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Investigation of Explosive Welding Using Plasticine as a Model Material.

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Committee Decision

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NOMENCLATURE

d	Diameter of flyer plate $[mm]$
L	Height of flyer plate$[cm]$
D	Diameter of cavity $[cm]$
h	Depth of penetration $[mm]$
v	Impact(incident) velocity $[m/s]$
Y	Yield stress $[MPa]$
V_p	Flyer plate velocity $[m/s]$
V_d	Detonation velocity $[m/s]$
m	The mass of flyer plate $[kg]$
m_r	The mass of the re-entrant jet $[kg]$
m_s	The mass of the salient jet $[kg]$
β	Angle of obliquity [o]
α	Incidence angle [o]
ρ	Density $[kg/m^3]$
η	Damage number [–]

ABSTRACT

The explosive welding process is one of the most useful and widely employed applications of the high energy rate forming methods to metal fabrication. Its major advantage lies in that it does not suffer from the limitations imposed on other welding processes due to its superior characteristics.

Most of the parameters affecting explosive welding have been widely investigated in the literature. However, little have been reported on the affect of the flyer plate velocity and the angle of incidence on the welding process and the mechanism of deformation.

Investigation of explosive welding using plasticine as a model material is reported and discussed in this thesis. Plasticine has been used for both the target and the projectile material to simulate the metallic materials . This permits the use of equipment based on industrial stud driver which is substantially cheaper than other equipment.

The various modes of deformation have been identified, and the results obtained on plasticine can be applied to metallic materials. .

Chapter 1

Introduction and Literature Review

1.1 Introduction

Explosive welding or cladding, as often called, is bringing together of two similar or dissimilar metals with sufficient impact velocity and pressure to cause them to bond.

Explosive have been used by military and mining engineers for hundreds of years. However, it has not been recognized until last century, that explosives can be used successfully in mining and quarry work. The big impetus to explosive working of metals came in mind in the 1950's with the demands of working large parts for the aerospace and other heavy industries [1].

Historically, explosive welding was noticed, if not recognized, as a solid state welding process during the First World War, when high-velocity pieces of shrapnel from the disintegration of metal casing of shells or bombs were observed to stick to steel stanchions or other metal surfaces. However, there appears to have no scientific investigation of this phenomenon at that time. It appears that Carl (1944) [2] was the fist to have noted welding under high-velocity impact, in experiments in which a detonator was separated by two half-hard brass shims from a booster charge of high-detonation-velocity explosive. Recovery of the brass disc after detonation of the charge showed that they had been welded together, and a micrograph of the section showed small poorly formed interfacial waves, now frequently associated with explosive welds. Carl concluded that the weld was not a fusion weld, but that it had been formed by a solid state mechanism.

In the late 1950s several research workers in different countries started to study the possibilities of explosive welding, and it is difficult to establish who was the first to realise its practical value.

Credit is frequently given to Philipchuk [3] who, in 1957 noted explosive welding when explosively forming an aluminium U-channel in a steel die, but perhaps more importantly, he recognised its potential commercial value in his patent which was granted in 1962 [4]. Pearson [5] was in the period 1956-1958 working on explosive processes for powder compaction, and he noted if the press plates were misaligned such that their faces were not parallel, the plates became explosively welded together. Waves at the weld interface were noted, which were similar to those observed by Allen et al [6]. According to Pearson [5] he and Allen concluded that the two phenomena were related to the same basic process, and they used the term, surface jetting , to describe this process.

This was perhaps the first appreciation of what is now recognized to be the basic mechanism of explosive welding. Other early workers in the field were Davenport and Duvall [7] Cowan, Douglass and Holtzman [8], who demonstrated the understanding of the jetting phenomena. It appears that the realization of the potential commercial value of explosive welding stimulated early work in Russia, Japan and the United Kingdom.

Since these early days explosive welding has become recognized as a practical process with the following advantages as reported by Zaid [1]:

1. Capital investment is low, in its simplest form the process requires only explosives, detonators, and the work piece.

2. Plates can be welded without prior elaborate surface preparation.

3. There is no limit to the size of the parts that can be welded. Surfaces up to $10m^2$ were successfully welded, and thin sheets or foils can be welded to much thicker plates and cylinders.

4. Strong metallurgical bonds can be produced even between combination which can not be welded by any other known method. For example, tantelum can be explosively welded to steel although the melting point of tantelum (5400F) is higher than the vaporization point of iron.

5. The process can be conducted at remote locations.

On the other hand explosive processes are not free from problems and possess the following limitations:

1. The process produces shock waves and a great deal of noise and, therefore, it can not be performed within a factory, but has to be carried out on an isolated area or when the factory has a vacuum chamber within limited sizes.

2. The plates welded by this method suffer some slight deformation during the bonding process and they would require rolling after welding [9].

3. Safety hazard. explosives are generally considered to be hazardous devices in handling and storing. This is not realistic, because the people who work with explosives, such as shock fires in coal mines, quarries and metal working processes have one of the lowest accident rates in industry [10].

1.2 Theory and Mechanism of Explosive Welding

1.2.1 Techniques

A number of techniques have been developed and used for the production of clad plates, the basic set-up to achieve welding between two metallic plate is illustrated in Figure(1.1) [11] in which the top, or the flyer plate is supported with the minimum of constraint at a small angle of incidence relative to the stationary, and the parent plate which is supported on an anvil which might be a metal pate. The upper surface of the flyer plate is covered with a protective layer or buffer, and a layer of high explosive, either in the form of a sheet explosive or powder laid above the buffer as discussed by Bahrani [11]. The explosive charge is detonated from one end by an electric detonator and the resulting detonation pressure imparts momentum to the flyer plate and causes it to move toward the parent plate with high velocity. The two plate eventually collide obliquely and as a [Bresult of this collision the plates become strongly bonded to each other.

1.2.2 The Mechanism of explosive Welding

Welding can be defined as a process of joining two or more materials, often metallic, by a localized coalescence or union. To achieve this, two basic requirements have to be satisfied [11]: first, to produce absolutely clean and uncontaminated surfaces, and second to bring these uncontaminated surfaces close together to be within the range of inter-atomic attractive forces [12].

These two conditions are basic to all welding processes even though the method of achieving them may differ. For example in fusion welding the two metal surfaces being joined and melted by application of heat, and the contaminated surface films are either brought to the surface of metal pool or are dissolved with the molten metal, while in explosive welding, the essential requirements for bonding are met by the production of a metallic jet which sweeps away the contaminants from the surfaces being bonded [13].

1.2.3 The Jet Formation

It has been known that the force of an explosive charge can be concentrated on a small area by hollowing out the opposite area, and this effect is known in the United States and the United Kingdom as the Munroe effect. In the early years of the Second World War, it was discovered that lining the cavity in the charge with a thin steel liner , it was possible to perforate armour plate, concrete walls and other structures with a small explosive charge.

The mechanism of the shaped charge with metal lining was studied by Birkhoff et al [14].

Bahrani and Crossland [15] use similar analysis to explain the mechanism of explosive welding.

Upon detonation Figure(1.2), if the collision velocity and the angle of incidence are controlled within certain limits, high pressure is developed in the vicinity of the collision point and distributed in such a way that the metal surface can hydrodynamically flow as a spray of metal from the apex of the angled collision. The flow process and explosion of the metal surface is known as jetting, under these circumstances the impinging jet divides into re-entrant jet and a salient jet Figure(1.3). The effect of this jetting is to remove the contaminated surfaces of both metals leaving contamination free surfaces, the virgin surfaces behind the jet make molecular contact under a true metallurgical bond of wavy interface as shown in Figure(1.4).

Various mechanisms have been proposed to explain the wave formation in explosive welding. Abrahamson based his proposed mechanism on the wave observed in the tray of sillicon putty, which was moved at a constant velocity under a fixed water jet.

A very useful experimental technique to obtain a better physical picture of the wave formation was used by Bahrani et al [15]. This consisted of electroplating a very thin layer of some trace metal on either or both the parent plate or the flyer plate, so that when the plates are welded together, it may be sectioned and the distribution of the trace material examined, in their experiments they used copper-plating to investigate the wave mechanism in mild steel to mild steel welds. An extension of this technique has been used to study the welding of copper to copper and copper to lead.

The mechanism proposed by Bahrani [15] appears to be in a reasonable agreement with their experimental observations, and it was also supported by the experimental work of Wilson and Brunton [16]. they were interested in wavy interface produced on metal surfaces by high speed impact of liquid drops, such as in the rain erosion of high speed aircraft and in steam turbine blade erosion by wet steam. Cowan and Holtzman [8]. were probably the first to recognize the obvious similarities between the interfacial waves in explosive welding and the fluid flow around an obstacle, in which regular formation of eddies is observed.

A simple method of measuring flyer plate velocity by using a pin contactor arrangement was carried out by Shribman et al [17], the non- dimensional plot for results of flyer plate velocity using Trimonite No.3 and No.1 as explosives show that thicker layers of explosive are less effective in acceleration the flyer plate to a given velocity.

A recent investigation on the topic was carried out by Salem [18], in which a short high speed water jet is used for spot welding metallic combinations of different materials and thicknesses. The jet, which is extruded from a specially constructed portable water jet gun, is made to impinge on a thin flyer plate, causing it to deform locally forming a dimple (bulge) which advances with a high speed. The impact of the dimple on the parent plate, which is separated from the flyer plate by a suitable gap, gives rise to a condition of oblique collision similar to that encountered in explosive welding causing the flyer plate to be welded to the parent plate.

1.3 Quality and Strength of the weld

1.3.1 The Main Variables in explosive Welding process

The quality and strength of the bond produced between plates depend on the welding conditions and parameters used. There are four main variables to be considered in the process, these are :

1. The angle of incidence .

2. The velocity of flyer plate .

3. The properties of materials being bonded .

4. The properties of explosive used .

The effect of some of these variables have been studied by Bahrani [15] and Pocalyko [19].A large number of mechanical tests have been carried out on explosively clad metals especially mild steel clad with titanium, these included tensile test, shear test, bend test, and micro indentation hardness test. In general most explosively welded metals showed the following characteristics at the joint as reported by Zaid [1].

1. Withstanding the 180° bend with out any separation at the weldment .

2. Failing at the weaker metal and not at the weld zone in the shear and tensile tests .

3. Meeting high temperature and quenching in water cycles without weld failure .

4. It can be cut, machined, rolled, flanged, blanked, drawn, and extruded successfully .

1.4 Application Of explosive Welding

Explosive welding has proven to be a practical and economical technique in the following applications :

1. Welding of plates and cylinders .

   Plate of similar and dissimilar metals were successfully welded by explosives over area ranging from few square centimeters up to $30m^2$. Figure(1.1) shows the experimental set up for welding two plates. In the case of welding two cylinders or two tubes, two systems are used, Explosive welding Figure(1.5), and Implosive Welding Figure(1.6).

   The explosive welding system consists of a constraining die with two coaxial cylinders placed inside and the explosive charge located in the bore of the inner cylinder. On detonation, the flyer cylinder expands and impacts the outer (parent) cylinder at high velocity and pressure causing welding

   The implosive system requires only a temporarily rigid inner cylinder bore support, and a charge enveloping the outer surface of the other cylinder . The outer surface or in this case the flyer surface collapses on the inner (parent) cylinder [13].

   The flyer and parent metals can cover a wide range of metals where corrosion resistance or other special properties of an expensive metal are combined with the strength and economy of an inexpensive one. The aim is to cut the cost of plant without sacrifice of any technical qualities.

   The welded parts can be machined, drilled and formed with out loss of bonding. In fabricated form, they can be subjected with confidence to high pressures, temperatures, vacuum, thermal cycling and heat transfer applications [1].

2. Fabrication of stiffened and fibre-reinforced structures.

Many designs require the use of integrally stiffened and cell supported structures in a wide variety of metal alloys ranging from high strength aluminium alloy through tetanium, iron, nickel base alloy to the refractory metals.

In many cases certain alloy can not be welded to fulfill these requirements. To fulfill these requirements the explosive welding process has been successfully applied.

Otto and Carpenter [20] produced TZM molybdenum wire reinforced C129Y columbam alloy composite by explosive welding, which has a potential application to the construction of the space shuttle.

3. Welding of tubes into tube-plates.

Tubes can be welded to tubed-plates by using explosive. An experimental set up for this process of welding using parallel clearance between the tube and the tube-plate is shown in Figure(1.7). Other set-ups using tapered clearance by either tapering the tube-plate hole outwards or tapering the tube surface inwards are possible and discussed by Chadwickd [21].

It is confidentially believed that this method can be industrially applied in power stations for welding of tubes of condensers, boilers and heat exchangers, especially where access is too difficult to allow conventional welding as in nuclear reactors.

4. Pipe lines

In joining of pipes in a high pressure pipe lines, e.g in the oil field, the method applied is welding to secure that the joint can withstand the high pressure, explosive welding can successfully applied for this purpose.

To obtain a good quality weld in pipe line, the pipes are flared at one end (female end) for a length of about $3cm$ at an angle ranging from 5^o to 7^o

and reamed. The other pipe end (male end) can be used in the as-supplied condition. Before the pipes placed to overlap each other, a mandril is inserted, which is attached to a cable to facilitate the removal after welding Figure(1.8). after the lining up of the pipes a rubber sleeve, i .e the buffer and explosives are attached and detonated resulting in a strong joint.

Chadwick [21] has reported different techniques of welding pipes by explosives together with the development of a technique for producing high integrity joints between 1", 3.5",and 8" diameter pipes.

5. Storage tanks

Depending on the purpose of storage tanks, their capacities range from few cubic meters up to $100000m^3$, the demand for large capacity tanks has led to the use of high strength steel. These storage tanks can be successfully welded by explosives with less costs than the conventional methods.

6. Welding of a patterned array of rods

A very recent application of explosive welding is the welding of an array of similar or dissimilar metallic rods. The main application of this method will be in the long- distance electric power transmission. For example in practice aluminium cables reinforced with steel cable cores are used for long-distance-electric power transmission in Norway [1]. Other application will be in the atomic power industry as a preliminary step to the production of more complicated shapes.

The experimental set up used is shown in Figure(1.9) where a 1/4" diameter steel is surrounded by six similar rods tangential to each other. The rods are contained in a thin copper casing tube of 0.765" inside diameter and 0.0075" thickness. The assembly is further contained in a plastic container which holds the explosive material, Termonite No.3 of 0.6" thickness.

Upon detonation of the charge, the copper casing will collapse and a metallic jet is extruded from its inner surface causing a cleaning of surfaces of the rods from any layers or contaminants. The high instantaneous pressure will bring molecular contact between rods resulting in a strong metallurgicall bond [1].

1.5 Objective of the present work

Based on literature review presented, a great amount of research has been carried out on the process, and its applications, little has been carried out on some of the important parameters affecting it, these are :

1. The velocity of the flyer plate .

2. The angle of incidence .

The object of this work is to investigate the effect of these parameters using plasticine as a model material.

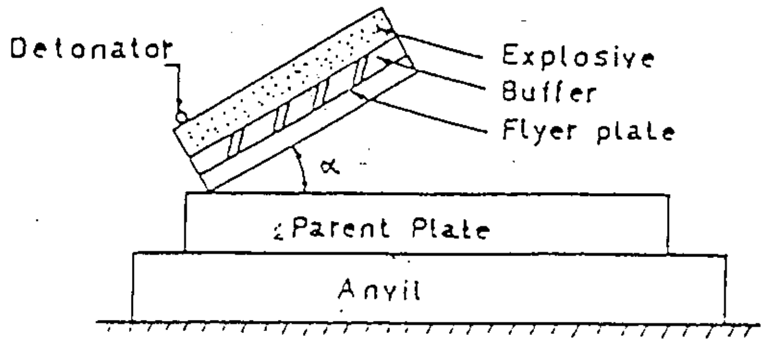

Figure 1.1: Arrangement of welding plates

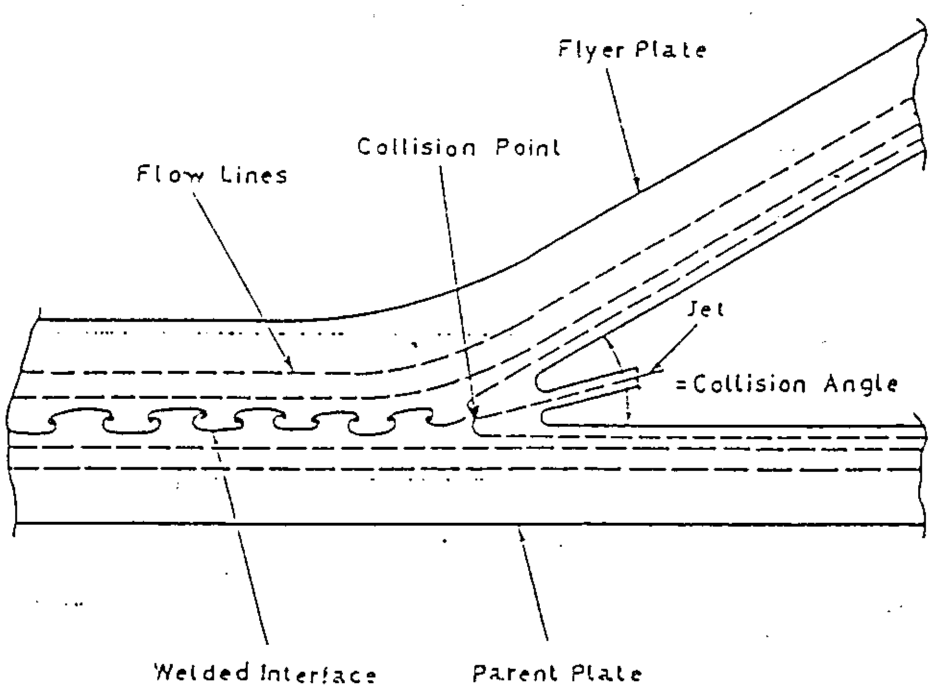

Figure 1.2: Illustration of plate-collision process and resultant jet during explosive welding

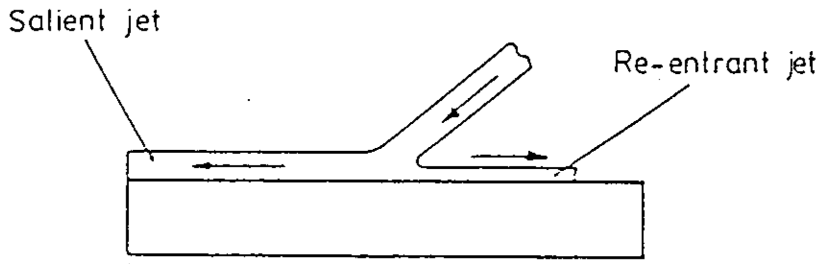

Figure 1.3: Division of flyer plate into salient and re-entrant jets

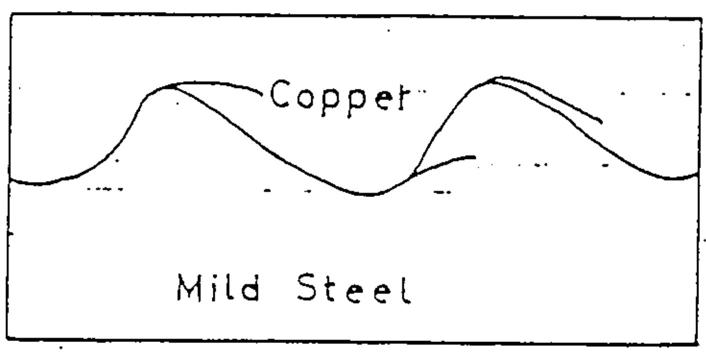

Figure 1.4: Interface of copper explosively welded to mildsteel

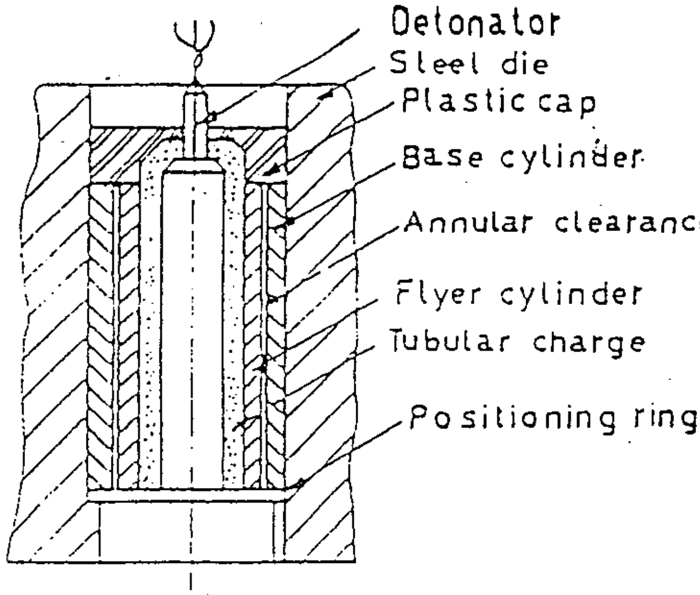

Figure 1.5: Explosive welding system after Ref.[1]

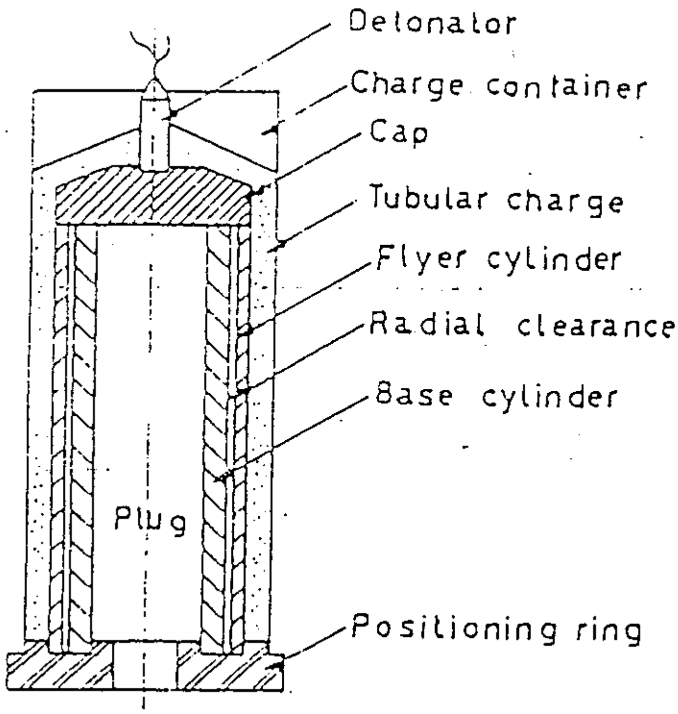

Figure 1.6: Implosive welding system after Ref.[1]

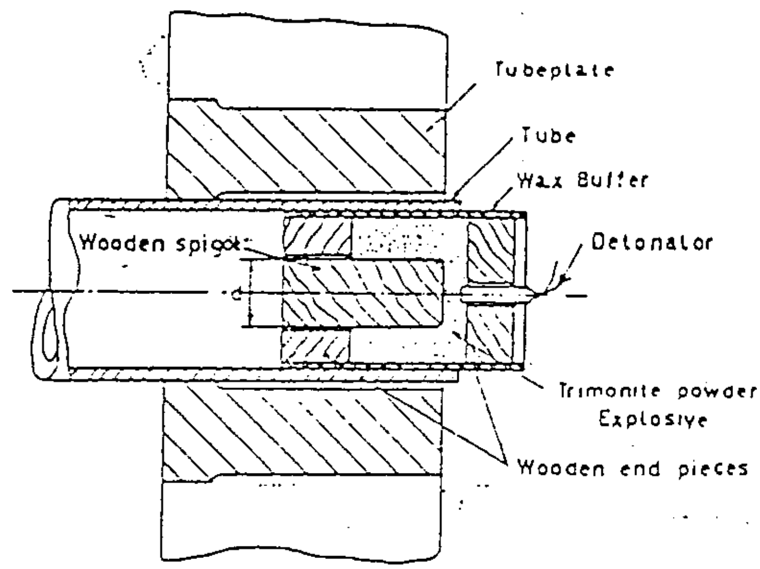

Figure 1.7: Experimental set-up for welding tubes to tube plates after Ref.[1]

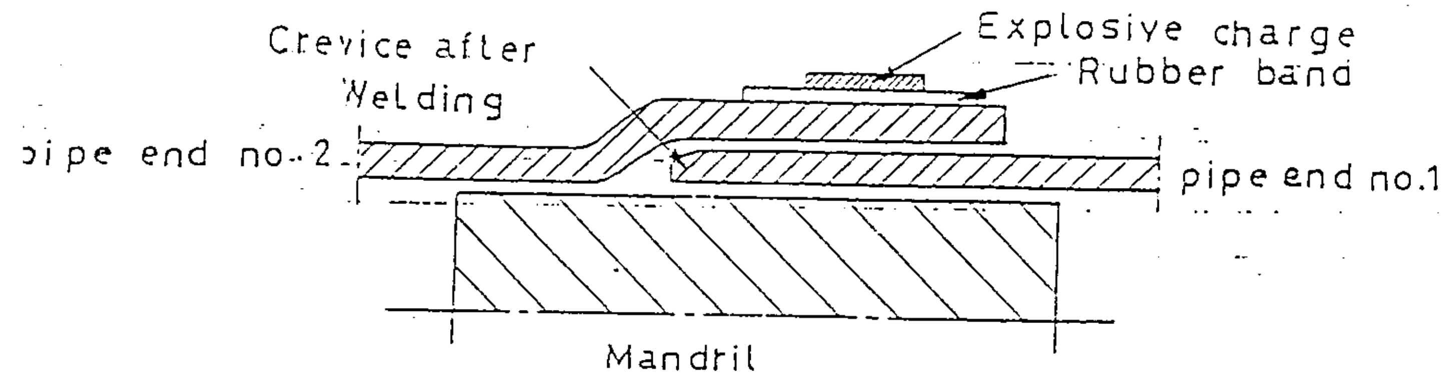

Figure 1.8: Arrangement of welding pipes

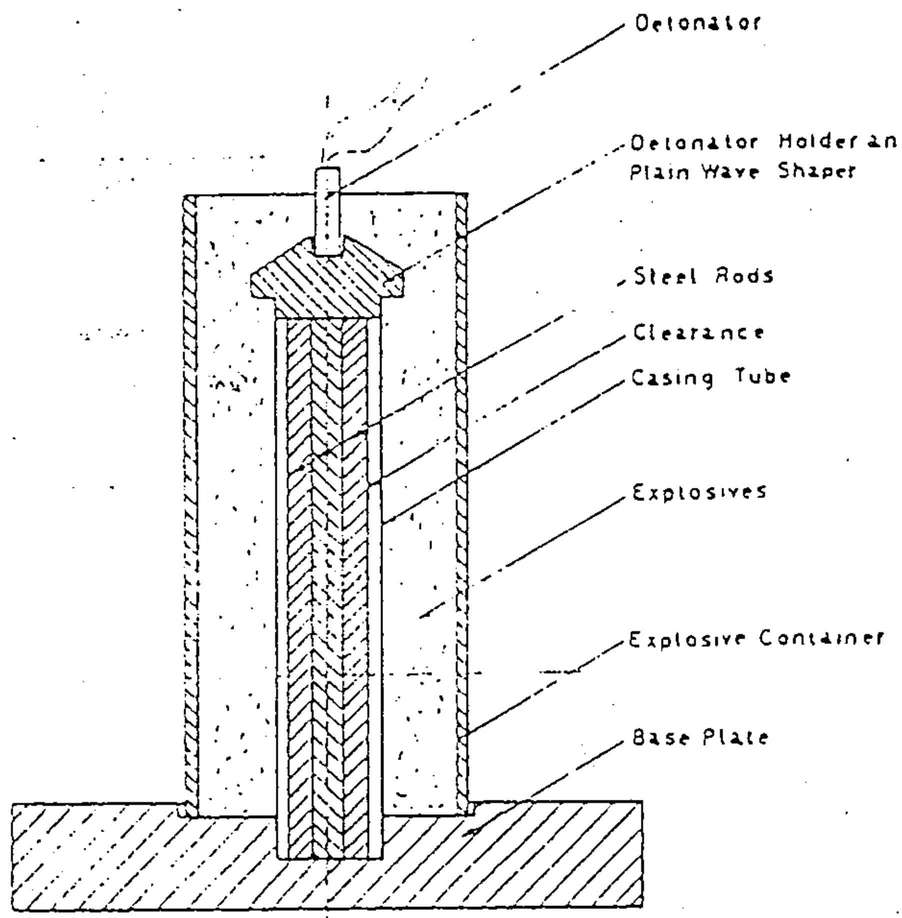

Figure 1.9: Implosive welding assembly of array of rods after Ref.[1]

Chapter 2

Materials, Equipment and Procedure

2.1 Materials

2.1.1 Flyer Plates

The flyer plates used throughout this work were made of plasticine, they were made by extruding a rod of plasticine through a circular die of $15mm$ diameter and cutting to the required length which were $15mm$, $22.5mm$,and $30mm$ corresponding to an aspect ratio of 1, 1.5, 2 respectively.

2.1.2 Target Plates (Parent Plate)

The target plates used throughout this work were also made of plasticine, they were shaped in cubes of the dimension $80mm$X$80mm$X$80mm$.

Plasticine was used in this work as a model material to simulate the mechanical behaviour of metallic materials, it behaves as a metal at high temperature above 800°C . A compression test was made in The Royal Scientific Society for specimens of plasticine and then the true stress-true strain curve was obtained Figure(2.1).

Plasticine has a comparatively low flow stress (between $10^{-2} - 10^{-3}$ times that of metals), plasticine projectiles need only be propelled at considerably lower velocities of impact to simulate comparable impact severity in metals, the latter is assessed by the damage (best) number- a dimensionless quantity given in equation(2.1) [22].

$$\eta = \rho V^2 / Y \quad (2.1)$$

where

- ρ is the density of the target material.
- Y is the yield strength.
- V is the impact velocity.

It is thus Possible to utilize very low-cost and simple experimental launching gun e.g (Hilti Gun), when using plasticine, where it is usually a relatively sophisticated, robust, and expensive apparatus - compressed air guns or light gas guns - are necessary when using metallic test specimens.

2.2 Testing Equipment

A sectional drawing of the test rig is shown in Figure(2.2), the equipment consists of the following main parts, the firing gun as a power source, the extension barrel, the velocity measuring unit, the base plates, and the protection shield.

2.2.1 Firing Gun (Power Source)

A DX 650 hilti fastening gun (commercial gun) was used to provide the energy required to fire the flyer plate with high speed against the target plate .

To obtain different levels of flyer plate velocity, any or combination of the following methods were used :

1. Use of different cartridge strengths .

   Three cartridges of different strengths were used, yellow, blue, and red classified by the manufacturer as medium, heavy and extra heavy respectively .

2. varying the length of the flyer plate and hence the mass .

3. Initial positioning of the flyer plate at different positions in the gun barrel with respect to the cartridge, allowing variation in the volume of the gases, hence variation in the pressure of the gases before reaching the flyer plate .

4. Varying the length of the extension barrel allowing acceleration of the flyer plate before the gases escape from the vent holes along the extension barrel.

Modification on the design of the gun was carried out to facilitate the necessary experiments . First, the inside original multi-section piston was replaced by another one with a 15mm inside diameter hollow stainless steel cylinder of 2mm thickness and fitted inside the gun's jacker, and extended from the explosion chamber to the outlet of the gun, and a 5mm groove was drilled over its length to allow the gases resulting from explosion to expand out of the gun barrel to stop the acceleration of the flyer plate.

Second, a 15mm diameter and 1mm thickness steel disc was used as a protection sheet above the flyer plate.

2.2.2 The Extension Barrels

Four extension barrels, made of high strength steel were machined to 38mm outside diameter and 15mm inside diameter and of different lengths to facilitate the variation of the velocity of the flyer plate. One of the extension barrel ends was screwed to the gun barrel, while its other end was screwed to the velocity measuring unit.

2.2.3 The Velocity Measuring Unit

It consists of a high strength steel hollow cylinder of 15mm inside diameter and 38mm outside diameter and 140mm length.

Four holes of $10mm$ each were drilled along the length of the cylinder. Each two were diameterically opposite and at $20mm$ axial distance . Four discs made of high conductivity copper were machined to $5mm$ diameter and $7mm$ thickness with four holes of $1mm$ diameter drilled through their centers to receive the two pencil leads which worked as a conductors. The copper discs were covered by teflon to provide electrical insulation between the copper disc and the cylinder. these are then inserted in the four holes and fixed by araldite.

When the flyer plate passes over the first conductor -pencil lead- it breaks and an electrical circuit receives a starting pulse which is fed to a digital oscilloscope causing it to trigger, while the break up of the second conductor stops the start signal of the oscilloscope and gives the time interval of the start-stop signals, Figure(2.3).

The flyer plate velocity is then obtained by dividing the fixed distance between the two conductors (pencil leads) over the time interval measured by the oscilloscope.

2.2.4 The Wooden Wedge

Five wooden wedges, with five different angles were machined , on which the parent plates were put to vary the incident angle between the flyer plate and the target plate.

The wedges were $90mm$ diameter with$5^o, 10^o, 15^o, 20^o, 25^o$ inclination with the horizontal base.

2.2.5 Protection Shield and Base Plate

A shield was necessary in order to protect against any fragments which may fly from the flyer plate and, or the parent plate.

A hollow steel cylinder of $100mm$ inside diameter, $11mm$ thickness and $600mm$ height with two thick flanges as a base and a holder to the gun assembly and extension barrel were used for this purpose.

A gate was opened in the shield to facilitate the placement of the target plates.

2.3 Procedure

The following procedure was followed in each test :

First, the gun barrel was removed and cleaned together with the explosion chamber and the extension barrels by a steel brash.

The flyer plate was laid in the predetermined position. at the front end of the extension barrel, then a steel disc is placed above the flyer plate used as a protection sheet. The target plate was then placed on the base plate at the required inclination angle using the proper wedge, after which the gate was closed. The pencil leads, conductors, are carefully placed through the holes in the velocity measuring unit and the electrical circuit is connected to the oscilloscope, checking that the oscilloscope is setting to be in the triggering position.

The cartridge is now fixed in position (for safety, the cartridges should be in the final step), and finally the gun is fired.

After each firing, the cartridges are pulled of the gun, and the target plates are sectioned diameterically through the center of the crater by using a piano wire to make the necessary measurements.Then the gun , the extension barrel, and the broken conductors (pencil leads) were removed and cleaned to be ready for the next test.

After sectioning, the interaction between the flyer plate and the target plate was traced carefully, and the depth of the penetration was measured using varnier calibre and profile projector.

To ensure that the results obtained using plasticine can be applied for other materials, lead, lead-tin,aluminium flyer plates were projected against lead, lead-tin, aluminium target plates, then the specimens were sectioned and prepared for scanning electro microscopy and photography.

2.3.1 Experimental Observations

1. The experimental tests were carried out at a room temperature ranging between 18°C-20°C, because any appreciable change in temperature will change the material (plasticine) mechanical behaviour.

2. The digitizing oscilloscope should be set to the suitable scale which will cover the time required by the flyer plate to pass the distance between the two conductors (pencil leads).

3. The effective way to obtain different levels of flyer plate velocity is by varying the length of the extension barrel above the flyer plate position, and hence the volume of the compression gases of the cartridge, by this way the flyer plates of all tests will travel the same distance to reach the target plate.

4. A hard material should be used for the extension barrels with thickness to prevent fracture due to high pressure.

5. The color of the flyer plate should be varied from the color of parent plate in order to get a clear interface between them after sectioning, and to facilitate the study of the mechanism of deformation.

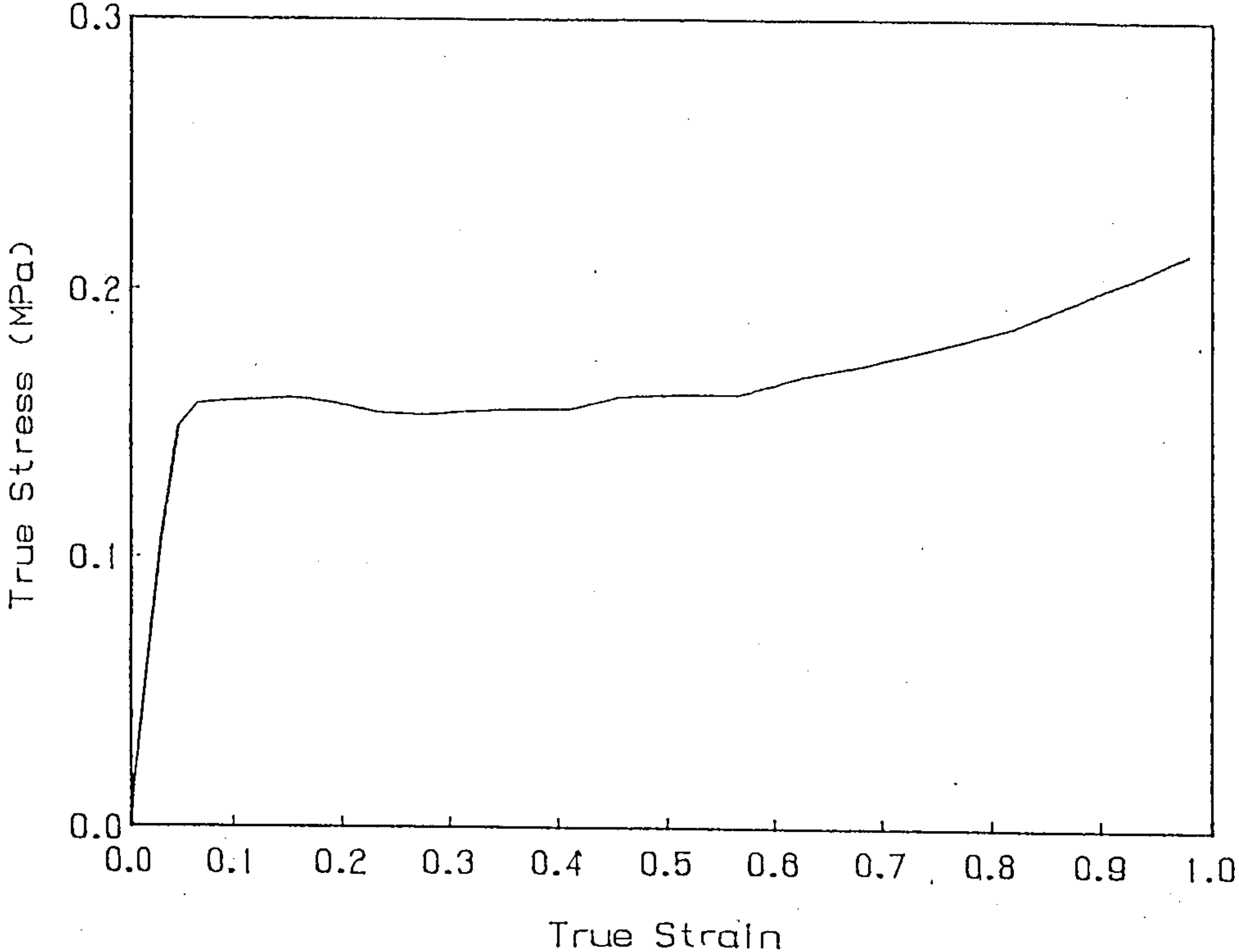

Fig.(2.1) True stress-True strain for plasticine.

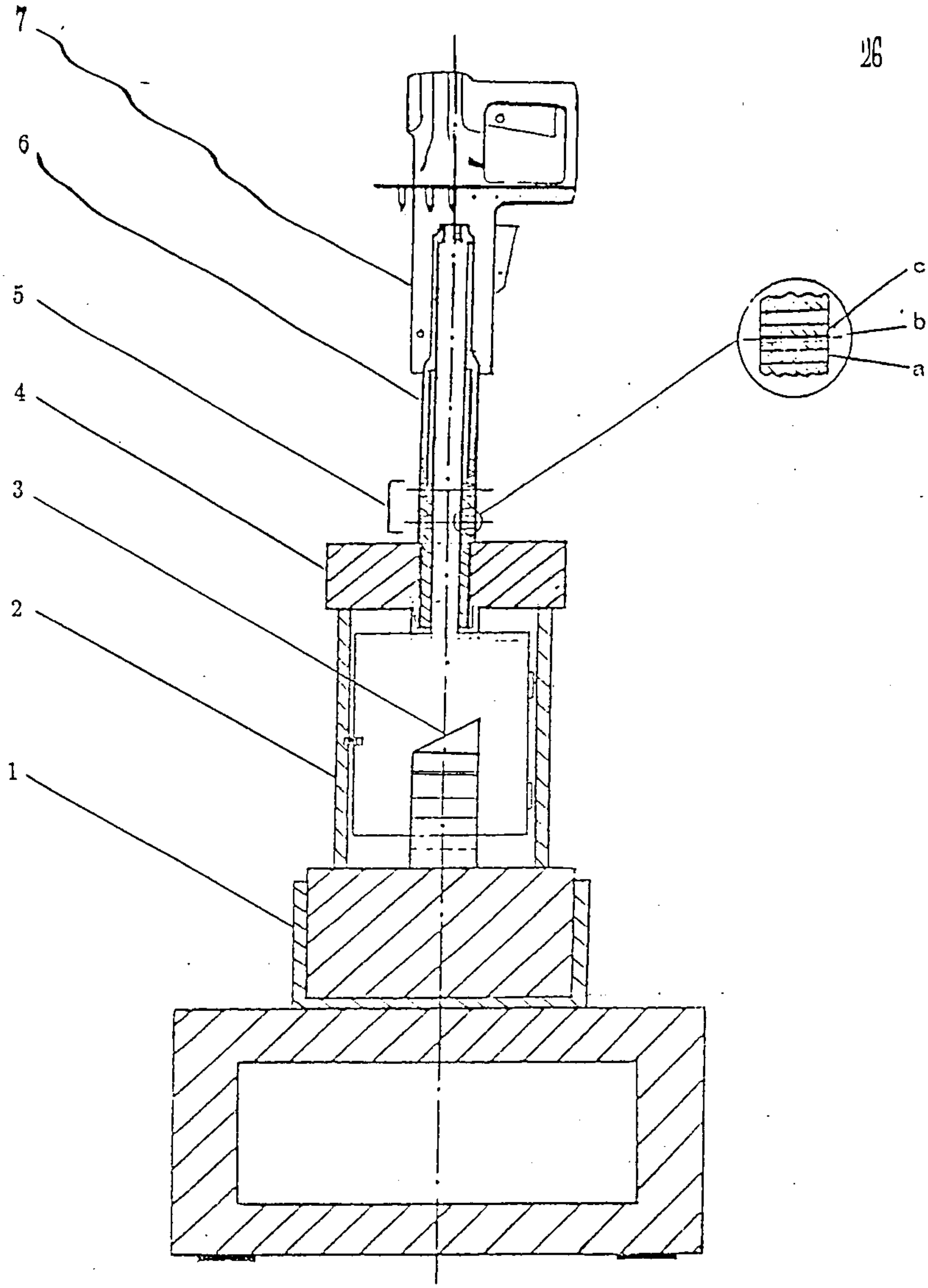

Figure 2.2: A sectional drawing for a test rig , 1-Base, 2-Protection shield , 3-Wooden wedge , 4-Bush , 5-Velocity measuring unit ,(a) Teflon (b) Conductor (c)Brass , 6-Extension barrel , 7-Gun

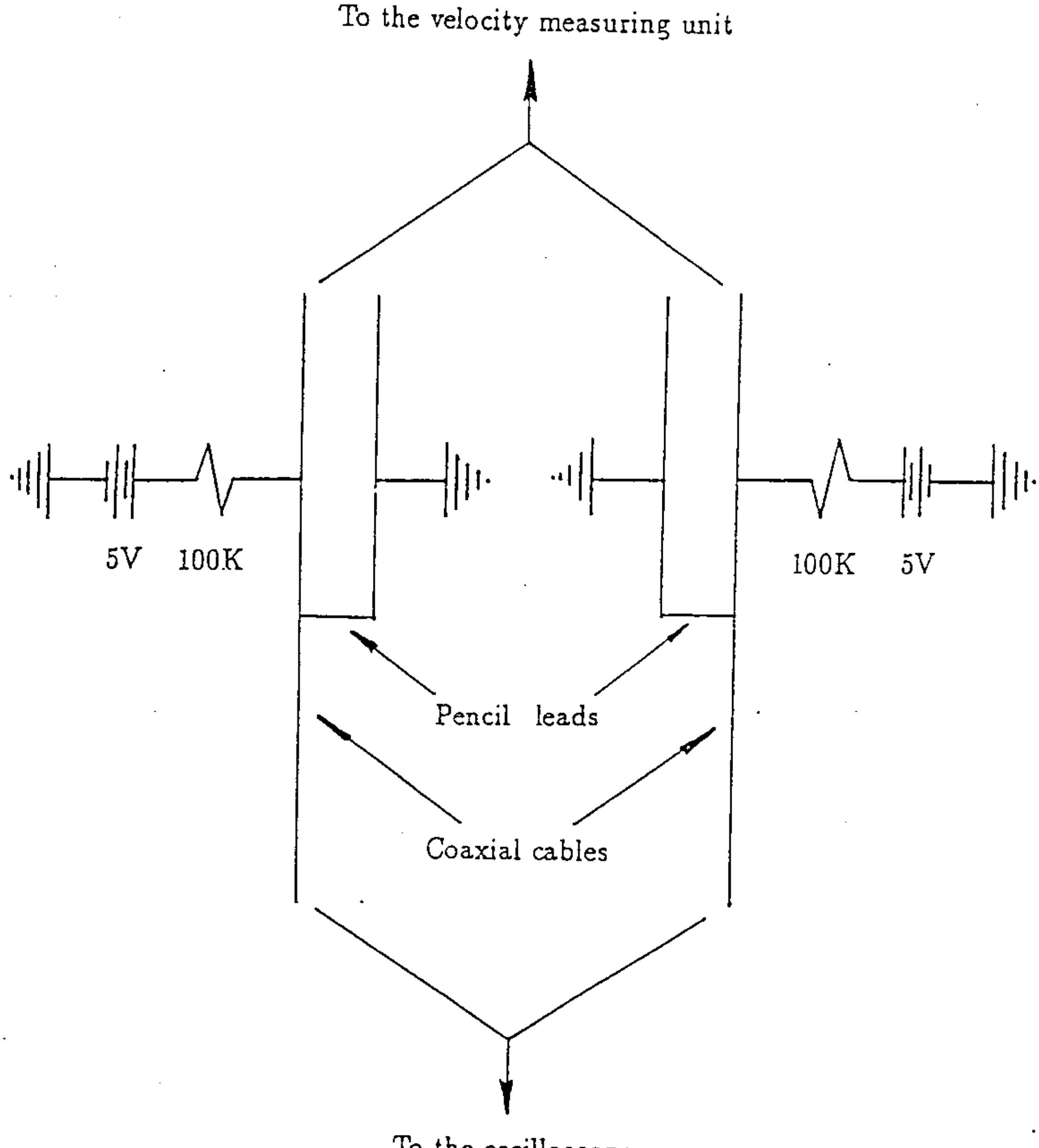

Figure 2.3: The electrical circuit connected to the velocity measuring unit

Chapter 3

Theoretical Analysis

Refering to Figure(1.1) which shows experimental set-up of explosive welding . After detonation of the explosive by an electrical detonator, the detonation wave travels along the explosive sheet causing acceleration of the flyer plate by means of shock wave reflections to give the required oblique high velocity collision of the two plates.

Figure(3.1) illustrates the mode of collapse of the flyer plate of Figure(1.1). All parts of the flyer plate behind the detonation front acquire a constant velocity V_p , until they strike the parent plate, all parts ahead of the detonation front are stationary and remain so until its passage. The flyer plate at all times appears to be hinged at S, and collapses onto the parent plate with the dynamic angle of obliquity β. The β angle is a function of detonation velocity V_d and the velocity imparted to the flyer plate, V_p. It will be seen that

$$V_p = V_d \sin \phi \qquad (3.1)$$

where $\phi = \beta - \alpha$.

On collision the kinetic energy of the flyer plate is dissipated to produce very high pressure in the region, S, so that the shear resistance of the materials of the plates is negligible in comparison with the high pressure produced, and as a consequence the materials in the impact region act as inviscid fluids. If the co ordinates of Figure(3.2) are altered to fix collision point, S, it will be observed that the flyer plate has a velocity $V_p/tan\beta$ in its own plane, and the parent plate has a velocity of $V_p/sin\beta$. As the materials in the region of impact act as inviscid fluids, the flyer plate becomes equivalent to a liquid jet of velocity $V_p/tan\beta$ impinging on a stream with a velocity at an angle of obliquity β.

Birkhoff, MacDougall, Pugh and Taylor [14] have shown that in these circumstances the flyer plate jet must divide into a salient and a re-entrant jet, whose masses can be simply calculated by means of the conservation of mass and momentum :

$$m_r = m/2\,(1 - cos\beta) \qquad (3.2)$$

and

$$m_s = m/2\,(1 + cos\beta) \qquad (3.3)$$

where m is the mass of the flyer plate jet.

The velocity of the re-entrant jet relative to the parent plate is:

$$\frac{V_p}{sin\beta}\,(1 + cos\beta) \qquad (3.4)$$

This gives the re-entrant jet a very high velocity with low mass, which provides it with high scouring ability for subsonic flow and it can be shown that as the flyer plate velocity $V_p/tan\beta$ slightly exceeds the sonic velocity in the flyer plate, then no re-entrant jet is formed.

According to the results obtained when firing plasticine flyer plate against plasticine target plate, this analysis seems to be unrealiable, because welding occurred in the hyper velocity region, where the velocity of the flyer plate exceeds the sonic velocity of plasticine, and the jet is also formed which differs from the statements given in Ref. [14].

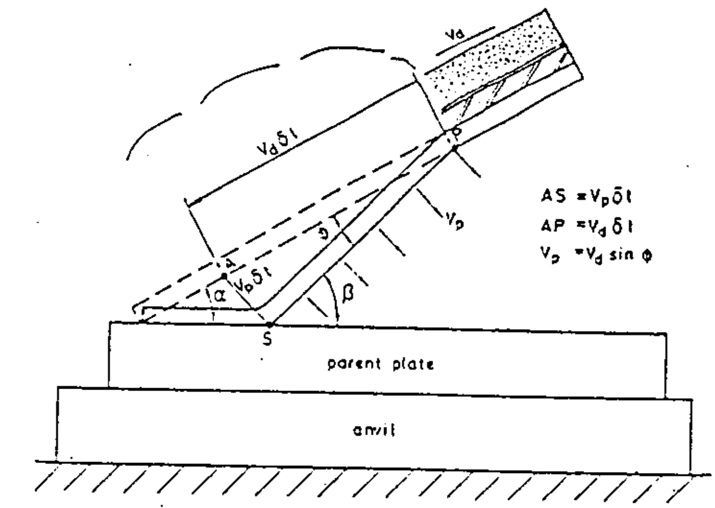

Figure 3.1 : Mode of collapse of flyer plate after Ref.[11]

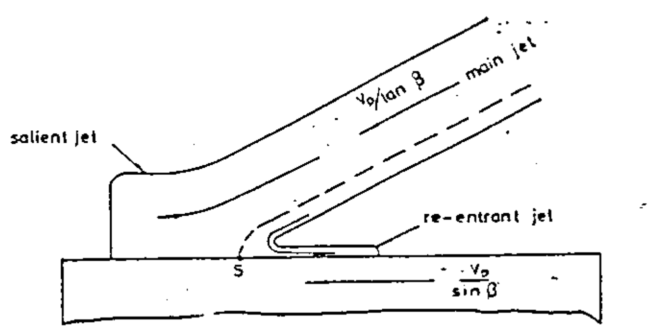

Figure 3.2 : Formation of the jet after Ref.[11]

Chapter 4

Results

4.1 Introduction

This chapter represents the results obtained during this work. The work is divided into two parts, the first part deals with the parameters affecting the explosive welding process-using plasticine as a model material-such as the angle between the flyer and the target plates, the flyer plate velocity,... .

The second part describes the results obtained when firing lead and lead-tin projectiles against lead target plates at different velocities.

4.2 Effect of Operating Parameters on Explosive Welding-Using Plasticine as a Model Material.

The effect of the above mentioned parameters is tabulated in table(1) through table(3) inclusive.

Table(1) for flyer plate of a fitness ratio of 1, while table(2) and table(3) are for flyer plates of a fitness ratios of 1.5 and 2 respectively.

4.2.1 Penetration Shape of Cavity Caused by Flyer Plates

Figures(4.1) through (4.3) inclusive represent the shape of cavity caused by plasticine flyer plates at different velocities into plasticine target plates after firing and welding.

The results of Figure(4.1) are for projectiles of fitness ratio 1, while in Figure(4.2) and Figure(4.3) the results are for fitness ratio of 1.5 and 2 respectively.

4.2.2 Variation of Depth of Penetration with Perpendicular Velocity

Figure(4.4) and Figure(4.5) show the effect of flyer plate perpendicular velocity on the depth of penetration for plasticine projectiles of fitness ratio of 1, the symbol o indicates penetration without welding, while the symbol * indicated penetration with welding.

Figure(4.4) was smoothed using second order polynomial regression, while Figure(4.5) was smoothed using fourth order polynomial regression.

4.2.3 Explosive Welding Regions

Figure(4.6) shows the variation of angle of inclination between the flyer and the target plates with the depth of penetration for plasticine projectiles of fitness ratio of 1.

4.2.4 Effect of Perpendicular Flyer Plate Velocity on the Diameter of the Cavity Produced

Figure(4.7) shows the effect of perpendicular velocity of the flyer plate on the diameter of the cavity when the cavity is hemisphere for projectiles fitness ratio of 1, the data concerning this range of velocity is tabulated in table(4).

4.3 Lead and Lead-Tin Flyer Plates

Figures(4.8) through (4.11) inclusive show the scanning microphotographs of lead/ lead weld, while Figures(4.12) through (4.15) inclusive show the scanning microphotographs of lead-tin/lead weld.

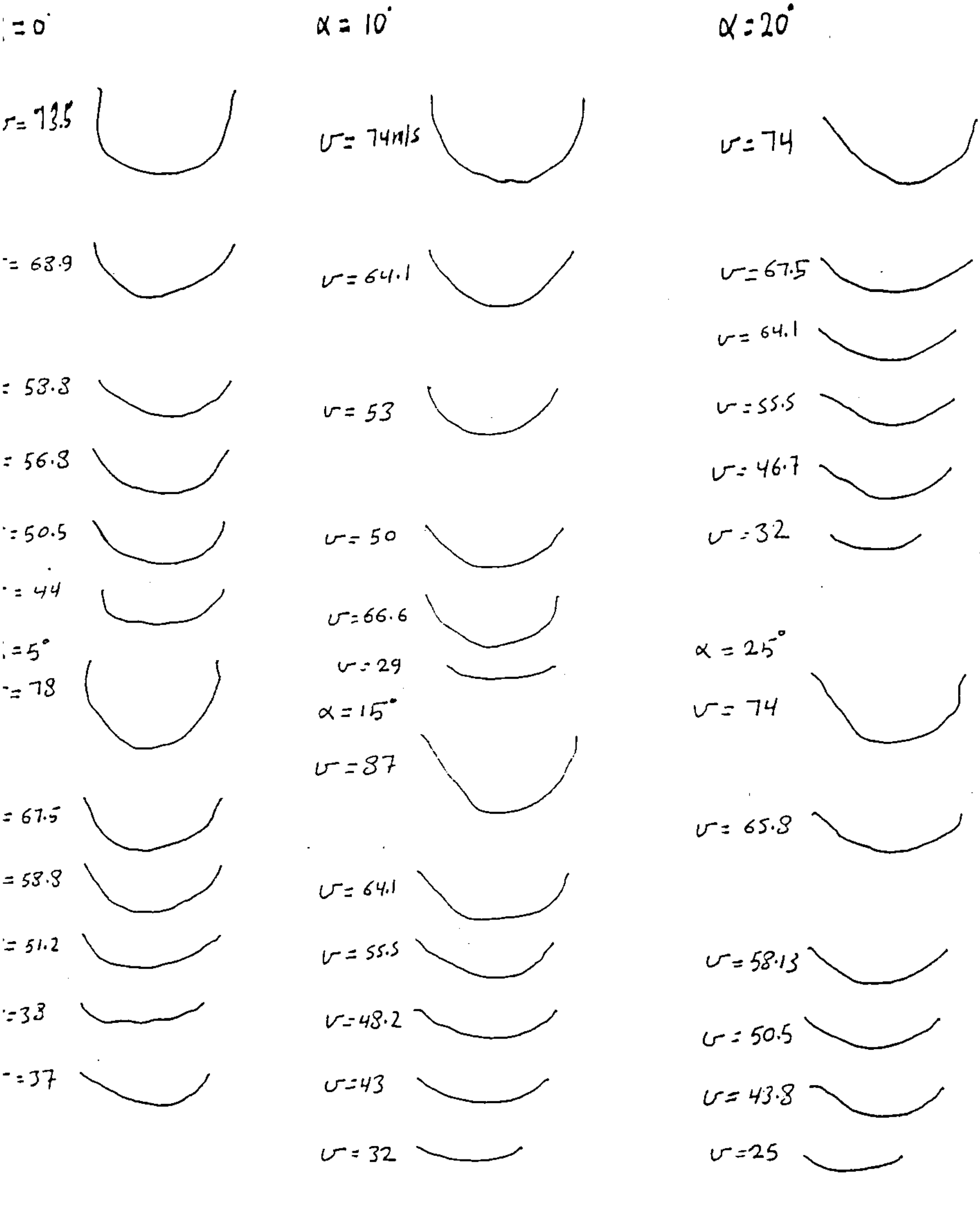

Figure 4.1: Tracings of sectioned targets welded by projectiles of a fitness ratio of 1

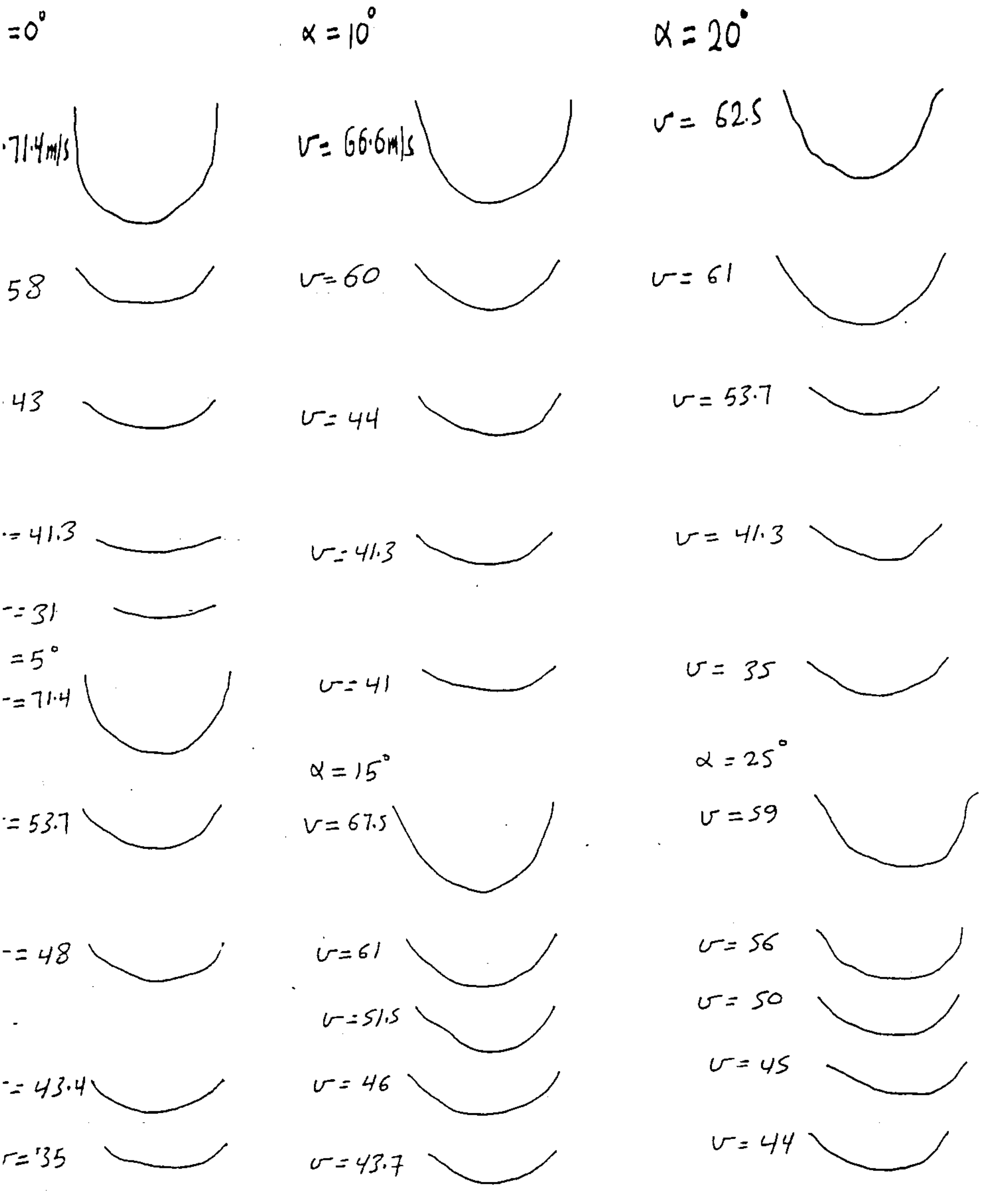

Figure 4.2: Tracings of sectioned targets welded by projectiles of a fitness ratio of 1.5

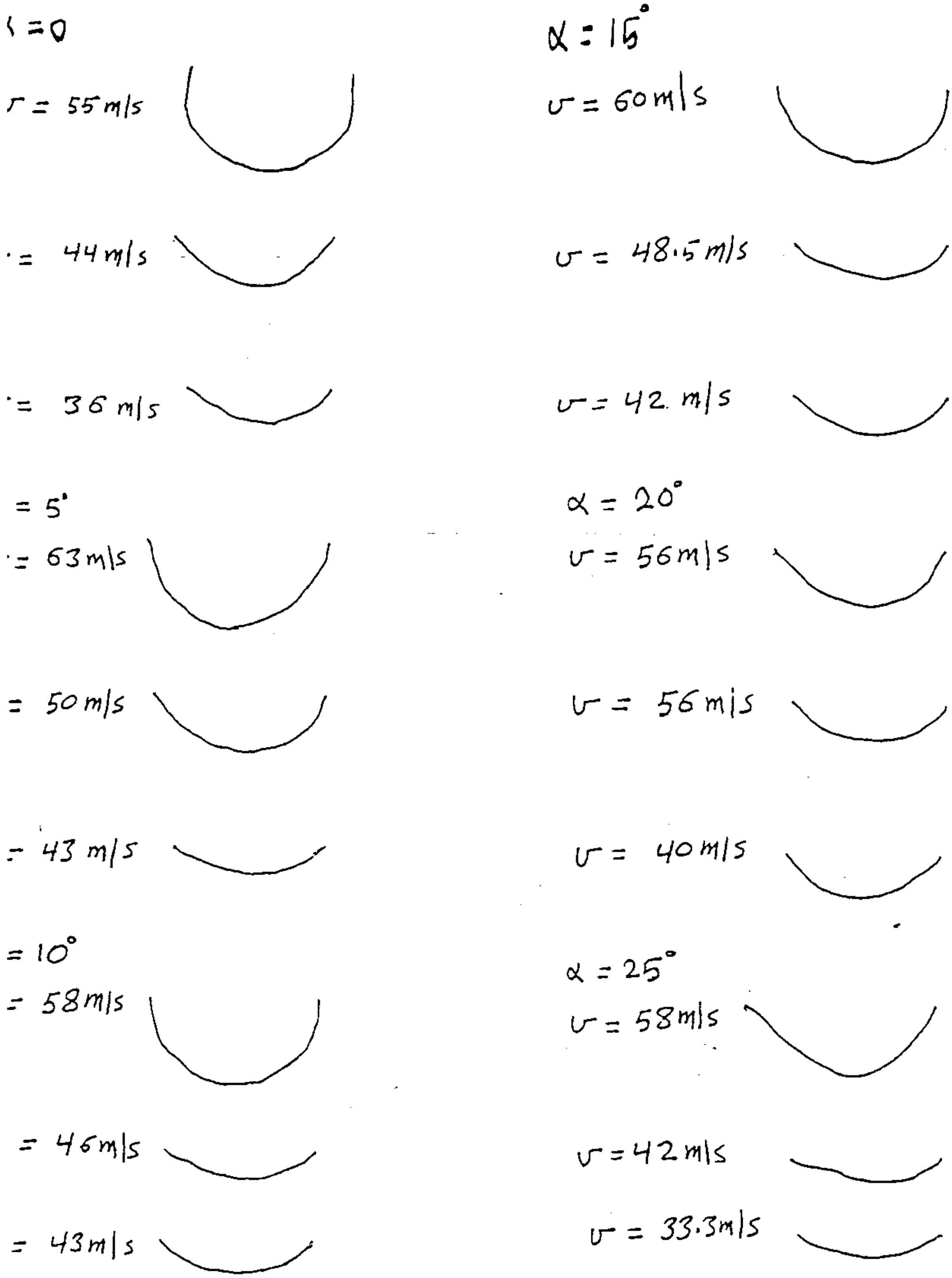

Figure 4.3: Tracings of sectioned targets welded by projectiles of a fitness ratio of 2

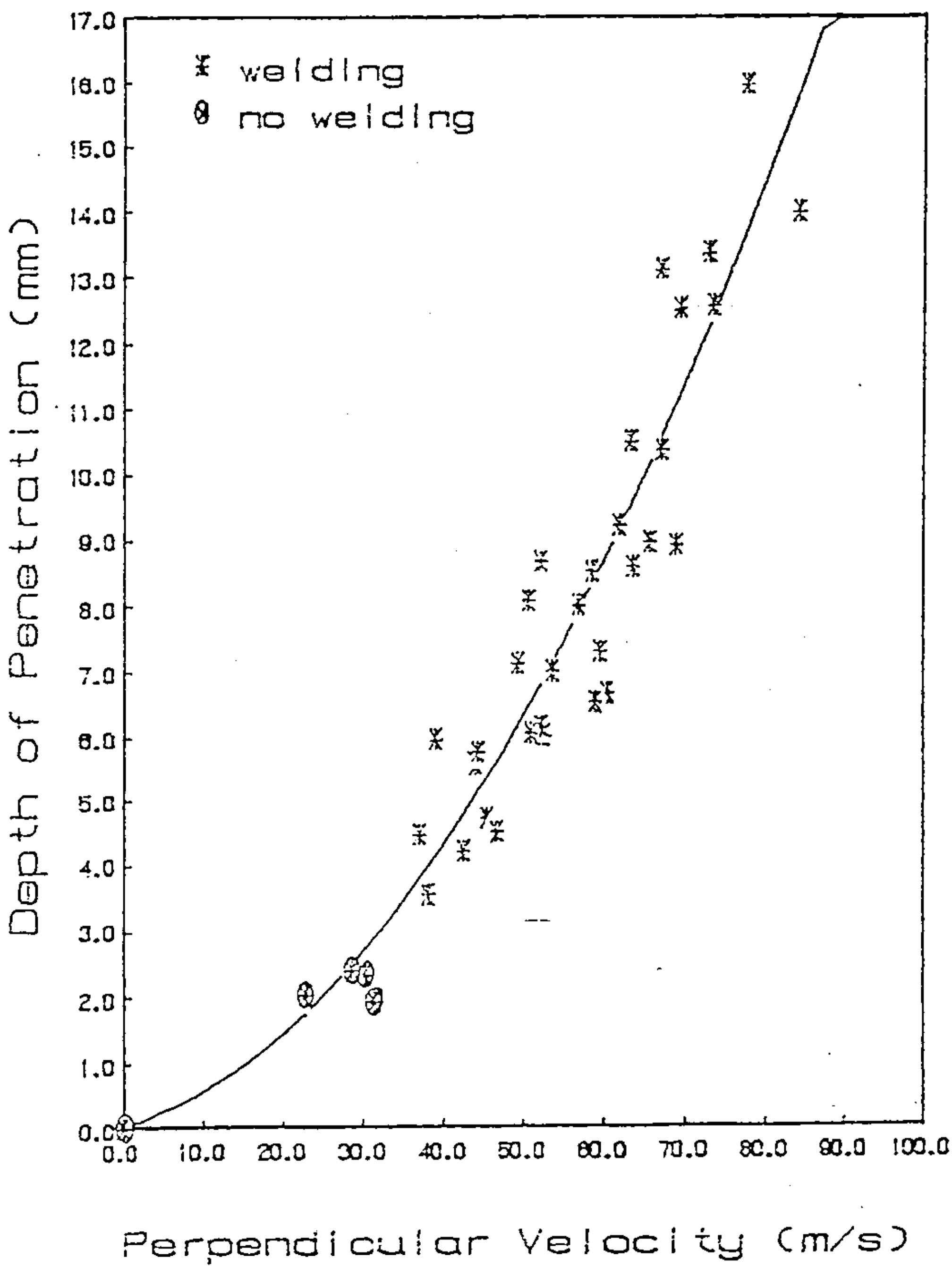

Figure 4.4: Variation of depth of penetration with perpendicular velocity- second order polynomial regression-

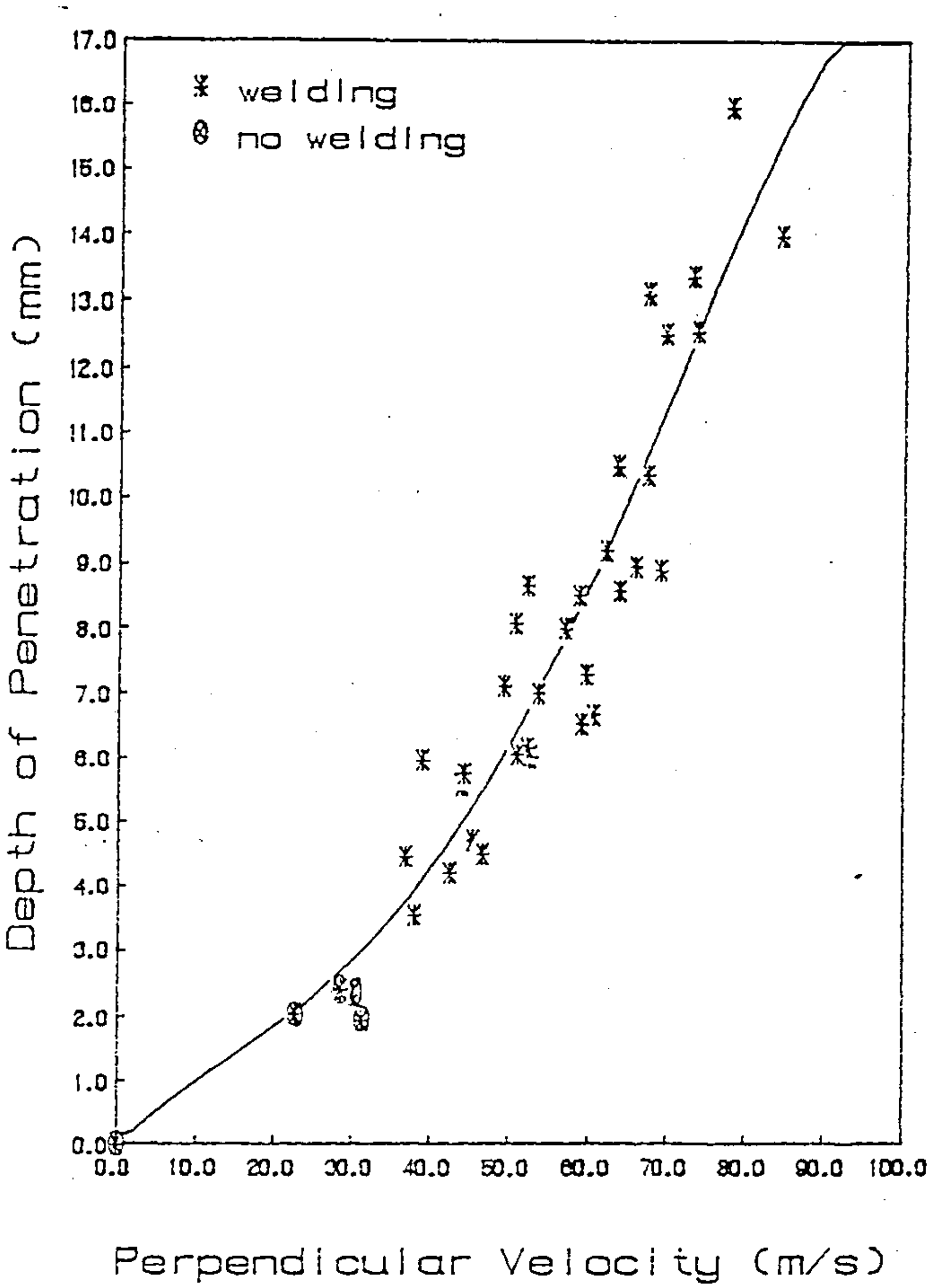

Figure 4.5: Variation of depth of penetration with perpendicular velocity- fourth order polynomial regression-

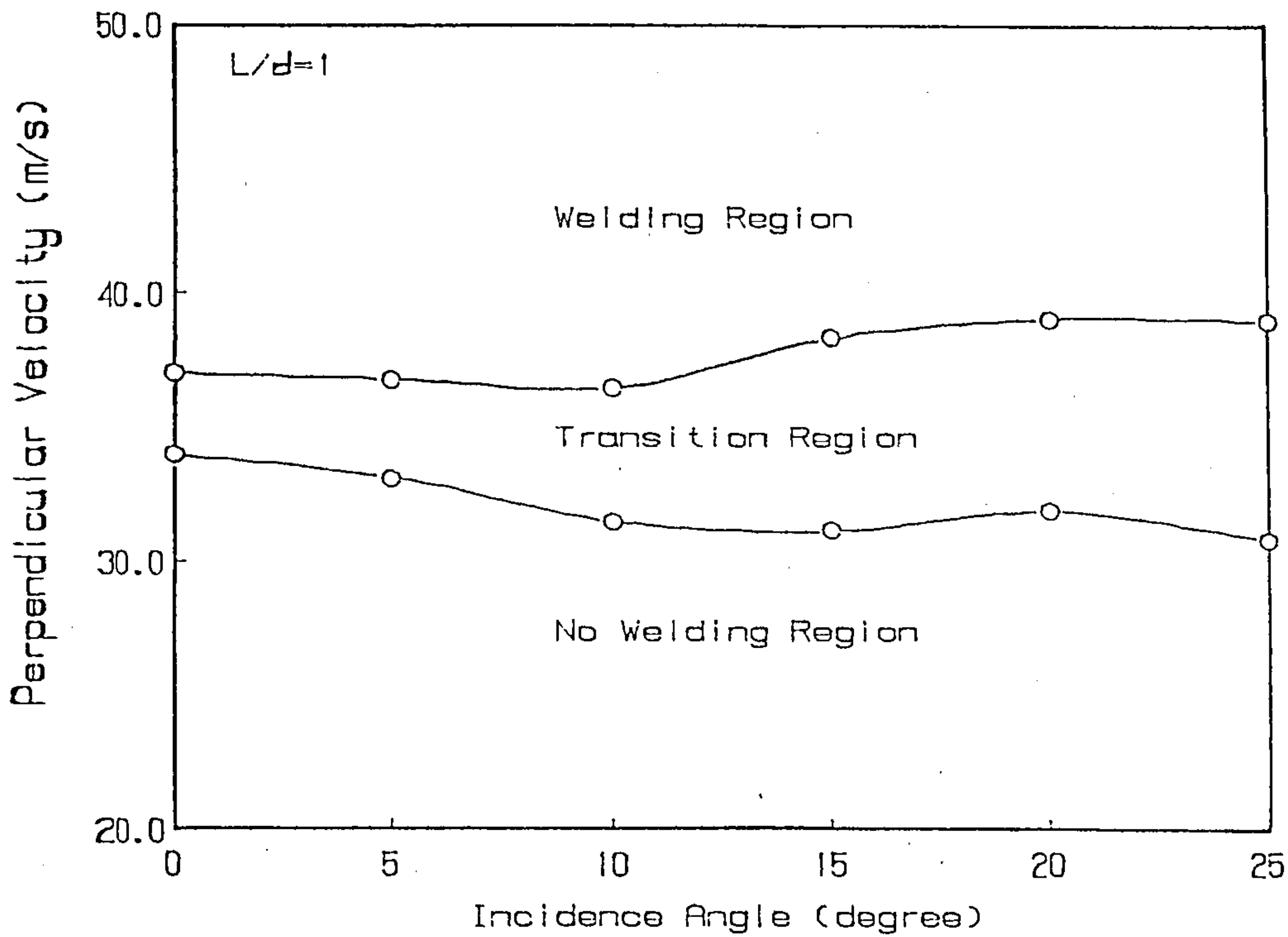

Fig.(4.6) Welding Regions for L/d=1.

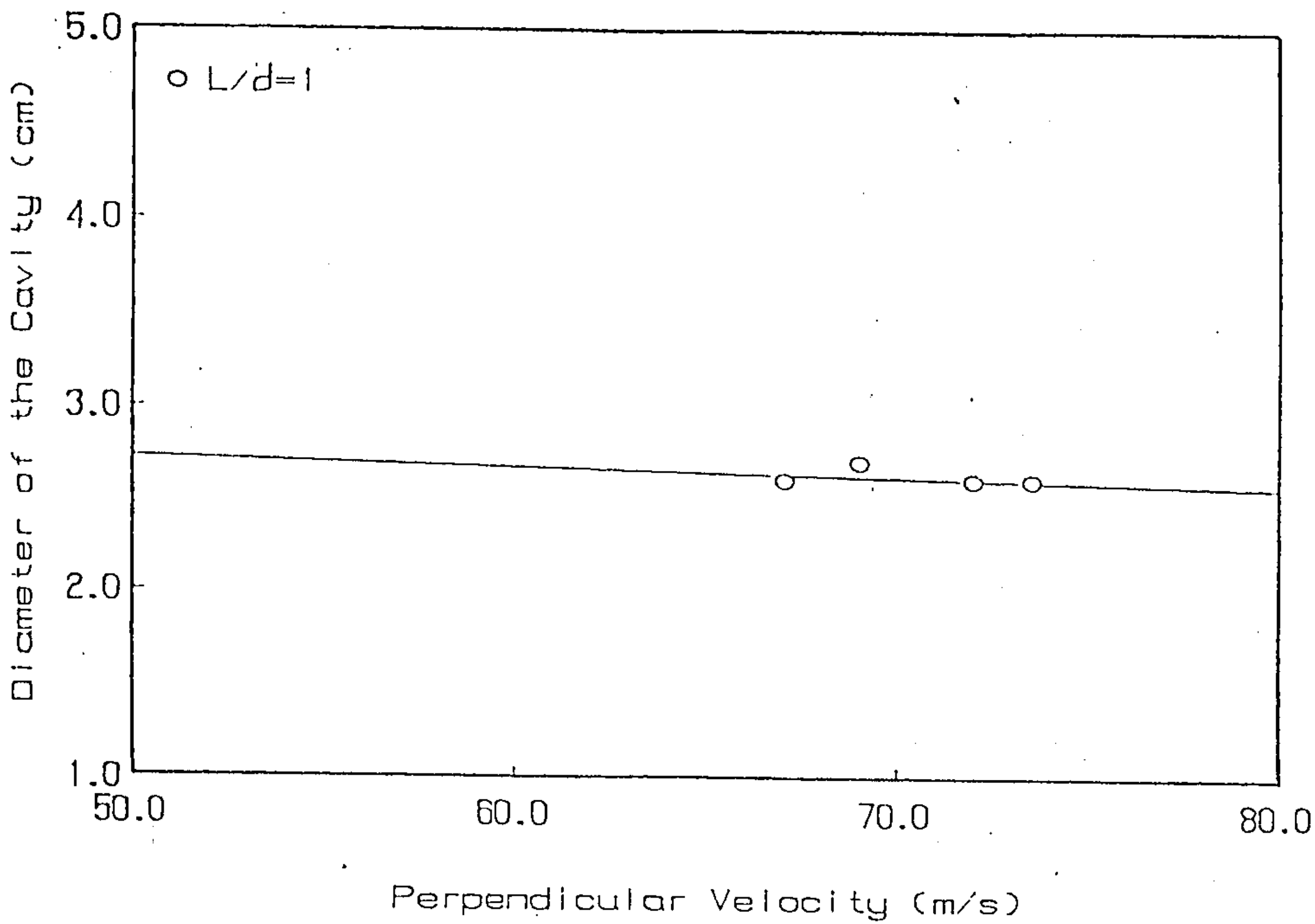

Fig.(4.7) Variation of Diameter of the Cavity with Perpendicular Velocity.

Figure 4.8: Photomicrograph of lead flyer plate welded to lead target plate (mag.X192)

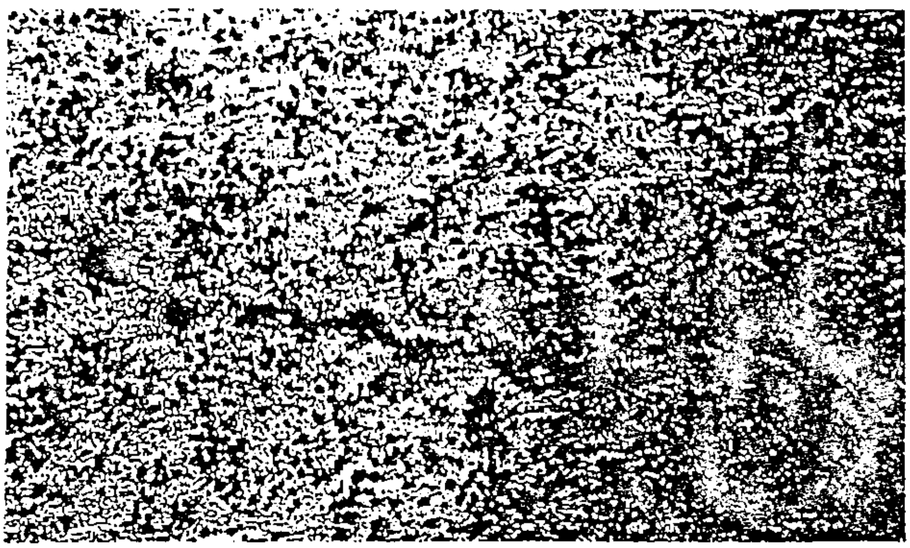

Figure 4.9: Photomicrograph of lead flyer plate welded to lead target plate (mag.X260)

Figure 4.10: Photomicrograph of lead flyer plate welded to lead target plate (mag.X444)

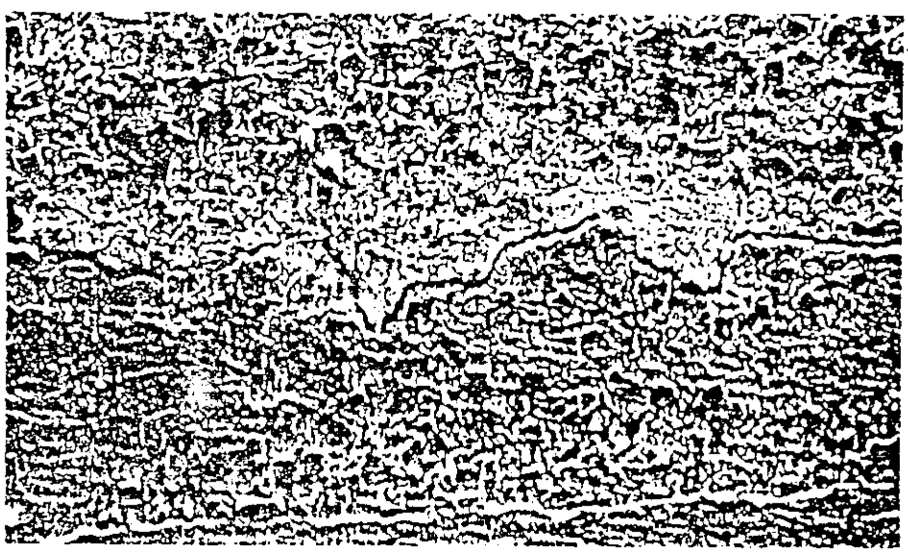

Figure 4.11: Photomicrograph of lead flyer plate welded to lead target plate (mag.X1080)

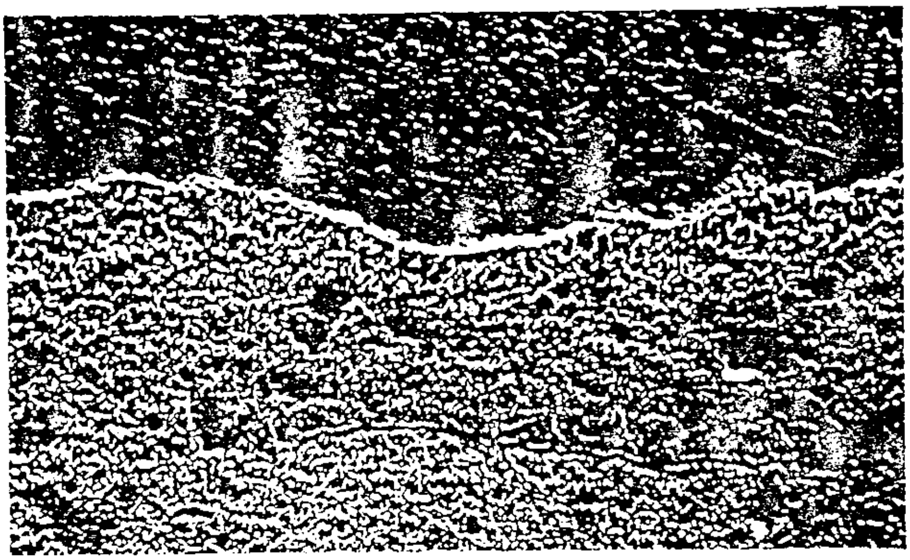

Figure 4.12: Photomicrograph of lead-tin flyer plate welded to lead target plate (mag.X592)

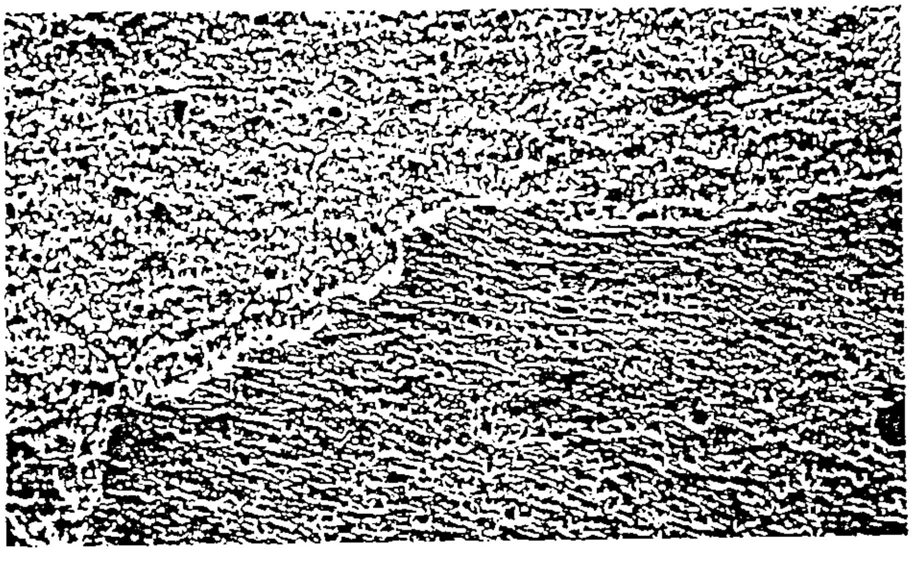

Figure 4.13: Photomicrograph of lead-tin flyer plate welded to lead target plate (mag.X920)

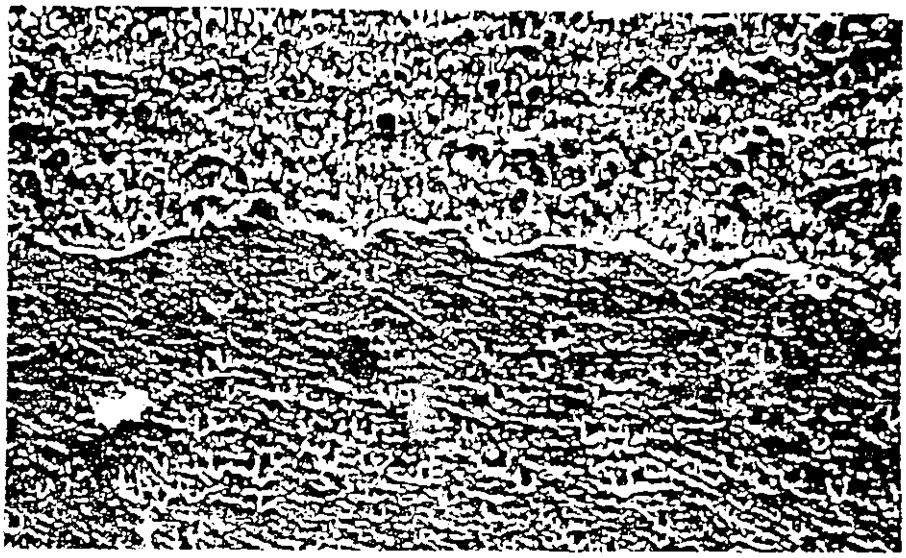

Figure 4.14: Photomicrograph of lead-tin flyer plate welded to lead target plate (mag.X1080)

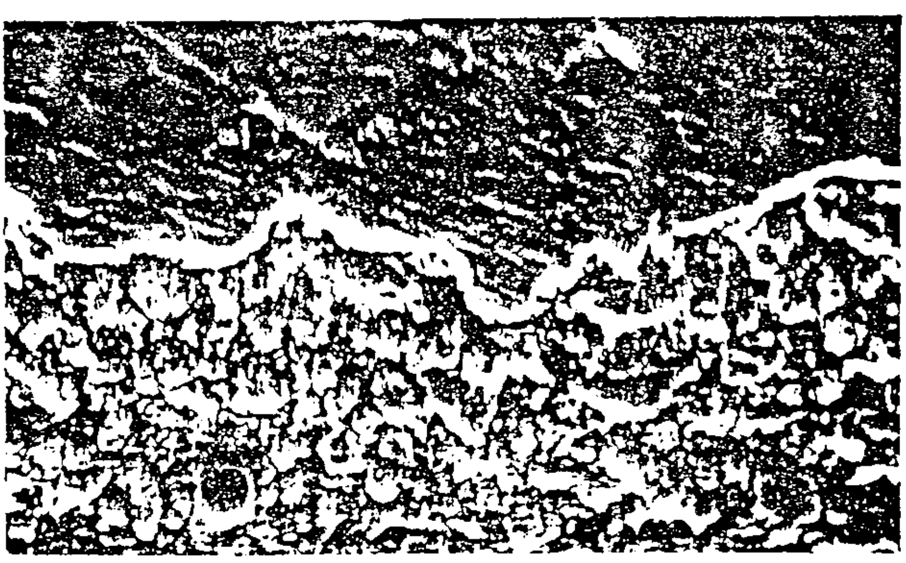

Figure 4.15: Photomicrograph of lead-tin flyer plate welded to lead target plate (mag.X2200)

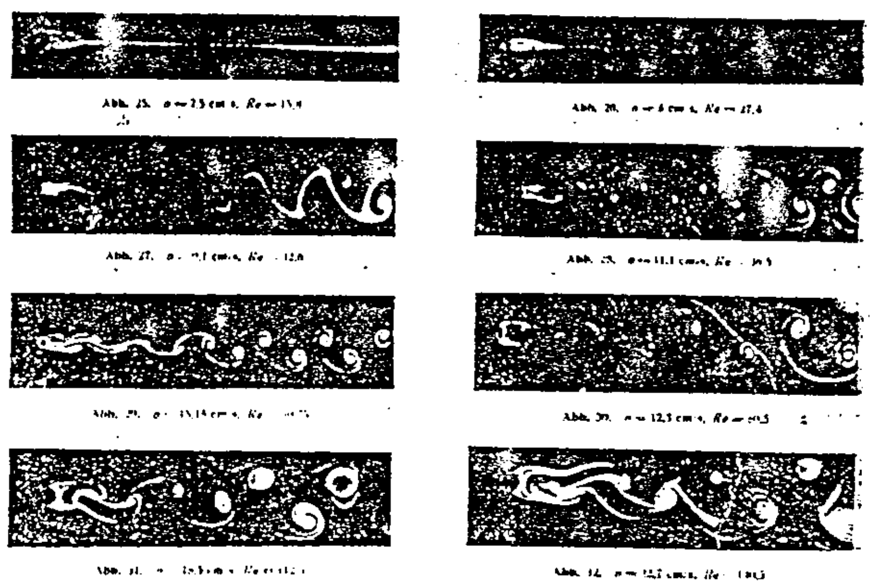

Figure 4.16: Karman vortex streets generated by a cylinder in fluid flow after Ref.[12]

Chapter 5

Discussion

5.1 Introduction

As previously mentioned, the work is divided into two parts, one part using plasticine as testing materials, and the other using metals as testing materials. In this chapter the results obtained for both parts are discussed.

5.2 Shape of Penetration and Cavity

Figures(4.1)through (4.3) inclusive illustrate that the cavity inside the target was consistently hemispherical in shape and was filled with the material from the flyer plate.

The depth of penetration increases with the increase of the impact velocity because the momentum of the projectile is increased. The influence of the length of the projectile-and hence the fitness ratio (l/d) against the depth of penetration is examined, Figures(4.2) and(4.3) show that as long as there is an increase in the fitness ratio, the kinetic energy of the projectile is increased and hence the depth of penetration.

5.3 Variation of Depth of penetration with Perpendicular Velocity

Figures(4.4) and (4.5) show the effect of perpendicular impact velocity on the depth of penetration.

Generally, as it may be seen from these figures, Penetration increases with the increase of the kinetic energy of the projectile and there is a minimum flyer plate velocity ($30m/s$) for the production of a bond.

Figure(4.4) was smoothed using second order polynomial regression which gives the depth of penetration as a function of the perpendicular velocity by the equation(5.1) :

$$y = 0.03727 + 3.44845\frac{x}{100} + 18.1555(\frac{x}{100})^2 \tag{5.1}$$

where y is the depth of penetration (d) in mm, and x is the perpendicular velocity in m/s.

5.4 Explosive Welding Regions

Figure(4.6) represents the effect of the angle of inclination on welding occurence, and from general look to this figure, it could be seen there is no effect of the angle on welding occurence, and this gives an obvious picture of the modes of deformation, which can be classified with respect to the velocity of impact of the flyer plate into three modes :

- Mode 1, Projectile deforming with out welding.

  This occurs in the low velocity range (hypo velocity$\leq 30m/s$) in which the plastic deformation is restricted mainly to the front end of the projectile causing mushrooming without significant damage to the target and no welding was observed.

- Mode 2, Projectiles penetration and pre-welding.

  This occurs in the transient region ($\geq 30m/s$ and$\leq 36m/s$) in which pre-welding may occur due to high velocity impact which causes plastic deformation of both the flyer and the target plates.

- Mode 3, Hyper velocity range.

  This occurs in the hyper velocity range ($\geq 36m/s$) where penetration cavity formation, and perhaps perforation of the target occur, and the flyer plate is completely embedded in the target plate and welding takes place.

5.5 Effect of Perpendicular Velocity of Flyer Plate on the Diameter of the Cavity

Table(4) and Figure(4.7) show that the diameter of the cavity does not vary with the angle of inclination, in such velocity range the width of the cavity and its diameter are also unaffected by the horizontal velocity component, unlike the case of the hyper velocity impact where it was claimed that the width of the cavity produced is mainly dependant on the angle of impact, where the horizontal component of velocity is responsible for the width of the cavity .

It is thus suggested that the depth of penetration and the shape of cavity are both affected by the oblique impact rather than the width of cavity, welding occurs in such velocity range irrespective of the angle of inclination with the range$0^o - 25^o$.

5.6 Lead and Lead-tin Flyer Plates

As mentioned previously, explosive welding is a solid phase mechanism,which involves no melting of the components as fusion welding. In explosive welding there is a high velocity impact between the components being welded , which cause the metals to behave like fluid due to high pressure developed at the interface between the metal surfaces. As a result, a high velocity jet is formed from the surfaces of both components, which leaves two virgin clean surfaces which are pressed together by high pressure developed to cause plastic deformation at the interface of the components being welded.

The interfacial waves observed in explosive welding when firing 15mm diameter lead and lead-tin flyer plates against lead target plates- Figures (4.8) through (4.15) inclusive is similar to Von Karman vortex streets in fluid flow passed an obstacle as shown in Figure(4.16).

The existence of welding between the metallic plates depends on the hardness of both the flyer and parent plates, if the hardness of the flyer plate is less than the hardness of the parent plate, then mushrooming of the flyer plate front end will occur, and when the hardness of the flyer plate is more or equal to the hardness of the target plate-as the case of firing lead and lead-tin against lead- welding will occur if the impact velocity is controlled to be higher than the velocity in the transition region obtained in plasticine.

Chapter 6

Conclusions

From the results obtained throughout this work. the followings are concluded :

- The commercial stud gun apparatus can be successfully used to investigate the explosive welding process with the projectile acting as a flyer plate and the target as a base plate.

- Plasticine is being proved to be successfully used as a model material because its mechanical behaviour is similar to metals at high temperature.

- It is confirmed that explosive welding is caused by a high velocity impact between the components being welded which cause the metal to behave like fluid due to high pressure developed at the interface between the metal surfaces, and not by fusion.

- The weld region (the interface) between the two welded parts has a wavy form which agrees with previous findings of other researchers.

- With the experimental limitation i.e $l/d=1$ for plasticine, there is a critical velocity below which welding does not take place, and above which welding occurs. For plasticine this velocity is found to be about $30m/s$. This differs from the results obtained in Ref.[14], where the re- entrant jet, responsable for the welding process does not form.

- Within the critical velocity range it is concluded that neither the horizontal component of impact velocity nor the angle of inclination between the flyer and the target plate has any appreciable effect on the crater formed by the flyer plate.

Chapter 7

Recommendations

Although extensive research work has been carried out on explosive welding, there is still considerable scope for improvement and development of the techniques. Concerning this work, the following points may be suggested for further investigations,

- The mechanical and metallurgical properties of the two materials being welded have an effect on welding conditions which have to be adopted.

- Welding of other metals which were not used in this work such as copper, brass...etc is recommended.

- The flyer plate in this work was of circular cross-section, it is recommended that other cross-sections e.g, square, rectangular...etc. should be investigated.

- Studying the effect of welding on the microstructure of both the flyer and the parent plates, specially in the affected welding zone is recommended.

- studying the strength of explosively welded metals using tensile test and shear test is recommended.

- Studying the dynamic buckling of solid and hollow columns of different materials is suggested using the same apparatus.

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Table .1: Results of flyer plates of a fitness ratio of 1

Angle (°) α	velocity m/s	depth mm d	width cm	area cm^2	vertical velocity m/s	horizontal velocity m/s
0	73.5	12.56	2.6	2.34	73.5	0
	68.9	8.92	1.68	1.68	68.9	0
	58.8	6.53	0.93	0.93	58.8	0
	56.8	7.98	1.1	2.4	56.8	0
	50.5	8.06	1.37	2.3	50.5	0
	44	5.75	2.6	1.06	44	0
5	78	15.96	2.4	2.87	6.79	77.7
	67.5	10.33	2.4	1.68	67.2	5.8
	58.8	8.49	2.4	1.43	58.5	5.12
	51.2	6.02	2.5	1.03	51	4.46
	38	3.55	2.2	.56	37.8	3.31
	37	4.46	2.3	.84	36.8	3.22
10	74	13.34	2.6	2.56	72.8	12.85
	66.6	8.95	2.4	1.5	6.5	11.56
	64.1	10.48	2.5	1.78	63.12	11.13
	53	8.63	2.2	1.5	52.19	9.2
	50	7.09	2.32	1.18	49.2	8.68
	29	2.4	2	.31	28.56	5.03
15	87	13.98	2.9	2.75	84	22.51
	64.1	9.21	2.7	1.78	61.9	16.59
	55.5	7	2.45	1.125	53.6	14.36
	48.18	5.48	2.6	.83	46.5	12.45
	43.8	4.21	2.22	.73	42.3	11.33
	32.25	1.9	1.9	.31	31.15	8.34
20	74	12.51	2.7	2.06	69.5	25.3
	67.5	8.58	2.7	1.87	63.4	23
	64.1	6.65	2.7	1.06	60.2	21.9
	55.5	6.13	2.5	.75	52.15	18.9
	46.7	5.55	2.4	.82	43.8	15.9
	32	2.32	1.6	.31	30	10.94
25	44	13.11	2.6	2.37	67	31
	65.7	7.3	2.6	1.34	59.5	27.7
	58	6	2.6	.93	52.5	24.5
	50	4.7	2.5	.81	45.3	21.1
	43	5.95	2.3	.81	38.9	18.1
	25	2.03	1.6	.31	22.65	10.56

Table .2: Results of flyer plates of a fitness ratio of 1.5

Angle (°) α	velocity m/s	depth mm d	width cm	area cm^2	vertical velocity m/s	horizontal velocity m/s
0	71.4	17.35	2.55	3.25	71.4	0
	58	6.7	2.4	1.18	58	0
	43	4.11	2.3	.75	43	0
	41.3	2.17	2.25	.375	41[B.3	0
	31	1.87	2	.31	31	0
5	71.4	15.87	2.6	3	71.12	6.22
	53.7	7.51	2.45	1.28	53.49	4.68
	48	6.5	2.4	1.187	47.81	4.18
	43.4	5.94	2.3	.937	43.23	3.78
	35	3.51	2.15	.56	34.86	3.05
10	66.6	15.12	2.9	3	65.5	11.56
	60	7.95	2.6	1.65	59	10.41
	44	7.54	2.5	1.31	43.3	7.64
	41.3	5.8	2.45	.968	40.6	7.17
	39	4.32	2.4	.68	38.4	6.775
15	67.5	17.69	3.5	65.19	17.47	
	61	9.59	2.8	1.68	58.9	15.78
	51.5	8.98	2.6	1.56	49.7	13.32
	46	8.12	2.7	1.5	44.4	11.9
	43.7	5.45	2.4	.875	42.2	11.31
20	62.5	10.79	2.9	2.18	58.7	21.37
	61	14.2	3.2	2.87	57.3	20.86
	53.7	5.56	2.4	.75	50.46	18.36
	41.3	6.55	2.5	.93	38.8	14.12
	36	7.03	2.6	1.06	33.8	12.31
25	59	14.26	3.1	2.87	53.47	24.9
	56	10.07	2.7	1.93	50.75	23.66
	50	7.98	2.6	1.37	45.31	21.13
	45	6	2.6	.9	40.78	19.01
	44	7.69	2.8	1.31	39.87	18.59

Table .3: Results of flyer plates of a fitness ratio of 2

Angle (°) α	velocity m/s	depth mm d	width cm	area cm^2	vertical velocity m/s	horizontal velocity m/s
0	55	14.31	2.9	3.32	55	0
	44	7.89	2.8	1.43	44	0
	36	5.39	2.4	.875	36	0
5	63	14.92	3	3.125	62.7	B 5.49
	50	9.1	2.8	1.937	49.8	4.35
	43	4.46	2.5	.8125	42.8	3.74
10	58	14.75	2.8	3.125	57.1	10.07
	46	4.3	2.6	.75	45.3	7.98
	43	5.29	2.55	.93	42.3	7.46
15	60	12.26	2.9	2.5	57.9	15.53
	48.5	5.45	2.6	.875	46.8	12.55
	42	6.5	2.55	.96	40.5	10.87
20	58	9.47	2.9	1.87	54.5	19.8
	56	6.25	2.55	1	52.6	19.15
	40	6.95	2.5	1.25	37.5	13.68
25	58	12.5	3.2	2.32	52.5	24
	42	3.57	2.61	.56	38.06	17.7
	33.3	2.78	2.4	.56	30.18	14.0

Table .4: Results of flyer plates of a fitness ratio of 1 when the cavity is hemisphere

Angle (°) α	velocity m/s	depth mm d	width cm	area cm^2	vertical velocity m/s	horizontal velocity m/s
0	73.5	12.56	2.6	2.34	73.5	0
10	74	13.34	2.6	2.56	72	12.85
20	74	12.51	2.7	2.06	69.5	25.3
25	74	13.11	2.6	2.37	67	31

الملخــص

عملية اللحام بالمتفجرات باستخدام الصلصال كمادة نموذج .

اعداد

ايمن بسـام قمـوه .

تعتبر عملية اللحام بالمتفجرات اكثر الطرق استخداما ونجاحا في تطبيقـات عمليات تشكيل المعادن ذات الطاقة العاليـة .

ونظرا لخصائصها المتفوقـه فان هذه الطريقه لا تعاني من المعوقـات الموجـوده في طرق اللحام الاخـرى .

لقد اجريت ابحـاث ودراسـات كثـيره على العوامـل الـتي تـوءثـر علـى اللحـام بالمتفجـرات الا ان القليـل منها تطرق الى تأثـير سرعـه الصفيحـه الطائـره (FLYER PLATE) وزاويـة التصـادم (INCIDENCE ANGLE) بينها وبـين صفيحة الـهـدف (TARGET PLATE) على عمليات اللحـام وميكانيكيـة التشكيـل اللـدن (PLASTIC DEFORMATION) في منطقـة اللحـام .

تم استخـدام الصلصـال (PLASTICINE) كمـادة نمـوذج لكـل من الصفيحه الطائـره (FLYER PLATE) وصفيحه الهـدف (TARGET PLATE) لان الصلصال يمثل سلوك المعادن عند درجـات الحراره العاليـه (٦٠٠) مما يسـاعـد فـي استخدام جهاز بسيط وبتكلفـه قليـلـه (INDUSTRIAL STUD GUN)

لقد حددت الاطوال المختلفـه من التشكيـل اللـدن (PLASTIC DEFOORMATION) في هذا البحث . والنتائج التى أستنبطت باستخدام الصلصـال أمكـن تطبيقهـا علـى المعـادن .