ON OBTAINING THE FIRST IMPACT RESPONSE OF SPLIT HOPKINSON PRESSURE BAR APPARATUS

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JUNE 2017

This dissertation is submitted to

Universiti Sains Malaysia

As partial fulfilment of the requirement to graduate with honors degrees in

BACHELOR OF ENGINEERING (MECHANICAL ENGINEERING)

School of Mechanical Engineering

Engineering Campus

Universiti Sains Malaysia

Title of thesis: **ON OBTAINING THE FIRST IMPACT RESPONSE OF SPLIT HOPKINSON PRESSURE BAR APPARATUS**

Date of submission (Academic year): **7/6/2017 (2016/2017)**

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ACKNOWLEDGEMENT

I would like to express my deep gratitude to School of Mechanical Engineering, Universiti Sains Malaysia (USM) led by our present Dean, Dr Zainal Alimuddin bin Zainal Alauddin for the given opportunities to further increase my knowledge related to mechanical engineering in undergraduate programme.

My honest and sincere appreciation to my supervisor, Dr. Roslan bin Ahmad for his patient guidance and regular supervision and encouragement in successfully completing this research. Also a special thank you to Mr Sareh and Miss Liyana Fadzieli that give a lot of effort for helping me during completing this final year project.

Thank you, my beloved mother, Mrs Norizan Binti Ismail for her constant support and leading me to end of the road of this study life. She deserve special mention for her inseparable support and prayers. I also want to thank all my family members and friends who motivated me in this project.

On the other hand, I would like to deliver my appreciation to all lecturers, technicians, staffs and members of the School of Mechanical Engineering for providing the facilities and supports during the progress of the final year project.

Lastly, I want to dedicate this final year project to my late father, Mr Zulkifli bin Busu who became my source of strength for all this time.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

ε	=	Strain rate
v	=	Velocity
Z	=	Impedance
ρ	=	Density
c	=	Speed of wave
ξ_1	=	Wave amplitude
L	=	Original length measured
ΔL	=	Extension measure of length
ε_T	=	Transmitted pulse
ε_I	=	Incident pulse
ε_R	=	Reflected pulse

ABSTRAK

Batang Membelah Tekanan Hopkinson (SHPB), yang juga dikenali sebagai batang Kolsky digunakan bagi mengkaji daya terikan tinggi. SHPB sesuai untuk ujian kadar terikan tinggi dan dikenakan beban dinamik. Sampel diapit di antara dua bar dan dimampatkan selepas mengalami hentaman daripada bar penyerang yang digerakkan menggunakan daya gas. Hentaman berulang kali ke atas sampel dipercayai wujud ketika menjalankan ujian menggunakan SHPB. Disebabkan terdapat hentaman berulang kali, ia mempengaruhi jenis kegagalan yang berlaku di dalam sampel.Tujuan kajian ini adalah untuk mereka bentuk, membina, dan menubuhkan satu perangkap momentum sesuai untuk radas SHPB dan untuk mendapatkan tindak balas kesan pertama dalam bentuk nadi impulsif. Perangkap momentum telah dipasang di hadapan SHPB yang sedia ada sebelum ujian. Ujian ini telah dilakukan dengan perbandingan tingkah laku graf voltan (v) vs masa (s) yang digunakan sebagai ukuran pergerakan alatan SHPB. Perbandingan kejadian nadi voltan Graf dibuat sebelum dan selepas menggunakan perangkap momentum. Akhirnya, hasilnya menunjukkan bahawa kesan berganda boleh dielakkan dengan menggunakan perangkap momentum.

ABSTRACT

Split Hopkinson Pressure bar (SHPB), also referred as Kolsky bar is commonly used setup for high strain rate testing. SHPB is suitable for high strain rate test for safety and structural integrity assessment of structures subjected to dynamic loading. A sample is sandwiched between two bars and compress after impact from striker bar that propelled via gas gun. During testing using SHPB apparatus, a multiple impact on sample is exist. The multiple impact came from disturbance wave inside the bar of the SHPB that effect failure behavior of the sample. The aim of this study is to design, fabricate, and commission a momentum trap suitable for SHPB apparatus and to obtain the first impact response of it in the form of impulsive pulse. The momentum trap were set up in front of the existing SHPB before test. The test were done with comparison the behavior of voltage (v) vs time (s) graph that used to indicated impact behavior of the apparatus. A comparison of incident pulse in voltage graph are made before and after using the momentum trap. Finally, the result show that the multiple impact can be avoid by using the momentum trap.

CHAPTER 1

INTRODUCTION

1.1 Background Research

The understanding of materials behavior is an important area of study in engineering. Material behave differently when subjected to different loading and rates. Hence, the characterization of material is a continuing study especially on a new material to obtain the stress-strain behavior and its fracture or failure behavior. There are two category of tests which involve material deformation that is static test and dynamic test. There are also several type of deformation like low strain rates and high strain deformation. Many applications experienced a high strain rates deformation like drop object, explosions, penetrations, and engineering application like bullet proof armors, and crash test of vehicle. Dynamic failure is suggest to has strain rates ε = 10 s-1 as lower limit [1-5]

In dynamic recovery experiment, the sample is subjected to strain pulse then recovered without additional loading. One of the apparatus that use for dynamic test is a Split Hopkinson Pressure Bar (SHPB).Split Hopkinson Pressure Bar (SHPB) named after Bertram Hopkinson, sometimes also called a Kolsky bar. SHPB technique involves two elastic bars called the incident and the transmission bars, and a dynamic loading device, usually a gas gun with an elastic striker bar, which imparts to the incident bar a uniaxial stress pulse (figure 1.1).

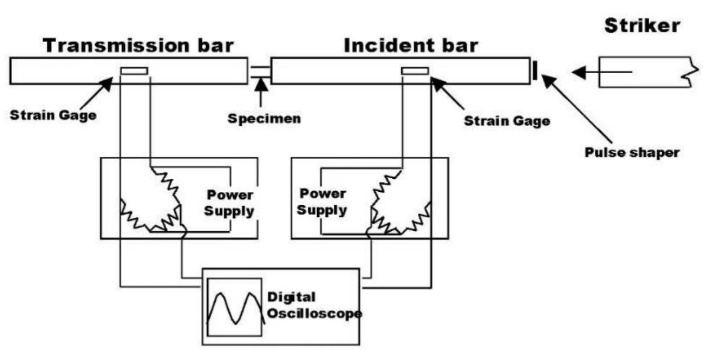


Figure 1.1: Schematic diagram of SHPB

The test specimen will be sandwiched between incident and transmitted bar. This apparatus attached with strain gage at both incident and transmitted bar and the recorded pulse will appear on computer showing two type of graph, there are voltage vs time and strain vs time graph. Then the specimen will be undergo scanning electron microscope (SEM) to study the behavior of its failure.

1.2 Problem Statement

The dynamic impact study of a material is less accurate during the compression test using the split Hopkinson pressure bar (SHPB) apparatus. A number of study discovered that SPHB apparatus has some disadvantage such as multiple impact or unnecessary impact that affect the failure in the sample. Additional impact is a reloading impact that came from incident bar that hit sample more than one time. The reloading impact can be discover via voltage graph by strain gage. From the voltage graph, it show the incident pulse (impact) that came from incident bar hit the specimen. After the impact from incident bar, some of the pulse will transfer into transmitted bar (transmitted pulse) and some will reflected back to incident bar (reflected pulse),[5]. As shown in figure 1.2, the reflected pulse will reflect back and forth in the incident bar, which resulting in additional reloading on the specimen. As a result, the failure in the sample will be affected and will result inaccurate image SEM.

To avoid the multiple impact and inaccuracy in the response of failure in the specimen, a design such as momentum trap need to be added into the SHPB apparatus. Hopefully this additional fixture will eliminate or reduce the multiple impact occur in the present set up of the SHPB.

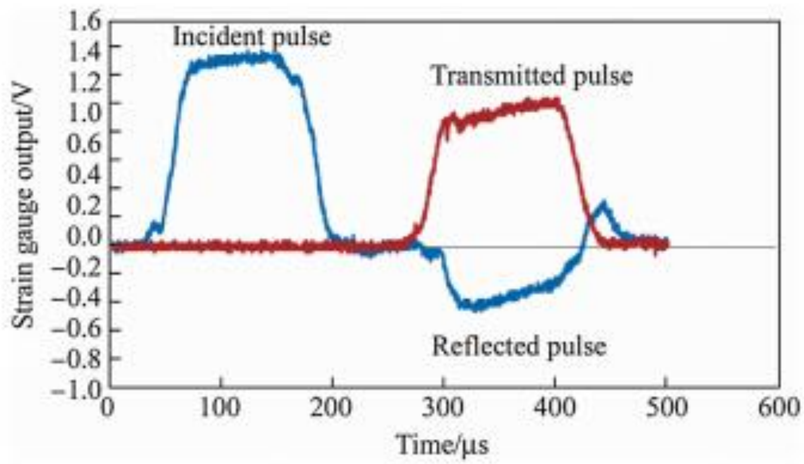


Figure 1.2: Voltage (V) vs time(s) graph of SHPB

1.3 Objectives

1. To design, fabricate, and analyze a momentum trap suitable for SHPB setup.
2. To obtain and verify the first impact response of SHPB apparatus.

1.4 Research Approaches

In this project, a momentum trap has been design is to obtain the first impact response of the SHPB apparatus. The momentum trap will avoid the reflected pulse from passing back and forth and avoiding multiple impact from incident bar to the specimen. The momentum trap involved three parts and will canceled out the reflected pulse after hitting the specimen for the first time.

The design are create using Solidworks CAD which involves all of three parts. The list of the parts is incident tube, reaction mass, and a transfer flange. The type of material selected based on the existing SHPB materials. The parameter of the design that has been considered are thickness, materials, and its individual functions. After completing designing the momentum trapping, it was fabricate and machined in the School of Mechanical Engineering. The fabrication involve several process such as cutting, drilling and threading.

The experiment of work commence after the momentum trap was assembled into the SHPB. The experiment use a kernaf material as a sample that sandwiched between the incident and transmitted bar. The distance between the incident tube and reaction mass was used as the parameter and the manipulated variable. The optimum gap between incident tube and reaction mass is investigate by analyzing the result of pulse in the term of voltage vs time graph gain from strain gage.

The voltage vs time graph of incident pulse from both using the momentum and non-momentum trap will be compared. The behavior and difference of having momentum trap based on the voltage vs time graph and the optimum gap length between the incident tube and reaction mass in the momentum trap will be discussed in chapter 4.

CHAPTER 2

LITERATURE REVIEW

2.1 Split Hopkinson Pressure Bar

Split Hopkinson Pressure Bar (SHPB) apparatus is an experimental technique created by John Hopkinson (1872) and continue by his son, Bertram Hopkinson [6] (105, 1914), that manage to establish the dynamic strength of metal wires, experimentally. Bertram Hopkinson is credited with developing the first time-resolved measurement technique to produce a pressure–pulse profile. For this major contribution and for the pioneering effort of his father, the technique has been named after them [7].

The next important contribution was made by Davies (1948) [8]. Davies, in his detailed critical study of the Hopkinson technique, describes a method in which the displacement of the free end of the bar is measured using a parallel plate condenser, in which the end of the bar serves as the grounded plate. The amplified output of this microphone is then recorded and used to obtain the displacement history of the bar's end. When the bar remain elastic, a technique for direct measurement of the stress (or strain) profile in the Hopkinson bar is established.

The third important contribution in the development of SHPB apparatus was made by Kolsky (1949), who use two elastic bars (in contrast to the Hopkinson and to Davies, who used a single bar) with the specimen sandwiched in between, and, hence, created a technique which has come to be known as the split Hopkinson bar method. This method is used for studying the dynamic properties of materials over the range of strain rates in essentially uniaxial stress states. Kolsky followed Davies's (1948) technique [9] to measure the stress profile in both bars, and related these to the stress-strain history of the sample, through a one dimensional elastic wave analysis.

2.1.1 Split Hopkinson pressure bar part

The split Hopkinson pressure bar involve several part like gas gun, striker bar, incident bar, transmitter bar, lead plate stopper, amplifier and monitor display. As in figure 2.1, the striker bar, incident bar, specimen and transmitter bar were align has the same diameter and align symmetrically.

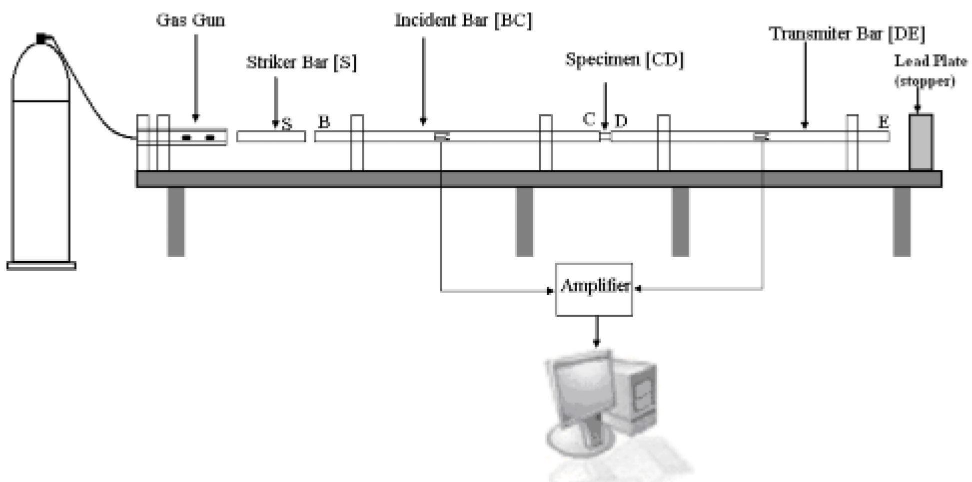


Figure 2.1: schematic of split Hopkinson pressure bar (s.sharma, V.M Chavan)(2011)

2.2 Working Principle of Split Hopkinson Pressure Bar

Split Hopkinson Pressure Bar (SHPB) works on the principle of one dimensional wave propagation. Its consist components like a gas gun, a striker bar, an incident bar and a transmission bar. The transmission bar, incident bar, and striker bar are all made with same material and same cross-section area. The striker bar place in the barrel at the gas gun chamber. The sample is sandwiched between the incident and transmission bar. The gas fill up in the gas gun by setting the pressure in the computer. Then, the striker bar is propelled by the gas pressure towards the incident bar. Then the incident bar later will impact the specimen.

Following the impact, there are pulse inside the bar. When the striker bar hit the incident bar, an incident pulse move along inside incident bar. After that, it transfer inside sample and some pulse is partly transmitted to the transmission bar (transmitted pulse). Some will reflected as tension back in the incident bar call a reflected pulse. From the transmitted pulse, the stress calculated in the sample, using the strain record obtain through a strain gauge placed appropriately on the transmission bar, and from the reflected pulse, one estimates the strain in the sample by integrating the strain measured by a strain gauge suitably attached to the incident bar. The strain gauges also mounted in the form of half Wheatstone bridge to remove the effect of any bending and measure only the axial strain. The theory for SHPB apparatus can be discuss more by using an equation especially wave propagation equation.

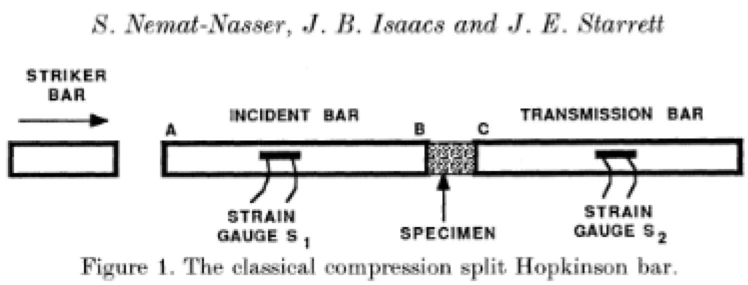


Figure 2.2 compression of split Hopkinson pressure bar (S. Nemat-Nasser, J.B Isaacs and J.E Starrett)

2.2.3Velocity after Impact of Two Bars

Figure 2.3 shows two bars, before and after impact. Consider pressure bar with different velocity, which V_1 has higher velocity than V_2 figure 2.3.

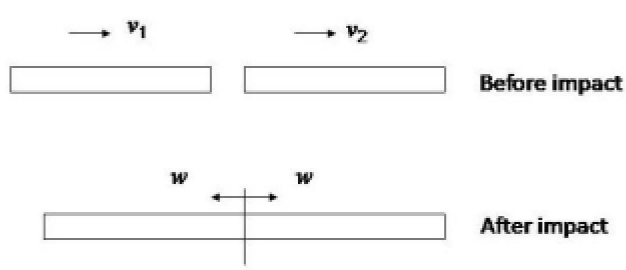


Figure 2.3 impact illustrator between bar (s.sharma, V.M Chavan)

The *w* is consider the velocity in each bar after impact.

$v_1 - w = w + v_2$,

so $w = (v_1 - v_2)/2$

But, usually in Split Hopkinson pressure Bar, the transmission velocity $v2 = 0$ then,

$$w = \frac{v_{SB}}{2}$$

2.2.4 Reflection of Wave

Wave reflection from boundaries are divide into three types which are soft boundary, hard boundary and from an impedance discontinuity (neither rigid (hard) nor free (soft). For SHPB apparatus, the exact behavior of reflection and transmission depends on the material properties for both incident and transmission bar. The impedance between two materials is the product of mass density and wave speed. $Z = \rho c$. If a wave with amplitude ξ_1 in medium 1 encounters a body with medium 2, the amplitude of reflected wave is

$$\xi_r = \frac{Z_1 - Z_2}{Z_1 + Z_2} \xi_1$$

For amplitude of wave transmitted in medium 2 is

$$\xi_2 = \frac{2Z_1}{Z_1 + Z_2} \xi_1$$

2.2.5 Strain in Bar Due to Pulse Loading

The ratio of extension to original length is call strain with no unit as it is ratio of two length measured in meter, if

$$strain = \frac{extension}{length}$$

So length,

$$strain = \frac{\Delta L}{L}$$

Where,

Strain = strain it has no limits

ΔL = extension measure in length

L = original length measured in meter

In SHPB there are compressive pulse that developed due to impact produces elastic strain in the incident bar. At time = 0, there is no strain in the bar. At time = t, the pulse length is C_0t. The elastic strain generated is,

$$\varepsilon = \frac{-u}{C_0 t} = \frac{-w}{C_0}$$

2.2.6 Impulse in Split Hopkinson Pressure bar

In experiment of SHPB, the result appear with three main impulse, which are, incident pulse, transmitter pulse, and reflected pulse. The path travel of each pulse can be easily illustrated with figure 2.4

The shape of the impulse obtained in voltage vs time graph has an influence on material behavior during the test [10], figure 2.4 show the three pulse shape, which are incident pulse, transmitter pulse, and reflected pulse. The relationship of all the pulse can be represent by

$$\mathcal{E}_T(t) = \mathcal{E}_I(t) - \mathcal{E}_R(t).$$

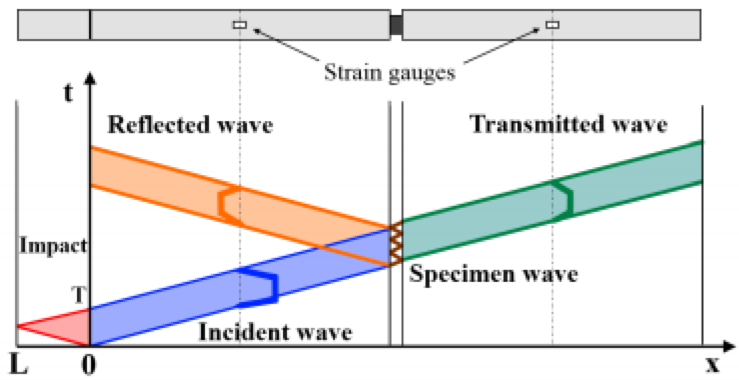


Figure 2.4 Path of pulse travel

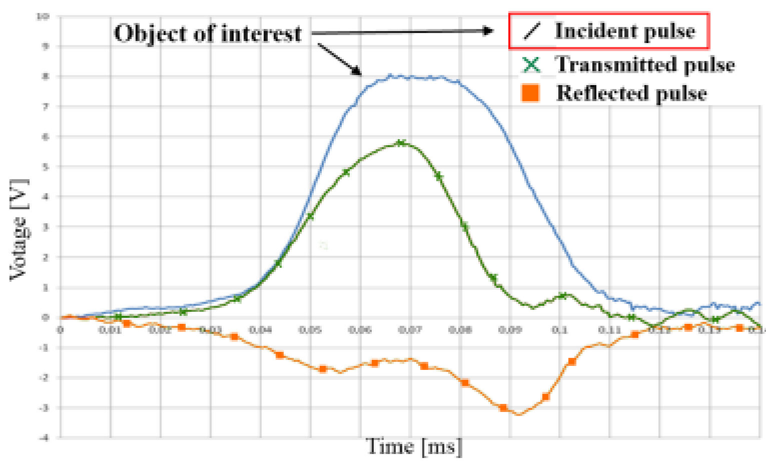


Figure 2.5 impulse shape of SHPB apparatus

2.3 Additional features in SHPB

2.3.1 Tandem Momentum Trapping

The standard split Hopkinson pressure bar (SPHB) apparatus cannot be employed for interrupted testing due to stress wave reflections from interrupted testing due to stress wave reflections from ends that reload the specimen, leading to its compaction. The technique is in the form of metal bar, with the same impedance as the input bar, aligned such that it was co-axial to the input bar and offset from the free end by a small gap. The problem is, the actual size of the gap must be determine by conduct the experiment for several time. This might be wasting time and effort.

The tandem momentum trap (TMT) concept does require accurate gap setting and cannot be used routinely. This technique recently is also used in tensile testing by Isakov, which has demonstrated the feasibility of this approach to different Hopkinson bar arrangement [11].

2.3.1.1 Operating Principle

The operating principle of tandem momentum trap, as adapted to a SHPB, is shown in the figure below. Firstly, the striker launch by a gas gun, it impact to the flange at the input bar. This results in two separate compressive waves, the first propagating through the input bar and the second through first momentum trap. Then, the striker will rebound after the impact, provided that its impedance is less than the combined impedance of the input bar and is less than the combined impedance of the input bar and the first momentum trap. Since both the momentum trap are designed to be impedance of the input bar, the second wave transfers to the second momentum trap without reflection. When the wave reaches the free end of the second momentum trap, it is reflected as a tensile wave. Due to the first momentum trap cannot support tensile load, the tensile wave reflects as a compressive wave and causes the separation of the second momentum trap from the first. Provided that the striker has the same wave speed but is shorter than momentum traps, all the energy of the second stress wave will be captured in the second momentum trap while the first momentum trap to remain in contact with the first transfer flange.

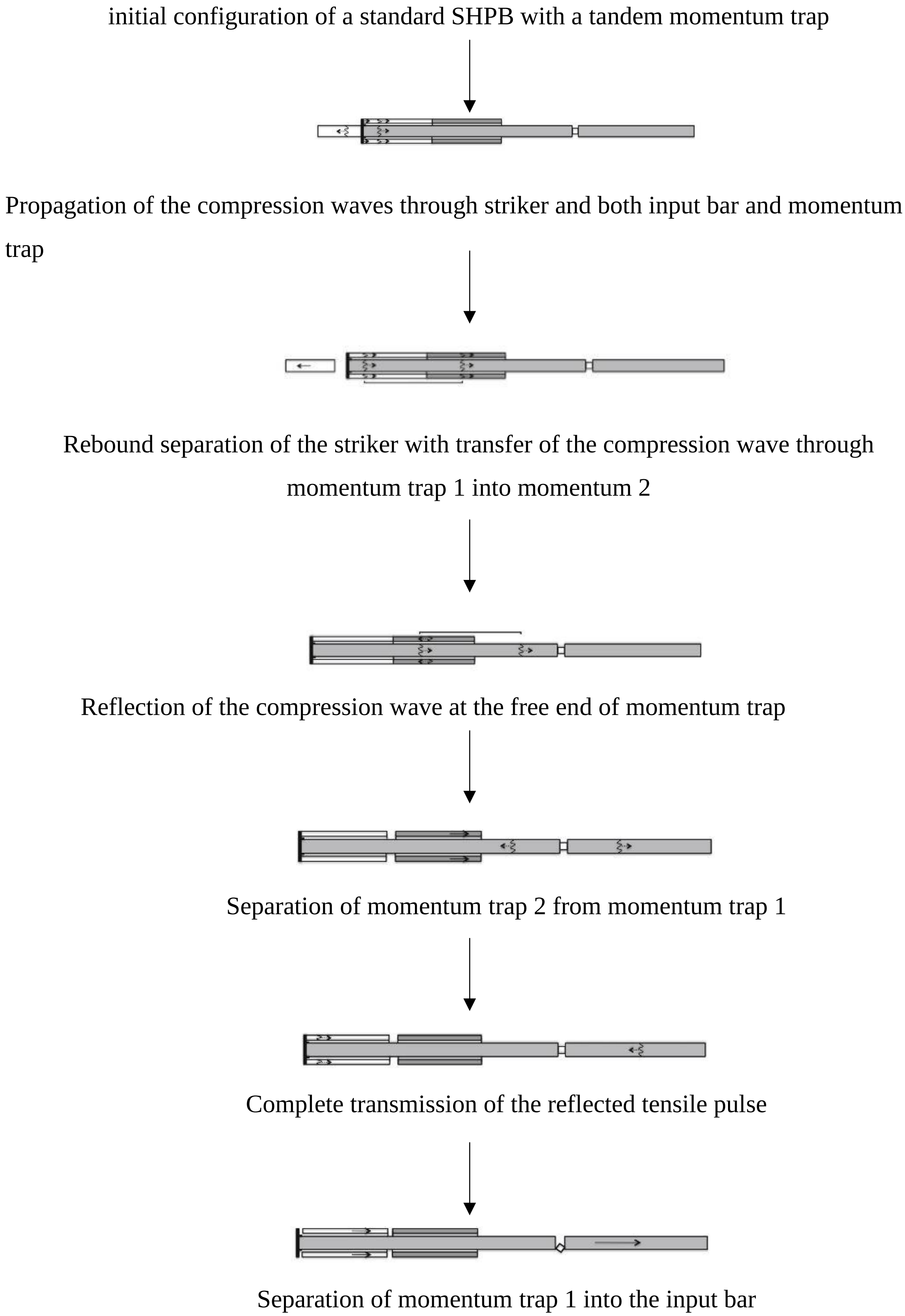


Figure 2.6: Phase of impact with momentum trap

2.3.2 Tandem Momentum Trap with another configuration

The concept use in this type of momentum trap is same with Tandem Momentum Trap (TMT), but it use a different configuration of input bar. As in figure 2.6, the output bar was supported by three Teflon bushings. Similarly, the midsection and specimen end of the input bar were supported by Teflon bushings, while the impact end of the input bar had to be indirectly supported due to presence of the first momentum trap. In this case the impact end of the first momentum trap was supported in an external Teflon bushing, while the input bar was in turn, supported by a Teflon bushing pressed into the first momentum trap.

The annular clearance between the input bar and first momentum trap was 1.6mm, which was dictated by the available standard aluminum tube sizes. This relatively large clearance resulted in the transfer flanges being more compliant that intended, which led to suboptimal behavior of the TMT concept. Different from previous momentum trap, this configuration is independently mounted in two external Teflon bushings and only made contact with the first momentum trap through the second transfer flange. The annular clearance between the first and second momentum trap in in this configuration is 0.75mm.

In this type of momentum trap, the material use for flange is Titanium (Ti). The selection of Ti material is more due to its stiff than Aluminum. Titanium also strong, corrosion resistant compare to aluminum.

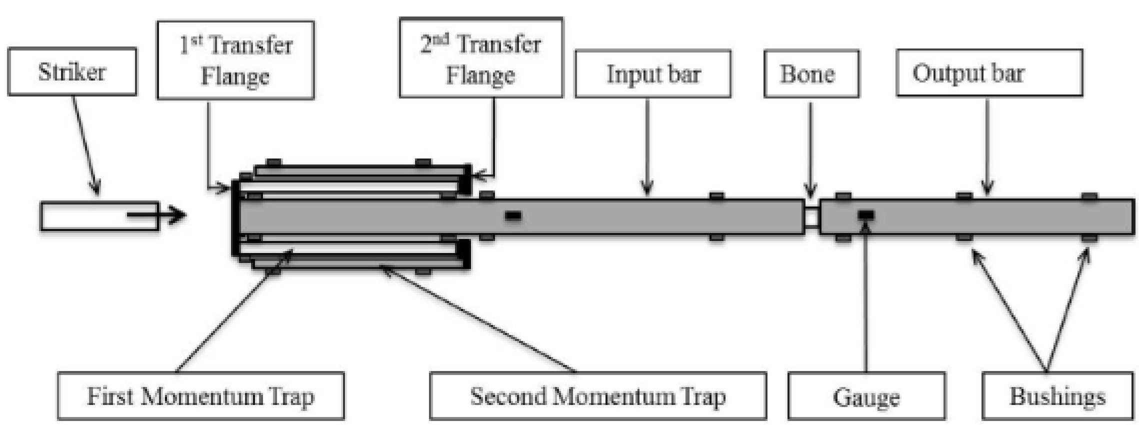


Figure 2.7: Different Configuration of Momentum Trap

In this configuration, compare to the previous Tandem Momentum Trap, does not need a gap presetting so will be simple than TMT and avoid repeating test. Series of strikers of differing length need to cover a range of strain rates. Higher impact velocity is needed and it will limits the upper strain rates.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this study, the first impact response of SHPB apparatus is obtain by using experimentally using additional momentum trapping technique. Stage I of the study is to study existing momentum trapping design by other researcher that using different configuration and technique. Then, the characteristics of the Split Hopkinson Pressure Bar that located in lab were study. Its dimension and materials are taken from its specification, the working principle were study by reading a journal and run a few experiment.

Then, the stage II is to design the momentum trap using a CAD which is Solidworks software. The design of momentum trap consist three part which are transfer flange, incident tube, and reaction mass (figure 3.1). The momentum trap is placed at the front of the incident bar as it works as a stopper to avoid the reloading effect. Each parts were design with specific function according to the momentum trap work. The transfer flange design should be fix with the incident tube while the incident tube and it need to use higher in hardness as it will be hit by the striker bar. The incident tube must sliding through the incident bar, so a perfect dimension and thickness of the design must be considered to avoid friction and vibration. The reaction mass working principle is as to absorb the impact carry from the sliding incident tube and the bounce the incident tube back to transfer flange, so also must fix to the SHPB apparatus and high in hardness.

After completing the design using a CAD software, the stage III of this study begin which is a fabrication process. The materials choose for each part is mild steel, due to its hardness, elastics modulus and economic. The machines use for this stage are, lathe machine, cutting machine, and drilling machine.

In stage IV, the momentum trap were install on the SHPB apparatus, and experiment were conducted. The experiment to get the pulse in the SHPB apparatus with the relationship between voltage (v) vs time (s) graph. To capture the movement of the momentum trap and impact of SHPB apparatus on sample, the high speed camera were used. The final or stage

V, is the analysis of the data by using i speed camera software, and discussion graph and impact behavior of SHPB apparatus using momentum trap.

Figure 3.2 shows the flow chart of the whole process to the improved design of SHPB which include the use of a momentum trap.

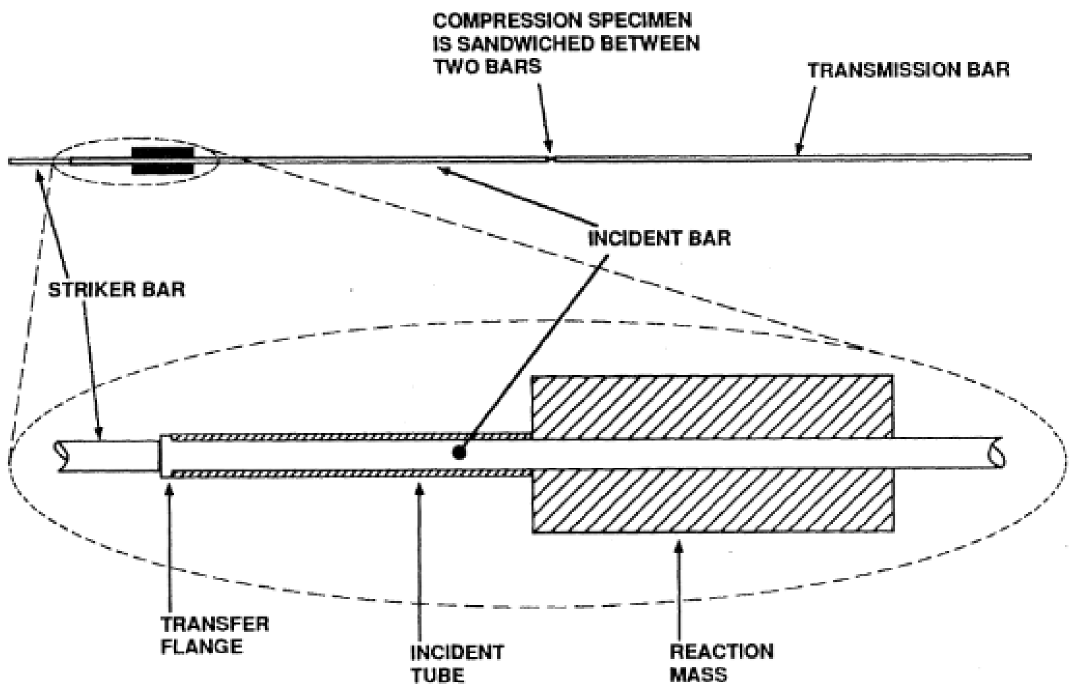


Figure 3.1: Part of momentum trap on SHPB apparatus

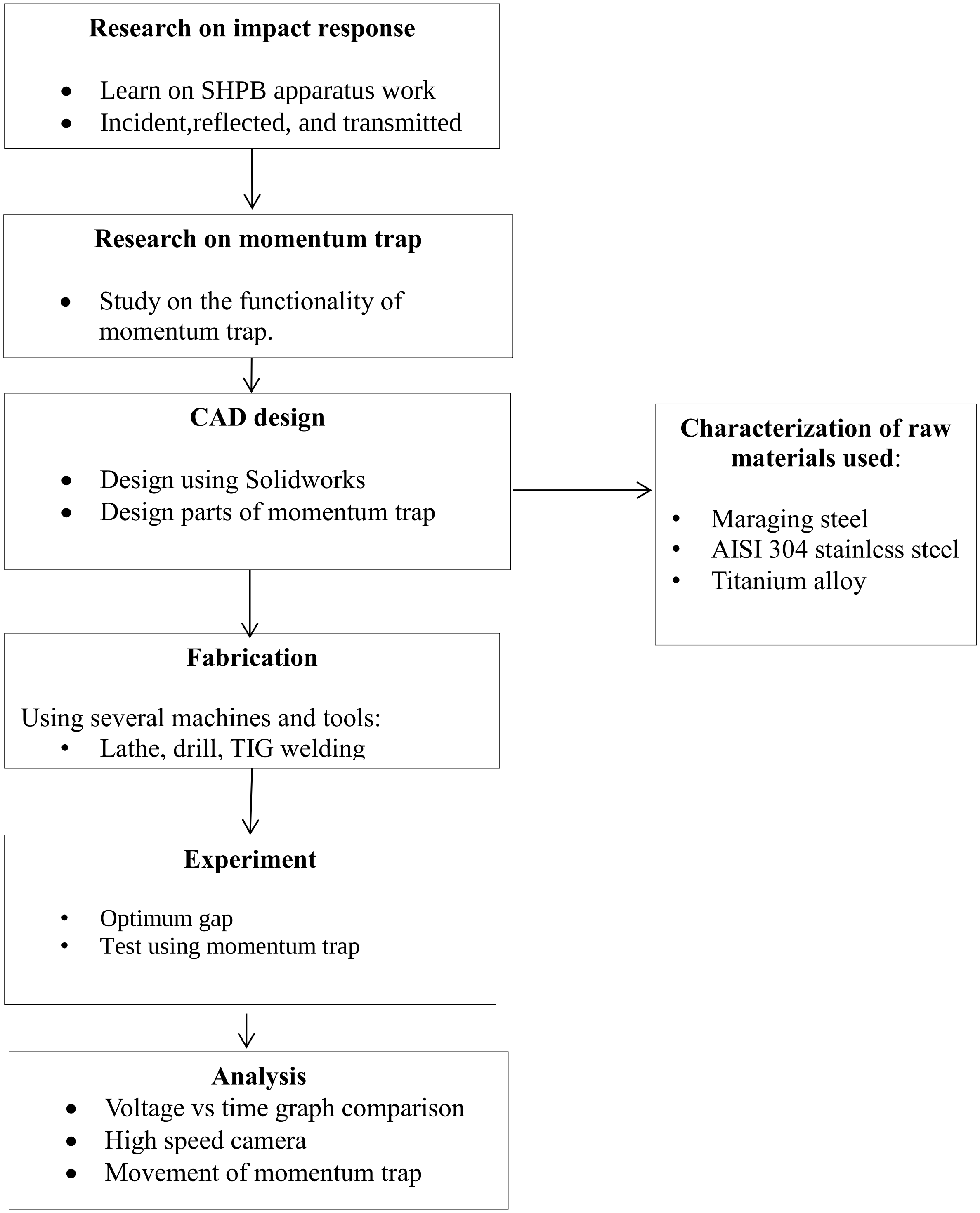


Figure 3.2: Flow chart of implementing momentum trap in SHPB

3.2SHPB Apparatus

Split Hopkinson Pressure Bar at USM engineering campus (figure 3.3).

Figure 3.3: Split Hopkinson Pressure Bar facility at USM engineering

3.2.1 Material

The material of SHPB apparatus is alloy of iron or call maraging (18Ni) steel. Other common name is grade 250 maraging steel. The UNS number for this material is K92890. The British Standard (BS) designation is S162. The properties of this material is shown in table A1. The table shows the properties of three different type of materials which are 250 Maraging steel, AISI 304 steel, and titanium Ti-8Al-1Mo-1V. The properties that important to momentum trap design is elastic young modulus, ultimate tensile strength (UTS), and yield strength (MPa). The momentum trap should have almost similar properties with material of SHPB apparatus. For this study, a 250 maraging steel is difficult to get, due to costs and its rareness. For young modulus, the AISI 304 steel has slightly higher than maraging steel, but it is much better than Titanium alloy that has low elastic young modulus compare to maraging steel alloy. For UTS, momentum trap should has a higher value of it and Ti alloy is a better choice compare to 304 steel. But, the UTS value of 304 steel is enough the requirement.

Finally, the AISI 304 steel is chosen for all three part in momentum trap as it fulfill the requirement from each parts

3.3 Momentum Trap Design

The momentum trap were set up in front of the incident bar (figure 3.4)

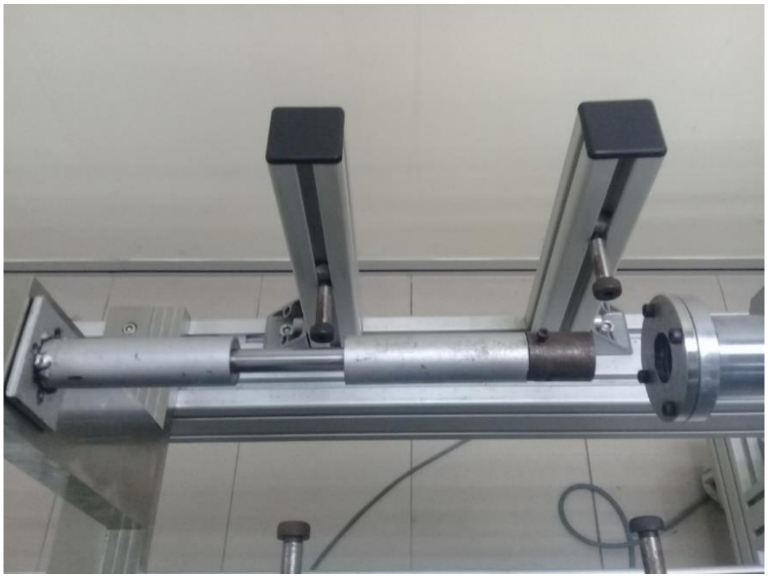
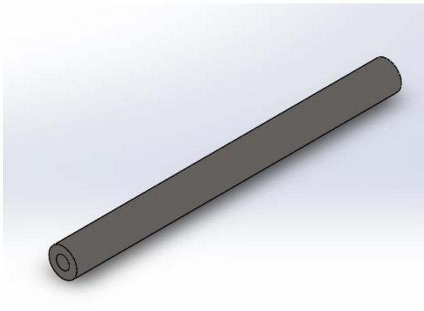
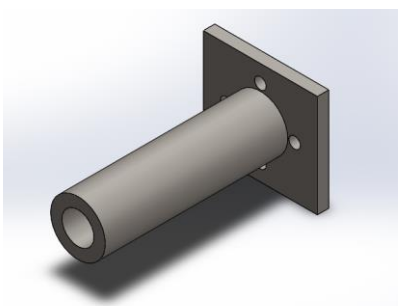
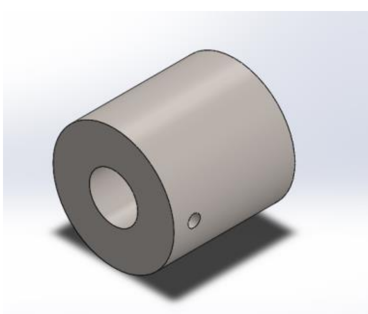


Figure 3.4 momentum trap set up on incident bar

Table 3.1: Momentum trap parts materials and dimension

Parts	Material & Dimensions
	• The inner diameter (ID) of this part is 12mm, and the outer diameter (OD) is 24mm. • The thickness of the cylinder trap must be same with incident tube diameter. • The selection of material is Steel AISI 304, which its young modulus is 190GPa.
	• Has a base that contain four holes to tight with stand on SHPB • The material selection for the reaction mass is AISI 304. • This is due to this material has high yield strength that is 710 N/mm2.
	• The transfer flange consideration is the material must be strong enough to experience the impact of the striker bar. • The inner diameter (ID) of this part is 12mm, and the outer diameter (OD) is 24mm. • Has tiny hole for screw to fit it into SHPB incident bar

3.4 Fabrication of Momentum Trap

Momentum trap fabrication is done by using all machines and material available in School of Mechanical engineering, USM. Three part were fabricate which are transfer flange, incident tube and reaction mass. Several process of machining has been done like drilling, cutting, welding and lathe.

3.5 Experiment Using Split Hopkinson Pressure Bar

3.5.1 Specimen preparation

The specimen dimensions is follow the below relation:

$$\frac{L}{D} = \sqrt{\frac{3\upsilon}{4}}$$

Where L is the length, D is the diameter and υ is the Poisson's ratio of the specimen.

The faces of the sample are parallel and stick with some grease just to make sure it stick to the incident and transmitted tube. After the test, the specimen diameter always smaller than the diameter both of pressure bars.

3.5.2 Selecting the bar

1. Determine the impedance (ρcA) of the specimen.

Where ρ the density, c is $\left(c = \sqrt{\frac{E}{\rho}} \right)$ is the wave speed and A is the area.

2. Then select the pressure bars (steel or Aluminum) closer to the impedance of the specimen. We also have different diameters for the pressure bars.

Note: The basic thumb rule is that we use steel bars for the harder materials (metals etc..) and Aluminum bars for the softer materials (polymers, foams etc..).

3. After the pressure bars are selected, make sure the end faces of the bars are flat and parallel.
4. Align the pressure bars and striker on the mounting frame.

3.5.3 Experimental procedure:

(a) Give all required connections. Connections include: Connect the BNC cables from the amplifier to the oscilloscope. Check the right channels and connect them. Make sure the amplifier (2310A) and oscilloscope are grounded. Do not change any settings on the amplifier. The amplifier has been calibrated for 350 ohms strain gages. Please refer to manual if you we wish to make any changes and let everyone in the lab know before you make any changes. Turn ON the amplifier and oscilloscope.

(b) The excitation voltage and gain are set to 10V and 100 respectively. Turn the reset switch ON for all the four channels.

(c) Check the resistance on the strain gauges and they should read around 350 ohms.

(d) Set the voltage levels, trigger position, data duration time (2ms-4ms), for all the four channels in Oscilloscope. These values depend on the experiments.

(e) Balance the Wheatstone bridge for all the four channels by turning the reset button.

(f) Check whether the bars are well aligned or not, and also the projectile should be well aligned to the impact end of the incident bar.

(g) Then make sure that the bars are moving freely, if not apply WD-40 lubricant and adjust the screws of the clamps.

(h) Clean the interfaces of the bar and the projectile with Kim wipes and ethyl alcohol.

(i) Push the projectile to the end of the barrel of gas gun assembly with a flexible poly rod.

(j) Measure the dimensions of both specimen and pulse shaper. Dimensions include: diameter and thickness.

(k) Select the striker depending on the strain rate you are trying to get. You can vary strain rate by using different pressures and different striker bars. Make sure the pulses are not getting overlapped. If the pulses are getting overlapped, use the shorter striker bar. (Thumb rule: The longer the striker, the lower the strain rate. The higher the pressure, the higher the strain rate).

(l) Lubricate both faces of the test specimen with Molybdenum disulfide lubricant and sandwich the specimen between the bars and align the specimen with respect to bar center.(figure 3.5)

(m) Place the pulse shaper at the impact end of the incident bar with a thin layer of Dow Corning lubricant (if you are using lead pulse shaper) and align it with respect to bar center. We generally use clay and lead pulse shapers. These give us very good results for harder materials, but for the softer materials, you can try different pulse shapers. These include paper, copper etc.

(n) Release the nitrogen gas from the gas tank into the gas gun chamber until the required pressure level is achieved.

(o) Arm the oscillation to capture the strain gage voltage signals and make sure the arm holds until you release the projectile. If the arm is not holding, adjust trigger levels. (Note: if you are getting high noise in your signals more than 20mv, turn off the tube lights before the experiment).

(p) Once again, ensure that the specimen is well aligned between the bars and verify the status of the trigger hold before pressing the solenoid valve release button.

(q) Press solenoid valve control box button to release the projectile.

(r) Save captured voltage pulses onto a USB drive for further analysis of the data.

After the experiment is completed, turn off the cylinder and make sure all the left over nitrogen gas in the gas chamber is released.

(s) After the data is transferred from the oscilloscope to USB drive, verify that in your computer and turn off the amplifier and oscilloscope.