COMPUTATIONAL PROPERTIES OF TITANIUM USING FINITE ELEMENT PREDICTION AND EXPERIMENTAL RESULT

NAFISAH ALMISRIAH BINTI MAIDIN

Thesis submitted in fulfilment of the requirements
for the award of the degree of
Bachelor of Mechanical Engineering

Faculty of Mechanical Engineering
UNIVERSITI MALAYSIA PAHANG

NOVEMBER 2009

STUDENT'S DECLARATION

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged. The thesis has not been accepted for any degree and is not concurrently submitted in candidate of any other degree.

Signature:
Name: NAFISAH ALMISRIAH BINTI MAIDIN
ID Number: MA06030
Date: 20 NOVEMBER 2009

ACKNOWLEDGEMENT

I would like to express profound gratitude to my advisor, Dr. Mon Thet Thet for her invaluable support, encouragement, supervision and useful suggestions throughout this research work. Her moral support and continuous guidance enabled me go through the rough road to complete my work successfully.

I am grateful for the cooperation of lab assistant by helping me in machine usage. First, I really appreciate the kindness of Mr. Mahdir, Assistant Laboratory, who gave me so much help in using laboratory computer. Secondly, Mr. Hazami Che Hussain, the Assistant Instructor Engineer who assist me in using the tensile machine during experiment. He was willing to help me answer all my questions about the experiment without hesitation. I am also thankful to Dr Md Mustafizur Rahman, Mr Mohd Hafizi Zohari and Mr. Mohd Akramin Mohd, my project panels which contributed some useful comments during my experiment. Moreover, I would like to acknowledge all of my friends especially Azrol Arof, Mohd Hasri Ibrahim who helps a lot in my project.

I am as ever, especially indebted to my parents, Mr. Maidin bin Parikutty and Mrs. Katijah binti KMA Bawal for their love and support throughout my life even I am so far away from them and spending most of my life abroad. I also wish to thank my bestfriend, Ms. Farah Bazilah binti Wakhi Anuar for his support and understanding during my study. Finally, I wish to express my appreciation to all my friends, who shared the love and experiences with me.

ABSTRACT

Titanium and its alloys are is widely used nowadays especially in aerospace applications, automobiles, building equipments and many more. Since, it was an expensive material, less research have been done to determine their actual properties. Finite Element (FE) method was applied to investigate response of titanium under different conditions. Computational model was developed in ALGOR FE code. The best model was choosen through mesh convergency analysis. Tensile experiment was carried out on ASTM standard titanium specimen and stress strain response was also obtained experimentally. The computational model was then validated with the experimental results. The results were found to be agreeable in terms of stress strain response both in elastic and plastic regions with error less than 2%. Further simulation were carried on with different strain rates. Stress strain response of titanium under different strain rates shows that strain increase monotonically at increased rate. Computational model can be used to economically determine material response under various conditions.

ABSTRAK

Aplikasi penggunaan titanium (T1-6A1-4V) pada hari ini amat meluas terutama dalam bidang aeroangkasa, kereta, kelengkapan bangunan dan banyak lagi. Titanium merupakan bahan yang mahal dan kerana itu kurangnya penyelidikan yang dibuat ke atas bahan tersebut. Kaedah elemen hingga diterapkan untuk menyiasat gerak balas titanium di bawah keadaan yang berbeza. Model komputasi dikembangkan dalam kod ALGOR elemen hingga. Model terbaik dipilih melalui konvergensi mesh analisis. Ujian ketegangan dilakukan pada standard ASTM titanium spesimen dan regangan stres respons juga diperolehi secara percubaan. Model pengkomputeran kemudian disahkan dengan keputusan eksperimen. Keputusan yang diperolehi memuaskan dalam gerak balas tekanan regangan di kawasan elastik dan plastik dengan kesalahan kurang daripada 2%. Simulasi dibuat dengan lebih lanjut pada tahap ketegangan yang berbeza. Gerak balas titanium di bawah tahap kadar ketegangan yang berbeza menunjukkan bahawa peningkatan beban meningkat secara monotonik. Model pengkomputeran boleh digunakan secara ekonomik untuk menentukan gerak balas bahan dalam pelbagai keadaan.

TABLE OF CONTENTS

Page

CHAPTER 1 INTRODUCTION

CHAPTER 2 LITERATURE REVIEW

CHAPTER 3 METHODOLOGY

CHAPTER 4 RESULTS AND DISCUSSION

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter gives a brief description of the project progress including approaches of method application. It includes project background, problem statement, objective and scope of the project.

1.2 Project Background

Titanium is used in aerospace applications, automobiles, prosthetics, buildings, and sporting equipment. It can be alloyed with iron, aluminium, vanadium, molybdenum, among other elements, to produce strong lightweight alloys for aerospace (jet engines, missiles, and spacecraft), military, industrial process (chemicals and petro-chemicals, desalination plants, pulp, and paper), automotive, agri-food, medical prostheses, orthopedic implants, dental and endodontic instruments and files, dental implants, sporting goods, jewelry, mobile phones, and other applications.

In this project, computational model will be developed using finite element method to predict mechanical properties of titanium. Different analysis types will be used to determine mechanical properties in statics and dynamics situations. Some static and dynamic response of titanium will be investigated experimentally. Finite elements results will be compared with experimental results in order to validate the FE model as well as to further simulate material response under various loading conditions.

Titanium is the fourth most abundant metals in the earth's crust. The capacity for production substantially exceeds long term forecast of demand. Product prices are low and stable. Titanium and rutile ore both sourced in friendly countries with stable regimes, unlike nickel or chromium, and so the price of titanium has never really been subject to crisis or political factors. The ready availability of titanium in a wide and ever increasing range of product forms has assured its growth as a basic, general engineering material. Today a network of mills, stockiest, machinists, and fabricators ensure that the demands of design quality and speed of delivery can be met to many businesses around the world. The extraction of titanium is a multi-stage process in that it is the first metallic product being "sponge". This product has no value as an engineering material, and needs to be consolidated and melted to produce ingots from which semi-finished products may be manufactured.

Titanium, when pure, is a lustrous, white metal. It has a low density, good strength, is easily fabricated, and has excellent corrosion resistance. It is ductile only when it is free of oxygen. The metal, which burns in air, is the only element that burns in nitrogen. Titanium is resistant to dilute sulfuric and hydrochloric acid, most organic acids, most chlorine gas, and chloride solutions. Natural titanium is reported to become very radioactive after bombardment with deuterons. The emitted radiations are mostly positrons and hard gamma rays. The metal is dimorphic. The hexagonal alpha form changes to the cubic beta form very slowly at about 880C. The metal combines with oxygen at red heat, and with chlorine at 550C. Titanium metal is considered to be physiologically inert. When pure, titanium dioxide is relatively clear and has an extremely high index of refraction with an optical dispersion higher than diamond.

Without titanium, our world may not be able to function or progress with the added bonuses it provides us with. It is a big part of our lives and has created news ways of thinking, working, and even inventing. This strong, but light steel, is not only a vital element because it has the ability to withstand extreme temperatures, Titanium also is twice as strong as aluminum. With all of this in mind it is not very hard to see exactly why it is considered one of the most cost efficient alternative to stainless and other high-alloy steels.

1.3 Problem Statement

It has been very difficult to find well-documented properties of titanium. Particularly, titanium properties at elevated temperature and high strain rate are hardly found in the literature. Some reasons, are because of being expensive material and trouble-some specimen preparation for extensive material testing. It is essential to develop computational model which needs limited experimentation to predict titanium properties.

1.4 Project Objective

The aim of this study is to developed the computational model to predict titanium properties. Secondly, to validate the model with tensile experiment. And the last one is to predict response of titanium at different strain rates.

1.5 Scope of Project

The study is focus on developing computational model using ALGOR FE code. The model geometry will be developed in SolidWork. The material model will be von mises with isotropic hardening and the computational model will be validated with tensile experiment.

Different strain rate will be used from 0.1/s to 3.5/s and the simulation will be done in ALGOR FE environment. Response curve will be developed from the simulated results.

1.6 Summary

Chapter 1 has been discussed briefly about project background, problem statement, objective and scope of the project in order to achieve the objectives as mentioned. This chapter is as a fundamental for the project and act as a guidelines for project research completion.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

From the early stage of the project, various literature studies have been done. Research journal, books, printed or online conference article were the main source in the project guides. The reference sources emphasize on important aspect of titanium alloy such as machining parameters, properties of titanium, mechanical properties, thermal mechanical properties as well as coordinate measuring machines which are directly incorporated in this project, and the appropriate titanium application.

2.2 Pure Titanium

Titanium was discovered in the late of 1500’s and was named for the mythological giants, the Titans. In the 1940's, it was used by the space and defense industries. Titanium is a chemical element with the symbol Ti and atomic number 22. It has a low density and is a strong, lustrous, corrosion-resistant transition metal with a silver color.

The unique and exceptional properties of Titanium make this possible. These excellent properties include the highest ratio between strength and density of all metallic structural materials, extreme mechanical and thermal loading capacity, extreme high tensile strength, stronger than steel but 42% lighter. Its high corrosion resistance, particularly against oxygen, its tissue-compatibility and vital and elastic attributes make it extremely biocompatible.

2.3 Mechanical Properties

In tensile properties unalloyed titanium may have tensile strengths ranging from 35,000 psi (250 MPa) for high purity metal produced by the iodide reduction process to 100,000 psi (690 MPa) for metal produced with sponge titanium of high hardness. The arc-melted unalloyed titanium products are reasonably ductile. In ductility the arc-melted commercially pure titanium products range in ductility from 20% to 40% elongation and from 45% to 65% reduction in area, depending upon the interstitial content. The iodide process titanium yields a product possessing 55% elongation with 80% reduction in area.

As is the case with steel, titanium is alloyed with other metals to increase its strength. Such metallic additions as **Al**, **V**, **Cr**, **Fe**, **Mn**, **Sn** are employed either as binary additions or as complex systems. The resulting increase in strength is accomplished, however, with a lowering of ductility.

For modulus of elasticity unalloyed titanium has a modulus of about $15x10^6$ psi and can be increased to about $18x10^6$ psi by alloying. Titanium's modulus compares favorably with those of aluminum ($10.4x10^6$) and magnesium ($6.4x10^6$) but poorly with that of steel ($29x10^6$). Like the modulus of elasticity the modulus in shear, modulus of rigidity, of titanium falls between that of aluminum and that of steel.

Moreover Titanium is a much harder metal than aluminum and approaches the high hardness possessed by some of the heat-treated alloy steels. Iodide purity titanium has a hardness of 90 VHN (Vickers), unalloyed commercial titanium has a hardness of about 160 VHN and when alloyed and heat-treated, titanium can attain hardnesses in the range of 250 to 500 VHN. A typical commercial alloy of 130,000 psi yield strength might be expected to have a hardness of about 320 VHN or 34 Rockwell C. Impact Resistance knowledge of tensile strength and ductility of a metal is insufficient for many engineering applications without the knowledge of toughness. Titanium falls among the few metals capable of possessing good toughness along with high strength and ductility. Titanium may have impact strengths ranging from more than 100 foot pounds Charpy for the higher purity iodide product and 30 foot pounds for the commercial unalloyed product to 1 or 2 foot pounds for some of the high strength but brittle alloys.

2.4 Thermo- Mechanical Properties

Generally, all the mechanical properties drop at increase temperature. This properties are also important to consider in the designing state. For example, stress strain response in increase temperature shown in figure 2.1.

The flow stress of isothermally compressed Ti–6Al–4V alloy is significantly sensitive to the strain, the strain rate and the deformation temperature. The steady and peak flow stress of isothermally compressed Ti–6Al–4V alloy decreases significantly with the increasing of deformation temperature and the decreasing of strain rate.

The isothermally compressed Ti–6Al–4V alloy exhibits two instability domains in the following, one is in the deformation temperature range from 1093K to 1183K and the strain rate range from 0.011 s^{-1} to 2.02 s^{-1}, and another in the deformation temperature range from 1243K to 1303K and the strain rate range from 1.0 s^{-1} to 10.0 s^{-1}.

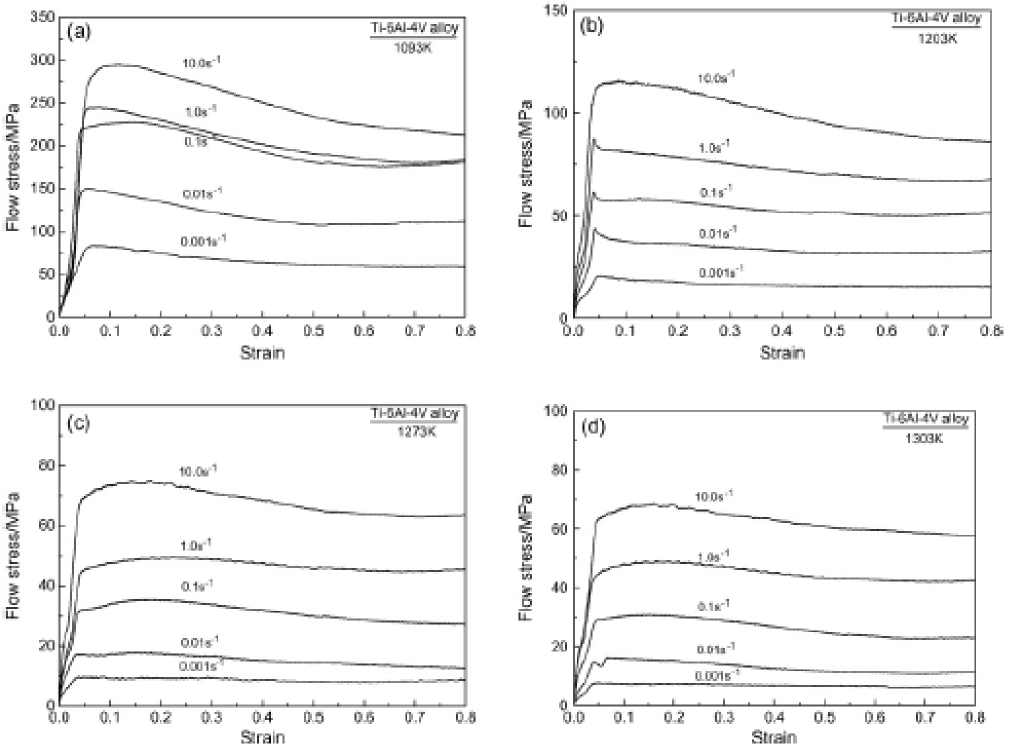
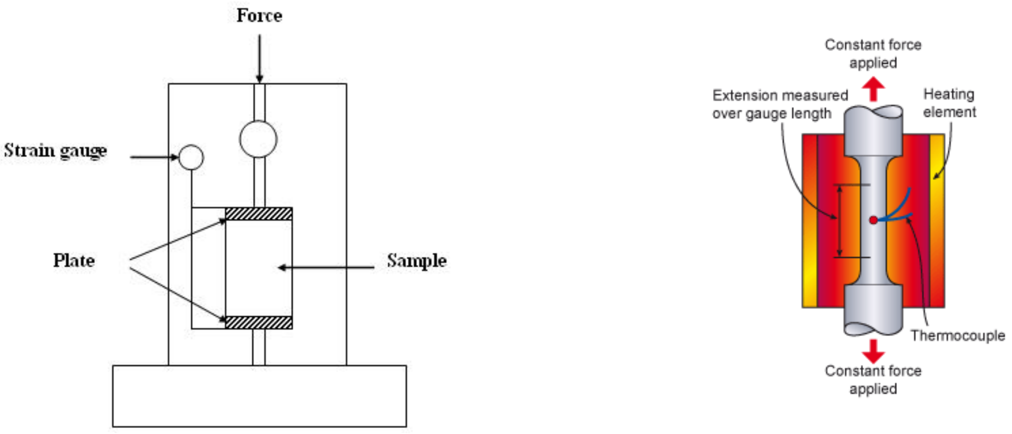


Figure 2.1: Selected flow stress curves of isothermally compressed Ti–6Al–4V alloy at the deformation temperatures of: (a) 1093 K; (b) 1203 K; (c) 1273 K; (d) 1303K.

2.5 Standard Material Testing

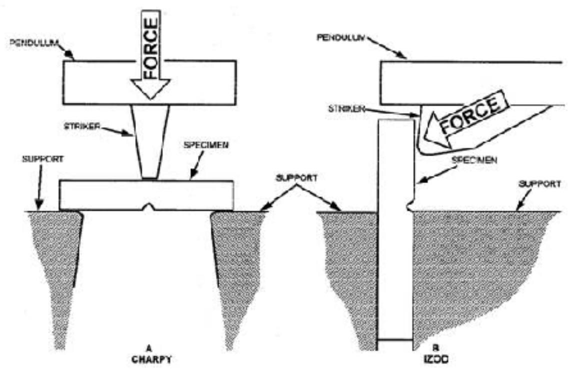
A tensile test, also known as tension test, was the most fundamental type of mechanical test you can perform on material. Tensile tests are simple, relatively inexpensive, and fully standardized. By pulling on something, it will very quickly determine how the material will react to forces being applied in tension. As the material is being pulled, the elongation and strength will be determined.

There are various type of mechanical testing namely compression test, creep test, impact test and many more. Figure 2.2 shown compression test, creep test, and impact test.



(a) Compression test

(b) Creep test



(c) Impact test

Figure 2.2: (a) compression test; (b) creep test; (c) impact test

Compression test is a test determines behavior of materials under crushing loads. The specimen is compressed and deformation at various loads is recorded. Compressive stress and strain are calculated and plotted as a stress-strain diagram which is used to determine elastic limit, proportional limit, yield point, yield strength and, for some materials, compressive strength.

While creep test is a test that involves a tensile specimen under a constant load maintained at a constant temperature. Measurements of strain are then recorded over a period of time. Creep occurs in three stages namely primary or stage I, secondary or stage II and tertiary or stage III. Stage I creep occurs at the beginning of the tests, and creep is mostly transiently, not at a steady rate. Resistance to creep increases until stage II is reached. In stage II, the rate of creep becomes roughly steady. This stage is often referred to as steady state creep. In stage III, the creep rate begins to accelerate as the cross sectional area of the specimen decreases due to necking or internal voiding decreases the effective area of the specimen. If stage III is allowed to proceed, fracture will occur.

Besides, impact testing is testing an object's ability to resist high-rate loading. An impact test is a test for determining the energy absorbed in fracturing a test piece at high velocity. Most of us think of it as one object striking another object at a relatively high speed. Impact resistance is one of the most important properties for a part designer to consider, and without question, the most difficult to quantify. The impact resistance of a part is, in many applications, a critical measure of service life. More importantly these days, it involves the perplexing problem of product safety and liability.

2.6 Finite Element Method

The finite element method (FEM), ssometimes referred to as finite element analysis (FEA) is a computational technique used to obtain approximate solutions of boundary value problems in engineering. Simply stated, a boundary value problem is a mathematical problem in which one or more dependent variablesmust satisfy a diffrential equation everywhere within a known domain of independent variables and satisfy specific conditions on the boundary of the domain. Boundary value problems are also sometimes called field problems.

The field is the domain of interests and more often represents a physical structure. The field variables are the dependent variables of interest governed by the differential equation. The boundary conditions are the specified values of the field variables (or related variables such as derivatives) on the boundaries of the field. Depending on the type of physical problem being analyzed, the field variables may include physical displacement, temperature, heat flux, and fluid velocity to name only a few.

FEM helps tremendously in producing stiffness and strength visualizations and also in minimizing weight, materials, and costs. FEM allows detailed visualization of where structures bend or twist, and indicates the distribution of stresses and displacements. FEM software provides a wide range of simulation options for controlling the complexity of both modeling and analysis of a system. FEM allows entire designs to be constructed, refined, and optimized before the design is manufactured.

This powerful design tool has significantly improved both the standard of engineering designs and the methodology of the design process in many industrial applications.The introduction of FEM has substantially decreased the time to take products from concept to the production line. It is primarily through improved initial prototype designs using FEM that testing and development have been accelerated. In summary, benefits of FEM include increased accuracy, enhanced design and better insight into critical design parameters, virtual prototyping, fewer hardware prototypes, a faster and less expensive design cycle, increased productivity, and increased revenue.

Nowadays, previous FE package are available such as catia, abacus, nastran patran and many more. There are certain steps in formulating FE analysis of a physical problem are common to all such analysis, whether structural, heat transfer, fluid flow, or some other problem. These steps are embodied in commercial FE software packages and are implicitly incorporated.

2.5.1 Preprocessing

The preprocessing step is, quite generally, described as defining the model and includes defining the geometric domain of the problem, defining the loadings, defining the material properties of the elements, defining the element connectivities and many more. The preprocessing step is critical. In no case is there a better example of the computer-related axiom “garbage in, garbage out”. A perfectly computed FE solution is of absolutely no value if it corresponds to the wrong problem.

2.5.2 Solution

During the solution phase, FE software assembles the governing algebraic equations in matrix form and computes the unknown value of the primary field variables. The computed values are then used by back substitution to compute additional, derived variables, such as reaction forces, element stresses and heat flow.

As it is not uncommon for a FE model to be represented by tens of thousands of equations, special solution techniques are used to reduce data storage requirements and computation time. For static, linear problems, a *wave front solver,* based on Gauss elimination, is commonly used.

2.5.3 Postprocesssing

Analysis and evaluation of the solution results is referred to as *postprocessing*. Postprocessor software contains sophisticated routines used for sorting, printing, and plotting selected results from a FE solution. Examples of operations that can be accomplished include sort element stresses in order of magnitude, check equilibrium, calculate factor of safety, plot deformed structural shape, animate dynamic model behavior and produce color-coded temperature plots.

While solution data can be manipulated in many ways of postprocessing, the most important objective is to apply sound engineering judgement in determining whether the solution results are physically reasonable.

2.6 Accuracy of FEM

FEM is applied to the practical designs and the research to improve the understanding the behavior of complicated structures. As the purpose of FEM can is about construction subjects, material, oundary conditions and loads, if the meshing is fine it will guarantee that solutions approaches correct answer. However, FEM is essentially the approximation analyzing method. Therefore, effeciently the analytical and dynamic judgement of how to search the for the results required capacity in the computer and calculation time.

2.7 Previous Study on Titanium Properties

Luo et. al (2009) were studied about the effect of the strain on the deformation behavior of isothermally compressed Ti–6Al–4V alloy. In this study, effect of the deformation temperature, the strain rate and the strain on the flow stress is analyzed to represent the mechanical behavior of isothermally compressed Ti–6Al–4V alloy, and the apparent activation energy for deformation of isothermally compressed Ti–6Al–4V alloy at different strains is calculated. And, the deformation mechanisms are clarified through the apparent activation energy for deformation of isothermally compressed Ti–6Al–4V alloy in the (α+β) two-phase region and/or the β singlephase region compared to the activation energy for self-diffusion of α-Ti and β-Ti. Finally, the processing map of isothermally compressed Ti–6Al–4V alloy at a strain of 0.6 is established so as to optimize the processing parameters.

Zeng et. al (2009) investigating about the constitutive equations for pure titanium at elevated temperatures. From the study, the authors found that isothermal compression of pure titanium has been conducted at different temperatures and strain rates to characterize the flow behaviour during hot working. Based on the experimental data, a set of constitutive equations incorporating the effects of strain, strain rate and temperature of the material are derived to describe the plastic flow properties in a form that can be used to model the forging response under the prevailing loading conditions. The reliability of the constitutive equations is also evaluated by the mean error of flow stress.

Marmy et. al (2000) were studied about the tensile and fatigue properties of two titanium alloys as candidate materials for fusion reactors. In the present investigation, alloys in the α and α+β phase fields are investigated under conditions relevant for the application as flexible connectors between ITER blanket modules and the vacuum vessel.

Results of the characterisation of the unirradiated materials are presented. The results shows Two different regimes have been observed in the behaviour under cyclic stresses. At a high imposed strain, softening is almost absent in the Ti 6Al 4V and is small in the Ti5Al2.4 Sn. At a low imposed strain, for both alloys, during the first period of life, cyclic softening takes place (up to about 800 cycles). But then a transition occurs after which a regime of cyclic hardening appears. The fatigue resistance of the Ti5Al2.4Sn alloy is higher than that of the Ti6Al4V alloy.

2.8 Summary

This chapter successfully discussed on the material, testing machine and software used in this project, the processes needed and the machine requirements and properties.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter generally discusses methodology of the project, with a focus on tensile test, finite element modeling (ALGOR), and computational tensile with different strain rates. Relevant data collection is done in order for further research analysis in subsequent chapter.

3.2 Methodology Flow Chart

The methodology flow chart is a visual representation of the sequence of the project. A completed flowchart organizes the topic and strategies done to ensure smooth working flow of project. Figure 3.2 illustrated a flow chart shows the flow processes of this project. As illustrated, the first step is literature study on related topic. Then, problem statement, and objectives was identified. The methadology consists of 2 major parts namely computational model of tensile test and another one is experimental using tensile test.

Computational model will be validated by experimental results. After model validation was completed, simulation of computational tensile properties of titanium at various strain rates was done using ALGOR FE environment. Before explaining details on the methods used, flowchart was made to show a little information for the overall project.

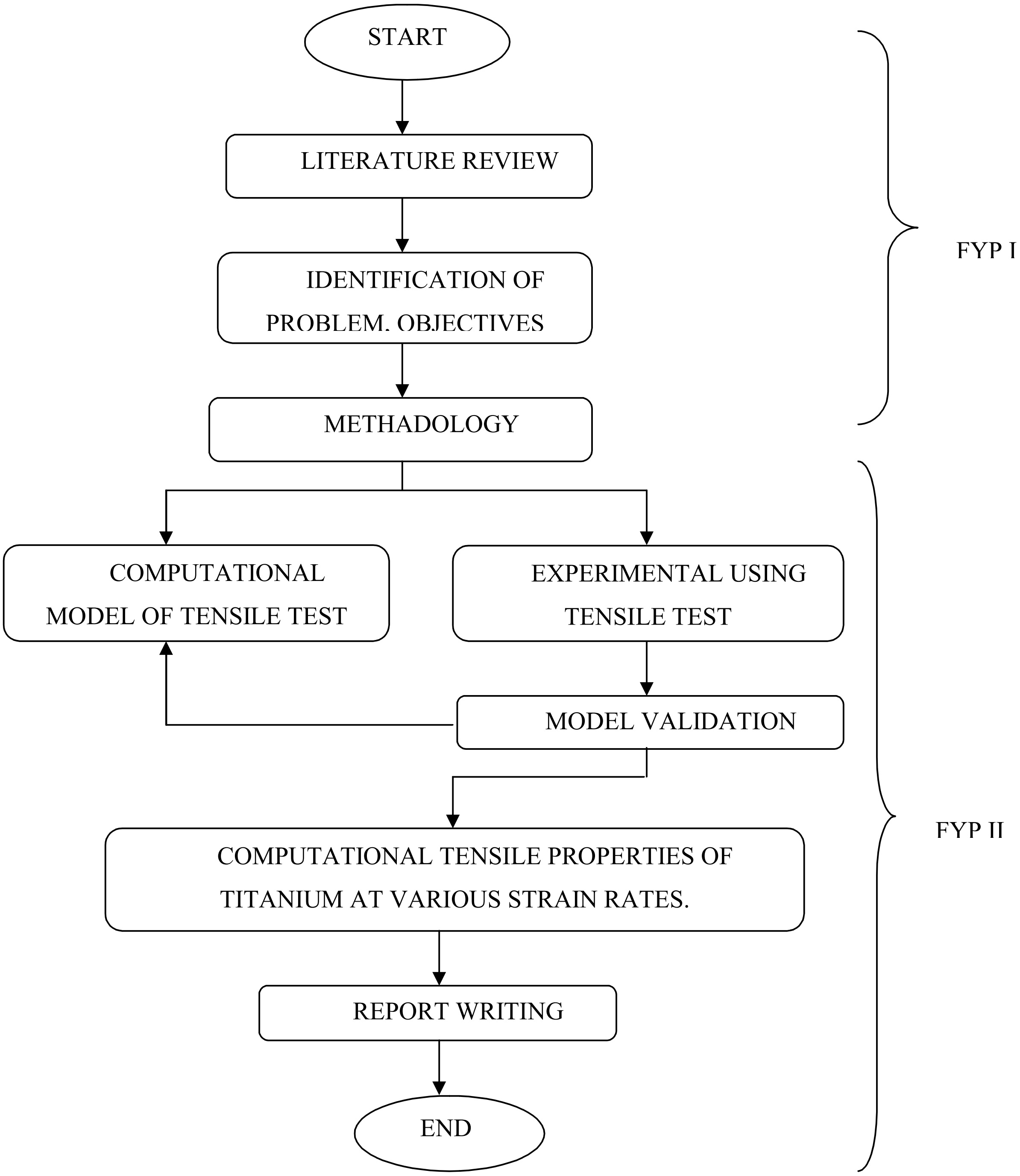
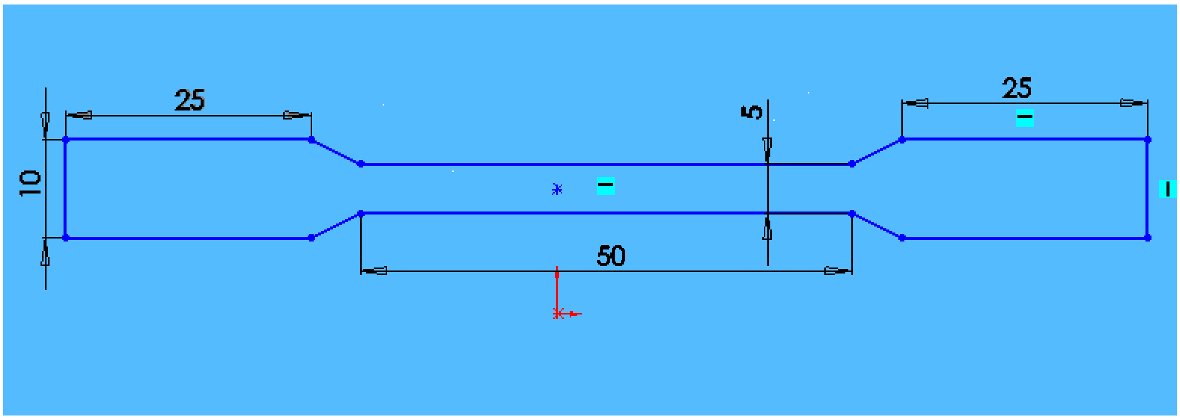


Figure 3.1 Flowchart for methodology of the project (For FYP1 and FYP2)

3.3 Specimen Preparation

Titanium specimen were prepared according to ASTM standard code namely E8 using CNC turning centre and figure 3.2 shows the schematic diagram of the specimen with the dimensions.



Figureb 3.2: Titanium specimen according ASTM standard code E8

3.4 Tensile Test

For testing using tensile test, 3 specimens of cylindrical titanium as an average will be used to get the accurate result. The specimen specifications is shown in table 3.1.

Table 3.1: Specimen Specifications

Specimen Specifications	
Strain rate	**0.1 s^-1**
Gauge length	**50 mm**
Average maximum load	**8.18 kN**
Grip distance	**100 mm**

Figure 3.3: Tensile Test machine

3.3 Finite Element Modeling

ALGOR FE code was used for stress strain analysis.The model generally was developed in Solidwork. Solidwork model was imported to ALGOR for FE modeling and analysis. Mesh convergency of different mesh density of 3 model would be carry out to choose the suitable model to get the response curve from simulation namely elastic and plastic region by comparing actual Young Modulus and from simulation. Then, using the suitable model, further simulation of different strain rate would be carry out to get stress strain response.

3.5 Summary

Turning process of pure titanium has been done using lathe machine and 3 specimens have been made. Then, all the 3 specimens will be test using tensile machine to get the stress strain curve. Using Solidwork, the material model will be validated and the results of response curve were compared at actual Young Modulus from experiment and simulated. The different strain rates of stress strain response also will be investigate.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

Chapter 4 is generally discussed the results obtained throughout the experimental using tensile test, and ALGOR FE for model validation different strain rates.

4.2 Specimen diagrams

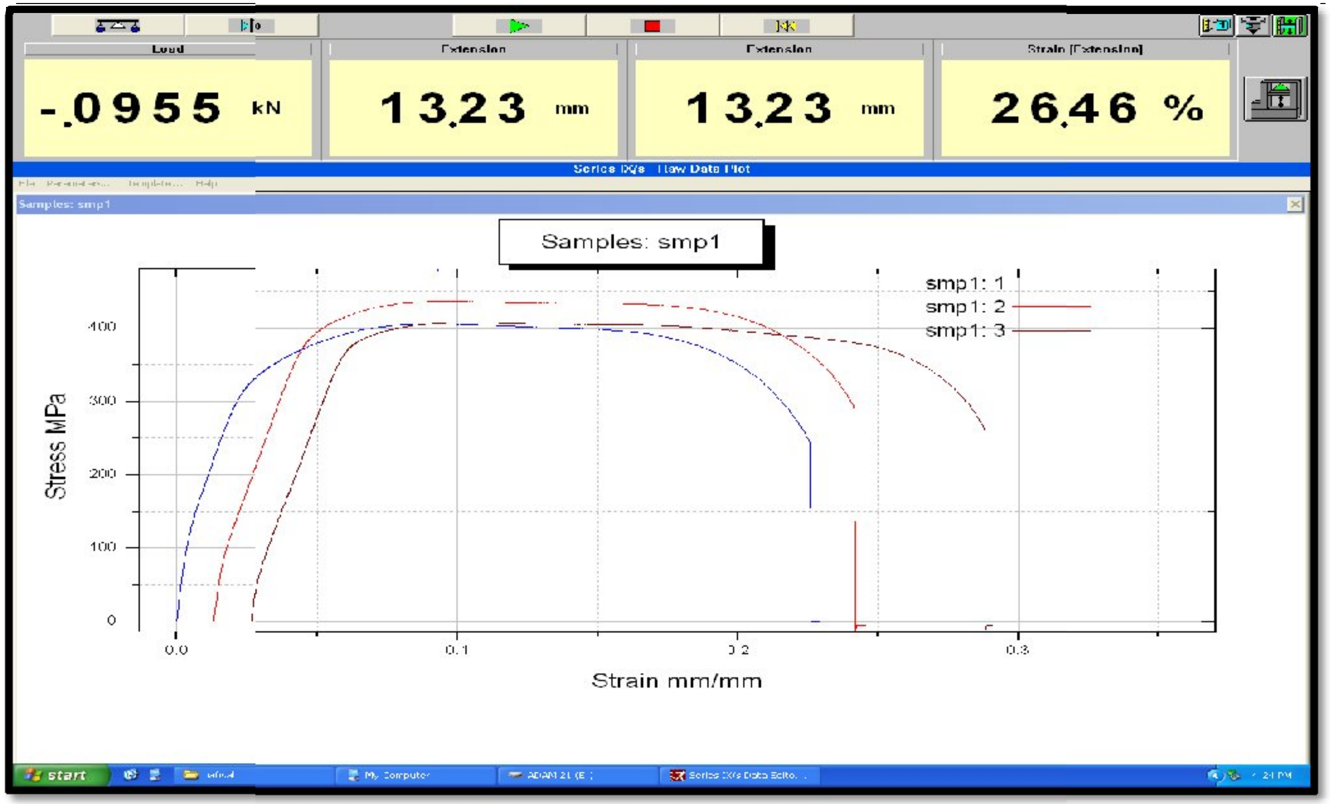
The 3 specimens of pure titanium were test using tensile test machine. By doing 3 times, it would be more accurated and the average of maximum load was determined. The responsed curve of stress strain showed 2 part namely elastic region and plastic region. Young Modulus, percent of elongation, yield strength and etc could be calculated in elastic portion of stress strain curve.

Figure 4.1 and 4.2 shows the titanium specimen before and after test went through tensile testing respectively. The specimen fracture point occured slightly away from central region, which is different from the material responsed in typical tensile test. This may be done to non-uniformity of central portion. However, stress strain response curve is reasonable from the view point of yield stress, elasticity and plasticity.

As shown in figure 4.3, the stress strain response of titanium is both elastic and plastic region is agreeable with the published report, where steep slope in elastic region and almost perfect plasticity are shown. Three curves are shown in the figure 4.3 as the experiments were repeated three times. The difference in the curves particularly maximum stress is due to dimensional error of the specimen.

Figure 4.1: The specimen before test

Figure 4.2: The specimen after test



Load -.0955 kN

Extension 13.23 mm

Extension 13.23 mm

Strain [Extension] 26.46 %

Figure 4.3: Graph stress versus strain from experiment

4.3 Material Model

The model geometry will be developed in SolidWork and only half of the actual size is modeled because of symmetry and to reduce the computational time.The mechanical properties of the tested material are shown in Table 3.2. Using ALGOR FE, the element type is brick, material model is von mises with isotropic hardening and the analysis type is static stress with non-linear material model. For the model validation, there have 2 boundary conditions namely translational of bottom nodes that are constraint in X, Y, and Z directions. For the top nodes, nodal force of 127.81 N was applied in yhe Z direction.

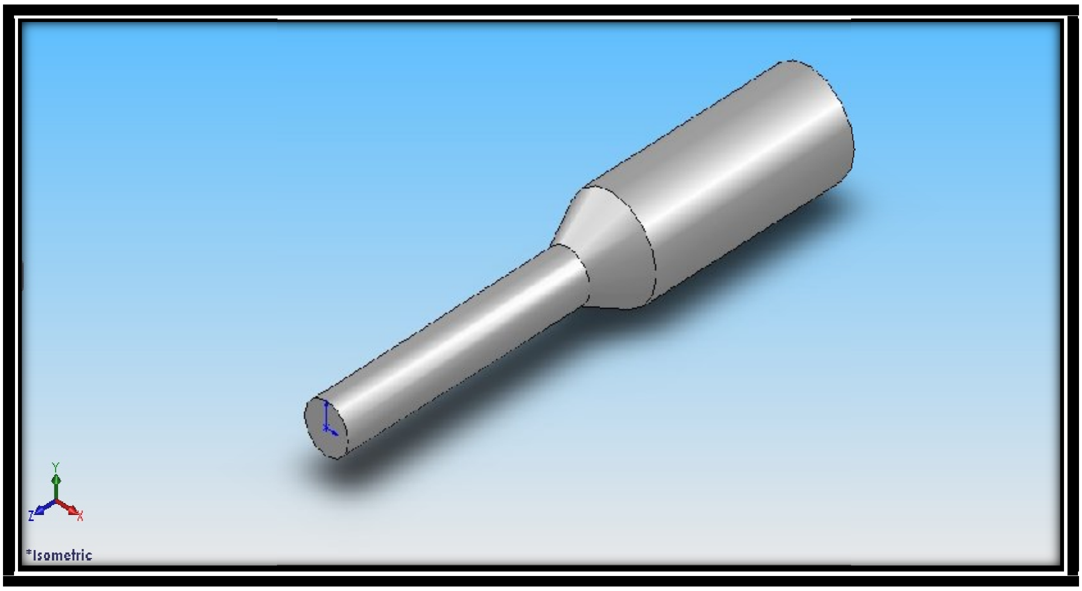


Figure 4.4: Model geometry in SolidWork

Table 4.1: Mechanical Properties of Titanium

Source: The free encyclopedia

MATERIAL PROPERTIES	
Mass density	0.0000004506 Ns^-2/mm/mm^3
Modulus of Elasticity	116 e^3 N/mm^2
Poisson’s ratio	0.32
Strain hardening modulus	0.1 N/mm^2
Yield strength	350 N/mm^2
Damping	0

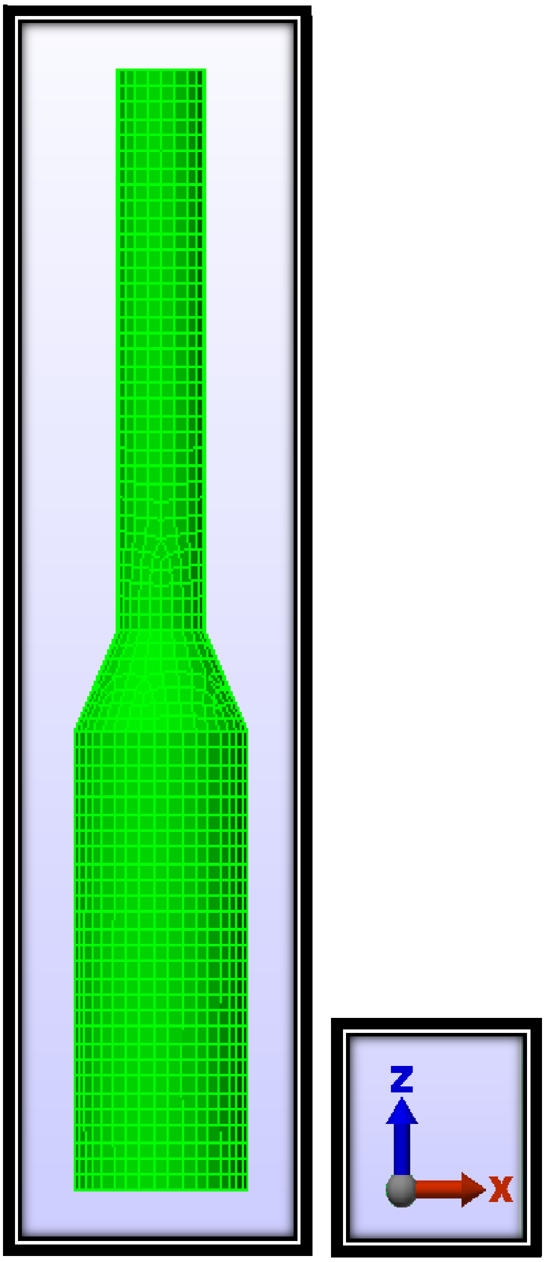


Figure 4.5: Model validation of 9517 number of element

4.4 Mesh Convergency

For mesh convergency, 3 model of different mesh density namely 30%, 40%, and 50% would be carry out to get the response curve of stress and strain. For 30% mesh density, the number of elements are 14711, 40% mesh density are 9517 and for 50 % mesh density are 4345.

Besides, stress strain curve for all these 3 mesh density would be plotted and all was linear. As the stress increased, the strain also increased with time. That means stress is propotionally with strain. According to the results also, it is convergence at number of elements 9517, so second model has been chosed for further simulation.

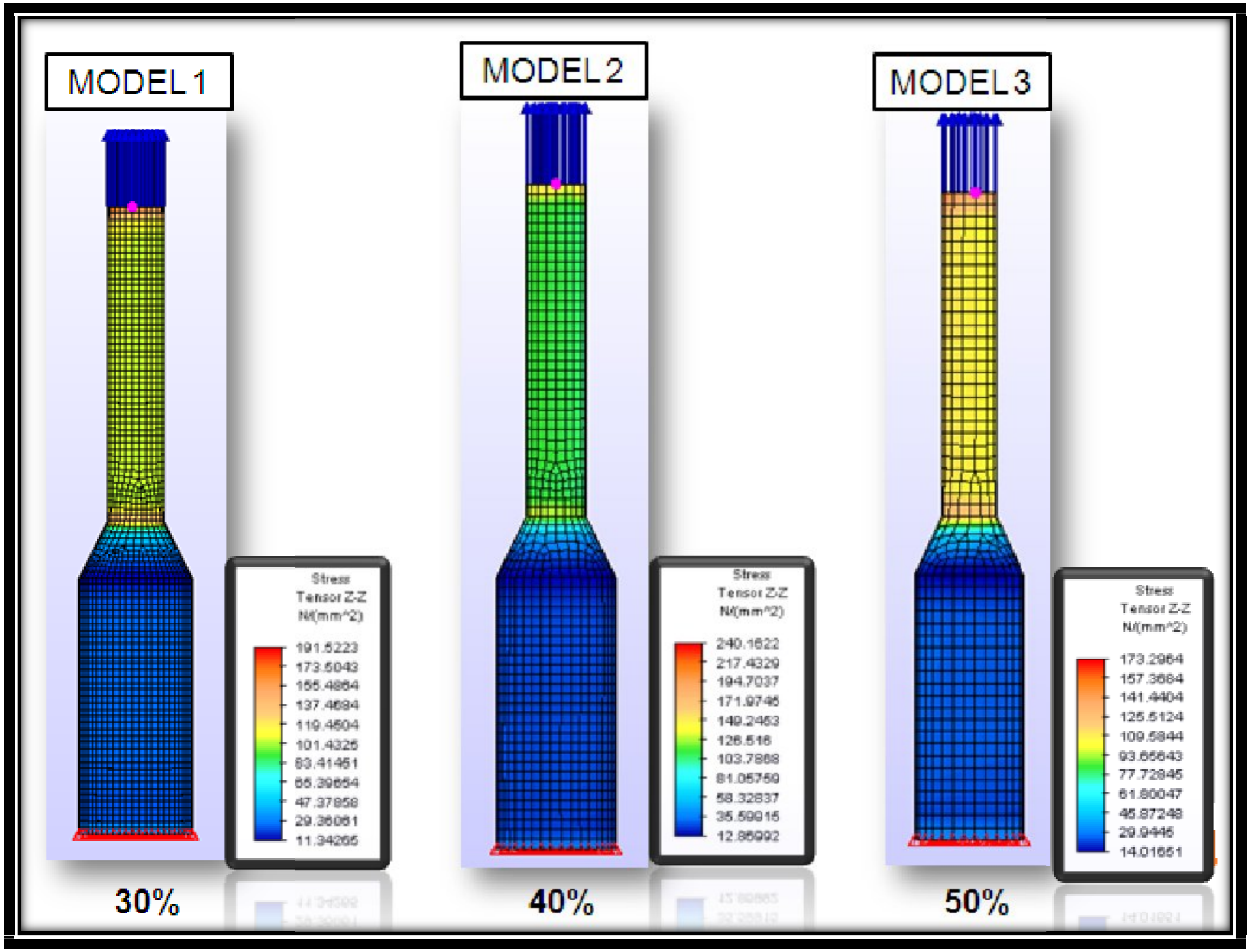


Figure 4.6: The simulated results for stress with different mesh density

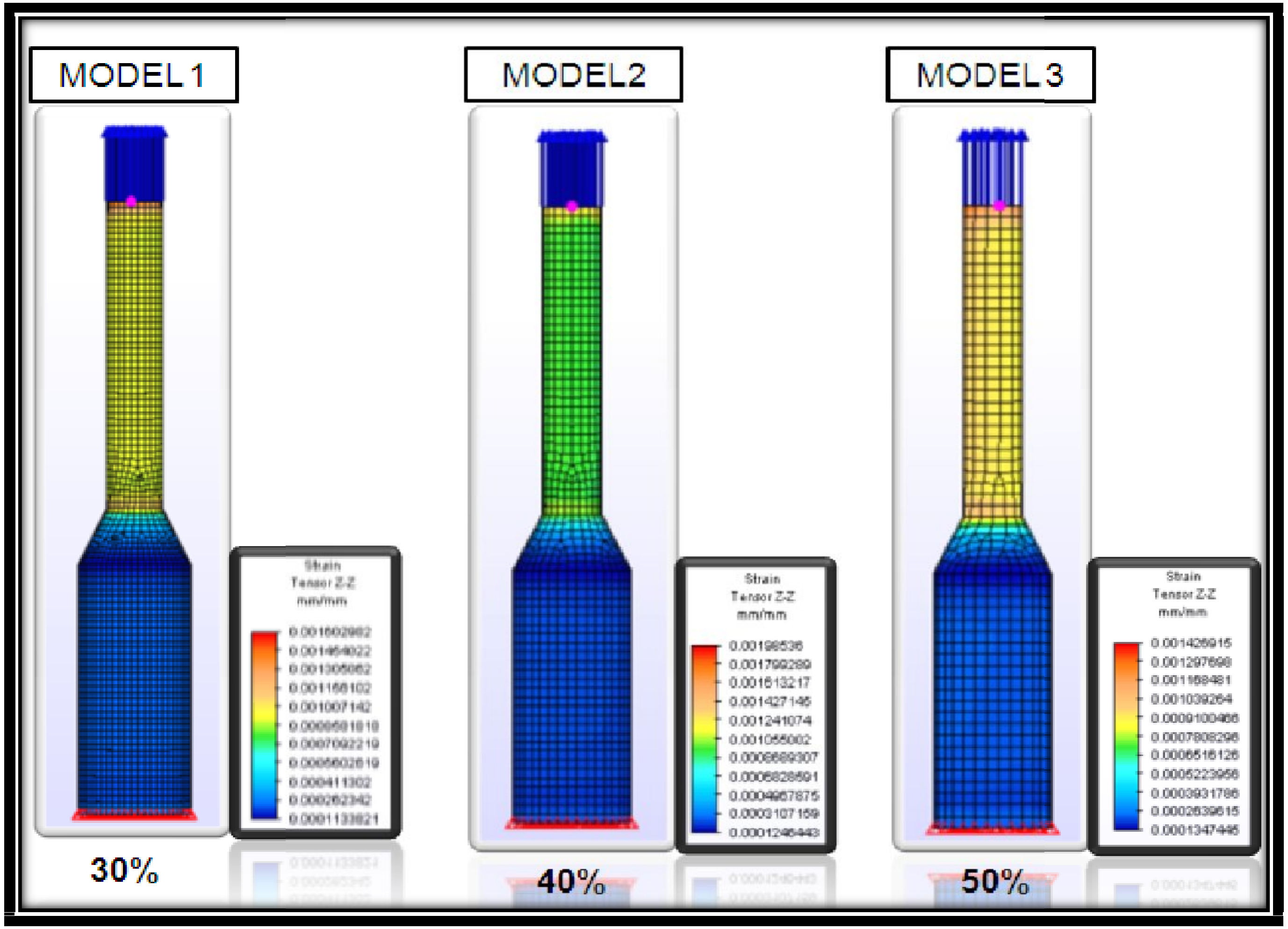
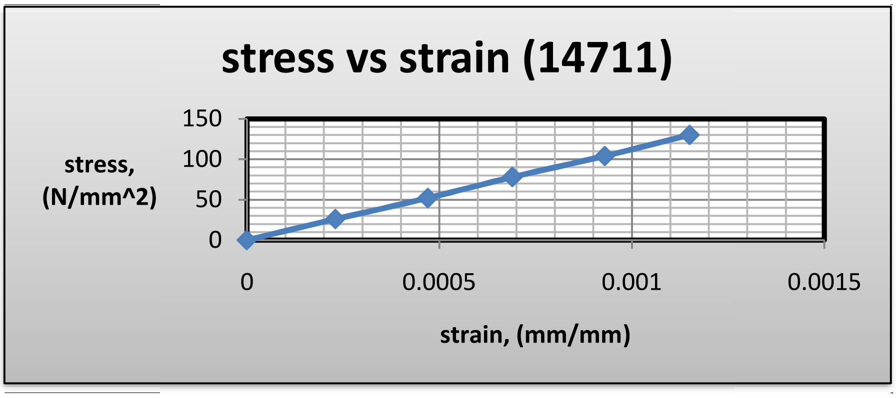
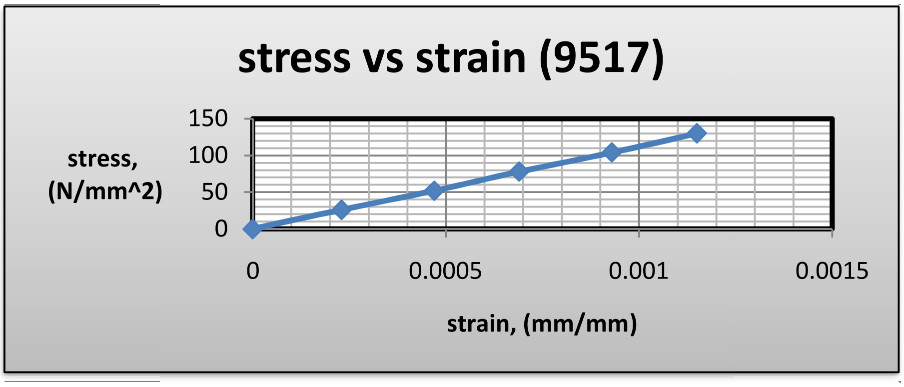


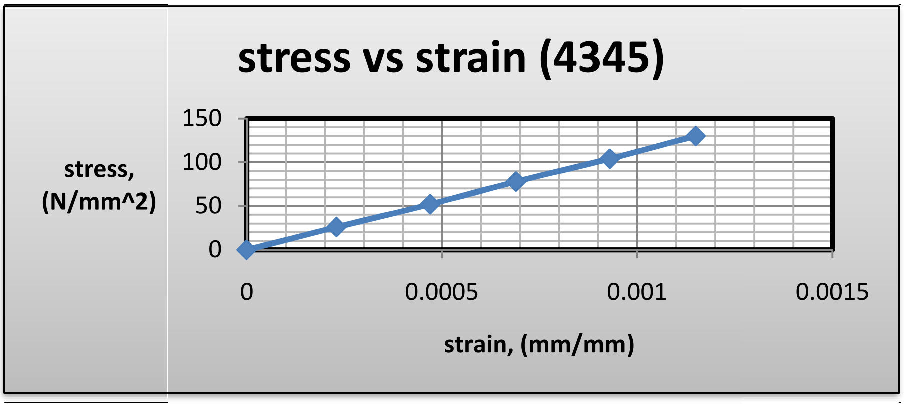
Figure 4.7: The simulated results for strain with different mesh density



First model: Mesh density 30%



Second model: Mesh density 40%



Third model: Mesh density 50%

Figure 4.8: The response curve of stress strain with different mesh density

4.5 Model validation

Figure 4.9 showed a stress strain curve for model validation. From the graph, the Young Modulus for simulation was 118.18 GPa. The actual Young Modulus from experiment was 116GPa. So, the error occured is less than 2% and the model are validated.

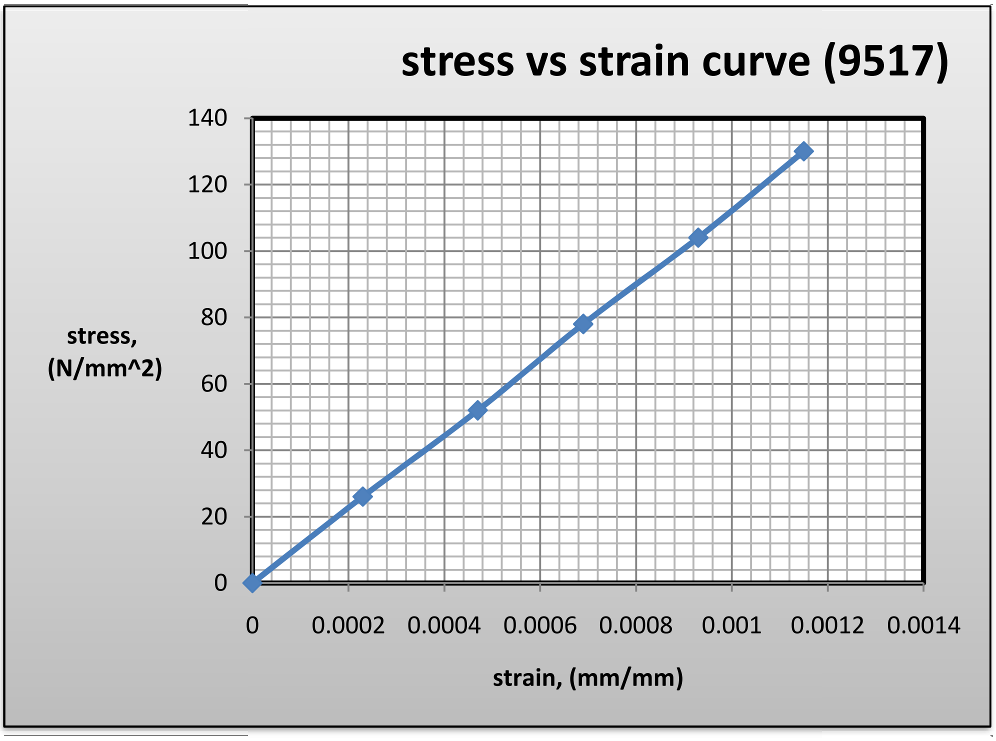
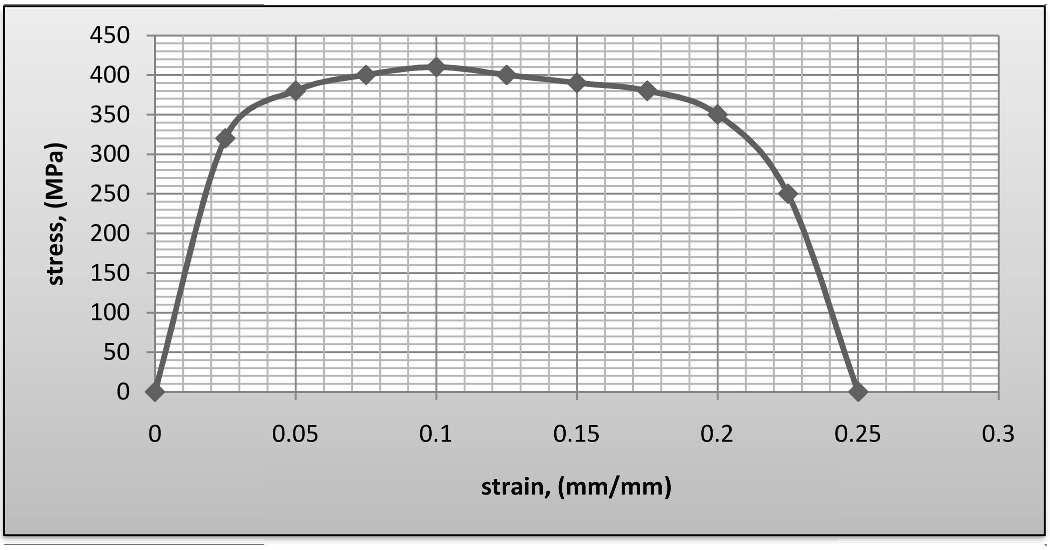


Figure 4.9: The response curve of stress strain for model validation

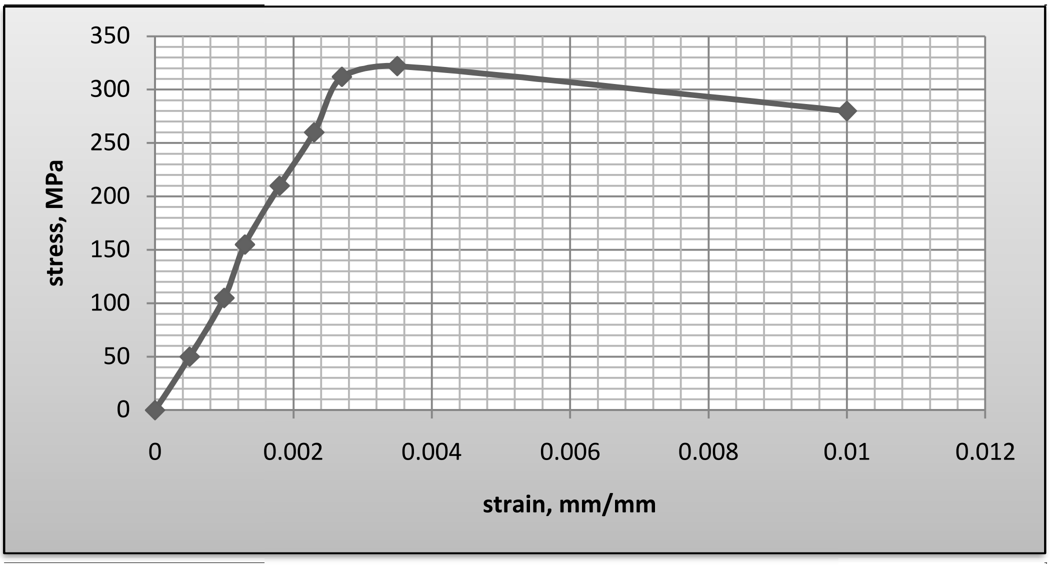
$$\text{Young Modulus} = \frac{(118.18 - 116)\ \text{GPa}}{116\ \text{GPa}} \times 100\ \%$$

$$= 1.88\ \%$$

Finite element model is also validated for plastic region. Graph 1, shows the stress strain response from experiment while graph 2 from simulation. The both graph is agreeable with each other.



1. Stress strain graph from experiment using tensile test



2. Stress strain graph from simulation using ALGOR FE

Figure 4.10: Graph of stress and strain for experimental and simulation

4.6 Strain Rate

For further simulation, second model (30% mesh density) will be used. The simulation is to investigate different strain rate on the model namely for 0.25s, 0.1s, 0.01s, and 0.001s. The table below show the number of simulation.

Table 4.2 : Number of simulation for different strain rate

Simulation number	Time,t (s)	Strain rate, $\acute{\varepsilon}$ (mm/mm)
1	0.25	0.006
2	0.1	0.1
3	0.01	1
4	0.001	3.5

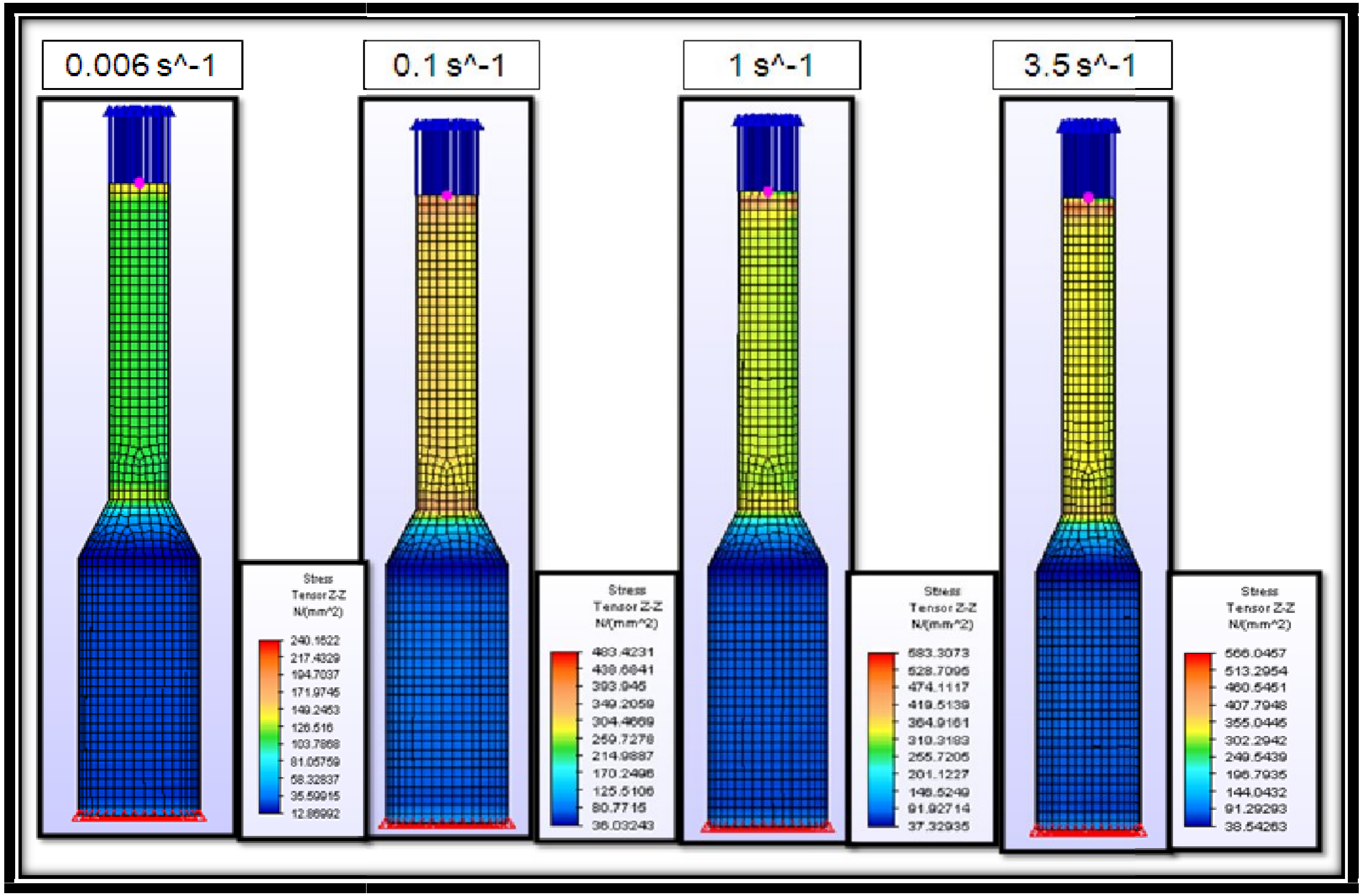


Figure 4.11: The simulated stress results for different strain rate

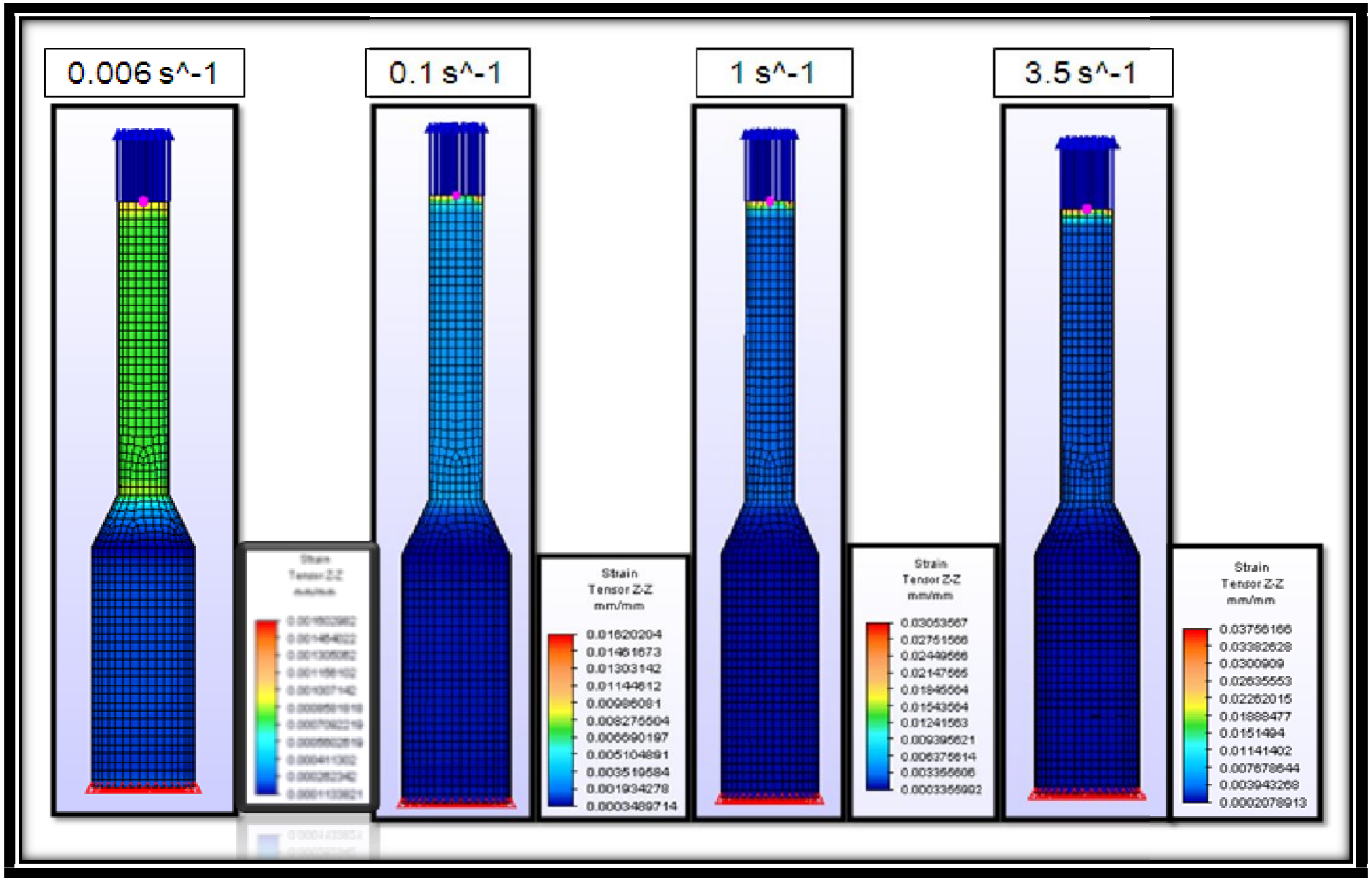


Figure 4.12: The simulated strain results for different strain rate

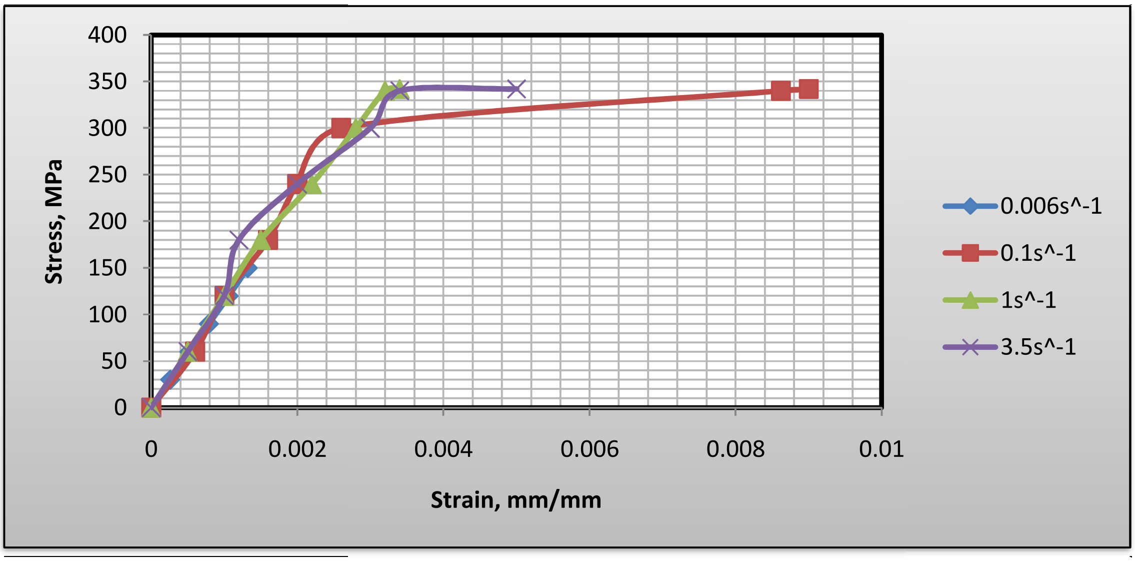


Figure 4.13: The response curve of titanium at different stress and strain rate

This graph showed a stress strain response of pure titanium for different strain rate. Generally, maximum stress induce the titanium higher at higher strain rate which is agreeable with publish report.

4.7 Summary

As a summary, model validation curve is quite same with the experiment and error was found less than 2%. At diffent strain rate, stress is proportional with strain rate namely if the stress increase, strain rate also increase. This conclusion is proven according to the literature that had been made.

CHAPTER 5

CONCLUSION

5.1 Introduction

Chapter 5 summarizes all the main research points of this project. It concludes the crucial information and observation obtained during the project.

5.2 Conclusion

In conclusion, computational model has been successfully developed to predict pure titanium response to tensile load under different conditions. Moreover, the computational model has been validated with experimental result of tensile test. With using ALGOR FE environment response of titanium under tensile loads at different strain rate shows that the stress generally increase as strain rate.

5.3 Recommendation

There are some recommendations to be considered in improving the details of this project. In future work, range of strain rate should be extended to above 1000/s and temperature effects should be included in the computational model. Since there are many applications of titanium at temperature. Experimental tensile test also should be extended to do at higher strain rate.

REFERENCES

Beer, F.P., Jr, E.R.J., and DeWolf, J.T. 2006. Mechanics of Materials. Fourth Edition in SI Units, New York: Mc Graw Hill.

Ertorer, O., Topping, T., Li, Li., Moss, W., and Lavernia, J.E. 2009. Enhanced tensile strength and high ductility in cryomilled commercially pure titanium. *Scripta Materialia* 60 (**7**): 586-589

Huang, H.H., 2002. Effects of fluoride concentration and elastic tensile strain on the corrosion resistance of commercially pure titanium. *Biomaterials* 23 (**1**): 59-63

Hutton, D.V. 2004. Fundamentals of Finite Element Analysis. International Edition. New York: Mc Graw Hill.

Lee, W.S., Lin, C.F., 1998. High temperature deformation behaviour of Ti6Al4V alloy evaluated by high strain rate compression rate. *Journal of Materials Processing Technology* 75 (**1-3**): 127-136

Luo, J., Li, M., Li, H., and Yu, W. 2009. Effect of the strain on the deformation behaviour of isothermally compressed Ti-6Al-4V alloy. *Materials Science and Engineering A* 505 (**1-2**): 88-95

Macdougall, D.A.S., and Harding, J. 1999. A constitutive relation and failure criterion for Ti6A14V alloy at impact rates of strain. *Journal of the Mechanics and Physics of Solids* 47: 1157-1185

Marmy, P., Leguey, T., Belianov, I., and Victoria, M. 2000. Tensile and fatigue properties of two titanium alloys as candidate materials for fusion reactors. *Journals of Nuclear Materials* 283-287 (**Part 1**): 602-606

Paulino, G.H., Carpenter, R.D., Liang, W.W., Munir, Z.A., and Gibeling, J.C., 2001. Fracture testing and Finite Element Modeling of pure titanium. *Engineering Fracture Mechanics* 68 (**12**): 1417-1432

Salem A.A., Kalidindi R.S., and Doherty D.R., 2002. Strain hardening regimes and microstructure evolution during large strain compression of high purity titanium. *Scripta Materialia* 6 (**46**): 419-423

Schneider, R., Goes, M.F.D., Henriques, G.E.P., and Chan, D.C.N. 2007. Tensile bond strength of dual curing resin-based cements to commercially pure titanium. *Dental Materials* 23 (**1**): 81-87

Sun, Q.Y., and Gu, H.C. 2001. Tensile and low- cycle fatigue behavior of commercially pure titanium and Ti-5Al-2.5Sn alloy at 293 and 77K. *Materials Science and Engineering* A316: 80-86

Tsuhiya Toshiyuki, Hirata Masakazu, and Chiba Norio. 2005. Young's Modulus, fracture strain, and tensile strength of sputtered titanium thin films. *Thin Solid Films* 484 (**1-2**): 245-250

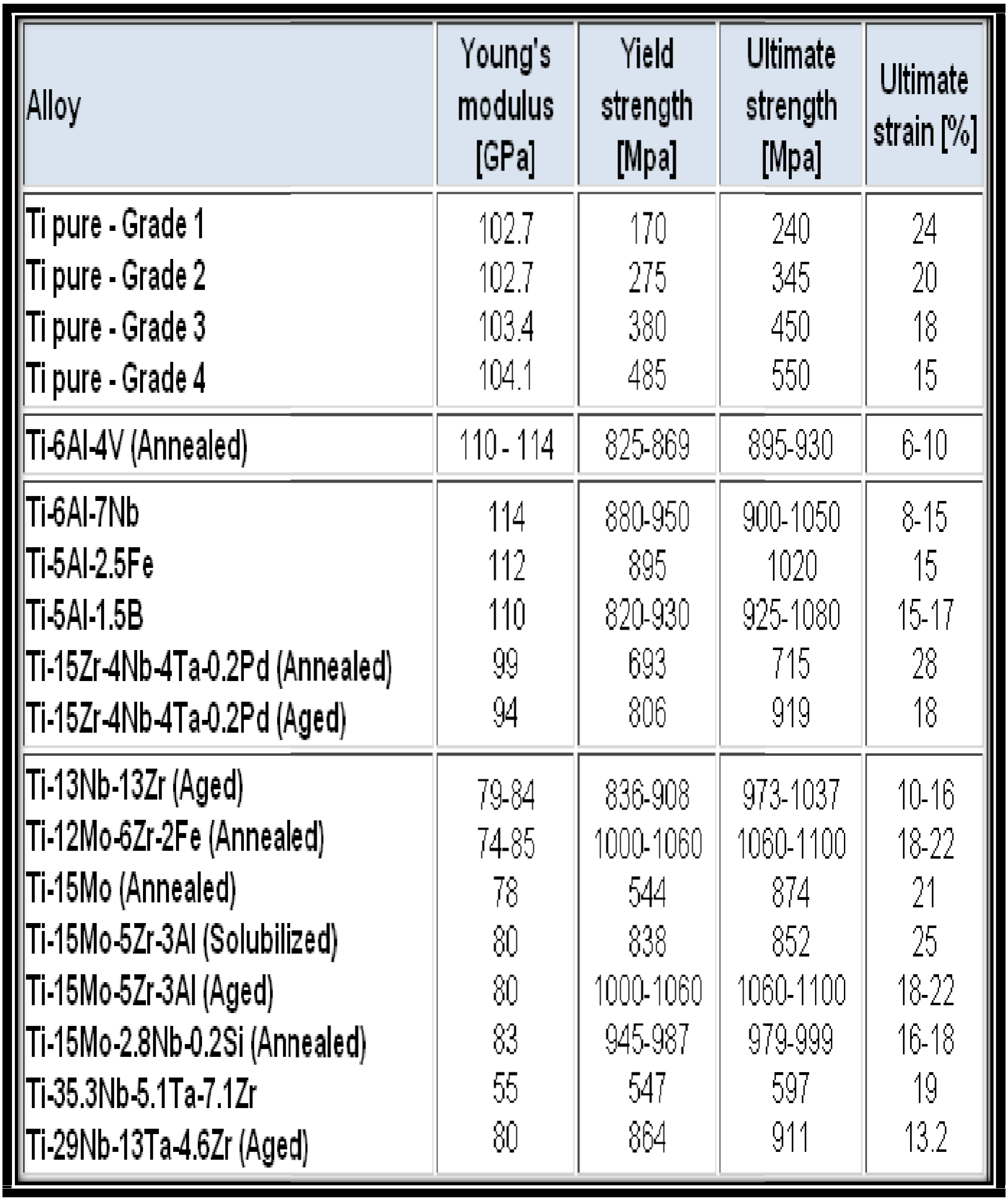
Vanderhasten, M., Rabet, L., and Verlinden, B. 2008. Ti-6Al-4V: Deformation map and modelisation of tensile behaviour. *Materials and Design* 29 (**6**): 1090-1098

Wen, M., Liu, G., Gu, J.F., Guan, W.M., and Lu, J. 2008. The tensile properties of titanium processed by surface mechanical attrition treatment. *Surface and Costings Technology* 202 (**19**): 4728-4733

Yuan, J.M., Shim, and V.P.W. 2002. Tensile response of ductile α-titanium at moderately high strain rates. *International Journal of Solid s and Structures* 39 (**1**): 213-224

Zeng, Z., Jonsson, S., and Zhang, Y. 2009. Constitutive equations for pure titanium at elevated temperatures. *Materials Science and Engineering A* 505 (**1-2**):116-119

Appendix A: Mechanical characteristics of pure titanium and titanium alloys



Alloy	Young's modulus [GPa]	Yield strength [Mpa]	Ultimate strength [Mpa]	Ultimate strain [%]
Ti pure - Grade 1	102.7	170	240	24
Ti pure - Grade 2	102.7	275	345	20
Ti pure - Grade 3	103.4	380	450	18
Ti pure - Grade 4	104.1	485	550	15
Ti-6Al-4V (Annealed)	110 - 114	825-869	895-930	6-10
Ti-6Al-7Nb	114	880-950	900-1050	8-15
Ti-5Al-2.5Fe	112	895	1020	15
Ti-5Al-1.5B	110	820-930	925-1080	15-17
Ti-15Zr-4Nb-4Ta-0.2Pd (Annealed)	99	693	715	28
Ti-15Zr-4Nb-4Ta-0.2Pd (Aged)	94	806	919	18
Ti-13Nb-13Zr (Aged)	79-84	836-908	973-1037	10-16
Ti-12Mo-6Zr-2Fe (Annealed)	74-85	1000-1060	1060-1100	18-22
Ti-15Mo (Annealed)	78	544	874	21
Ti-15Mo-5Zr-3Al (Solubilized)	80	838	852	25
Ti-15Mo-5Zr-3Al (Aged)	80	1000-1060	1060-1100	18-22
Ti-15Mo-2.8Nb-0.2Si (Annealed)	83	945-987	979-999	16-18
Ti-35.3Nb-5.1Ta-7.1Zr	55	547	597	19
Ti-29Nb-13Ta-4.6Zr (Aged)	80	864	911	13.2

Appendix B: Gantt Chart for Final Year Project I

SUBJECT / WEEK	1	2	3	4	5	6	7	8	9	10	11	12	13	14
LITERATURE REVIEW	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩					
SET OBJECTIVE, SCOPES AND PROBLEM STATEMENT				🟩	🟩	🟩								
METHADOLOGY							🟩	🟩	🟩	🟩	🟩	🟩		
LEARNING NASTRAN/PATRAN						🟩	🟩	🟩	🟩	🟩	🟩			
TENSILE TEST								🟩	🟩	🟩				
FYP REPORT I					🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
SLIDE PREPARATION												🟩	🟩	🟩
FYP I PRESENTATION														🟩