], [9], which means PMMA's product will easily break or fracture under any load. Many studies notably showed the mechanical properties of PMMA as high brittleness [1], [8], [10]–[13].

2.3 Rubber Toughened PMMA

The main properties of PMMA, which has vast advantages over glass and polycarbonate, are the transparency yet has high resistance and lightweight. However, the PMMA is brittle, and then many researchers performed a study to improve the brittleness to produce the improved PMMA. One of the evolutions was the idea to blend the rubber particle into the matrix of PMMA. The commonly known properties of rubber particles are their elasticity which will improve the ductility of the PMMA.

Therefore, emulsion polymerisation prepares rubber particles to produce rubbery and glassy crosslinked particle layers [14]. Y. Gui et al. [15] emphasised the crosslinking density at 2.52×10^{25} crosslink/m^3 was the maximum to hold the stress intensity factor, crack propagation energy. The optimum size of the particle to have the maximum strength was $250\ \mu$m. While Lovell et al. used the relative mass of the comonomer mixture per unit volume of water and stated the size particle of 50 μm to 400μm produced. Next, the fraction was blended in the matrix PMMA via an extrusion process, as shown in Figure 2.1, before being compressed at high temperatures and slow cooling process [12]. The preparation process of the rubber particle was to control the mixture's enhanced properties, known as rubber toughened PMMA (RT-PMMA).

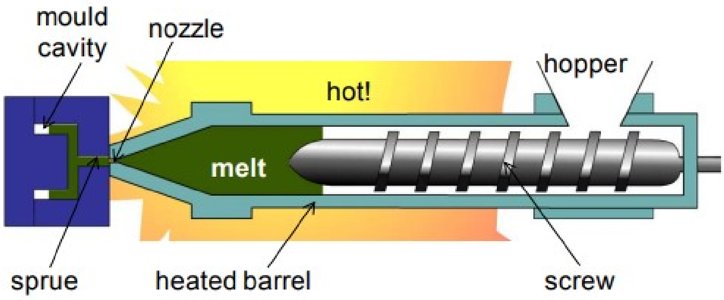


Figure 2.1: Basic injection moulded machine [4]

2.3.1 Toughening Mechanism

Rubber is known for its elasticity properties. The presence of the rubber particle within the matrix of PMMA will enhance the elasticity of the combined materials. Thus, the RT-PMMA will have elasticity and plasticity behaviour. During loading on RT-PMMA, the elastomer particles reinforced the PMMA matrix against an external impact by a cavitation mechanism. The rubber particles tend to dissipate the energy from the impact to its surrounding. Thus, it increased the strength of the whole RT-PMMA before fracture or failure. Rubber particles dissipate energy from the impact load throughout their particles, naturally elastic to the polymer matrix with low energy dissipation. Thus it will increase the fracture toughness of the RT-PMMA.

2.3.2 Factors Affecting Preparation of Blended Rubber

P.A. Lovell, et al. [14] showed that particle preparation affects the rubber particles' numbers and size. Those will generate different final properties, where the larger the rubber particles within, the higher the fracture toughness of the RT-PMMA. C. Wrotecki et al. [8] attributed that the lower the size of the rubber particle, the better the strength of RT-PMMA. The yield stress determination, K_{IC} and G_{IC} were conducted under static loading in an Instron machine and dynamic loading in a Charpy impact tester. The smaller size of the rubber particle was to reduce the void between the rubber particle and the matrix PMMA. C.B. Bucknall et al. [11], [12], [16] notably showed that rubber particles' cavitation in the rubbery layer would relieve tri-axial stress around the particle. Then generate shear yield, crazes, or whitening in the material RT-PMMA, reducing the transparency properties.

Even though the rubber particle presence enhanced the fracture toughness of RT-PMMA, the rubber particle manufacturing affected the final product properties. For example, the production of RT-PMMA has to maintain transparency by ensuring the compositions of the rubber (black layer) and glass layer (cross-hatches) refractive indices are equal to the matrix PMMA, which has $n_D^{20} = 1.489$ [14]. The transparency of RT-PMMA is maintained by rubbery and elastomer layers construction. Figure 2.2 shows the schematic diagram of three different sizes and the internal construction of the particles; rubbery layers are shown in black, and glassy layers are cross-hatched.

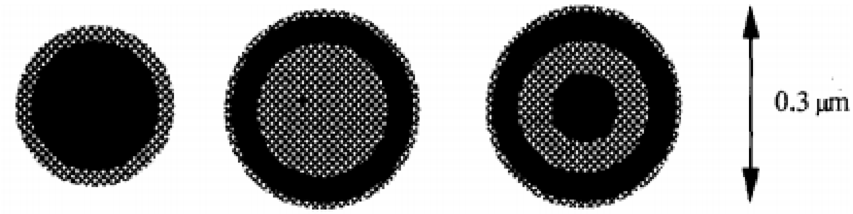


Figure 2.2: Schematic diagrams of sections of toughening particles [14]

Two parameters that affect the transparency are the nature of the rubber given by the refraction index and the rubber particle size, which must be small [8].

Moreover, the reinforcement process, rubber nature, and particle size influence the effective properties of toughened PMMA, such as transparency and strength [8].

A few studies showed the effect of the temperature on the mechanical properties of the PMMA. Ghatak A. and Dupaix R.B. [17] notably showed the closer and higher the operating temperature to the glass transition temperature (below 115ºC), PMMA shows significant softening and more fluid-like behaviour. Deformation for the mechanical properties of PMMA due to the different temperature and strain rates have been performed [18], [19].

2.4 Impact Loading

Impact loading is typically subjected to loading in projectile motion, or hammer struck at a short period. The impact speed is higher than the strain rates tested in the static loading test. One impact loading test is the *Kalthoff and Winkler*-impact test (KW) [20].

The KW test studies the crack propagation and fracture toughness of material under impact loading [21]. The KW test is conducted on a specimen with double notches pre-cracked on the material specimens plate. The notch is prepared to see the crack propagation and how the material will fracture under a certain magnitude of impact load.

2.4.1 Impact Loading on RT-PMMA by Experimental

The KW test was conducted using a gas launcher impact on the pre-cracked area with high impact velocities, as illustrated in Figure 2.3. N.M.Jali and P.Longere [5] have conducted an impact loading experiment on three plates with double notches (U fillet at the notch tip with opening height was 300 μm) of different grades of RT-PMMA by KW-type impact test in a closed chamber at room temperature. The gas launcher steel projectile has inner diameters of 40 mm, a weight of 92 g, with speeds ranging between 50 m/s to 100 m/s. The high-speed camera was set to capture the impact in sequence until the specimens were damaged.

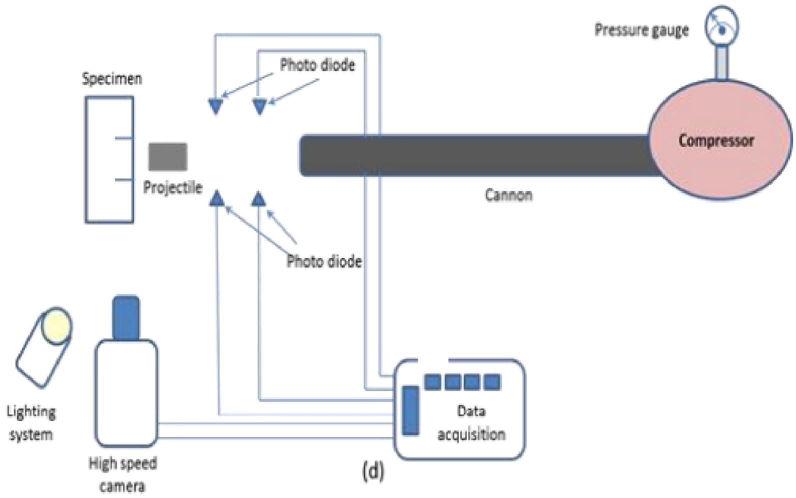
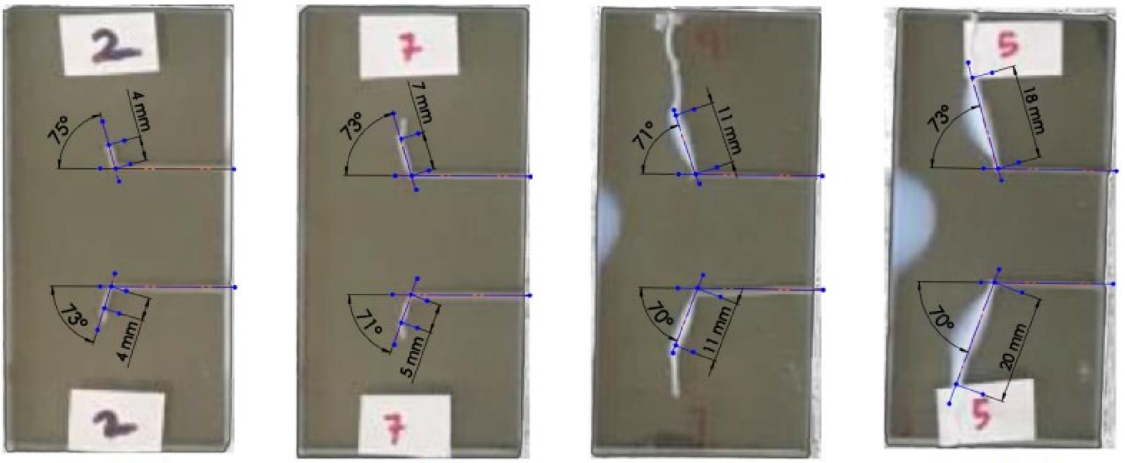


Figure 2.3: Schematic view of the experimental KW-impact test setup [22]

The investigation showed that RT-PMMA 60 and RT-PMMA 100 formed the stress whitening at 30 μs (see Figure 2.4). The higher the proportional rubber particle, the better the material's ductility, where the whitening indicated the plasticity region was formed before the material fractured. RT-PMMA tends to propagate along the direction of 70° from the notch axis [5], [23]. However, Ulmer. et al. [24] notably showed the changes in the crack propagation angle due to higher impact.



$v_i = 20\text{m/s}$ $v_i = 25\text{m/s}$ $v_i = 30\text{m/s}$ $v_i = 40\text{m/s}$

Figure 2.4: Crack line in 70° from the notch axis for RT-PMMA under impact test [23]

Koop et al. [25] performed the impact study on RT-PMMA and showed the profilometric imaging of the fracture surfaces to determine the fracture energy based on the surface analysis. Fond et al. [26] study the topothesy ratios significantly affect surface roughness amplitude. However, neither study did not compare different grades of RT-PMMA or the pure PMMA. Wang et al. [27] notably conducted the dynamic fracture on PMMA specimens. The study has more data than the high-speed camera and also fitted with the strain gauge, which collects the acquisition frequency during the impact. The frequency can determine the crack propagation during the impact.

2.4.2 Impact Loading on RT-PMMA by Simulation

In the numerical simulation, Belayachi et al. [28]–[30] notably showed that the mechanical properties of the macrostructural can be presented by representative volume element (RVE). This technique is known as the microstructural modification