A COMPARATIVE STUDY OF THE EFFECT OF STATIC AND DYNAMIC FORMING ON THE BIAXIAL NOTCHED FATIGUE STRENGTH OF 1100 SH 14 ALUMINUM

A Thesis Submitted

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by

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Abstract

To determine the relative effects of explosive and static forming on the fatigue life of 1100 SH 14 Aluminum, commonly known as commercially pure Aluminum, biaxial fatigue tests were performed on statically and dynamically formed domes. It was found that the life of the statically formed material was significantly more than the explosively formed material. It is proposed that the reduction in fatigue life may be due to the higher hardness of the statically formed material, and/or the formation of microcracks due to the explosive shock wave.

Acknowledgements

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CHAPTER 1

Introduction

1.1 Background

The advent of a new generation of "high-velocity metal working processes" including electromagnetic, electrohydraulic, pneumatic-mechanical and explosive metal working, was a major breakthrough in sheet metal forming technology in recent years. In general these most recent high-velocity metal working techniques differ from conventional processes in that the forming velocity is at least one order of magnitude higher as compared in Figure 1.1. The characteristics of various high-velocity metal working processes are given in Table 1.1.

As process techniques became more refined and the limitations of the process became clearer, the role of high-velocity metal forming became increasingly important. The technical requirements of the United States space program gave an impetus to the developement and refining of high-energy forming techniques. The demands of the aerospace industry included the following: the forming of metal parts and components beyond the then present capabilities of conventional equipment, parts made of exotic alloys which were difficult to form, parts requiring very close tolerances, and parts required in such small numbers that the cost of conventional equipment was not justified.

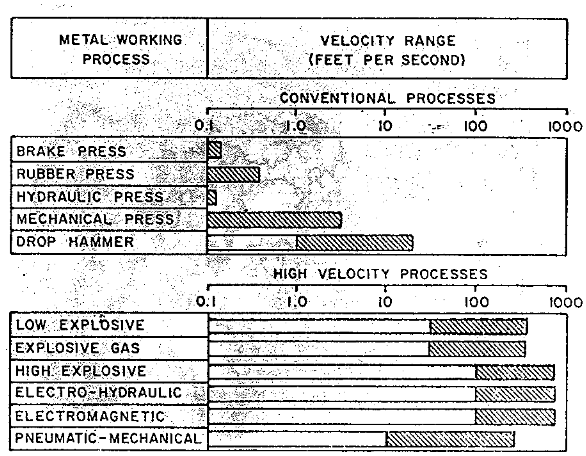


Figure 1.1 Deformation Velocities in High-Velocity and Conventional Metalworking Processes (Ref. 1)

	High explosive—standoff	High explosive—direct contact	Propellant closed die	Gas mixtures		Electromagnetic	Electrohydraulic		Pneumatic-mechanical
				Combustion	Detonation		Exploding bridgewire	Spark discharge	
Metalworking operations.	Draw forming, expanding, flanging, stretch forming, coining, blanking, sizing, heading.	Hardening, welding, cutting, perforating, cladding, powder compacting.	Tube bulging, powder compacting, sizing, perforating, flanging.	Tube bulging, flanging, sizing, stretch forming, draw forming.	Draw forming, stretch forming.	Swaging, tube bulging, sizing, flanging, shallow drawing, coining, blanking.	Tube bulging, drawing, flanging, coining, blanking, sizing.	Tube bulging, drawing, flanging, coining, blanking, sizing.	Forging, powder compacting, extruding.
Size limitations	Limited only by available blank size, presently ~ 12 ft.	Part size not limiting.	1-in. to 5-ft. diameter. Limited by equipment.	Up to 5-ft. diameter.	Present: 1 ft. diameter. Future: 9 ft. diameter.	1-in. to 1-ft. diameter; 4-ft. diameter and larger in sizing operations.	¼-in. to 4-ft. diameter or larger.	¼-in. to 4-ft. diameter or larger.	Up to ~ 2-ft. diameter; larger on future machines.
Shape complexity	Small and intricate, large and simple.	Simple shapes	Compound surfaces, nonsymmetrical shapes.	Compound surfaces, nonsymmetrical shapes.	Simple dishes, domes, surfaces of revolution.	Compound surfaces, corrective forming on large complex shapes.	Complex surfaces and shapes, especially tubular.	Complex surfaces and shapes, especially tubular.	Complex shapes, thin forged sections.
Principal advantage	Neither pressure nor energy limited; i.e., large parts.	Extremely high pressures (1.5 to 7 million psi).	Reduces number of operations to produce complex parts.	Uniform pressures permitting accurate forming of thin parts.	Adaptability to production forming.	Controllability and repeatability, swaging operations.	Controllability and repeatability.	Controllability and repeatability.	Controllability and repeatability, close tolerances on forgings.
Capital investment	Low	Low	Low	Moderate	Moderate to high	Moderate to high	Moderate	Moderate	Moderate.
Tooling costs	Low	None to low	Moderate	Moderate to high	Low	High if work coil is regarded as part of tooling.	Low	Low	Moderate. (See ch. 6.)
Labor costs	High	Moderate	Low to moderate	Moderate to high	Moderate	Moderate	Moderate	Moderate	Moderate.
Production rate	0.5 to 4 parts per hour or less depending on part and facility.	0.5 to 4 parts per hour depending on part and facility.	2 to 12 parts per hour depending on part and facility.	2 parts per hour or less.	6 to 12 parts per hour.	Up to 1,000 parts per minute for simple parts and automated transfer equipment.	4 to 12 parts per hour or more depending on part complexity and equipment.	Up to ~ 50 parts per hour depending on part complexity and equipment.	Up to ~ 200–300 parts per hour with automatic equipment; depends on part complexity.
Energy costs	Low	Low	Low	Low	Very low	Moderate	Moderate	Moderate	Low.
Leadtime required to place facility in operation.	Short	Short	Short	Moderate	Moderate to long	Moderate to long	Moderate to long	Moderate	Moderate.
Safety considerations.	Operation with trained personnel, safety equipment, and shielding.	Trained personnel	Trained personnel.	Trained or experienced personnel.	Trained or experienced personnel.	Equipment interlocks, high voltage safety practices, trained personnel.	Equipment interlocks, high voltage safety practices, trained personnel.	Equipment interlocks, high voltage safety practices, trained personnel.	Guards and shields, trained personnel.
Facility location	Usually requires remote or special facility.	Field or plant	In-plant or separate facility.	Separate facility	In-plant	In-plant	In-plant	In-plant	In-plant.
Energy range	Detonator to ~ 100 lb. high explosive at $1–2 \times 10^6$ ft-lb per lb.	0.5 to 8 lb. per ft² high explosive.	Low to moderate (squib, smokeless cartridge).	Low (burning gas mixtures).	Low to moderate (detonation wave in gas).	4 500 to 175 000 ft-lb.	20 000 to 175 000 ft-lb.	10 000 to 100 000 ft-lb.	Up to 500 000 ft-lb.
Workpiece deformation velocity.	60–400 ft/sec	Not applicable	50–200 ft/sec	60–100 ft/sec	60–200 ft/sec	50–200 ft/sec	50–200 ft/sec	50–200 ft/sec	50–200 ft/sec.
Energy transfer medium.	Water, elastomers, sand, molten salts.	Direct contact or buffer material.	Air or water; high-velocity projectile or ram.	Gas pressure	Gas pressure	Air (could be operated in vacuum).	Water or other suitable liquid.	Water or other suitable liquid.	High-velocity ram.

Table 1.1 Charactaristics of High-Velocity Metalwork Processes (Ref. 1)

Because explosives were found to be the most compact and the cheapest energy source available (one pound of dynamite will release approximately two million joules of energy, yet costs less than $0.40) explosive forming has been utilized more in industry than most other high-energy forming processes.

Not only was explosive forming being used in the aerospace field but also in such diverse applications as the formation of stainless steel dentures, missile nose cones, propeller hubs, helicopter crew leg armour, railway tank car bulk heads, pressure vessel heads, and prototypes in the automotive industry.

The changes in mechanical and metallurgical properties of materials formed by high strain rates are not fully understood. Moreover, the relative effect of explosive forming on material properties as compared to the effect of static forming requires further investigation. Most results published have given qualitative rather than quantitative figures. There has also been considerable lack of agreement in published research.

In recent years one of the more important fields of endeavour involved the comparative fatigue life of explosively and statically formed materials. Findings have ranged from negligible differences between static and dynamic forming to significantly reduced fatigue life due to explosive forming. This decreased fatigue life has been attributed to microcrack formation and nonuniformity in straining. Due to the uncertainty of the cause of the decreased fatigue strength more research is required to clarify the effect of explosive forming on fatigue strength.

1.2 Statement of Problem

This thesis is principally an experimental study of the comparative effect of dynamic and static forming on the fatigue life of 1100 SH 14 Aluminum.

1.3 Scope of Thesis

The thesis is divided into five chapters. Chapter One is an introduction to the field of explosive forming.

A review of literature associated with the comparison of the effects of dynamic and static forming on materials is given in Chapter Two.

Chapter Three describes all experimental studies carried out relating to and including the relative effect of explosive and static forming on the fatigue life of 1100 SH 14 Aluminum.

Test results and discussion of results are presented in Chapter Four.

The thesis is summarized and the author's conclusions are presented in Chapter Five.

A bibliography is presented at the conclusion of the thesis.

CHAPTER 2

A Review of Investigations Concerning Comparisons of Static and Dynamic Forming

2.1 Introduction

In recent years high strain rate forming has become an increasingly important method of metal working. Since most of the early work in the field of dynamic high energy forming considered only the practical aspects of the process, little experimental research was carried out to find the effect of dynamic forming on material properties, as compared to the property changes occuring in conventional forming processes.

Although many theories have been postulated regarding property changes produced by explosive working as opposed to conventional forming, few have been substantiated. Some of the experimental evidence has even been contradictory. In this literature review past findings as to process characteristics, effect on mechanical properties, and effect on metallurgical properties of both static and dynamic forming will be presented.

2.2 Process Characteristics

a) Introduction

The process of explosive forming involves the transmission of a pressure pulse produced by a detonation through a medium (e.g. water) to a work piece. The duration of the pressure wave is in the order of a few microseconds and the velocity imparted to the work piece ranges from 200 to 800 feet per second.[1] These high velocities are sufficient to cause air entrapment and cushioning between the die and the work piece. In order to achieve proper tolerances a vacuum must therefore, be created between the die and the blank. This requirement results in a greater set up time than that required for static forming. Thus for the forming of a large number of pieces, the forming time per work piece is higher than that for conventional forming.

b) Strain Distribution

In order to achieve a meaningful comparison between dynamic and static forming, a particular part shape which is common to both processes is desirable. The shape most common to both processes is the deep recessing of spherical segments from flat plates.[2] Conventional deep recessing is done by hydraulic presses, rubber bladder presses, or direct hydraulic pressure. The limiting radial strain distribution for a pure stretch recessing in three processes is shown in Figure 2.1.

TYPE 1 of Figure 2.1 illustrates the use of a conventional

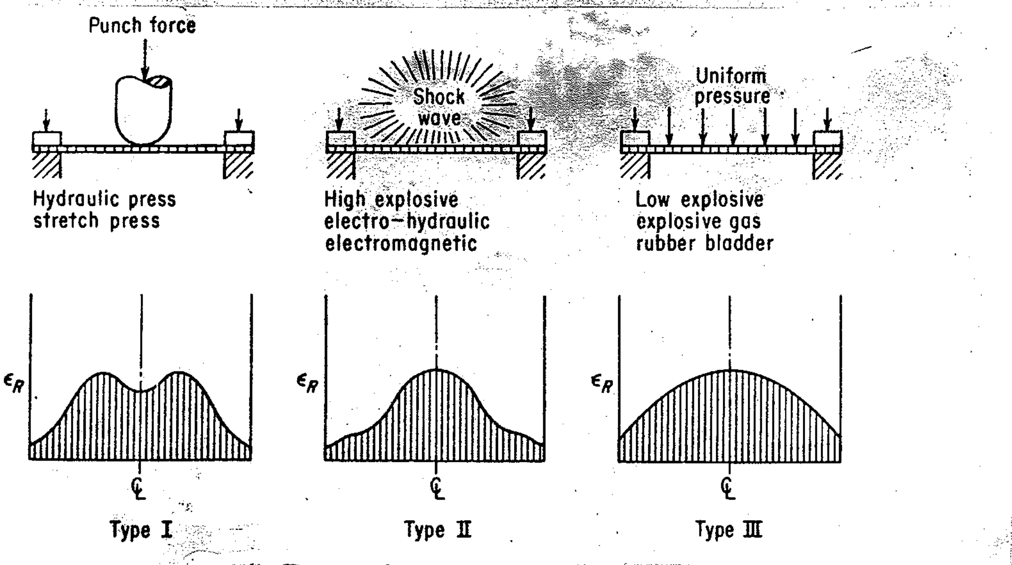


Figure 2.1 Three basic types of strain distribution (Ref. 2)

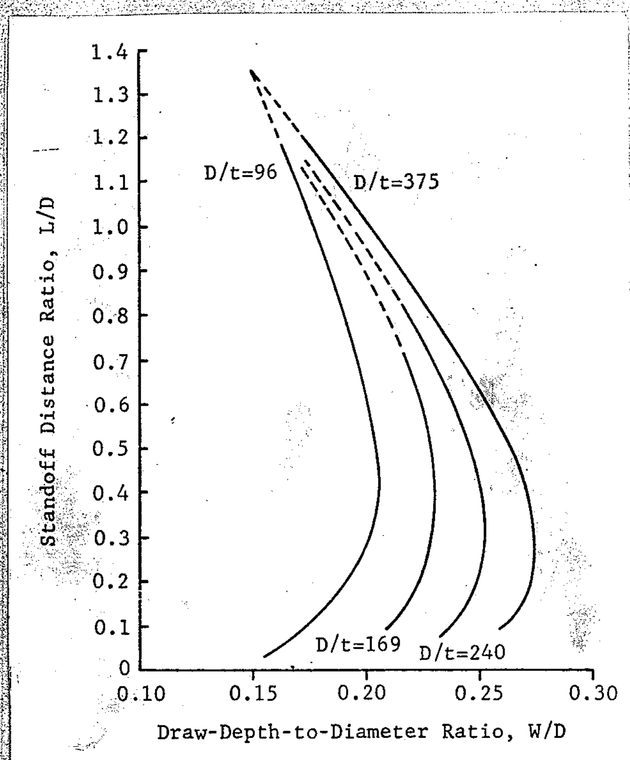


Figure 2.2 Optimum standoff distance (Ref. 3)

punch press arrangement for deep recessing. A uniform straining occures at the point of contact between the punch and the work piece until the friction at the interface results in a localized static condition.[2] Stretching continues in the unsupported region around the punch. In this region of instability diffuse necking and ultimate strain occur.

TYPE 2 of Figure 2.1 shows the strain distribution for deep recessing employing high-energy techniques such as high explosives, electrohydraulic, and electromagnetic forming. The blank loaded by a point high-energy source will deform vertically as a flat plate forming a conical shape having maximum strain at the apex and much less strain in the circumferential direction. The strain at the apex is greater than the strain required to form a hemispherical dome from the conical shape.

TYPE 3 of Figure 2.1 is the strain distribution curve for deep recessing employing conventional rubber-bladder process or chemical-deflagration processes. A uniform pressure is exerted throughout the forming. Since no friction or shock wave effects are present the strain distribution closely approaches the theoretical strain distribution for spherical segments.

c) Charge and Standoff

The exact placement of the charge and its size is all important in explosive forming. This is due to the peak pressure exerted by the shock wave being inversely proportional to the distance from the charge.[4] A critical standoff distance exists at which a central charge will produce the maximum blank deformation.[3] At smaller or larger standoff distances the draw depth of the blank decreases, as shown in Figure 2.2.

d) Springback and Recovery

In a review of explosive metal working M.C.Noland et al [4] reported on research carried out by Martin Co., Denver Division in the field of springback as associated with explosive forming.

Springback, generally defined as the tendency of a part blank to return to its original shape after forming, was mitigated by straining the complete cross section of the blank above the elastic limit. By shifting the neutral axis, where the strain was zero, well above the face of the blank, the entire blank thickness would be plastically deformed. This was accomplished by two methods, by providing blank restraint around the perimeter and by placing a plug cushion, a pseudo integral part of the blank, above the blank.

When the material was stretched the edge restraint caused a uniform tensile stress to be superimposed across the entire cross section of the material blank. This superposition of stresses (as shown in Figure 2.3) was responsible for raising of the neutral axis. Thus the entire cross section was strained into the plastic range and would remain permanently deformed.

The plug cushion (usually made of soft metal or rubber) transmitted the explosive shock wave to the work piece, increasing the strain on the portion of the blank at the draw ring. Not only did this cushion prevent pitting of the blank but also the local material thin out was reduced and the formability of the material was increased.[4,6] Being a pseudo integral laminate the plug cushion effectively increased the thickness of the blank so that the neutral axis was shifted above the blank face, as shown in Figure 2.4. The complete blank cross section was thus strained into the plastic range.

In both explosive and conventional forming a small amount of springback is inevitable. In comparison with conventional forming many reports[1,6,7,8,9] state that springback is reduced and in some cases eliminated with explosive forming. If the springback can not be totally eliminated, it must be compensated for in the die design.

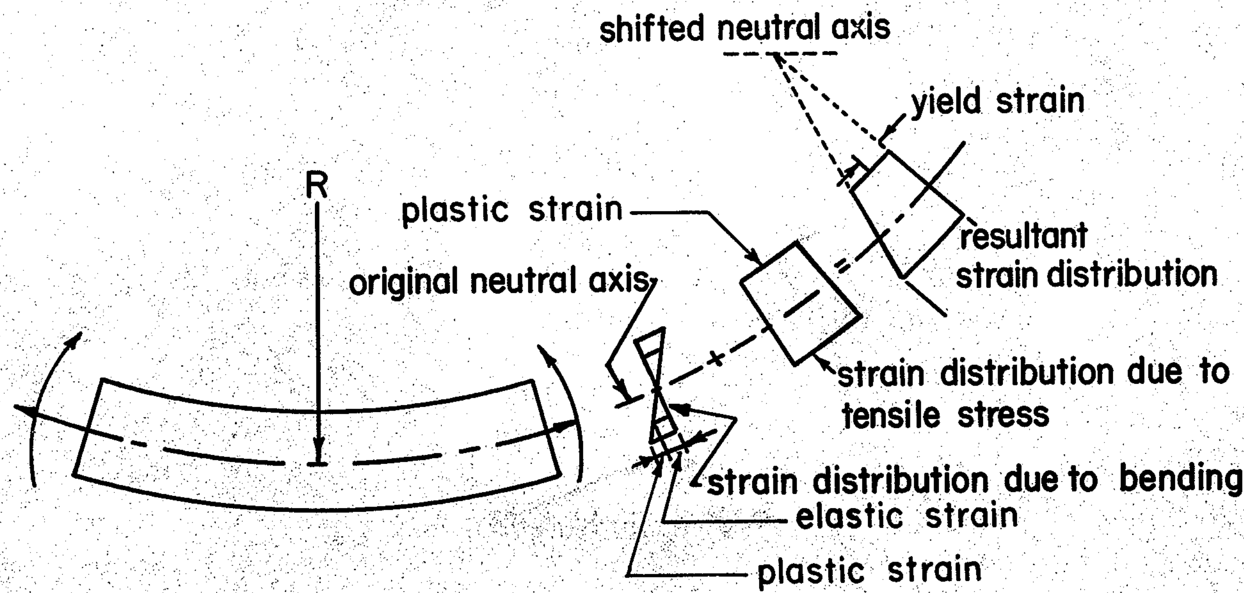


Figure 2.3 Shift of neutral axis due to edge restraint

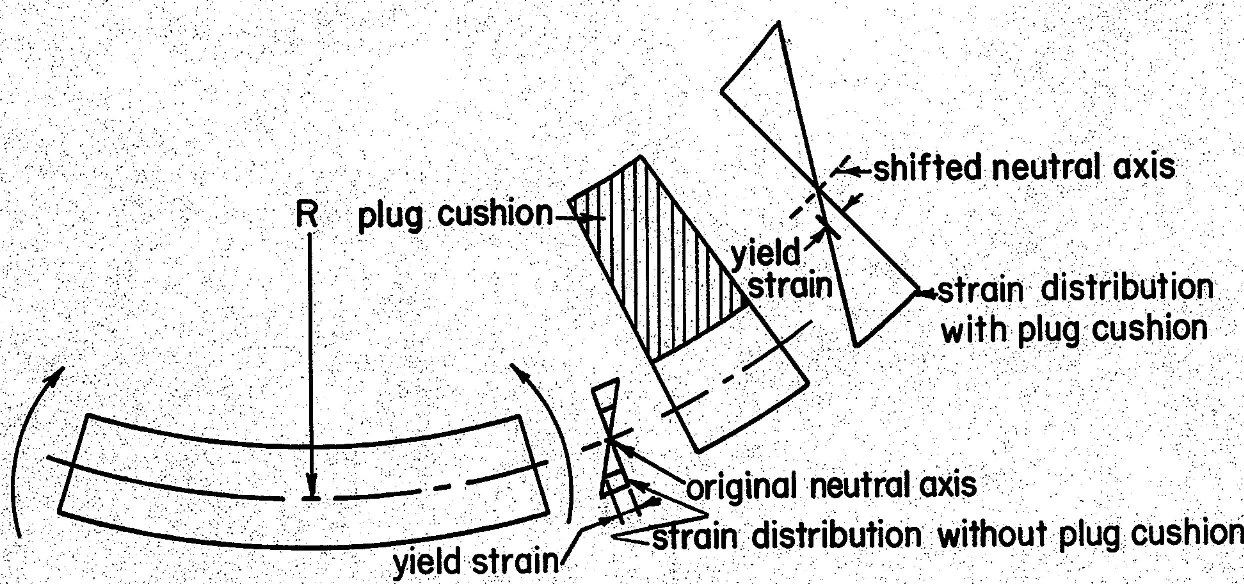


Figure 2.4 Shift of neutral axis by addition of a plug cushion

e) Formability

In many cases the reports regarding the comparitive effect of explosive forming on the formability of metal were contradictory. In a survey conducted by M.C.Noland et al[5] on research carried out by three authors[10,11,12] it was found that certain metals could be plastically deformed to a greater extent by explosive forming than by conventional processes. Later reports published by Suiter[1] and Rowden[13] contended that although explosive forming permitted greater elongation than hydrostatic expansion, these elongations were not as great as those produced by pressing. Suiter went on to say that the greater uniformity across the blank produced in explosive forming as compared to press forming resulted in the impression that formability was increased.

2.3 Mechanical Properties

a) Elastic Modulus

Very little work has been done to find the effect of increased strain rate on elastic modulii. The only reference to this property[12] indicated a neglegible change in Young's Modulus due to increased strain rate.

b) Ductility

Many authors including Bridgman 15 , Wood 16 , Pugh and Green 38 have shown that ductility increases with an increase in hydrostatic pressure. This type of pressure may be found in explosive forming.

W.W.Wood et al 10 studied the effect of impact velocity on the uniform strain in tensile specimens. Since strain can be defined as the per cent strain in the specific region where necking does not occur, the strain was a measure of ductility. Tests were carried out on the following metals: Ti(6Al-4V), 17.7 PH, VASCOJET 1000, A-286, RENE 41, USS 12 MOV, Ti(13V-1Cr-3Al), Maynes Alloy, 25(L-603), 2024-O Al, Columbium (10Mo-OTC) and Molybdenum (5% Ti).

Strain distributions for metals tested at low and high strain rates were obtained. Improved stability in dynamic forming of specimens at high strain rates with an increase in uniform strain was observed. At low strain rates necking over a small area with little plastic deformation in the rest of the specimen before fracture was observed. At high strain rates the encking region strain hardened and did not fracture until energy was distributed over the other portion of the specimen, therefore an increased uniform strain was present.

It was also found that a critical impact velocity existed over which there was a sharp decrease in ductility. The critical impact velocity occurred when the impact speed exceeded the strain wave propagation velocity through the specimen. Thus a high critical impact velocity caused the exhibition of a high value of maximum elongation and vice versa.

Further work has been done by W.Wood et al[10] on free formed dome shapes and bulged tubes to give some indication of the actual stress distribution in forming. The same twelve metals were tested to find the effect of velocity on the formability of domes two and one-half inches in diameter. The data showed a significant increase in ductility at different velocities for most of the metals tested. The forming velocity associated with the increased ductility and the critical velocity were separated by a range of 100 to 150 feet per second. This was the maximum formability region as shown in the maximum dome depth versus forming velocity curves in Figure 2.5. Tube bulging tests using five metals gave the effect of an approximate plane strain although no critical forming velocity was found. It was concluded that for each material and each forming operation an optimum velocity range existed.

From the results it was found that the materials tested could be grouped into the following three categories:

1) Materials which exhibited high ductility under static conditions and substantially higher ductility in optimum strain rates. An example of this is 17-7 PH semiaustentic stainless steel.

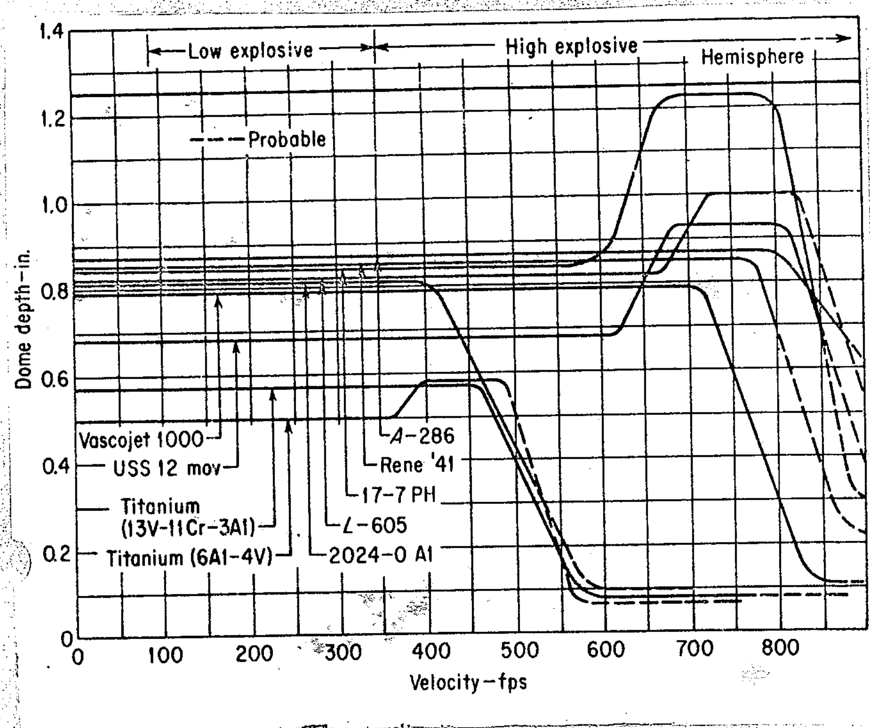


Figure 2.5 Dome depth versus velocity (Ref. 10)

2) Materials which exhibited moderate ductility under static conditions and equal or greater ductility in the optimum strain rate range. This is illustrated by the following: VASCOJET 1000, Martensitic tool steel, RENE-41-nickel base superalloy, Haynes 25 Cobalt-base superalloy, 2024 Al and USS 12 Molybdenum martensitic stainless steel.

3) Materials which exhibited low ductility under static conditions and equal or slightly greater ductility in optimum dynamic range as shown by 13V-11Cr-3Al and 6Al-4V Titaniums.

It was also shown that materials with low hardenability could be expected to show a higher ductility in the complex strain states (plain strain or balanced biaxial strain) than in the simple tension strain state and vice versa.

c) Work Hardening

Most of the research work carried out has resulted in the conclusion that there is no marked change in the hardness produced by explosive forming as compared with static forming. The most extensive work, carried out by Williams[17], showed only a slight variation in work hardening. Tests were carried out using a hemispherical punch and explosives to form domes. In both cases the mode of formation was stretch-forming. The results indicated that the face-centered cubic metals, Nimonic 75 and 90, aluminum alloy HS 15, and austenitic stainless, hardened more under dynamic loading than under static forming. On the other hand pure titanium, a hexagonal close packed metal, and mild steel, a body centered cubic material hardened less under explosive forming. Annealed steel showed greater work hardening in explosive tensile impact tests conducted by Harris and White. Campbell and Duby[32], and Tardif and Erickson[40] showed that for compressive impact, materials work hardened less under dynamic forming.

d) Yield and Ultimate Strengths

The greatest amount of work has been done to evaluate the effect of explosive forming on the tensile properties of metals. Generally the results indicated that ultimate and yield strengths obtained by explosive forming were higher or at least comparable to those obtained by static forming. In a comparison of static and dynamic forming, after tensile prestrain, both Henriksen[12] and Wilken[21] found in static forming a marginal increase in yield, ultimate and notch strengths of 5456-0 Aluminum. In both cases the forming was uniaxial. In the same investigation Henriksen's results also showed that the strain rate sensitivity was generally greater for the weaker metals and decreased with increasing strength. It was also noted that the yield strength was more rate sensitive than the ultimate strength. Regardless of the property a strain rate effect wholly or partially increasing with increasing strain rate was noted.

In biaxial comparisons of high and low strain rate forming, as presented by Otto and Orava[19] for 2014 Aluminum, no marked difference in yield and ultimate strengths were noted. In the above report reference to the work of D'Aguanno and Pfanner[41] revealed a more marked contradiction. Working with 2219-0 Aluminum D'Auanno and Pfanner found that hydrostatic forming gave a much higher increase in yield and ultimate strengths than explosive forming.

Wilken et al[21] again working with 2219-T37 and 2219-T87 Aluminum found that for the two forming processes the hardness, proportional limit, yield stress, ultimate strength, total elongation, and reduction in area to fracture were indifferent to the type of forming.

In a summary of the effects of explosive forming compared with static forming Otto[20] divided the materials investigated into two main groups: firstly materials which exhibited higher yield strength, ultimate strength, and hardness, and a slight reduction in ductility on explosive forming as compared to hydrostatic forming. This group included aluminum and aluminum alloys, high strength low alloy steels, austenitic stainless steels, copper base alloys and titanium. The second group was made up of the low carbon steels which exhibited no change in material properties.

e) Impact Strength

Although no comparitive data was available, Verbraak[25] stated that increased brittleness was found in explosively formed steel products, but no data was given. The decreased strength of explosively formed steel was attributed to the mechanical twinning in the body centered cubic lattice. Verbraak suggested choosing a steel with a low ductile-brittle transition temperature to decrease the embrittlement. A larger charge at a greater standoff rather than a smaller charge at a smaller standoff in forming was also advocated. Verbraak also suggested the possibility of microcrack formation at the intersection of Neumann bands[23]. This phenomena had been seen by Hull[24] in his work with silicon-iron.

f) Corrosion and Stress-corrosion

In most references found, explosive forming had a detrimental effect on the stress-corrosion of metals. In comparative stress-corrosion tests with 18/8 stabilized austenintic steel in a $MgCl_2$ environment, Verbraak[18] found that the explosively formed specimens broke in less than one-third of the time it took for the statically formed specimens to break. These results were attributed to the appearance of mechanical twinning and slip, on the cubic planes. As a solution to the degradation, Williams[17] suggested that the explosively formed materials should be either stress relieved or fully annealed.

Tests performed by Holtzman and Cowan[27] to show the general corrosion rate of 304L stainless steel and Titanium 55A in ferric sulphate/sulphuric acid showed a slight increase in the attack rate on 304L due to explosive forming, as compared to static forming. No significant increase was found with Ti 55A.

In Otto's survey[20] of a number of materials the findings were as follows:

No effect in stress-corrosion life was noted for 2010 Aluminum from the annealed state to T5, 2014-T6 and 7075-T6 were less susceptible to stress-corrosion after explosive forming.
There was no difference for 321 stainless steel, whereas 316 and 1818 English stainless steels showed a higher susceptibility to stress-corrosion. The method of formation had no effect on

the resistance of maraging steels. Otto also reported the possibility of a lower resistance of explosively formed super alloys such as VASCOJET 1000, AM350 and D6AC.

g) Fatigue

In 1962 Williams[17] reported on the changes in the fatigue strength of thirteen materials due to explosive forming. He stated that the fatigue life was comparable to that obtained from static forming. J.L.Remmerswaal (Metaalinstitut T.N.O., Delft)[17] stated that work carried out at Delft indicated that fatigue strength for explosively formed materials might be lower than that produced by conventional methods, depending on the material. Verbraak[18] postulated that the drop in fatigue life may have been caused by submicroscopic cracks which formed during explosive deformation. Reporting on work by Baudry and Cooper, Rowden[13] stated that for low-cycle fatigue on austenitic manganese alloys, the explosively formed material showed an improvement over the conventionally formed specimens. Later work by Bennett[28] comparing the fatigue strength of explosively formed 5052-0 Aluminum to statically formed 5052-0 Aluminum showed a significant reduction in fatigue properties due to explosive working. This drop was attributed to the non-uniform work-hardening of the explosively formed material.

Work accomplished by Mikesell[29] on explosively free-formed and hydraulically formed 2014 Aluminum revealed no reduction in the fatigue life due to explosive forming. Additional results reported by Otto[20] show no change in fatigue properties for 6000 and 7000 series aluminum alloys, and 316 stainless steel. The 304 and 347 stainless steels on the other hand had an improved fatigue life with explosive forming.

2.4 Metallurgical Changes

The principal mechanisms responsible for plastic flow in materials are slip and twinning. Twinning, which is a reorientation of part of a crystal with respect to the rest of the crystal, accounts for only small strains, its main function being to reorient the grains into a more favourable position for slip. In many poly-crystalline metals, twinning occurs only after some plastic deformation or when a stress has been applied very rapidly. Tennesse[30] noted that this may account for explosive forming increasing the ductility of some metals, in that the higher strain rate may cause a reorientation of the grains so that plastic flow can continue more favourably. Some metals on the other hand decrease in ductility with increased strain rate because the dynamic stress exceeds the critical-fracture stress (that component of the shear stress which causes cleavage between the molecular planes).

In his studies, Wood[16] concluded that the critical resolved shear stress (which is that component of the shear stress acting parallel to the slip plane causing flow to occur), mechanical twinning, and brittle fracture are functions of the deformation speed and temperature. The critical stress for slip increased with increasing strain rate while the critical stress for twinning is not as dependent on stress rate. Thus at higher strain rates twinning becomes the more important phenomena.

Verbraak[23] noted that for austenitic steel, in which slip occured normally on octahedral planes, slip during explosive forming also occured on cubic planes. With body-centered cubic materials mechanical twins always appeared.

In the explosive loading of annealed mild steel, Williams[17] noted the formation of Neumann bands or shock twins, which increase in number with the amount of deformation up to about 30 per cent reduction of thickness. Further deformation did not increase the number of bands although slip lines appeared in the grains.

Other authors, including Suiter[1] working with aluminum, and Campbell, Duby, and Puttich[33] using low and medium carbon steels, noted a difference in slip patterns as a result of explosive forming. In every case the slip lines appeared to be finer and more closely packed with less slip in each band with the explosive forming than was present with static forming. Pipher et al[26] did not observe any unusual features in explosively formed VASCOJET 1000 (5% Cr, 0.3% Ni, 0.05% V), AM 350 (17% Cr, 4% Ni, 1% Mo), and a Ti-Al-V alloy.

A report published by Clark[34] on the work of Zukas and Fowler, stated that the Neumann twin marking could be suppressed by prestraining prior to shock loading. Smith[31] suggested that the Neumann twins were generated by a discontinuity between the Hugoniot elastic limit (the stress at which plastic flow begins) and the transition pressure between the low and high pressure phases. This discontinuity will show up on the pressure-distance profile of the elastic and plastic waves moving through the material.

Several workers have produced evidence of the above mentioned phase change occuring in explosively formed materials. The extreme pressures encountered in explosive forming may produce phase changes at lower temperatures than normal. Williams[17] produced evidence supporting the foregoing statement in that he found more martensite in explosively formed austenitic steel than in statically formed steel. Smith[31] noted that a phase change occured in steel at pressures in excess of 130 kilobars ($2x10^6$ pounds per square inch), the structure after explosive shock resembled carbon-free martensite. In a discussion reported by Clark (34) it was pointed out that the high pressure phase in iron is more dense than the low pressure phase and probably forms rapidly by a shear process.

2.5 Summary and Conclusions

The literature survey indicates that although some observations are consistent, discrepencies between authors' analysis of results illustrate that voids remain in our knowledge of the comparitive effect of explosive and static forming on material properties. The relative lack of conclusive data and the scatter of results may be responsible for the different findings that have been published.

From the reports compiled a number of general claims or observations can be made. The advantages of explosive forming over conventional forming include:

1. There is no limit to the part size that can be formed, other than that imposed by the available blank size.

2. Capital investment is lower than for conventional forming because only a female die and no heavy machine is required.

3. Tolerances are usually closer regardless of the size of the part, because springback is reduced and in some cases virtually eliminated.

4. Since for some materials formability increases with increasing strain-rate, greater versatility of material applications is possible.

5. Lead time is greatly reduced compared with conventional processes, thus making explosive forming more applicable to prototype building.

6. Ultimate strength, yield strength, and proportional limit are usually higher with dynamic forming than with static forming

7. The ductility of most materials increases over a particular range of strain rates.

The explosive forming process has several undesirable features such as:

1. The production rate is slower than for conventional processes.

2. The operator employed must be both experienced and skilled. Men trained in this work are not readily available.

3. The use of explosives makes forming in built up areas unfeasible due to the noise and danger involved.

4. In comparison to conventional forming explosive forming, in some cases, decreases the fatigue life of formed parts.

5. In most cases explosive forming has a detrimental effect on the stress-corrosion life of materials.

Thus it is apparent that explosive forming will take its place in industry as a manufacturing process. Although the process may have deleterious effects on material properties, if no microcracks due to high speed deformation are present, properties may be restored to a permissible level by heat treating[13]. The effects of explosive forming must be recognized and compensated for in order to avoid difficulties in applying the process and using its products.

CHAPTER 3

Experimental Study

3.1 Introduction

There have been a number of investigations to find the relative effect of explosive and static forming on the fatigue life of commercially used alloys, often with contradictory results. Since no work has been done to date to compare the effects of these processes on the fatigue life of commercially pure aluminum, it was considered that such an endeavour would make a valuable and original addition to our fund of engineering knowledge.

The comparison of fatigue life was made at two stress levels and an attempt was made to explain the deterioration in fatigue life in the explosively formed specimens.

3.2 Materials and Specimens

The material investigated was 1100 SH 14 Aluminum, commonly called commercially pure aluminum. The blanks were cut from rolled sheets 0.064 inches thick. All blanks were obtained from two sheets which came from the same pour. The approximate chemical composition and mechanical properties are given in

Tables 3.1 and 3.2 respectively. Both static and dynamic specimens were die formed hemispherical domes, one and one-quarter inches in depth and three inches in spherical radius.

A fatigue failure may be caused by either an external or surface flaw or by a flaw in the material itself. The method of forming (dynamic versus static) may have a unique effect on either of these sources. It was desirable to say with certainty that any difference was due to a change in material properties rather than surface effects, therefore surface effects were eliminated by use of a constant stress concentration factor. Specifically this stress concentration was achieved by a V notch at the apex of the dome as shown in Figure 3.1 a,b, and c. The depth of the notch was one-half of the thickness of the dome at the apex. Both the inside and outside of the domes were polished with jeweler's rouge to remove any small surface irregularities caused by forming. Any burrs formed at the edges of the V notch by machining were removed using 600 grit Silicon carbide paper.

3.3 Test Equipment

A hydraulic fatigue machine based on a similar principle as

Table 3.1

Approximate Chemical Composition of 1100 SH 14 Aluminum

Al minimum	99.00 %
Si plus Fe maximum	1.0 %
Cu	0.05 %
Mn	0.10 %
Zn	0.05 %
Others	0.15 %

Table 3.2

Mechanical Properties of 1100 SH 14 Aluminum [42]

Ultimate tensile strength	18,000 psi
Tensile yield strength	17,000 psi
Elongation at rupture	20 %
Fatigue limit	7,000 psi @ 5×10^6 cycles
Modulus of elasticity	10×10^6 psi
Poisson's ratio	0.33

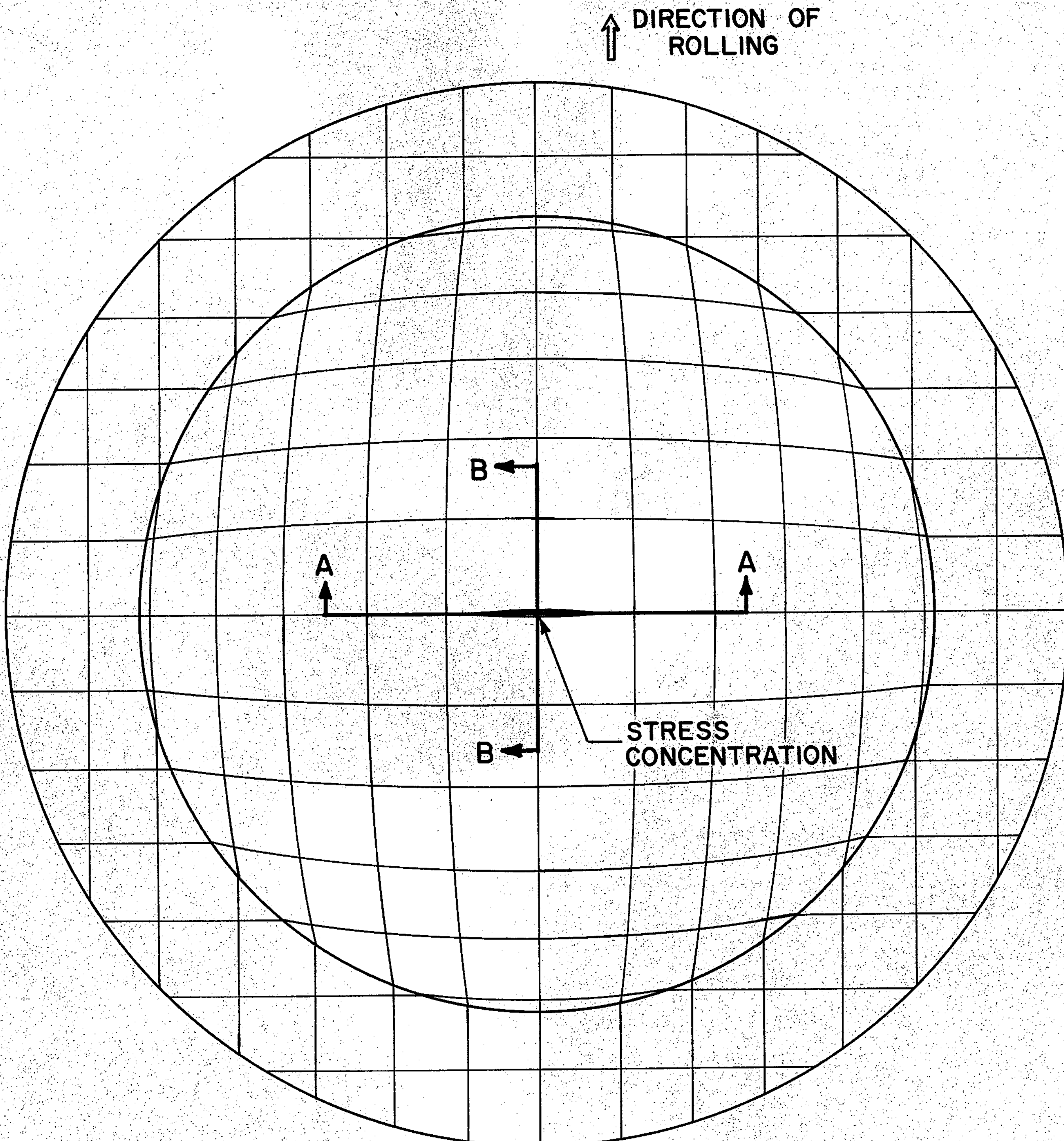


Figure 3.1a DOME SPECIMEN SHOWING STRESS CONCENTRATION

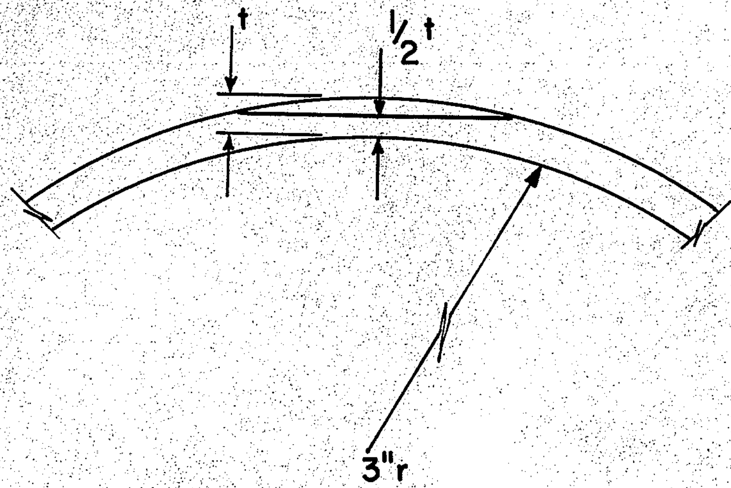


Figure 3.1b SECTION A-A

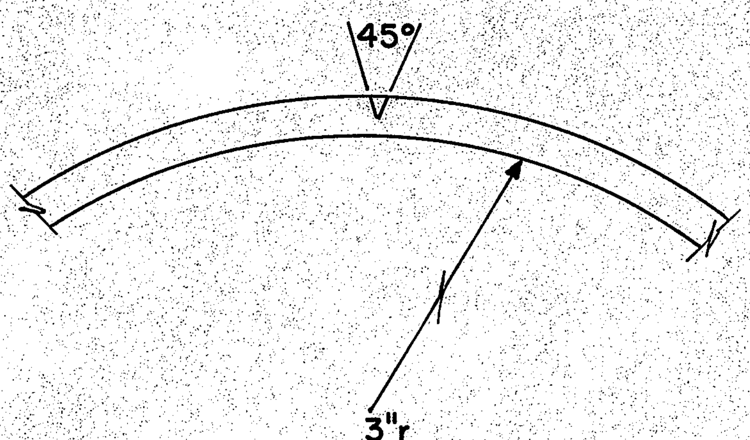


Figure 3.1c SECTION B-B

DOME SECTIONS SHOWING STRESS CONCENTRATION that used by Shewchuk[35] was designed for use in plate bending experiments and modified for dome testing. The machine is shown in Figure 3.2 a,b, and c.

The main components of the hydraulic fatigue machine are: (a) the pressure chamber, (b) the specimen holder, (c) the pressure control circuit, and (d) the hydraulic pressure supply. A detailed description of each is given below.

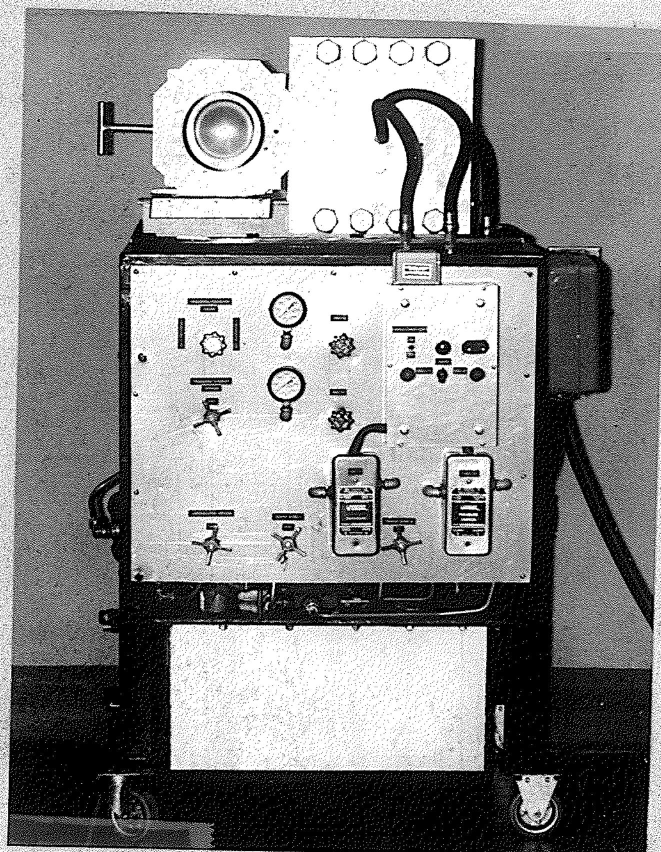
(a) Pressure Chamber

The pressure chamber as shown in Figure 3.2 b is a semi-enclosure of two heavy parallel steel plates two inches thick. The specimen holder can be slid into the slot between the plates and tightened in place by eight bolts. Pressure and vent ports are located in each plate of the pressure chamber, at the center and the high point of the positioned specimen, to allow for efficient venting.

(b) Specimen Holder

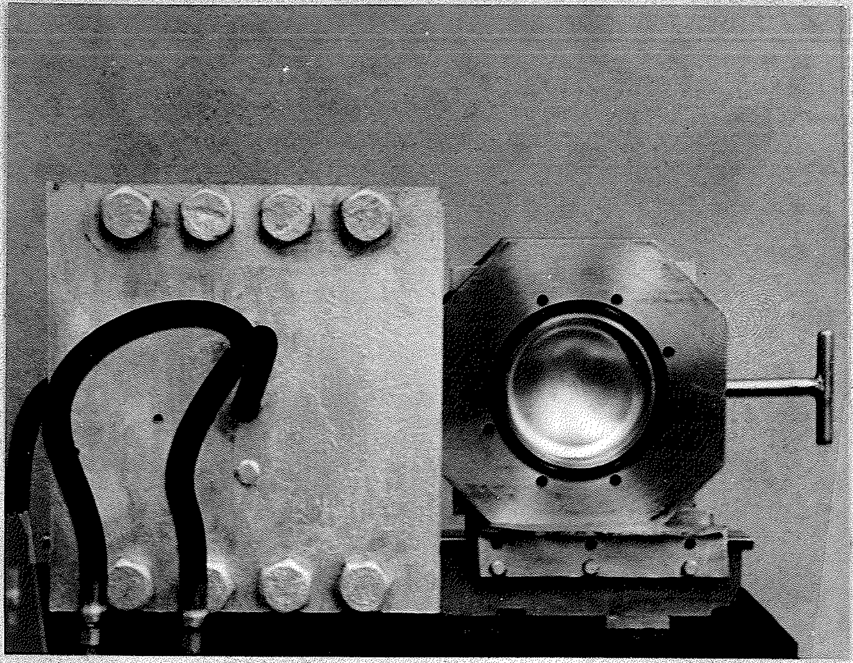
The specimen holder as shown in Figure 3.3 performs a dual role. It seals the dome specimens so that no oil leakage occurs and at the same time it supports the dome so that only the hemispherical section of the dome is stressed.

The oil seals on the face plate of the specimen holder are formed by O rings. These O rings are located inside the bolt

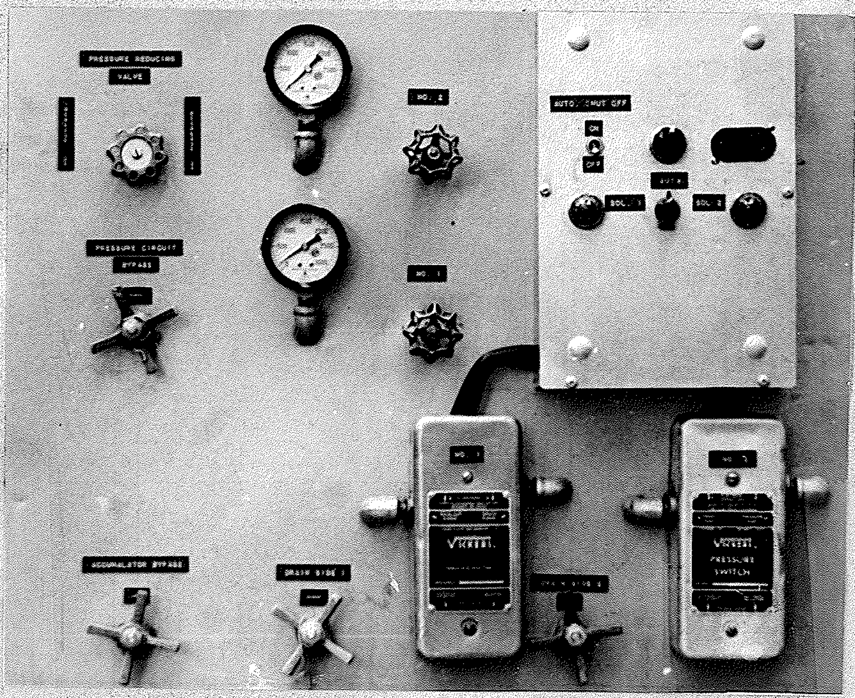


(a)

Figure 3.2 Hydraulic Fatigue Machine



(b) Pressure Chamber



(c) Control Panel

Figure 3.2 Hydraulic Fatigue Machine

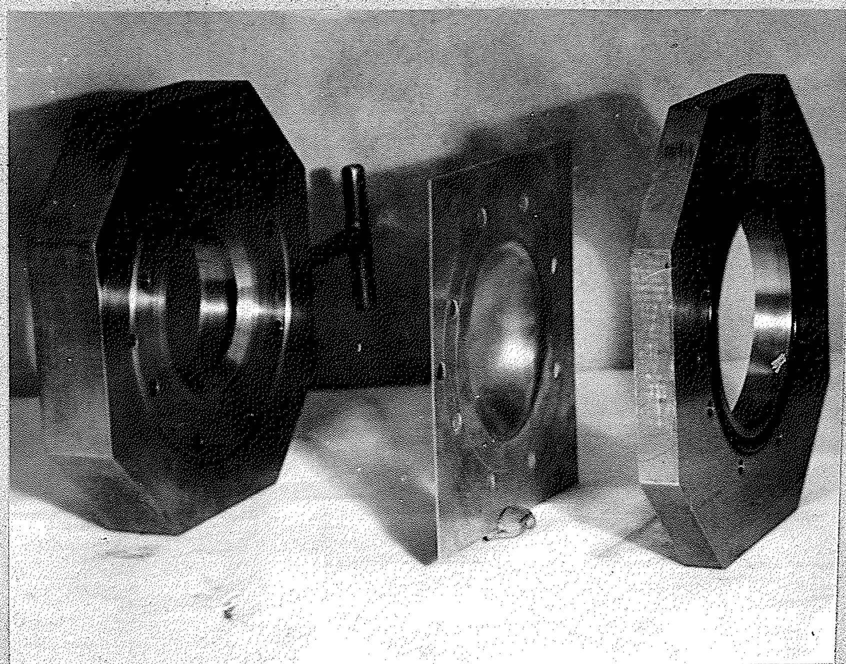
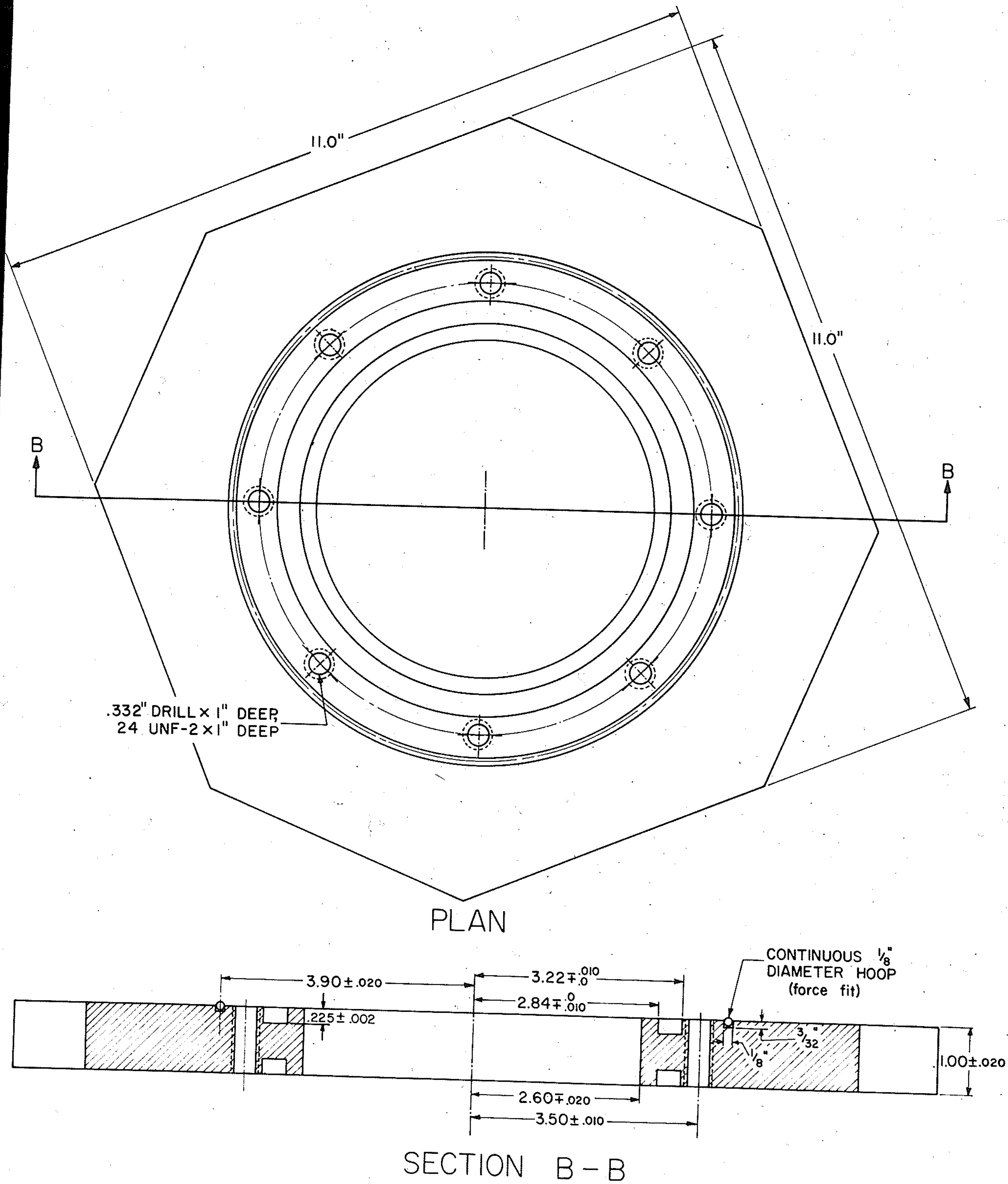


Figure 3.3 SPECIMEN HOLDER
(exposed view)
exploded

circle on both sides of the plate. A groove and ring combination outside the bolt circle on the specimen side of the plate also aids in oil sealing. The face plate is shown in Figure 3.4. The back up plate incorporates a support ring which follows the contour of the dome and gives support so that only the hemispherical portion of the dome is affected by the hydraulic pressure. The back up plate is shown in Figure 3.5.

(c) Pressure Control Circuit

Figure 3.6 illustrates the operation of the hydraulic pressure control circuit and Figure 3.7 shows a schematic of the electrical circuit. Pressure switches are placed in line before the pressure chamber and before the hydraulic short circuit. This short circuit is produced by a hydraulic hose connecting the pressure and vent lines to the pressure chamber. The two position microswitches of the pressure switches are normally held closed by spring pressure. The pressure required to trip open the microswitches can be varied from 50 to 2000 pounds per square inch. Oil pressure in the pressure chamber and in the hydraulic short circuit acts against the respective spring pressures and when the oil pressure exceeds the spring pressure, the microswitch trips open. The microswitches used are, by manufacturer's specifications, accurate within five pounds per square inch of the set pressure.



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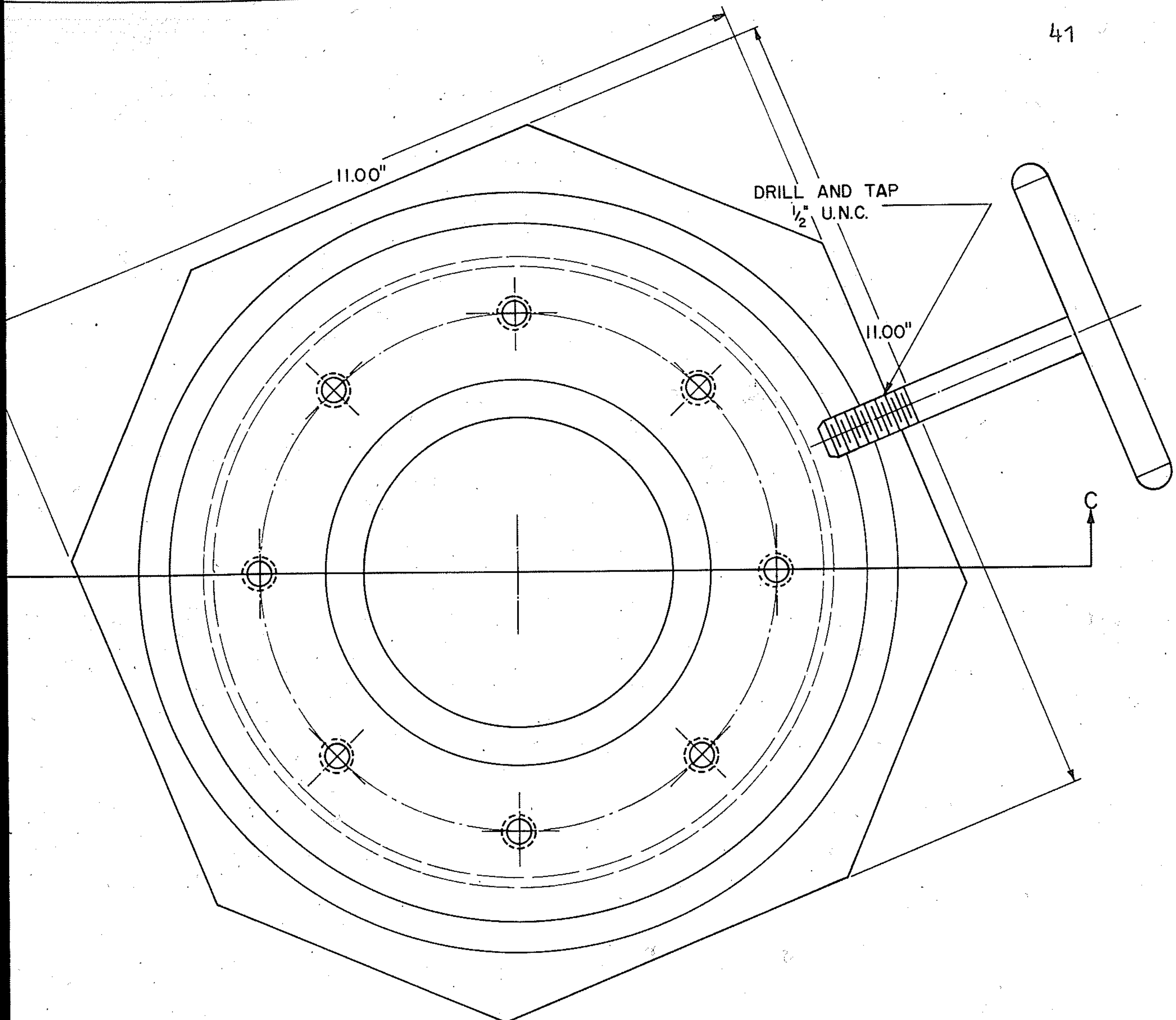
DETAIL OF SPECIMEN HOLDER FACE PLATE			FIGURE 3.4



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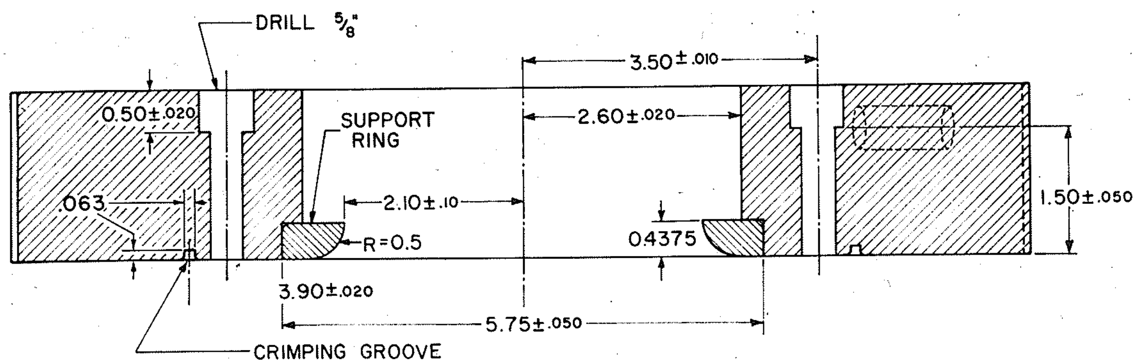

SECTION C - C

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DETAIL OF SPECIMEN HOLDER BACKUP PLATE			FIGURE 3.5

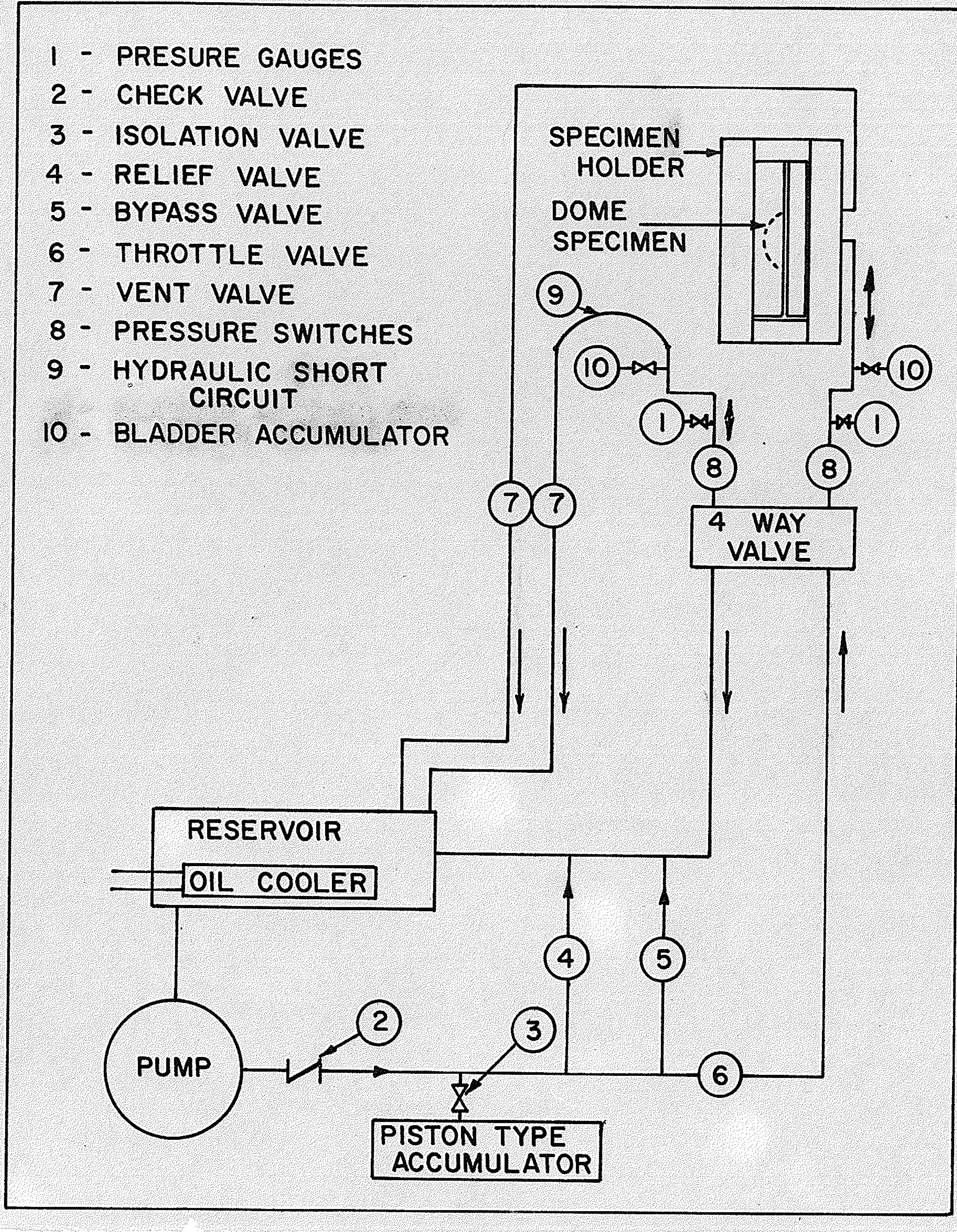


Figure 3.6 Hydraulic circuit for pulsating fatigue machine

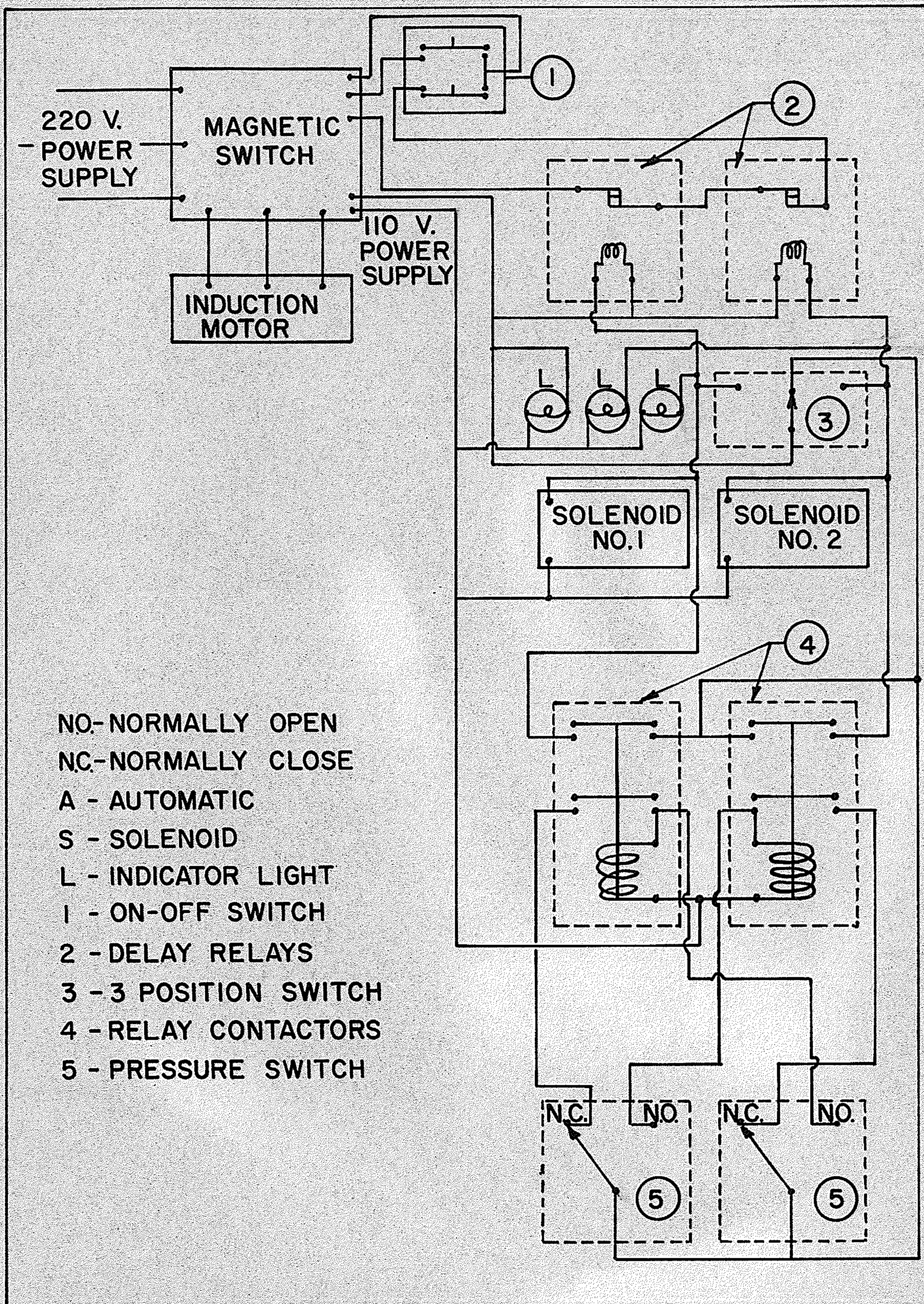


Figure 3.7 Schematic of electrical circuit-hydraulic pulsating fatigue machine

The microswitch action energizes and de-energizes relays which control the current flowing to the solenoid coils of the four-way valve. When the pressure in the dome reaches the set pressure the microswitch is thrown open, thereby de-energizing relay 1, and at the same time energizing relay 2. The current flow is redirected from solenoid 1 to solenoid 2. The high pressure oil flow then changes from the dome to the hydraulic short circuit. The oil in the pressure chamber then drains to the oil resevoir.

Employing two heater tubes the electric circuit is so designed that if the specimen breaks, the resulting excessive leakage in the system will cause a large reduction in the pressure cycling rate which will in turn cause the machine to stop automatically.

The speed of cycling is controlled by adjusting the pressure in the bladder accumulators. By increasing the pressure in the accumulators the initial volume of the system is decreased and the time required for the whole system to reach the cycling pressure is reduced. Thus the cycling rate increases. The additional advantage of the bladder type accumulators is that some of the pressure shock is eliminated from the system.

(d) Hydraulic Pressure Supply

The hydraulic pressure is supplied by a 3000 pounds per square inch, 3 gallons per minute constant displacement pump driven by a 5 H.P. motor. The flow circuit involves pressure relief, throttle, bypass, and flow control valves. Also incorperated are a piston-type accumulator, two bladder-type accumulators, an oil cooler, and an oil reservoir. By adjusting the relief valve, discharge pressures up to 2000 pounds per square inch could be obtained. Pressure in both sides of the system were monitored by hydraulic pressure gauges. The four-way valve was so connected that it could be operated either automatically or manually. An electric reset digital counter was connected in parallel to one relay.

ESSO UNIVIS N-42 hydraulic oil was used as the operating fluid.

3.4 Specimen Forming

a) Explosive Forming

The arrangement for explosive forming is shown in Figure 3.8. A hemispherical die and hold down ring were designed and machined, as shown in Figures 3.9, 3.10, and 3.11. The vacuum lead was positioned just inside the perimeter of the hemispherical portion of the die.

The charge was formed by cutting strips of "Deta - sheet A" explosive (85% by weight PETN) manufactured by Dupont, and rolling

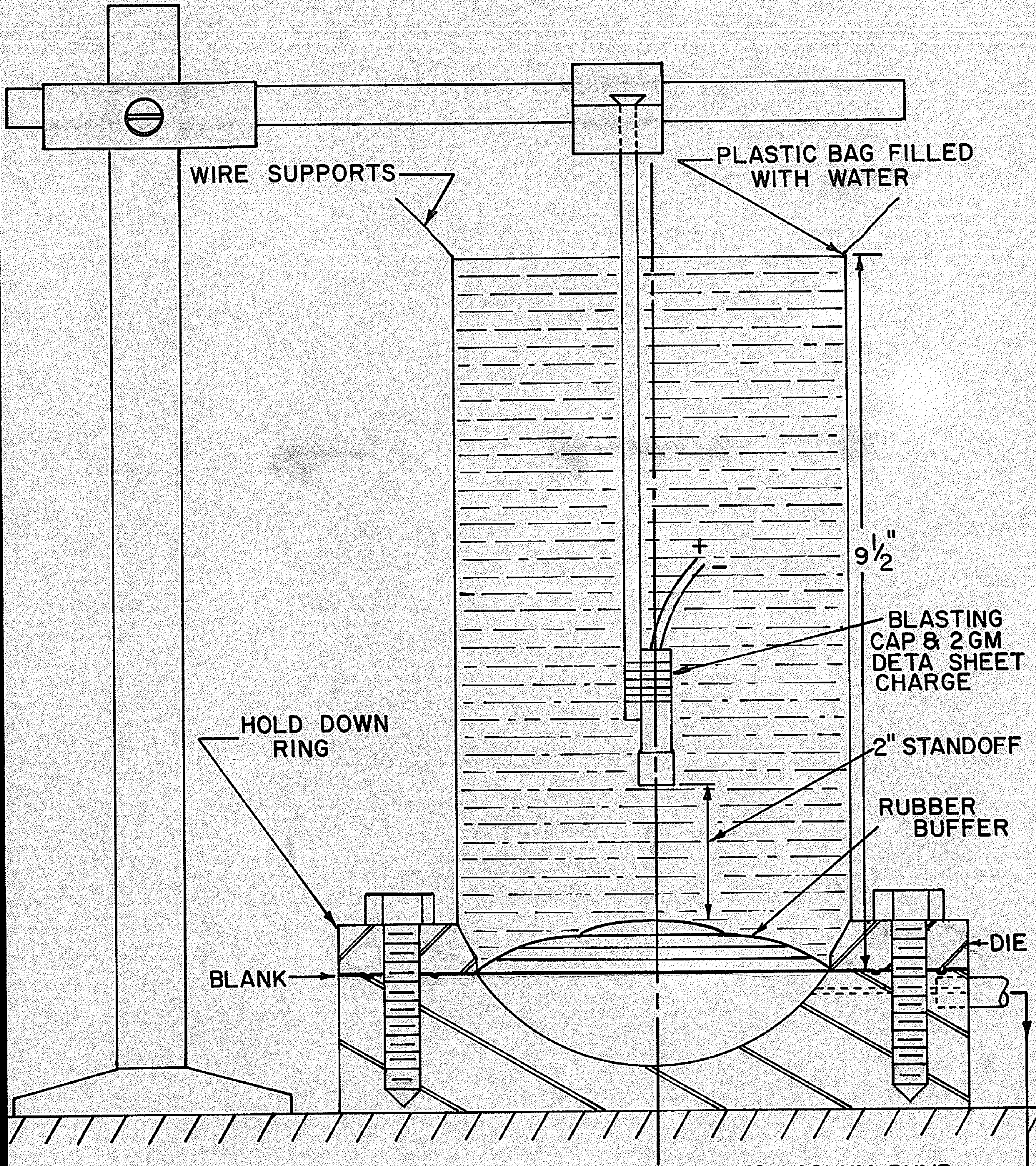
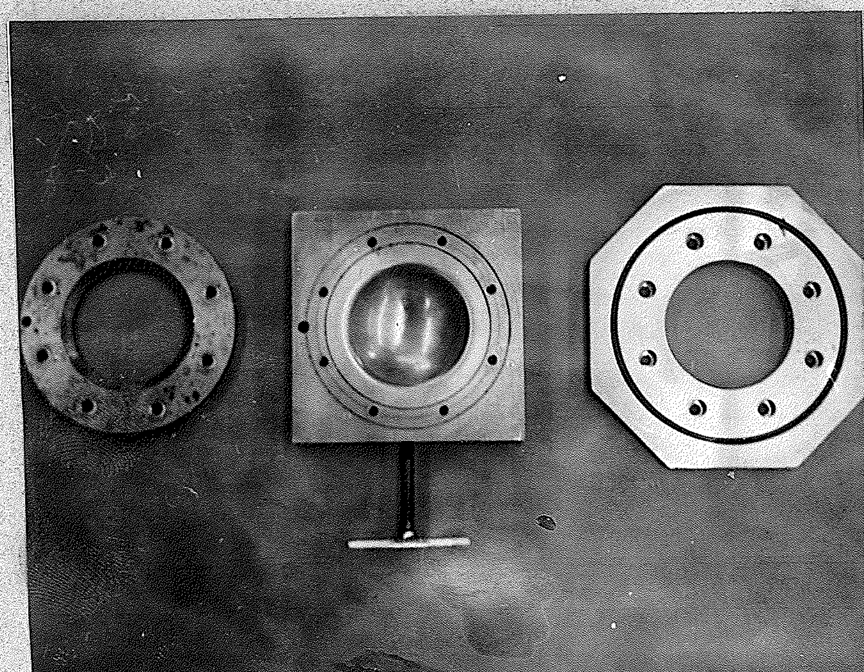


Figure 3.8 Arrangement used for explosive forming



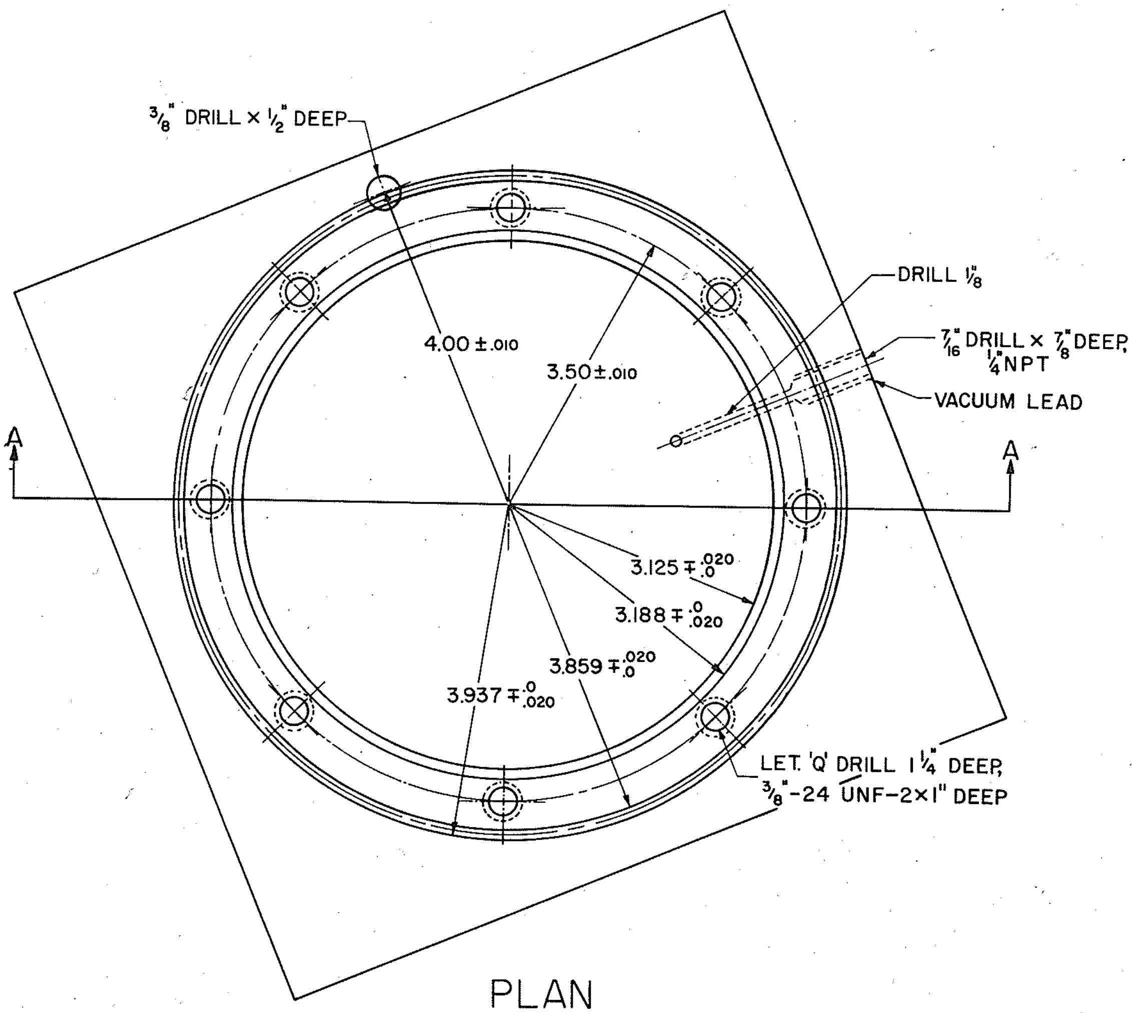
(a) (b) (c)

Figure 3.9

(a) Explosive Forming Hold Down Ring

(b) Explosive Forming Die

(c) Static Forming Hold Down Ring



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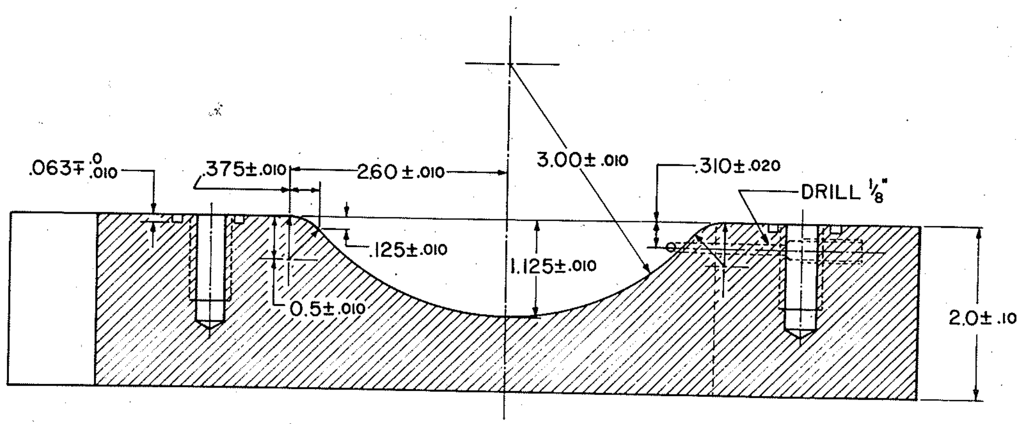

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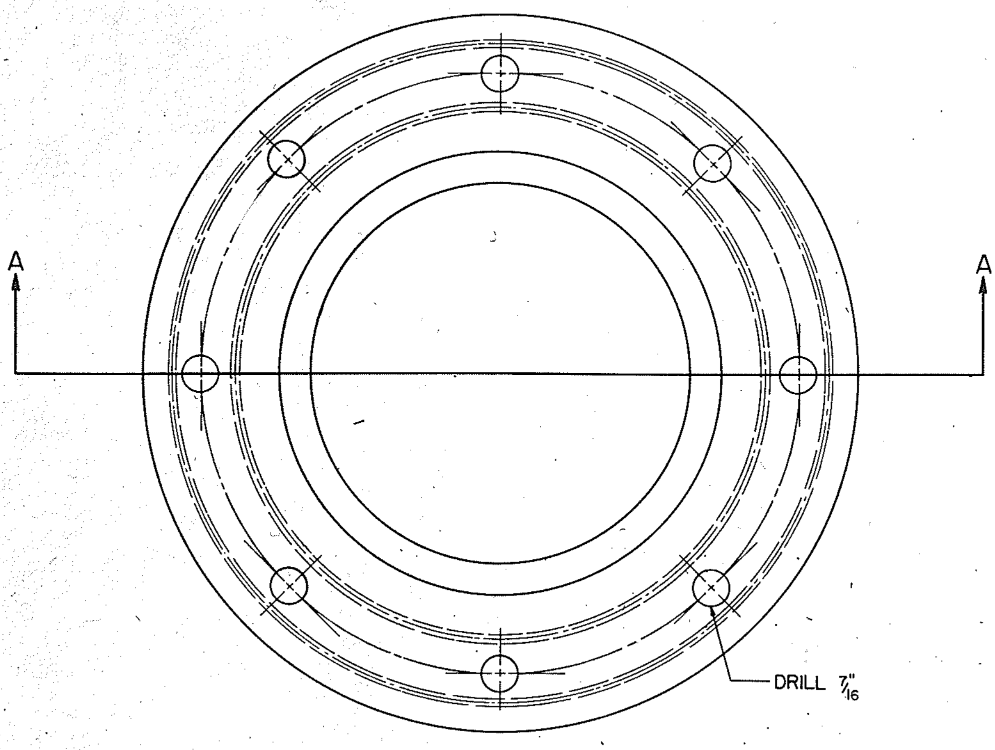
DIE FOR DYNAMIC AND STATIC FORMING			FIGURE 3.10



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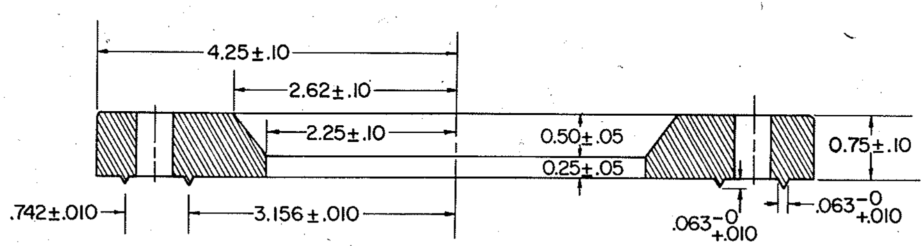

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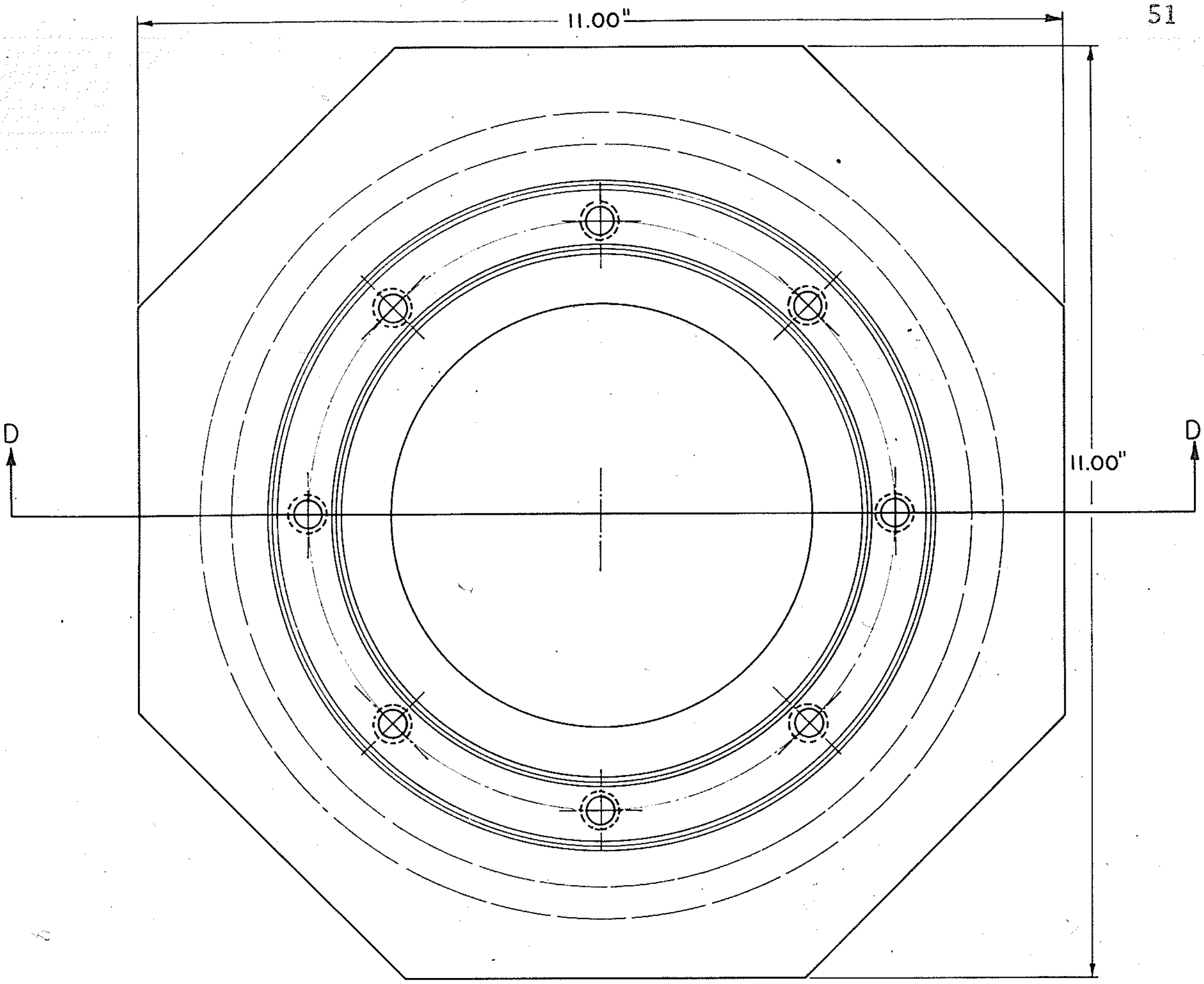
HOLD DOWN RING FOR DIE EXPLOSIVE FORMING			FIGURE 3.11

the strips into cylinders of two grams weight. Number six blasting caps were used. These were aligned with the cylindrical charge and attached thereto with "plasticine". An effective buffer, one which would eliminate pitting and irregularities in the surface finish of the specimens, was experimentally developed. The buffer used was made of concentric circles of rubber gasket material glued together with contact cement as shown in Figure 3.8.

The charge and cap were positioned with a 2 1/4 inch standoff distance (2 1/4 inches from the bottom of the charge to the face of the blank). The space between the blank and the die was evacuated to 28 inches of mercury. The charge was detonated in a water filled plastic bag, set over the blank and die.

b) Static Forming

A hold-down ring shown in Figure 3.12 was machined so that a crimp seal could be made against the blank and an O ring seal could be made against the pressure chamber wall. The 9 inch x 9 inch blank was mounted between the hold-down ring and die, and the eight bolts were tightened to 30 foot-pounds torque. The assembly was slid between the two plates of the pressure chamber of the hydraulic fatigue machine and the eight retaining bolts were tightened. The by-pass valve was slowly closed so that the pressure increased to 950 pounds per square



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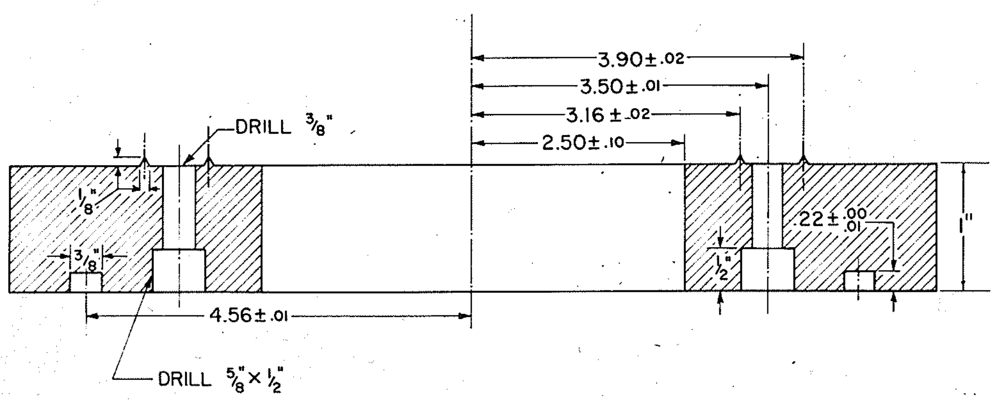

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DETAIL OF STATIC FORMING HOLD DOWN RING FOR DIE			FIGURE 3.12

inch. The pressure was then slowly decreased and the formed dome removed.

3.5 Calibrations and Measurements

A check was made on the biaxiality of stress at the apex area of the dome employing C12-121-A Budd strain gages in conjunction with Budd bridge amplifier and switch and balance box as shown in Figure 3.14. The strain gage positioning is shown in Figure 3.13.

In order to determine the stress required for plastic flow strain gaged specimens were cycled from zero to progressively increasing pressures until permanent set was recorded. The stress/strain verses pressure profile and the strain cycle are shown in Figures 3.15 and 3.16 respectively.

The correct pressure settings, based on pressure = 2(Stress) (Thickness)/(Spherical radius), for varying apex thicknesses were calculated and plotted as per Figure 3.16(a).

The thickness of the specimen after polishing was determined by a frame jig as shown in Figure 3.17(a). The final depth of the V notch stress raiser was determined by the specially made deep throat micrometer shown in Figure 3.17(b).

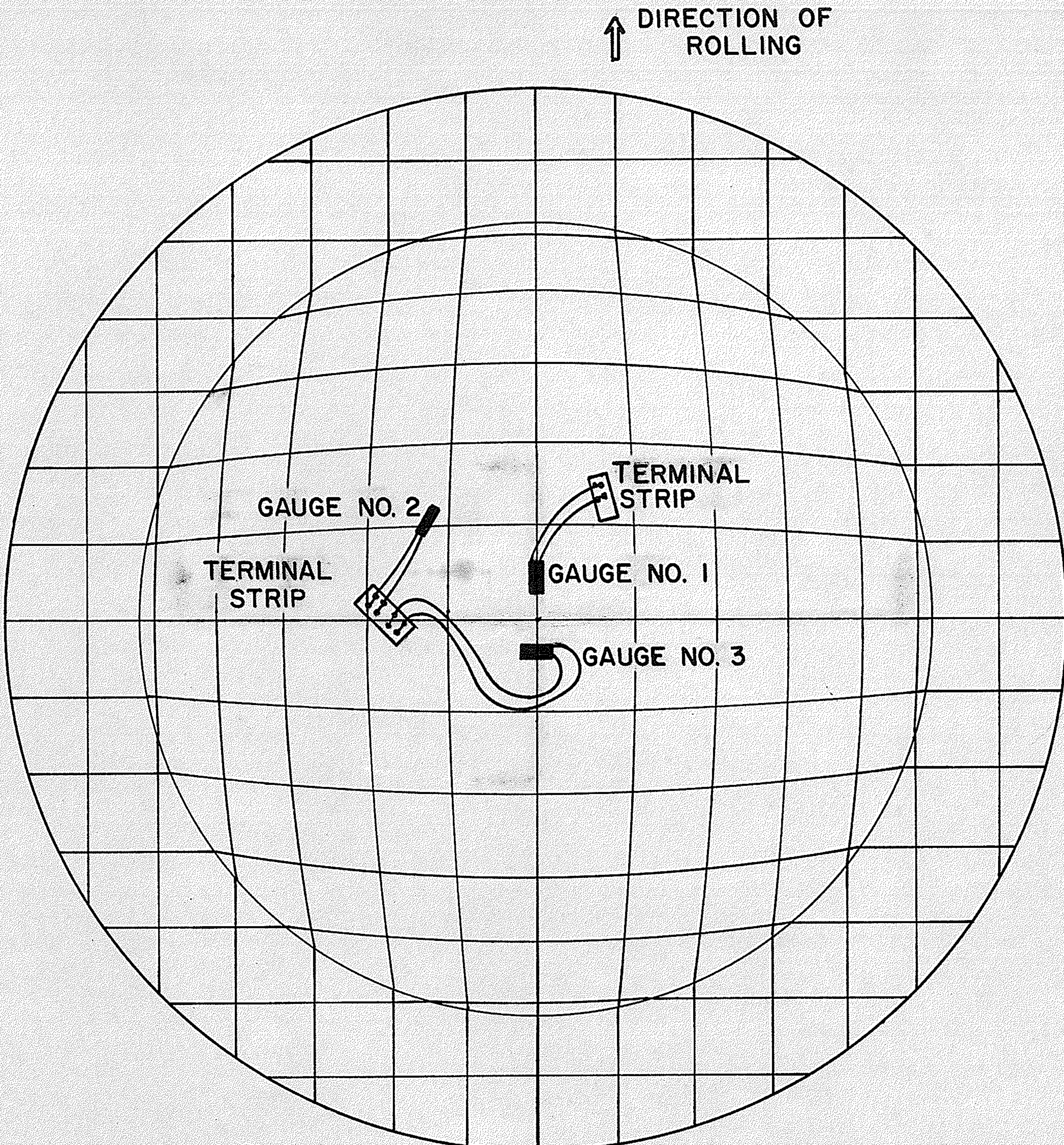
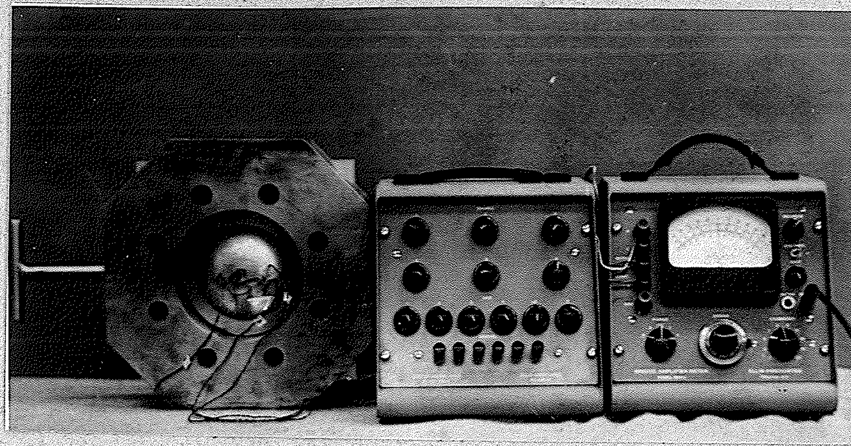
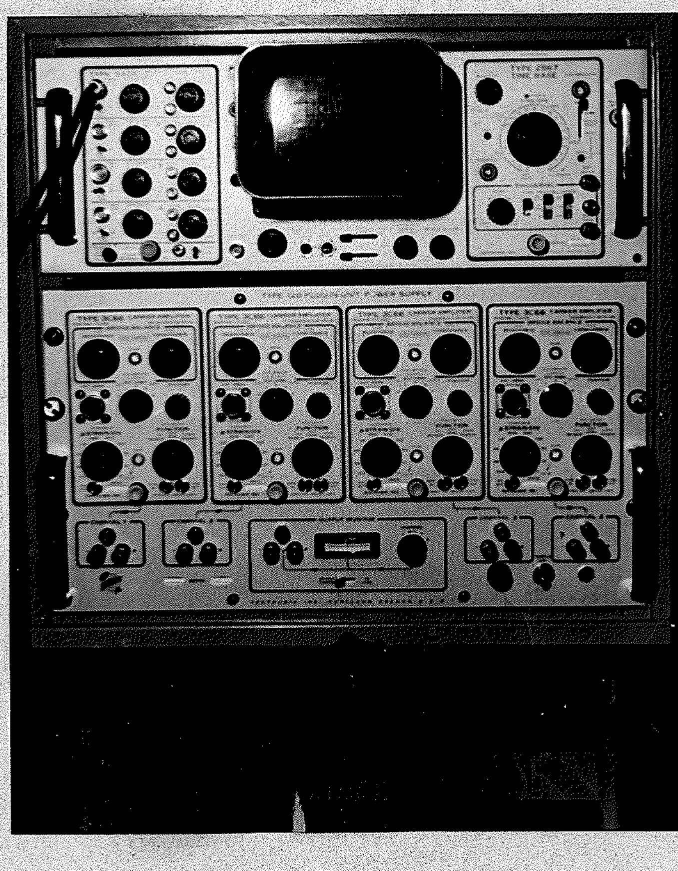


Figure 3.13 Dome with strain gauges mounted showing grid deformation after forming



(a) (b) (c)

(a)Specimen Holder
(b)Switch and Balance Box
(c)Bridge Amplifier, and Gauges



(d) Storage Oscilloscope

Figure 3.14 Strain Measuring Components

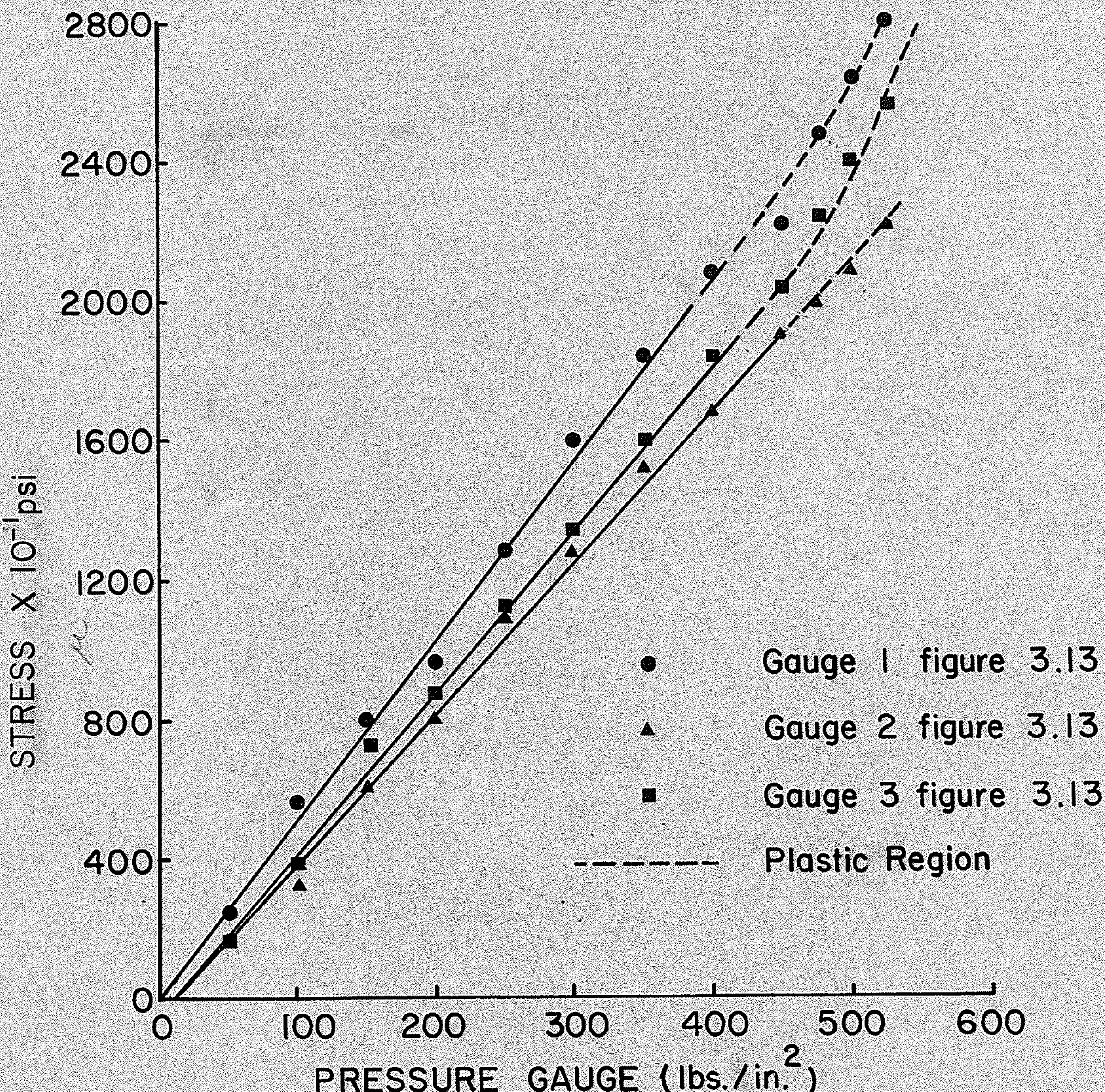


Figure 3.15 Pressure Strain Curves from Strain Gauge Readings

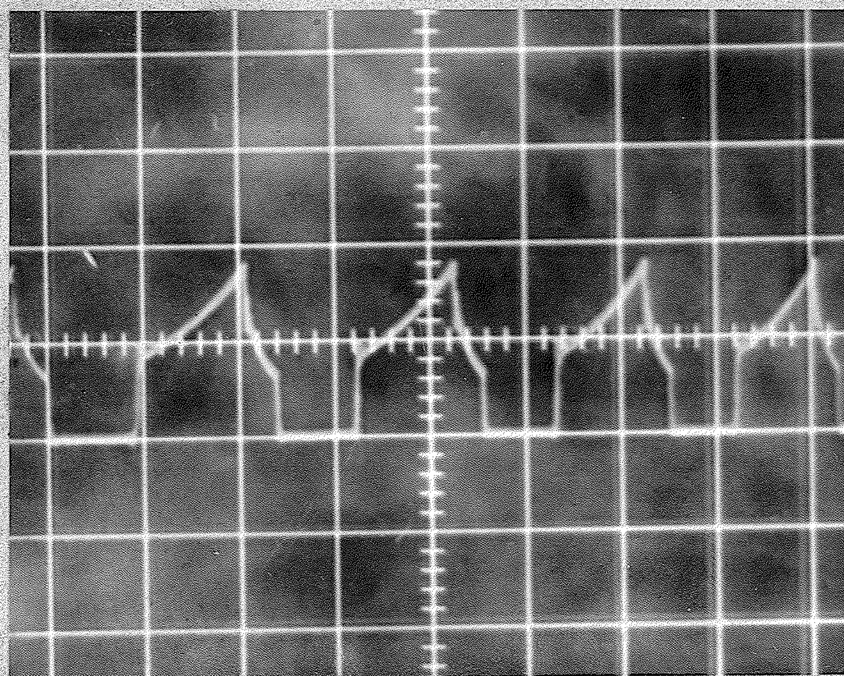


Figure 3.16 Strain Cycle For Hydraulic Fatigue Machine

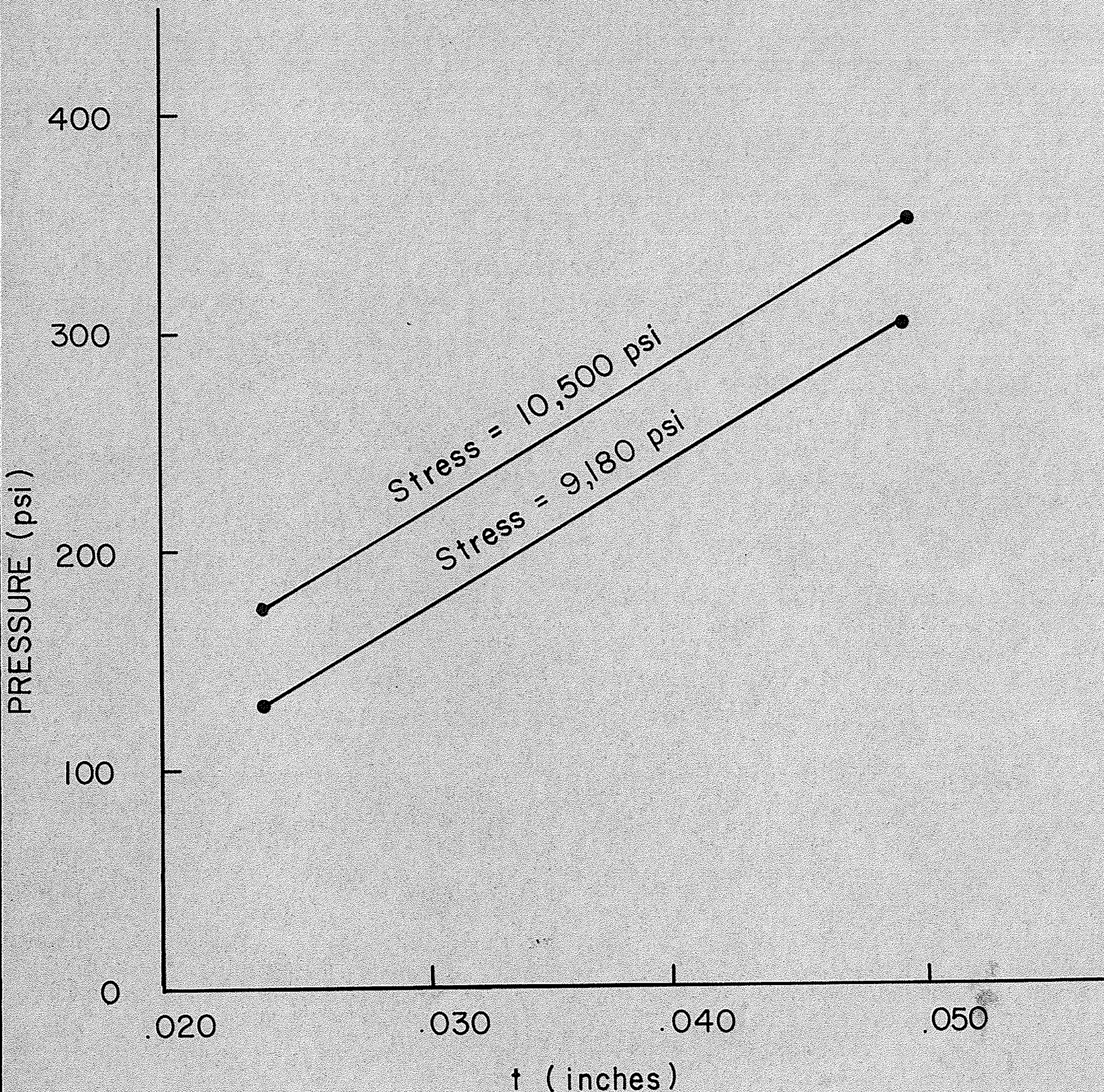
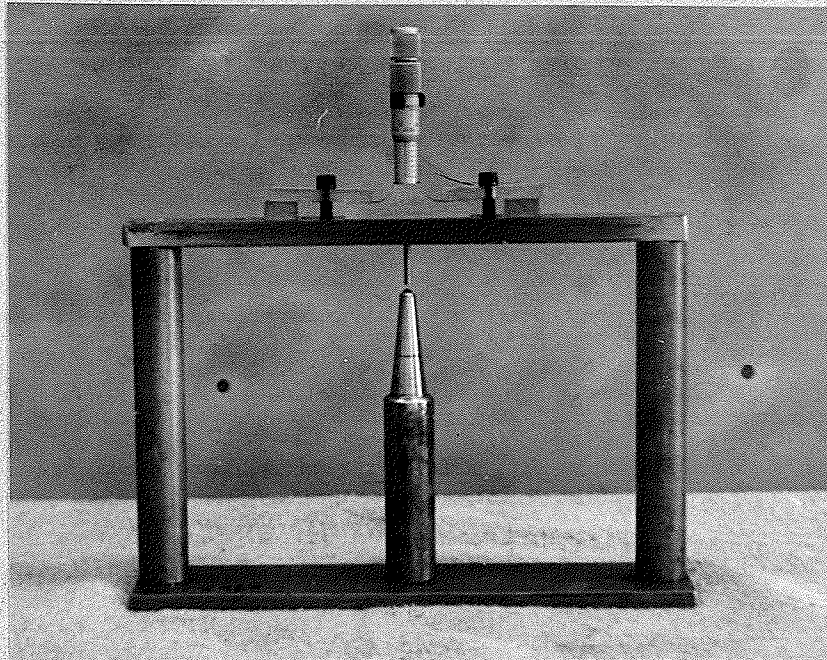
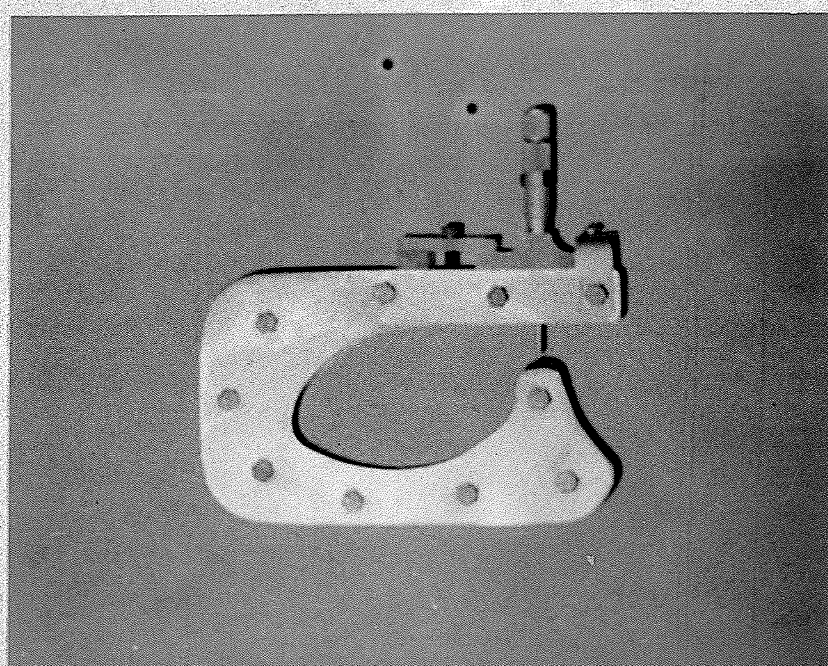


Figure 3.16 (a) Required Pressure Verses Thickness For Fatigue Tests



(a) Thickness Indicator Jig



(b) Deep Throated Micrometer

Figure 3.17 Measuring Instruments

3.6 Testing Procedure

a) Strain, Hardness, and Reduction in Thickness

To give meaningful results to the fatigue work a number of related properties were resolved. These were the unit strain, the reduction in thickness, and the hardness.

The strain profile was established by the first drawing a one-half inch square grid on the blank using a number H pencil. After forming, this grid was removed using Scotch cellulose tape. By placing this tape on a piece of glass the distance between the graphite markings on the tape was measured and the per cent strain over a one-half inch distance was plotted. Using the frame jig which incorporated a depth micrometer, the thickness along the grid points was calculated. The hardness at the grid intersections was found using a Rockwell hardness tester set at the B scale (100 kilograms weight and 1/16 inch diameter ball).

b) Stress Concentration

As a preliminary to the fatigue tests a controlled stress raiser, as mentioned earlier, was developed. A 45 degree included angle groove cut to a depth of one-half the final thickness at the apex was agreed upon. The remaining thickness was measured with a deep throated micrometer. To ensure control four statically formed specimens and four dynamically formed specimens were pressured to failure. As the difference in fracture pressure in each group was under 20 pounds per square inch the stress concentration was assumed uniform between experimental and control groups.

c) Fatigue Tests

The test program was set up so as to give failure in a range below 15,000 cycles. These convenient stress levels were obtained by trial and error. The test program is shown in Table 3.1

The procedure employed in testing is as follows. Firstly, to adjust the pressure level to the correct cycling pressure, a trial dome, without a stress concentration, was mounted in the specimen holder. The holder was next slid into the pressure chamber and the retaining bolts were tightened. The vent valve was slowly closed to ensure no air was trapped in the dome. By leaving the bypass valve partly open the cycling rate was slow enough so that the delays in the pressure cycle were negligible. The pressure switch on the working side was then set at the desired pressure while the machine cycled. Next, the opposite pressure switch was adjusted to give the same pressure build up time.

In order to adjust the machine to give a speed of 100 to 120 cycles per minute, the pressure in the bladder accumulators was varied. The cycling rate was determined by means of a stop watch and the counter.

The trial dome was then replaced with a test dome and the test

Stress Level	Number of Specimens	
(Lb/in^2)	Statically formed	Explosivily formed
10,500	8	9
9,180	9	8

Table 3.1 Test program

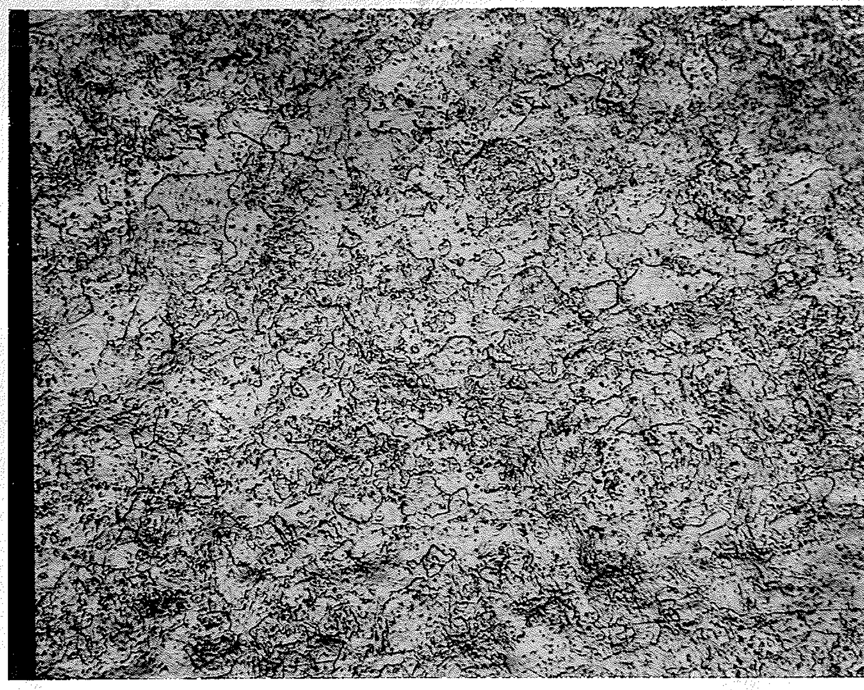
for the particular stress level carried out. With the selector solenoid switch on automatic shut off turned on, the machine cycled until the specimen broke. The loss of oil through the crack caused the cycling to cease.

d) Metallurgical Investigations

In order to obtain a comparison of the effect of the two forming processes on the grain size, specimens were cut from the apex of an explosively formed dome and a statically formed dome. The specimens mounted in bakelite were mechanically polished down to 600 grit Silicon carbide paper. This was followed by chamical polishing in a solution composed of the following: (80 ml. ortophosphoric acid, 12 ml. sulphuric acid, 8 ml. nitric acid). The etching was accomplished using a combination of immersion and swabbing with modified Keller's etch (1 ml. hydrofluoric acid, 10 ml. nitric acid, 87.5 ml. water) and followed by nitric etch (20 ml. nitric acid, 80 ml. water). The cycle of 30 seconds Keller's etch followed by 20 seconds nitric etch was continued until the grain boundaries appeared. The photomicrographs taken are shown in Figure 3.18.

e e) Fatigue-life Reduction Factor Tests

In order to obtain the fatigue-life reduction factor for the stress concentration, ten specimens with a stress



(a) STATICALLY FORMED (X100)

(b) EXPLOSIVELY FORMED (X100)

Figure 3.18 Micrographs of Dome Specimens concentration and ten without a stress concentration were tested at two stress levels. A typical specimen is shown in Figure 3.19.

The stress concentration was produced by milling a groove with a 6 inch diameter 45 degree included angle cutter, the depth of the groove being half the thickness of the specimen. The specimens were tested at two stress levels 16,000 pounds per square inch nominal and 15,000 pounds per square inch nominal. The stress cycling was from zero to maximum in uniaxial tension. The tests were carried out in a Baldwin 2000 pound capacity Universal Fatigue Tester.

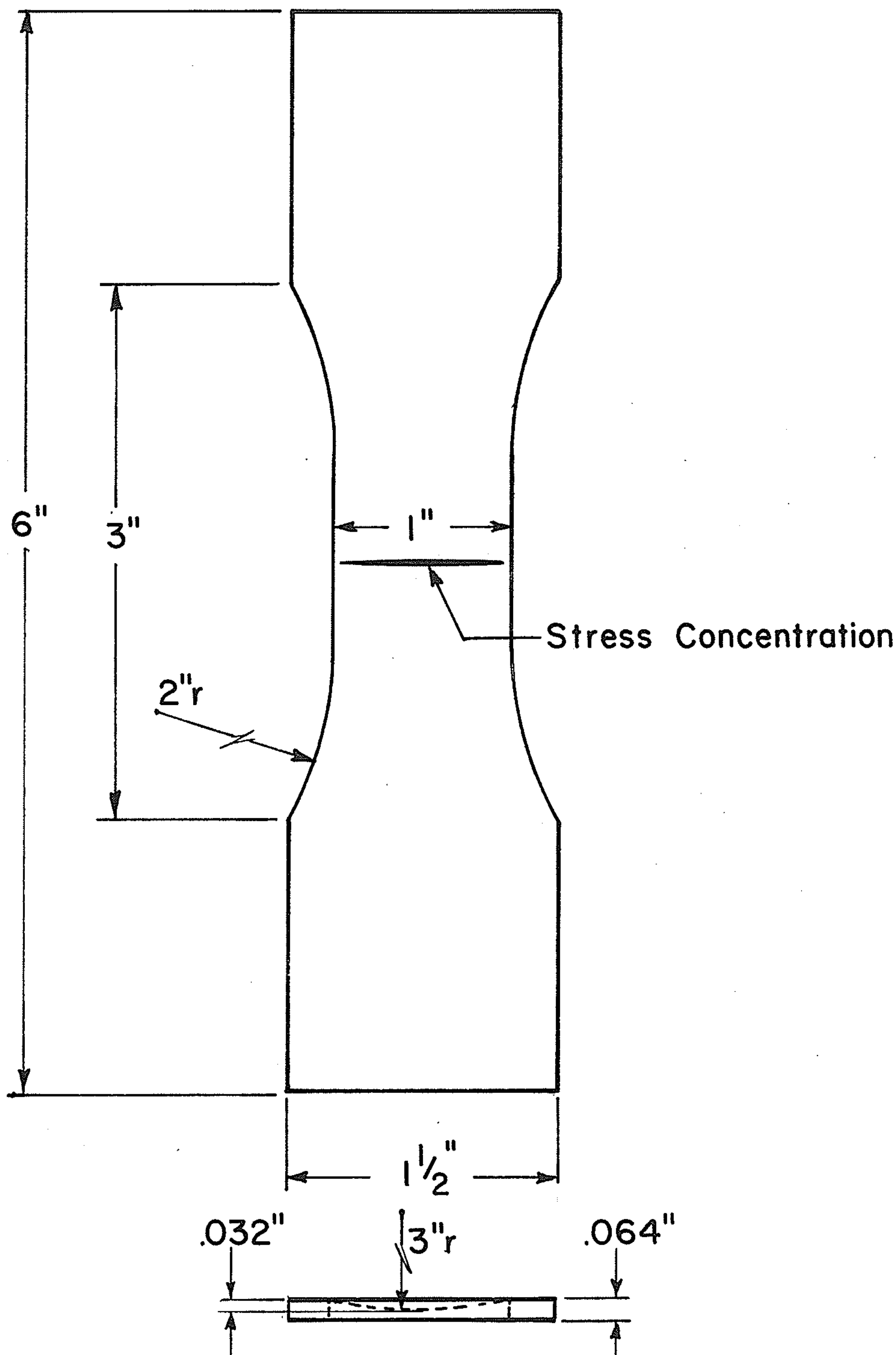


Figure 3.19 SPECIMEN FOR FATIGUE-LIFE REDUCTION TESTS SHOWING STRESS CONCENTRATION

CHAPTER 4

Test Results - Analysis and Discussion

4.1 Results and Analysis

a) Hardness and Reduction in Thickness

Hardness readings were taken at one-half inch intervals along four radii, 90 degrees to one another. The comparative hardness profiles are shown in Figure 4.1. The results and statistical analysis of the hardness test results are given in Table 4.1. The percentage reduction in thickness at grid intersections for both static and dynamic specimens is given in Table 4.2. Figure 4.2 shows the graph of percentage reduction in thickness versus distance from the apex.

The tests for both static and dynamic specimens showed greater hardness in the region of the apex which is the region of maximum straining. The explosive specimens gave lower hardness readings than the static specimens in this region. The magnitude of the stress concentration was such that failure invariably initiated at the notch. Therefore the characteristics of the material within a one-half inch radius of the apex had influence on the fatigue tests.

b) Work-hardening

Comparing the increase in hardness with the percentage

Table 4.1

Hardness Results

Dist. from Apex Inches	Explosively Formed Rockwell B Hardness No. Radius Number 1	2	3	4	Mean	S.D.	Statically Formed Rockwell B Hardness No. Radius Number 1	2	3	4	Mean	S.D.	Stat. Analysis Sig. Level
0	34	34	34	34	34	0	43	43	43	43	43	0	00
1/4	35.2	34.9	35.8	35.3	35.3	.37	42	39.2	38.7	42	40.5	1.78	.07
1/2	36	34	36	39.2	36.3	2.15	38	36	36.2	35.5	36.6	1.09	.48
1	38.2	33	37.8	37	36.5	2.39	36.2	34.5	31.2	30	33.0	2.87	.32
1 1/2	33	33.7	36.5	34	36.8	1.53	31	25.4	27.8	26.2	27.6	2.48	.06
2	23.8	23	29.3	25.6	27.6	2.81	27.5	23	23.5	21.8	24.0	2.47	.32

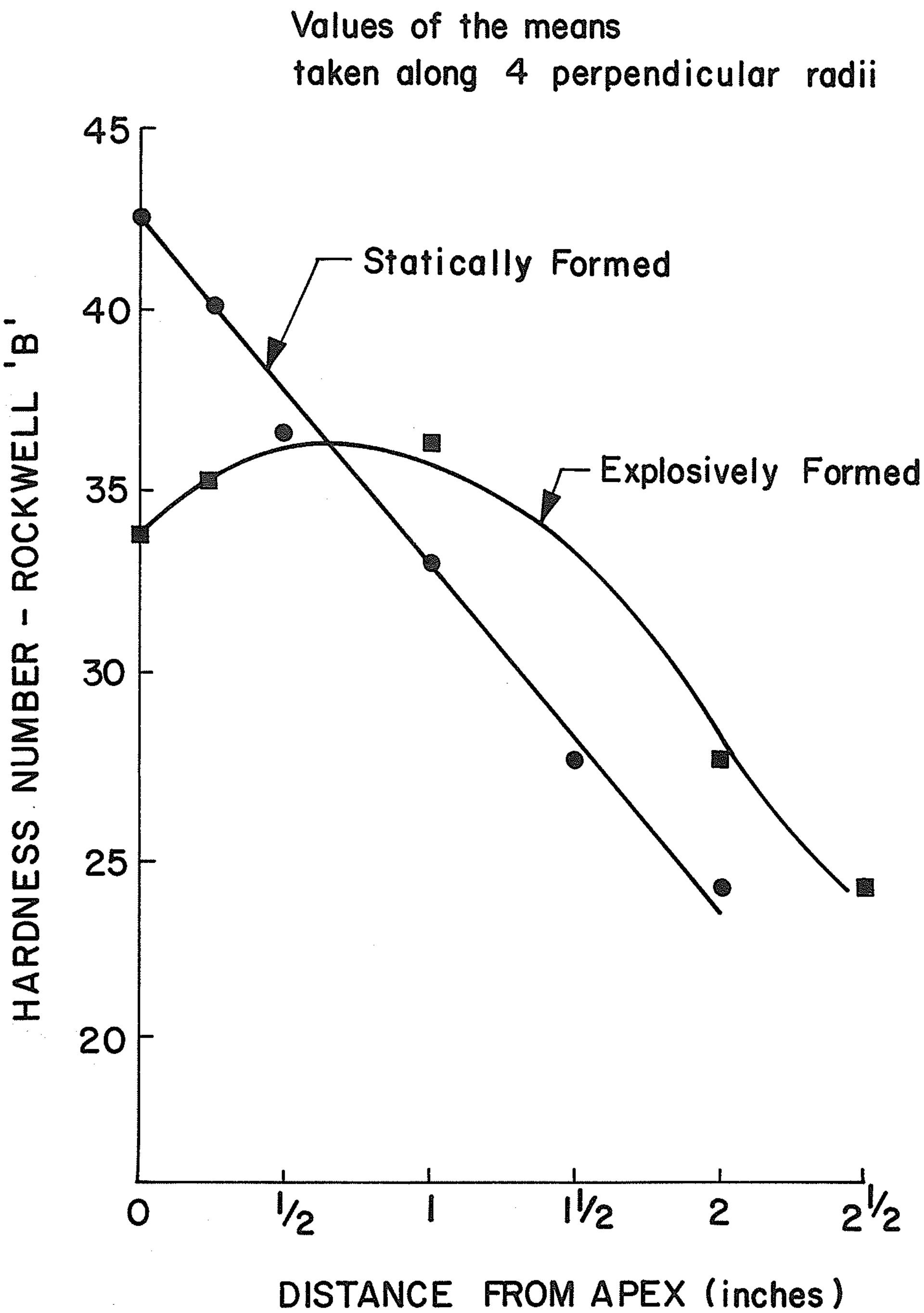


Figure 4.1 Hardness Profiles

Table 4.2

Percentage Reduction in Thickness

Distance from Apex (inches)	Explosively Formed Radius No. 1	2	3	4	Mean	Statically Formed Radius No. 1	2	3	4	Mean
0	18.8	18.8	18.8	18.8	18.8	42.2	42.2	42.2	42.2	42.2
1/4	20.3	20.3	18.8	20.3	19.9	37.5	37.5	37.5	37.5	37.5
1/2	21.9	21.9	18.8	23.4	21.5	36.0	36.0	31.2	34.4	34.4
1	25.0	25.0	21.9	28.1	20.0	26.6	29.7	25.0	25.0	28.1
1 1/2	15.1	18.8	17.2	23.4	18.6	15.1	18.8	15.1	15.1	16.0
2	7.8	9.4	7.8	10.9	10.1	4.6	7.8	4.6	6.2	5.8
2 1/2	0	0	0	0	0	0	0	0	0	0

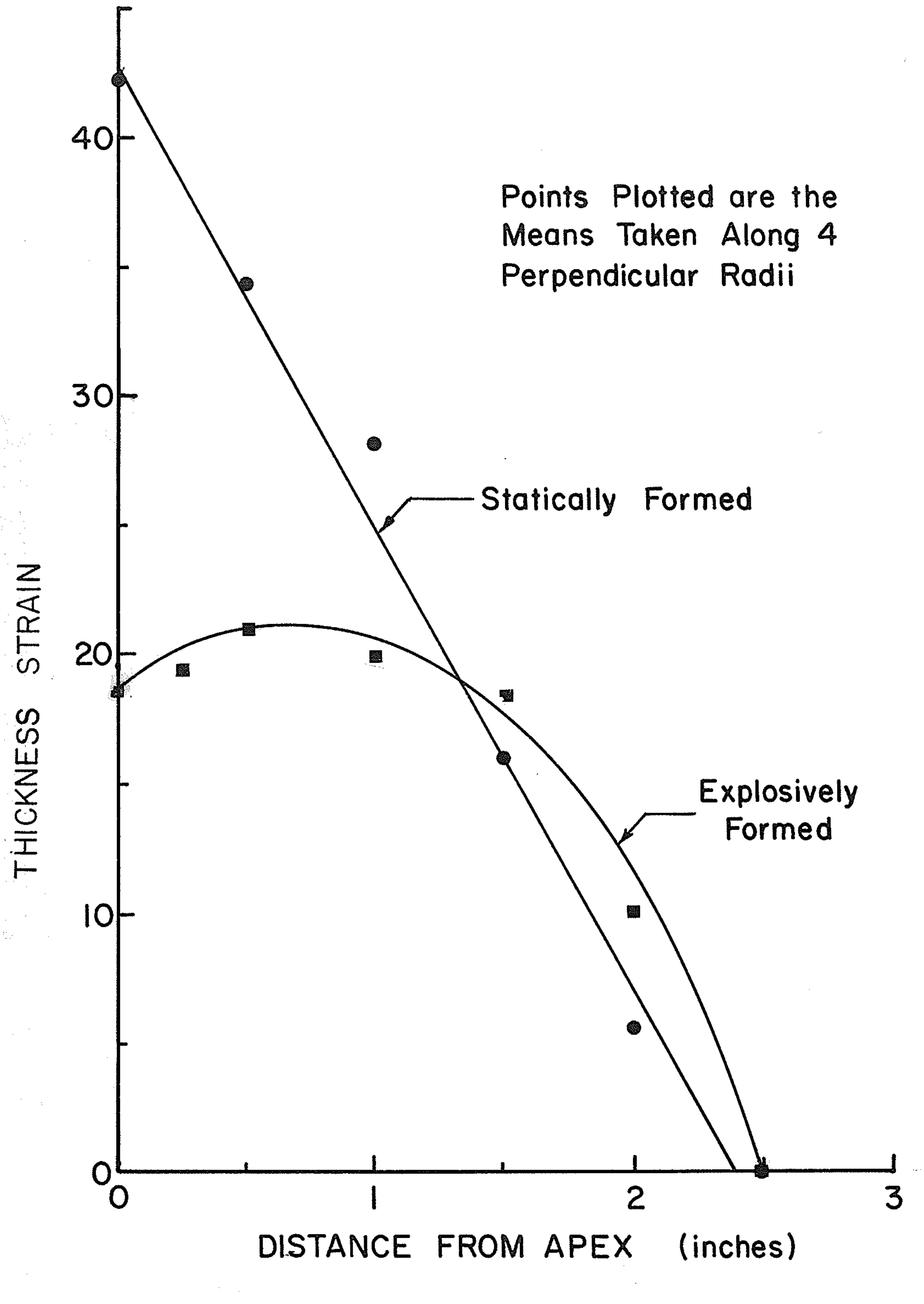


Figure 4.2 % Reduction in Thickness Curves for Static and Dynamic Forming

reduction in thickness at the grid points gave an indication of the relative work-hardening effect of the two forming processes. This comparison is shown in Figure 4.3.

The results showed that the explosively formed aluminum hardened more than statically formed aluminum for the same reduction in thickness. The trend established in the tests compared favourably with the results of Williams[17], as shown in Figure 4.4.

c) Strain Distribution

The strain distribution as obtained by the penciled grid method is shown in Figure 4.5.

This strain distribution varied less uniformly in the explosively formed specimens than in the statically formed specimens. Small variations in strain were also noted from specimen to specimen in each group.

d) Fatigue

A total of thirty-four specimens were tested in the fatigue program. The nominal stress with no allowance for stress concentration for series one tests (17 specimens) was 10,500 pounds per square inch, while the nominal stress for the series two tests (17 specimens) was 9180 pounds per square inch. The results of these tests' cycles to failure,

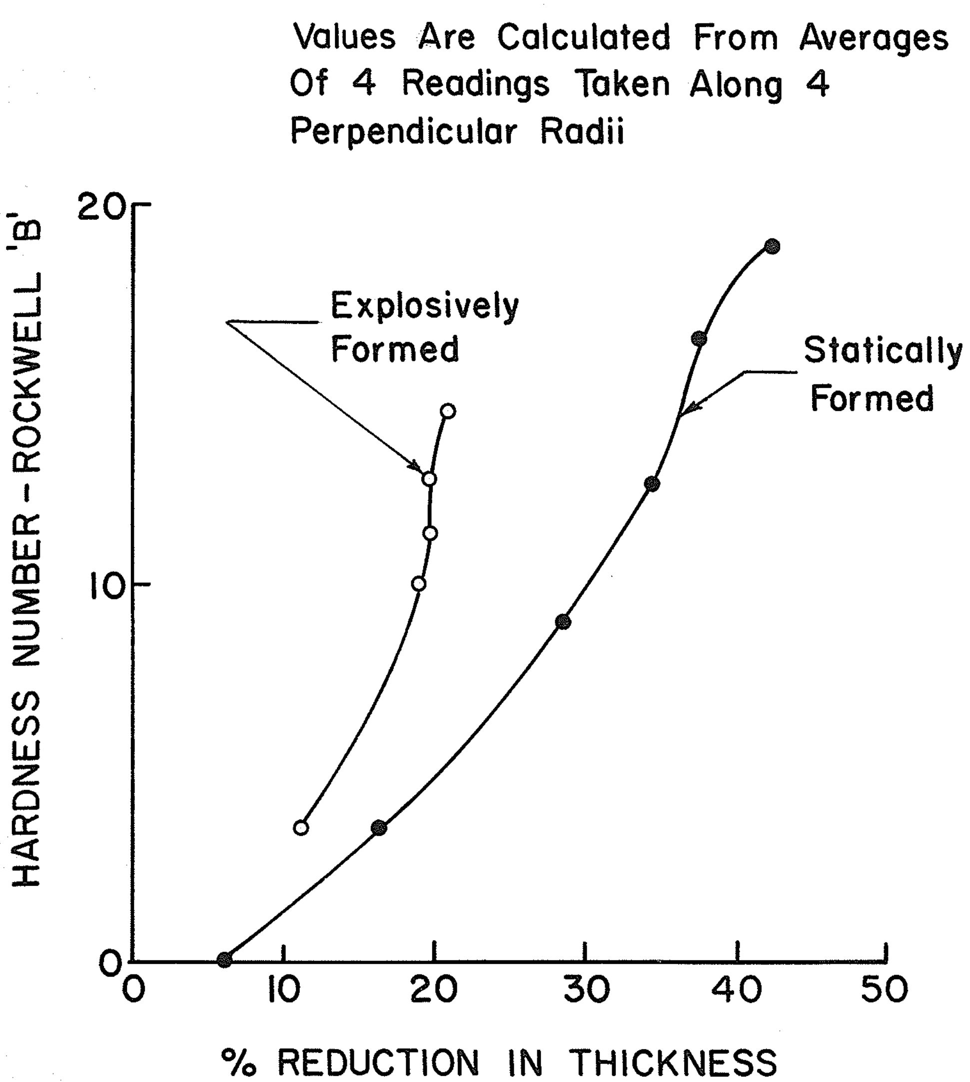


Figure 4.3 Work Hardening Curves For 1100SH14 Aluminum

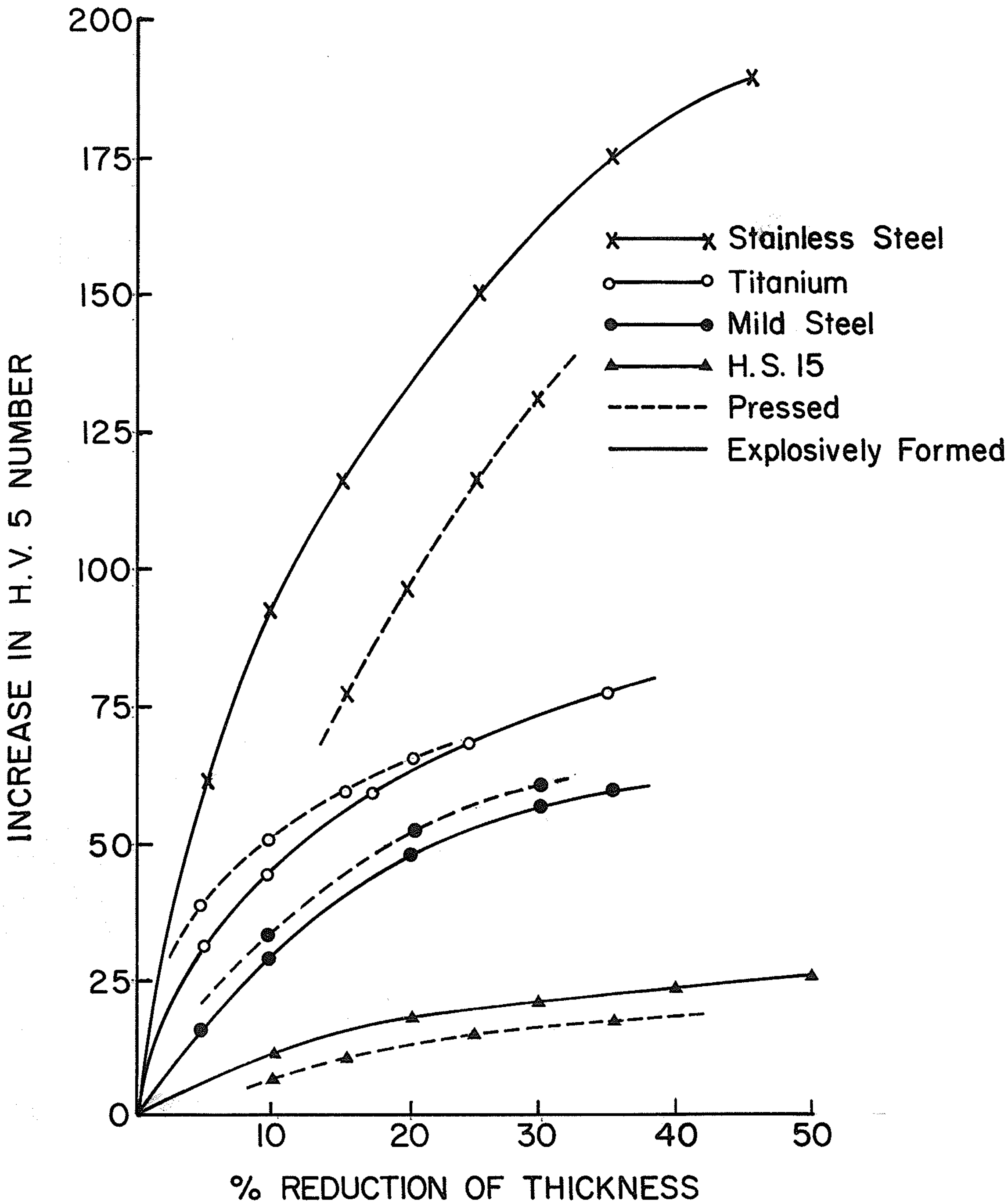


Figure 4.4 Comparison of work-hardening arising from explosive forming and form pressing (Ref. 17)

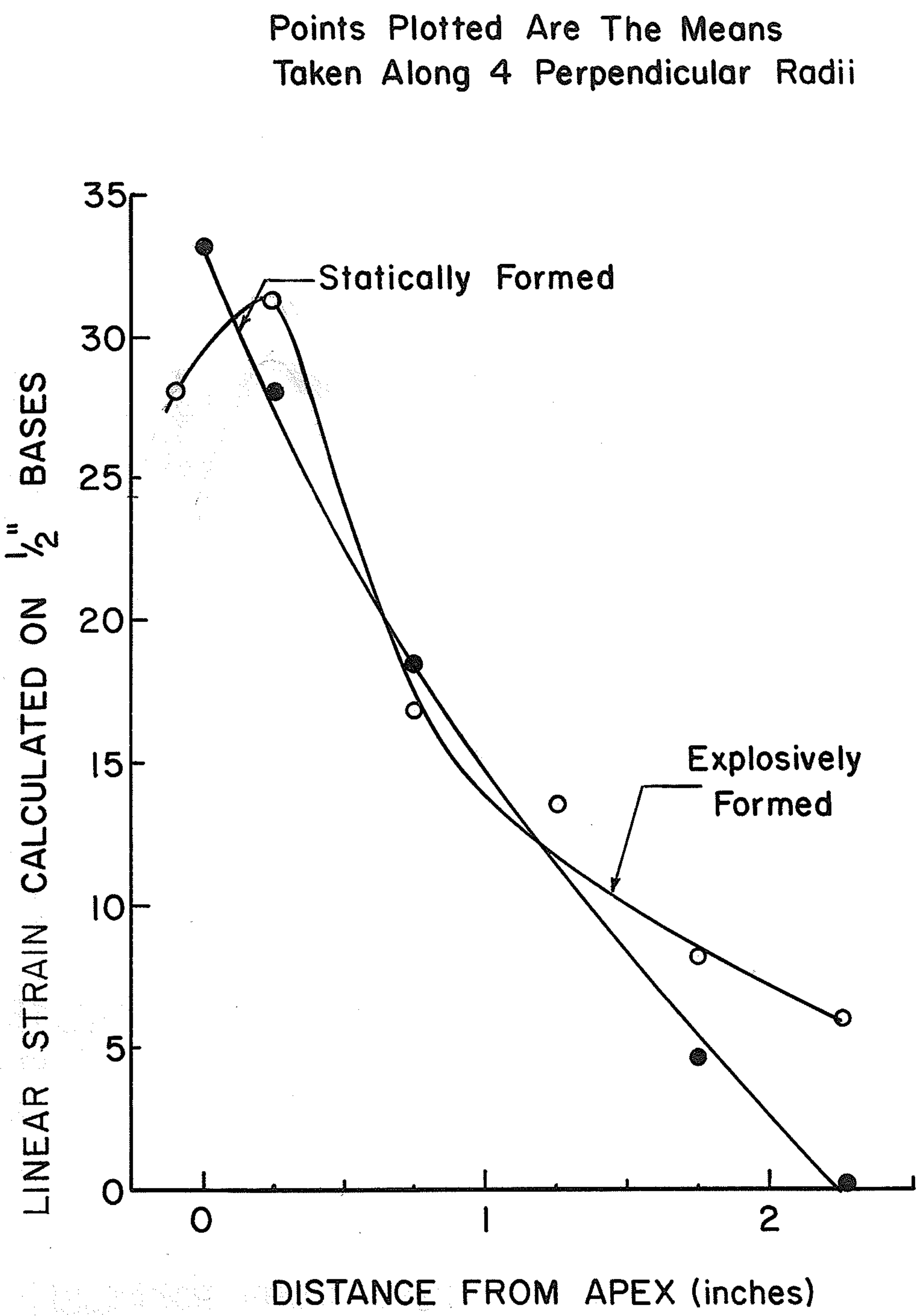


Figure 4.5 % Strain Curves For Static And Dynamic Forming

mean cycles to failure of each group, standar- deviation, and the level of significance of the difference in means, are presented in Tables 4.3 and 4.4.

For the materials tested as described the statistical results show that there is a real difference in the fatigue life of explosively and statically formed 1100 SH 14 Aluminum. The explosively formed material had a lower fatigue life than the statically formed material. The explosively formed control groupes had a fatigue life about 63% less at the 10,500 pounds per square inch level and about 26% less at the 9,180 pounds per square inch level.

e) Fatigue-life Reduction Factor

The results of the fatigue-life reduction factor tests for the stress concentration used are shown in Table 4.5. The mean fatigue-life reduction factor was calculated to be 11.075

4.2 Discussion of Results

From the results of the tests preformed it is clear that explosive forming did cause a decrease in fatigue life of 1100 SH 14 Aluminum. Although surface effects had been eliminated, further studies are needed to isolate the causes

Table 4.3

Fatigue Test Results (Stress Level 1)

Stress Level 1 - 10,500 psi nominal

Cycles to Failure

Specimen Number	Explosively Formed	Hydraulically Formed
1	23	5,635
2	256	5,220
3	17	4,225
4	45	6,000
5	19	6,479
6	12	4,703
7	4,748	5,750
8	3,932	6,178
9	2,185	
Mean	804	5,524
Median	1,102	5,350
Standard Deviation	1,894	764

Level of Significance = 0.001

Table 4.4

Fatigue Test Results (Stress Level 2)

Stress Level 2 - 9180 psi nominal

Cycles to Failure

Specimen Number	Explosively Formed	Statically Formed
1	6,925	9,520
2	5,960	7,875
3	5,699	9,323
4	6,260	3,272
5	6,466	15,420
6	7,137	13,645
7	10,051	11,560
8	5,642	5,622
9		7,247
Mean	7,265	9,832
Median	7,846	10,521
Standard Deviation	1,683	3,158

Level of Significance = 0.01

Table 4.5

Results of Fatigue Life Reduction Tests

Stress Level	Cycles to Failure: Notched	Without Notch
15,000 p.s.i.	33,000	734,000
	34,000	209,000
	32,000	287,000
	45,000	526,000
	34,000	285,000
Mean Life	35,600	407,600
Fatigue Life Reduction Factor	11.45	
16,000 p.s.i.	200,000	717,000
	357,000	5,607,000
	173,000	1,009,000
	422,000	7,102,000
	277,000	820,000
Mean Life	285,200	3,051,000
Fatigue Life Reduction Factor	10.70	

Mean Fatigue Life Reduction

Factor is 11.075

of the difference in fatigue life. For example this deterioration could be a result of microcracking. This would not be a constant and indigenous feature of explosive forming but might be expected to change with such things as deformation velocity and standoff distance.

Since the stress concentration was introduced at the apex, only the material in this region was tested. In this region static forming produced higher reduction in thickness, higher hardness, and greater strain than the explosively formed counterparts. All the preceding factors, which are related to each other, influence fatigue life in a benefical manner. Thus it might be expected that the explosive forming should give a lower fatigue life all else being equal.

The effect of explosive forming on notch sensitivity may also be an influencing factor in the reduced fatigue life. The higher strain rate forming may make 1100 SH 14 Aluminum more notch sensitive, thus the fatigue life will drop for a given stress level.

The results of strain measurements agree with the results of Bennett[28] in that a non-uniformity of strain gradient was found. Bennett concluded that the non-uniformity in straining resulted in a portion of the specimen receiving more strain than the average (as compared with its statically formed counterpart). The remainder of the specimen was subjected to a lesser strain than the average. This material which was deficient in strain hardening being weaker than the statically formed part failed prematurely in fatigue.

The theory that microcrack formation during explosive shock causes a decrease in fatigue life of explosively formed materials, has been related by Verbraak [18] and Rowden [13]. Electromicroscopy work pursued in this direction may bring to light evidence affecting the fatigue mechanism.

Since the geometry of the stress concentration with respect to the geometry of the best specimen was the same for uniaxial and biaxial tests, the effect of the stress concentration of the fatigue life may be considered equivalent. The fatigue life of the domes without stress concentration may be estimated at eleven times the test specimens.

CHAPTER 5

Summary and Conclusions

5.1 Summary

A comparison of the fatigue life of statically and dynamically formed 1100 SH 14 Aluminum has been made.

The main purpose of this work has been to compare low to medium cycle biaxial fatigue life characteristics of 1100 SH 14 Aluminum, both explosively and hydraulically formed. The comparison was carried out at two stress levels. Ancillary work included redesign of a hydraulic fatigue machine. Hardness, reduction in thickness and straining during formation of the domes were investigated. The fatigue reduction factor for the stress concentration was determined. Possible reasons for the lower fatigue life of the explosively formed specimens were presented.

5.2 Conclusions

Supported by the test data obtained from the experiments described in this thesis and by data obtained in a literature survey as acknowledged by references, the following conclusions were made:

a. The equipment designed and constructed for the experimental portion of this thesis is quite satisfactory for investigation of low to medium cycle fatigue of dome specimens. The maximum speed of the machine is 7200 cycles per hour, this limits the use of the machine to medium cycle fatigue experiments by time considerations.

b. There was a reduction in fatigue life of die formed 1100 SH 14 Aluminum due to explosive forming as compared to its statically formed counterpart.

c. The increase in hardness due to explosive forming is less than the hardness increase due to hydraulic forming at the apex or test section.

d. The lower fatigue life of the explosively formed specimens may be attributed to any or all of the lower hardness, increased notch sensitivity, or the possibility of microcracks produced on forming.

5.3 Suggestions for Further Study

1. Completion of S-N curve for 1100 SH 14 Aluminum so that a more complete comparison of fatigue life can be presented.

2. Electmicroscopy studies to establish whether microcracks

were caused by explosive forming.

3. A series of tests to compare fatigue properties of die formed and free formed specimens. These tests may determine if the loss of fatigue life is due to impulsive contact with the die or the velocity of deformation itself.

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