THE UNIVERSITY OF MANITOBA

A COMPARATIVE STUDY OF THE EFFECT OF STATIC AND DYNAMIC FORMING ON THE UNIAXIAL NOTCHED FATIGUE STRENGTH OF AMS 6435 AND AMS 6520 STEELS

by

Thomas Gray Livingston

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT OF MECHANICAL ENGINEERING

WINNIPEG, MANITOBA

February 1974

ACKNOWLEDGEMENTS

The author expresses his gratitude to Professor C.P. Bennett, thesis advisor, Dr. J. Shewchuk, thesis co-advisor, both of the Department of Mechanical Engineering, for their suggestions throughout the research program, and to Mr. L. Wilkins and the technical staff for their assistance in constructing the experimental apparatus.

Financial support consisting of an operating grant from the Defence Research Board, the rocket motor casings supplied by Bristol Aerospace (1968) Ltd., and a departmental assistantship in the Department of Mechanical Engineering are also gratefully acknowledged.

THE UNIVERSITY OF ALBERTA LIBRARIES

ABSTRACT

To determine the relative effects of explosive and static forming on the fatigue life of AMS 6520 and 6435, notched fatigue tests were performed on specimens taken from formed cylinders and in the as-received condition for comparison. No discernible effect in the fatigue life of either material appeared to result as a consequence of these two different treatments.

TABLE OF CONTENTS

Page

ACKNOWLEDGEMENTS i

ABSTRACT ii

LIST OF FIGURES vi

LIST OF TABLES viii

Chapter I INTRODUCTION 1

1.1 Background 1

1.2 Statement of Problem 4

1.3 Scope of Thesis 5

Chapter II A REVIEW OF INVESTIGATIONS CONCERNING COMPARISONS OF STATIC AND DYNAMIC FORMING 6

2.1 Introduction 6

2.2 Process Characteristics 7

(a) Introduction 7

(b) Explosive Charge and Standoff Distance 7

(c) Springback and Recovery 9

(d) Formability 10

2.3 Mechanical Behavior 13

(a) Ductility 13

(b) Yield and Ultimate Strengths 15

(c) Fatigue Behavior 17

(d) Stress Corrosion 18

(e) Work Hardening 19

Page

2.4 Metallurgical Properties 20

(a) Slip 22

(b) Twinning 22

(c) Banding and Grain Distortion 24

(d) Thermal Effects 25

2.5 Summary and Conclusions of Literature Survey 27

Chapter III EXPERIMENTAL STUDY 31

3.1 Introduction 31

3.2 Materials and Specimens 32

3.3 Specimen Forming 32

(a) Explosive Forming 32

(b) Static Prestraining 37

3.4 Prestrain Measurements 40

3.5 Testing Procedures 45

(a) Strain and Hardness 45

(b) Stress Concentration 46

(c) Fatigue Tests 46

Chapter IV TEST RESULTS - ANALYSIS AND DISCUSSION 49

4.1 Results and Analysis 49

(a) Strain Distribution 49

(b) Hardness 55

(c) Work-Hardening 55

(d) Fatigue 60

Page

4.2 Discussion of Results 60

4.3 Sample Calculation to Determine the Statistical Significance of the Sample Results 65

Chapter V SUMMARY AND CONCLUSIONS 65

5.1 Summary 65

5.2 Conclusions 65

5.3 Suggestions for Further Study 66

LIST OF FIGURES

Page

1.1 Deformation Velocities in High-Velocity and Conventional Metalworking Process 2

2.1 Shift of Neutral Axis By Addition of a Plug Cushion 11

2.2 Shift of Neutral Axis Due to Edge Restraint 11

2.3 Schematic Representation of Flow Characteristics After Static or Dynamic Prestrain 21

3.1 Arrangement For Explosive Forming 35

3.2 Cylindrical Die 36

3.3 Vacuum Chamber 38

(a) Chamber Exterior with Vacuum Pump and Control Panel . . . 38

(b) Chamber Interior with Die Assembly 38

3.4 Top and Bottom Die Lids 39

3.5 Explosive Forming Cylindrical Die 39

3.6 Strain Effected by the Removal of Curvature 41

3.7 Instron Tensile Tester 42

(a) Instron Chart and Control Cabinet 42

(b) Extensometer Positioned on a Specimen 42

3.8 Tensile Test Specimen 43

3.9 Prestrain Specimens 43

(a) AMS 6520 43

(b) AMS 6435 43

3.10 Fatigue Specimens 43

(a) AMS 6520 43

(b) AMS 6435 43

Page

3.11 Knife-Edge Vernier and Dividing Head 44

3.12 Vernier Microscope and Dividing Head 44

3.13 Baldwin Fatigue Testing Machine 47

4.1 Fracture Adjacent to the Weld Seam Caused by the Explosive Overstraining of Two AMS 6520 Cylinders 50

4.2 HERF Fractures Situated 90° From the Weld Region of a Statically Prestrained (1.7%) AMS 6520 Cylinder 51

4.3 A Typical Explosively-Bulged Cylinder 51

4.4 AMS 6435 Strain Profiles 53

4.5 AMS 6520 Strain Profiles 54

4.6 AMS 6435 Hardness Profiles 56

4.7 AMS 6520 Hardness Profiles 57

4.8 Hardness vs Percent Strain Curves For AMS 6435 and AMS 6520 59

4.9 Fatigue Life Comparisons for AMS 6435 61

4.10 Fatigue Life Comparisons for AMS 6520 62

LIST OF TABLES

Page

1.1 Characteristics of High-Velocity Metalwork Processes 3

3.1 Approximate Chemical Composition of AMS 6520 (250 Grade Maraging Steel) 33

3.2 Mechanical Properties of AMS 6520 33

3.3 Approximate Chemical Composition of AMS 6435 34

3.4 Mechanical Properties of AMS 6435 34

4.1 Explosive Forming Strain Results 52

4.2 AMS 6435 Hardness Results 58

4.3 AMS 6520 Hardness Results 58

4.4 Fatigue Results - AMS 6435 63

4.5 Fatigue Results - AMS 6520 64

CHAPTER I

Introduction

1.1 Background

Within the past fifteen years, a new technology has developed in the field of metalworking. The availability of unlimited forces generated by explosive charges has resulted in the development of techniques for explosively forming metals, welding, cutting, swaging, drawing, compacting metal powders, and work hardening.

For centuries explosives have been utilized to do work constructively by mining and civil engineers, and destructively in military operations. Not until after World War II, however, were explosives adopted as an effective tool by metalworkers.

Explosive forming itself is only one member in a relatively new family of high-velocity metalworking processes which includes electrohydraulic, electromagnetic and pneumatic-mechanical processes as well.

Figure 1.1 illustrates the differences between the deformation velocities of the high velocity processes and conventional processes. Various high velocity metalworking processes are listed with the most salient characteristics of each in Table 1.1.

The principal advantage to date of explosive forming as a metalworking process has been the substantial saving made possible where the number of parts being produced was low. The aerospace

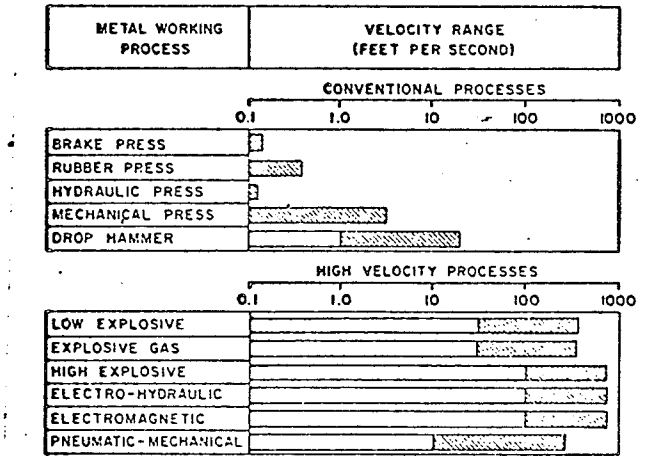


Figure 1.1 Deformation Velocities in High-Velocity and Conventional Metalworking Processes (Ref. 1)

	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, beading.	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 ft³ 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 Characteristics of High-Velocity Metalwork Processes (Ref. 1)

industry has supplied the greatest demand for explosive forming as a means of forming high strength alloys into parts for which exceptionally close tolerances are required. Many unique applications have been found in the manufacture of prototypes for the automobile industry and armour plating for the military. Stainless steel dentures have been formed inexpensively and with unexcelled precision employing this technique.

The terminal mechanical properties of different metals have been investigated following explosive forming and complete agreement has not yet been realized on the changes found in mechanical behavior. Contradictory results occur where the techniques of deforming a particular metal have differed, and, in addition, where one method had been used for deforming several different metals, results again differed from metal to metal.

In comparing the fatigue life of explosively and statically formed materials, the majority of reported data indicated a reduction in fatigue life due to explosive forming. Further investigation into both mechanical and metallurgical properties of the as-formed material is necessary to ascertain the causes of inferior terminal properties.

1.2 Statement of Problem

This thesis is principally an experimental study of the comparative effect of dynamic and static forming on the notched fatigue life of AMS 6520 (18% Nickel Maraging Steel) and AMS 6435.

1.3 Scope of Thesis

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

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

Chapter Three is comprised of experimental studies related to and including the relative effects of explosive and static forming on the fatigue life of AMS 6520 and AMS 6435 high strength steels.

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

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

A Bibliography concludes the thesis.

CHAPTER II

A Review of Investigations Concerning Comparisons of Static and Dynamic Forming

2.1 Introduction

Explosive forming as a high energy rate metalworking technique has achieved much prominence and success in recent years. Most of the initial work with high energy rate forming (HERF) involved only practical aspects of the technique, and not until recent years was experimental research undertaken to determine the effects, if any, of dynamic forming on material properties.

The terminal mechanical properties resulting from HERF have been the subject of considerable controversy in the field of metalworking. Some believe that high energy rate forming is detrimental to material properties, while others contend that there is no significant change. Also, the terminal behavior of metal following HERF is held by a third group to be improved as compared with that after a more conventional forming process. Regarding material property changes produced by explosive forming as compared with changes resulting from conventional metalworking, few theories have been substantiated. In this literature review, previous findings regarding the effects on process characteristics, mechanical and metallurgical properties of both static and dynamic forming will be presented.

2.2 Process Characteristics

(a) Introduction

For greatest clarity and meaning in discussing the effects of explosive forming, the processes adopted in the major portion of experimental work reported on have been standardized. Two specific forming processes, dome forming and tube bulging, comprise the major sources from which data on the subject have been compiled. Of these, the former has achieved the greater degree of standardization. Explosively forming a metal into a hemispherical shape, or dome, entails firstly, the provision of a female die with an adequate drawing ratio, secondly, the use of the proper lubricant and clamping force for the metal, and finally, an adequate vacuum system, quintessential to the success of the forming operation.

The conditions of strain are more severe in dome forming than in tube bulging, hence, the greater employment of the former technique in ascertaining the as-formed mechanical behavior of various metals. Though of less importance in providing general knowledge of the forming properties of a metal, tube expansion, as a research technique, possesses considerable applicability to the problems facing industry in the manufacture of tubular products, such as rocket motor casings and fluid system components.

(b) Explosive Charge and Standoff Distance

In theory, for an explosive charge detonated in water, the gaseous products of combustion, being at high temperature and pressure, expand causing the water to be compressed suddenly, and the impulse

produced is propagated as a shock wave. The intensity and configuration of the shock wave will depend on the weight and shape of the charge. Only a few microseconds are necessary for the conversion of the explosive into the high pressure, high density, gaseous products of detonation. And, for high explosives, the velocity with which this conversion front moves through the explosive is called the detonation velocity.

Parameters controlling the magnitude and distribution of pressure are: the type, amount and shape of charge used, the energy transfer medium (e.g. water), and finally the standoff distance. The shape of the charge is usually related to the geometry of the desired part. A length of Primacord, for example, is frequently used in bulging cylindrical specimens. In establishing the standoff distance, two considerations are involved: the first is that peak pressure falls off inversely as the distance from the charge, and is, therefore, ineffective if positioned too far from the blank to be formed. The second consideration arises due to the high compressibility of air. The air pressure remaining after evacuating the underside of the blank is normally still a few millimeters Hg, and, since air encounters a high temperature rise with the passing of the shock wave, this amount of air may be sufficient to cause severe burning of the blank. In fact, more failures in forming and sizing operations occur due to entrapped air than any other fault (1).

Apart from the pressure decay effect of an explosive charge on standoff distance is the effect on pressure of the charge geometry. While a spherical charge provides uniform radial pressure, a line

charge arrangement exhibits an end pressure approximately five times less than the side pressure (2).

There are three types of standoff operations:

i) free forming (cupping, flanging, deep drawing)

ii) cylindrical forming

iii) bulkhead forming (sheet and plate)

As mentioned previously, more has been written on dome and tube forming than any other type. In all standoff operations, however, the system components are the same, being comprised of: explosive charge, energy transmitting medium, die assembly and workpiece. Auxiliary components may consist of: a forming tank, an air compressor, a vacuum pump, and, for handling heavy dies, a crane device may be needed.

(c) Springback and Recovery

There are essentially two factors involved in springback; the first is rebound when the blank and die collide, and the second is elastic recovery, which is related to the amount of elastic strain present. The amount of rebound is proportional to the terminal velocity with which the blank hits the die wall and the coefficient of restitution between the die and the blank. Springback due to elastic recovery is most severe when the yield strength of the metal is high and a shallow draw depth is required (3).

With water as the transfer medium, the momentum of the water follows the shock wave and resists springback as this delayed force strikes the rebounding metal. Springback may be best controlled, however, by overstraining. This may be accomplished by several methods.

One technique is to utilize a cushioning layer of material, usually rubber, to shift the neutral axis as shown in Figure 2.1. This cushion, a pseudo-integral part of the blank, causes the neutral axis of the composite to be shifted above the blank face. The entire cross section of the blank is thereby strained into the plastic range. Another highly successful method of increasing the proportion of plastic strain to effect a reduction of springback is to weld a rim along the outside edge of the blank. This allows no outside flange material to flow inwards past the hold-down point. The blank being formed is forced to stretch as the edge restraint causes a uniform tensile stress to be superimposed across the entire cross section as shown in Figure 2.2. Pretensioning the metal blank prior to explosive forming has also been effective at reducing springback by raising the neutral axis (4). These techniques have received considerable application in the shallow and deep drawing of thin circular plates.

(d) Formability

Due to the cutting ability of the explosive force with thin sheet metal, avoidance of sharp edges and provision for smooth transition sections is necessary. Cylindrical shaping can be achieved by either closed or open die systems, with low explosives being employed in the former and high explosives in the latter (5). Welds, and the heat affected zones adjacent, generally are less ductile than the parent metal (6). However, forming welded blanks may be accomplished by annealing the weld prior to forming. Limiting the maximum plastic strain on the weld for each shot to a value below the allowable,

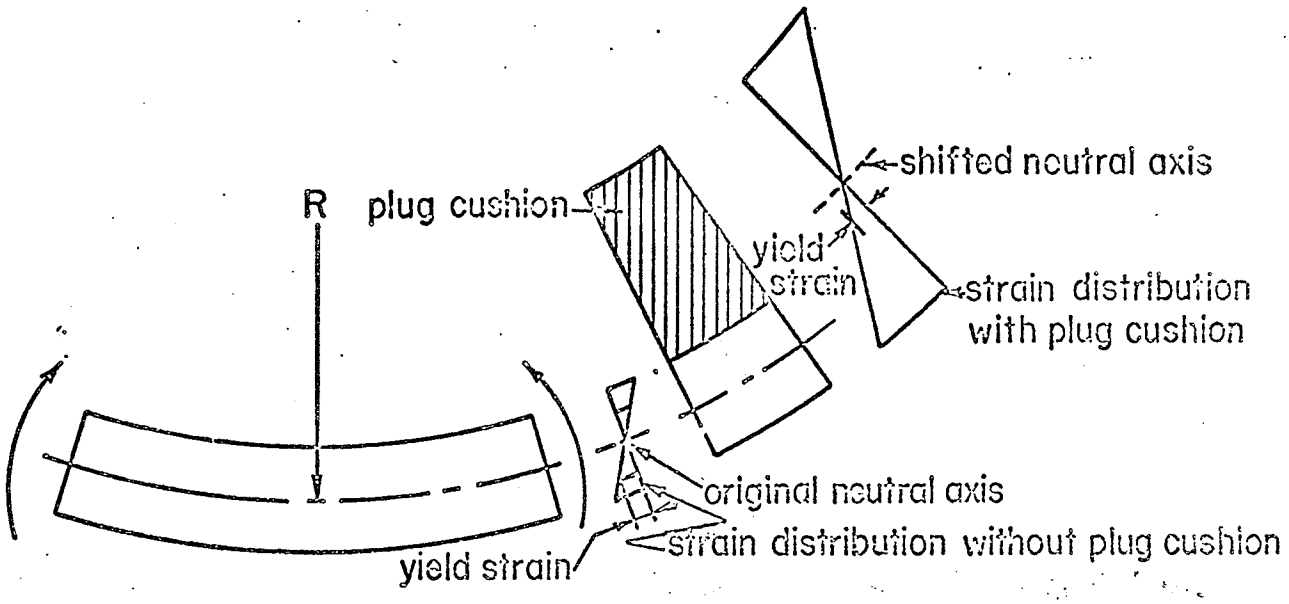


Figure 2.1 Shift of neutral axis by addition of a plug cushion

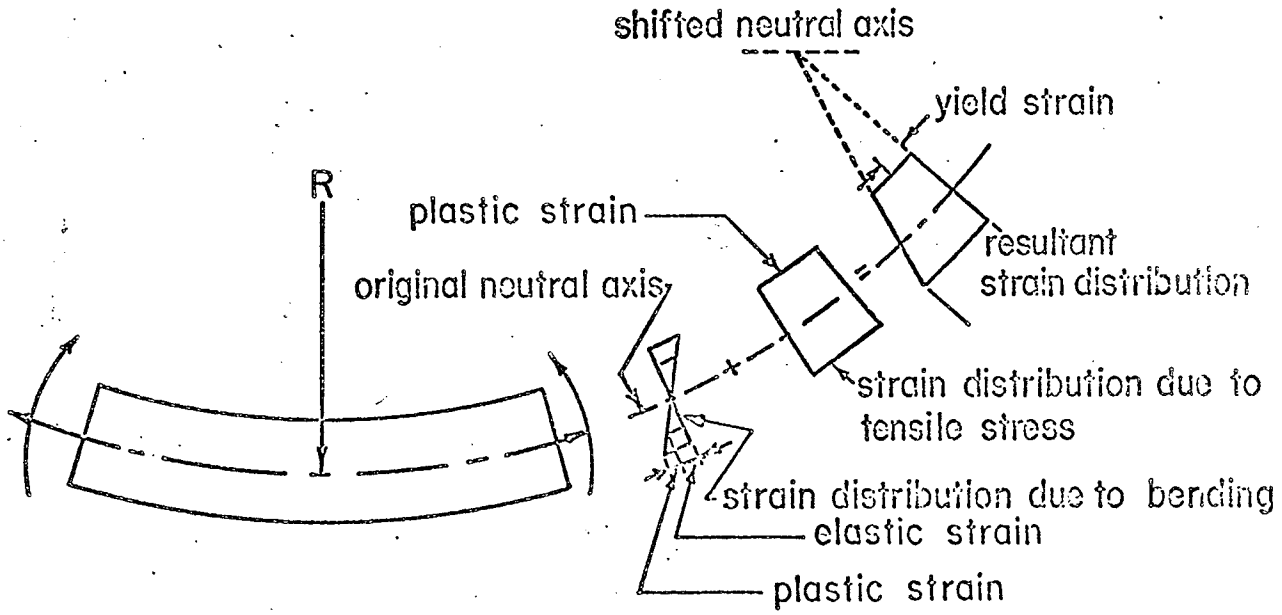


Figure 2.2 Shift of neutral axis due to edge restraint

is used in conjunction with interstage annealing. An in-process anneal after eighty percent deformation has been found to prevent weld failure (3). In addition to annealing, another technique employed quite successfully to form welded, dome or cylinder blanks has been to tape rubber pads over the weld area or use bonded adhesive and position the weld in an area least susceptible to stretching.

Bridgman(7) found that air-melted 18% Ni Maraging Steel could be explosively formed into hemispherical shapes using multiple shot sequences without interstage annealing. On the other hand, Campion(8) claims that even with the aid of interstage annealing explosive forming was not used successfully to form hemispheres with maraging steel. The 250 Grade Maraging Steel has been pressed into hemispherical forms by annealing at 850 degrees Centigrade for one hour between pressing operations; however, thirteen draws were necessary with this technique (8).

Since these tests, some success has been achieved by sandwiching the metal blank between two thicker sheets of steel and increasing the charge size. In addition, a welded gore construction and conventional drawing equipment have been used to fabricate large pressure vessel closures from 18% Ni Maraging Steel (9). A successful procedure has been adopted whereby the metal blank is heated above recrystallization (A_s) temperature, and by using a press which is maintained at a temperature of approximately 250 degrees Centigrade, the drawing operation is carried out (10).

Vernon(9) concludes that, when the process requires considerable stretching, maraging steel is not amenable to the deformation mechanism

involved. And, in their preliminary investigations into the feasibility of cold forming air-melted maraging steel, Agricola and Tate(11) found that, due to the tendency of the metal to buckle and wrinkle, it can at best be considered difficult to form.

2.3 Mechanical Behavior

The behavior of metals at high strain rates has been the subject of a considerable amount of theoretical and experimental work in the past decade. Recent studies have been concerned with the mechanisms of deformation and failure as well as relationships between stress, strain, and velocity measurements (5). As a result of the explosion, an intense transient shock wave is induced which may considerably affect the mechanical properties of the metal. In general, hardness, yield and ultimate tensile strengths increase, while toughness and ductility decrease.

(a) Ductility

For many metals ductility has been significantly increased by raising the velocity of deformation (12, 13). Beyond a certain velocity, however, ductility remains constant until the critical velocity is reached, at which point it falls to zero. In the deformation of metals, critical velocity is considered to be the impact velocity equivalent to the velocity at which plastic strain can propagate through the metal, and beyond which fracture occurs (14). Little is known of this phenomenon in the context of tube bulging in which case the velocity of deformation would be circumferential. Fracture

will occur in HERF, as in conventional forming, if the elongation limit is exceeded.

Two metals which exhibit no increase in ductility with forming velocity for tube bulging are A-286 Austenitic Stainless Steel and 6 Al-4 V Titanium (12). Since this titanium alloy exhibits an increase in ductility with dome bulging (14), the need for further comparisons between dome and tube bulging for other high strength metals seems evident. The yield and ultimate strengths of 4140 Steel gun tubes were raised approximately nine percent by explosive forming, but ductility in the circumferential direction was reduced eleven percent (15). Vascojet was similarly tested with a reduction reported in both strength (6%) and ductility (20%).

A significant increase in ductility has been observed in metals tested at high hydrostatic pressures (10). In explosive forming, both high strain rate and high pressure effects occur, but the mechanisms for greater plasticity under these conditions are not understood.

In a review of the mechanical properties of maraging steel, the literature has revealed elongations at fracture of ten to twelve percent in the solution-heat-treated material, referred to as the "as-received" condition. However, these results apply to bar material, and, in considering the forming capabilities of sheet metal, such a high percentage elongation cannot be expected by conventional means (8). Further to this, data reporting elongation at fracture can be misleading, since as much as fifty percent occurs after necking begins. Campion(8) reports elongations of approximately three percent for this metal, and

of this, only one percent is uniform. A characteristic of maraging steel which makes it undesirable for sheet metal forming is a pronounced tendency to neck (9).

Rinehart (13) claims that a few metals, notably the high manganese and high nickel steel alloys manifest increased ductility when strained rapidly. Tension tests on fully aged AM 350 Stainless Steel indicated that greater ductility existed in the material which had been explosively formed than in that deformed an equivalent amount by static means (16).

Brittle fracture is determined by the normal stress on planes of cleavage and is characteristic of failure at both low temperatures and high strain rates. Blazynski (5) investigated the behavior of cold drawn steel tubing which was annealed before explosive free-forming. The strains at fracture in static bulge tests were much higher than those of explosive forming. He concluded that brittle fracture is little affected by temperature but very susceptible to high strain rates. Following explosive forming tests made with thin plates, Schmidtman et al (17) concluded that BCC materials are more prone to brittle behavior than FCC material.

(b) Yield and Ultimate Strengths

Increasing strain rates will, for most metals, greatly lower the impact energy to fracture. Wood (18) has shown that, for plots of true stress versus true strain, this is indeed the case. Increasing static prestrain reduces the difference in terminal flow stress that exists between static and dynamic loading rates. However, no general

rule has yet been formulated regarding the prestrain-rate dependence of ductility for any given alloy.

The mechanical properties of 2014-0 Aluminum are reported affected to the same degree by forming, irrespective of rate (19). D'Aguanno and Pfanner (20) free-formed 2014-0 by hydrostatic, electromagnetic, electro-hydraulic and explosive techniques, whereupon no significant forming-rate dependence was revealed after comparing yield strength and ductility. Subsequent to the explosive forming of one-quarter inch 2219-0 Aluminum plate, there was little change in UTS, but yield strength improved approximately 65 percent with only a slight drop in elongation (21). Tests were also performed on AISI 321 Stainless Steel, indicating both yield and ultimate strength (7.5%) to be higher for explosive forming than static. Pearson and Heyes (22) reported marked increases in strength for 1015, 1030, 1050 and 4130 Steels following HERF.

Ambiguous HERF effects continue to appear in the literature with conflicting data being received recently, on the newer, high-strength alloys, such as maraging steel, which is known to have high annealed strength and hardness. Potteiger (23) maintains that the hardness increase in explosively formed maraging steel is insignificant. Air melted 18% Ni Maraging Steel was found by Fowler (24) to be significantly stronger following explosive forming. On the other hand, Agricola et al (25) compared the same metal, explosively formed, with parent stock. The metal was formed in the annealed condition, then maraged to achieve optimum strength. The YS and UTS were lower after explosive forming as compared with the parent stock. The parent and formed materials were elongated 5% for comparison of the relative strengths. The ambiguity arises, however,

due to the variation in the heat treatment provided with different experimenters.

One of the most substantial increases in YS reported, as a result of explosive cold-working, occurred in the explosive forming of non-magnetic retaining rings from cylindrical ingots for use in large electric generators (26). Mechanical properties improved to the extent that the yield strength slightly more than doubled in value, but no comparison was made with conventional forming.

(c) Fatigue Behavior

Mikesell (27), in his comparison of the fatigue life of explosively formed and rubber-pressed 2014-T6 Aluminum alloy, found no significant difference and only a nominal change over that of the undeformed metal. Williams (28) completed fatigue tests on thirteen metals following explosive forming in a cup-shaped die and found, in general, no difference from the fatigue behavior of similarly formed static specimens. Similar comparisons were made in the fatigue behavior of commercially pure aluminum by Dalebozik (29), with a reduction in the life of the explosively formed domes being reported. Verbraak (30, 31) suggests the introdution of microcracks during explosive forming as a possible cause of reduced fatigue strength.

Pipher et al (15) determined S-N curves for explosively formed Vascojet 1000, AM 350 and Ti-8 Mn, and compared them with the fatigue behavior of the undeformed parent metal. The endurance limit of the parent metal was approximately 20% greater than the prestrained specimens; however, the data are incomplete since no comparison was made with statically prestrained specimens.

From studies of 5052 Aluminum explosively die-formed, and statically deformed in uniaxial tension, Bennett (32) concluded that explosive forming appears to have a harmful effect on fatigue life. He found the strain distribution to vary in proportion to the distance from the centre of the specimen, and that fatigue failure occurred at the section of least straining or work hardening. However, evidence has since been presented in which, for this work-hardenable alloy, higher strains yield a longer fatigue life (33). The conclusion reached by Bennett would then seem plausible, due to the lowest explosive strains generally being less than the more uniform static prestrains.

(d) Stress Corrosion

Explosive forming has been shown to be considerably more detrimental to stress corrosion resistance than conventional forming for stainless steels (12). The stress corrosion cracking resistance of 304 was enhanced by explosive sizing operations, consisting of small strains of the order of 2% or less. The reverse effect has been noted for 2014-T6 and 7075-T6, (34) Aluminum Alloys. Verbraak (31) observed that explosively die-formed 304 Stainless Steel dishes, when immersed in $MgCl_2$ solution, exhibited cracking in one-third the time required by conventionally pressed dishes. Here, the strains were much higher than those in the sizing operation and a more significant effect of stress corrosion would be expected.

Agricola and Snyder (35) made corrosion resistance tests on four high-strength steels (12% and 18% Ni Maraging Steel, HP 9-4-25, and D6 AC) and an aluminum alloy (7039). Before exposure, the materials

were explosively die-formed in the annealed condition, and following this, a heat treatment was applied. A 200-hour immersion period in a 3.5% NaCl solution at 80% of the yield stress caused substantial strength reductions in D6 AC and 7039, but not to maraging steel.

Orava and Whiting (36), in their investigation of the corrosion resistance of 2014-T6, compared the resistance of explosively formed metal with that of metal formed statically by rubber pressing. The stress corrosion properties were greatly affected by the latter, and no change was evidenced in the resistance properties of the explosively formed metal. In stress corrosion tests with 7075-T6 Aluminum, Jacobs (34) reported that the dynamically strained aluminum required 30 days to fail while the undeformed metal failed in less than two days. Orava and Whiting (36) suggest this may be a special feature of this precipitation hardened alloy.

(e) Work Hardening

Rowden (37) contends that the degree of strain hardening, and not the rate of strain, is the most important criterion in influencing terminal mechanical properties. He maintains further that, no matter what process of deformation the material is subjected to, where it undergoes an equivalent amount of strain hardening, its mechanical properties will be similar.

The precise effect of forming rate on terminal ductility has not yet been determined. Generally, if, following dynamic and static prestrain, the static yield strengths are compared with the result that the dynamically prestrained metal is found to be superior, then the

terminal work hardening rate is lowered as shown in Figure 2.3. The opposite effect is observed if the static yield strength of a specimen, prestrained dynamically, is less than, or equal to, the static yield strength of the statically prestrained metal.

Williams (38) has reported less strain hardening in titanium and mild steel when explosively deformed. On the other hand, aluminum and nickel alloys exhibit more work hardening during explosive forming than during the static equivalent. In general, if the structure is FCC, dynamic deformation produces work hardening to a greater degree than that evidenced in the static counterpart. The reverse is true for mild steel and iron (39), both of which are BCC. Sernka (40) states that maraging steel possesses a low rate of work hardening during plastic deformation but makes no comparison between high and low strain rates. A stabilizing effect against necking has been attributed to an increased rate of strain hardening with the deformation velocities of HERF (12).

2.4 Metallurgical Properties

A review of the available literature on the microstructural differences following conventional forming and HERF depicts current understanding of the mechanisms involved to be inadequate. The microstructure of material strained by multiaxial loading, understandably, continues to be quite difficult to analyze, but there is also general incongruity where loading was uniaxial. The differences in microstructure following conventional forming and HERF occur primarily in the density and distribution of lattice defects, such as dislocations, mechanical

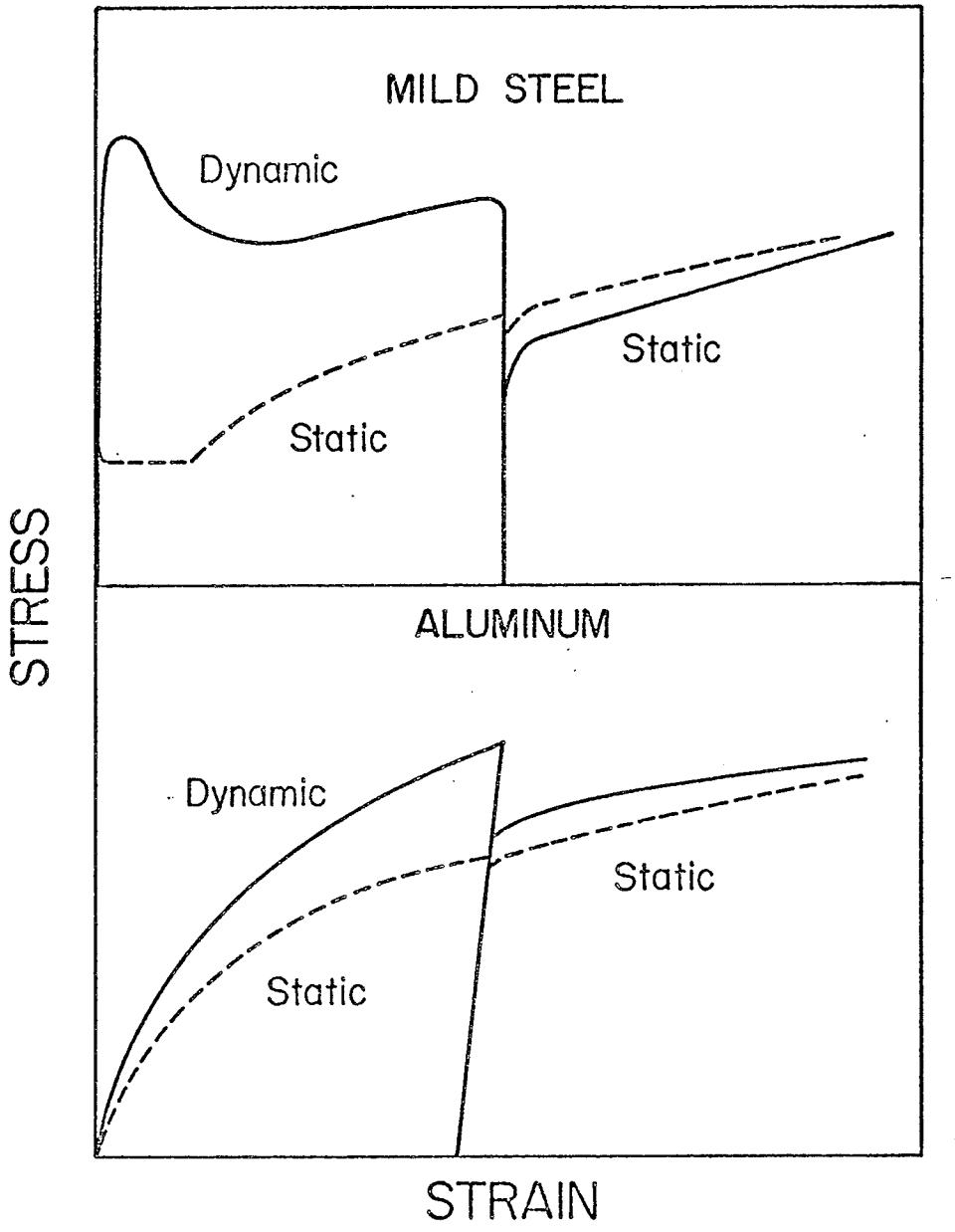


Figure 2.3 Schematic Representation of Flow Characteristics after Static or Dynamic Prestrain

twins and stacking faults (42). The principal modes of microscopic deformation subsequent to impulsive loading are known to be slip, twinning, banding and grain distortion (43).

(a) Slip

The slip band morphology resulting from uniaxial loading has been the subject of a number of investigations into the mechanism of dynamic deformation as compared with the static counterpart. Results indicate an appreciably higher density of finer slip bands in iron, medium-carbon steels and aluminum (44, 45). Since this refinement of slip due to dynamic loading does not occur in all metals, Orava (42) speculated that it is only associated with BCC or FCC metals. Explosively formed Nimonic 90, a nickel-base alloy, evidenced finer strain markings than after static forming (38). Hollis (46) has shown that finer slip results from high rate straining compared with coarse slip at low rates. At higher temperatures the reverse effect should be true, but in fact it is not. From this, Hollis concludes that at least some of the adiabatic effects during explosive forming may be overridden by the mechanism controlling dynamic deformation.

(b) Twinning

Considerable difficulty has been encountered in attempting to distinguish the contributions that twinning and dislocation substructure make to strength and hardness. Consequently, no conclusion on the influence of mechanical twins on post-forming properties has been made. Several specific findings have permitted some gain in insight into the effect twinning has on terminal properties.

Explosive deformation occurs initially by twinning and secondly by slip (43). However, Hollingum maintains that low- and high-alloy, high-strength steels should have no twinning present following HERF (47). Static prestraining has been found to inhibit twinning in iron during HERF (48). This effect has also been observed in the dynamic loading of prestrained Armco iron and molybdenum (49). Uniaxial dynamic loading at room temperature has caused mechanical twinning in high purity iron (50), Swedish iron (48) and zinc, as well as some low-carbon steels. However, no mechanical-oriented twinning structures were observed in the uniaxial deformation of medium-carbon steels (51), aluminum, or any aluminum alloys (47, 50). Explosive forming has caused twinning in single crystals of many BCC metals, notably molybdenum, tungsten and ferritic steels (30).

Verbraak (30) states that he has found increased brittleness in explosively formed steel (BCC), and this, he contends, is due to the large amount of mechanical twinning present. Otto and Mahajan (52) hold that twinning does not significantly affect hardening.

Generally, the number and size of twins decrease through the thickness of the material with distance from the explosively loaded surface (43). Following shock loading, twins formed within a cylinder tend to be wider and more continuous than those in a plate subjected to an equal explosive charge (53). With annealed SAE 4130, formed by explosive contact, only extremely isolated twinning resulted. Hollingum (47) observed the density of twins in explosively formed mild steel (0.08% carbon) to increase with strain up to 30% reduction in thickness, whereupon the number of slip bands increased. No twins appeared in this same

metal deformed statically. Little is known of the terminal characteristics of beryllium and zirconium, and the occurrence of twins in titanium alloys is still subject to further experimental investigation.

(c) Banding and Grain Distortion

The microstructures of Maraging Steel and other nickel-base alloys frequently show distinct banding due to shock-induced segregation. Thin, crystallographic lamellae, known as Neumann Bands, are common when steel is explosively formed. Bands are most numerous in the region of maximum deformation; however, little else is known of their occurrence (53).

Explosively formed metals commonly exhibit evidence of grain fragmentation and grain flow (53). The latter is present whenever a ductile type shear fracture develops and grain fragmentation is observed in a brittle metal. There is some grain refinement due to explosive shock hardening, but less than is found in cold working to similar hardness levels. Upon examining 2219, 2014 and 321 alloys, Swann (54) was unable to distinguish between the samples explosively and electrohydraulically formed. Only in 2014 alloy was sub-grain cell size higher after explosive forming than hydrostatic forming. A higher density of dislocation dipoles has been observed in explosively formed 321 Stainless Steel and 2014-0 Aluminum than after hydrostatic forming (20). As yet, however, no significant correlation has been made between the presence of dislocation loops, larger cell size, and yield strength after work hardening.

(d) Thermal Effects

The desired mechanical properties of new ultra-high-strength steels are achieved by age hardening; therefore, determining the nature of changes in aging response as a result of explosive forming has become important. The reason for improved mechanical properties upon aging is that precipitates act as barriers to dislocation movement. Rowden (37) contends that by a simple heat treatment, properties subsequent to explosive forming may be restored to an acceptable level. No data was provided to support this theory. While increased temperature usually lowers the critical shear stress, virtually eliminating springback, increased strain rates generally raise it. Thus, the age hardening properties of precipitation hardenable alloys are normally altered by explosive forming, but the detailed mechanisms are not fully understood.

Where high-temperature, high-strength considerations are not so important, 6 Al-4 V Titanium Alloy, used extensively in critical structural applications, is being replaced by maraging steel (22). This is an iron-base alloy which is strengthened by a combination of a martensitic transformation followed by an age hardening reaction (55). A minimum of 18% nickel is necessary to ensure a martensitic transformation under all cooling rates. The comparative high price of maraging steel is offset by excellent production features resulting from simple heat treatment, good machinability, weldability and hardening without decarburization or excessive scalding. The first alloy was made by Bieber in 1958, but little is known about the strengthening mechanisms and deformation behavior (56). The aging process for 18% Ni Maraging Steel is one hour at $900^{o}F$, with the result that the yield strength increases to 300 ksi from 110 ksi (57).

Pearson et al (22) examined the behavior of titanium alloys after heat treatment and forming. If lattice defects or phase changes occurred during HERF, then following heat treatment, they probably would still have been effective as strengthening mechanisms. Since this was not the case, however, strain hardening was said to have caused the strengthening observed in the as-formed condition. The same authors went on to say that, regardless of the deformation rate used, lost ductility could not be restored by normal strengthening heat treatment. Following explosive expansion and a full heat treatment of 4140 Steel tubes, Campiogne and Colangelo (58) observed a reduction in impact resistance.

Agricola (25) investigated the 12% and 18% Ni Maraging Steels for the influence of explosive forming on fracture toughness, and found that, in general, a heat treatment restored the toughness to nominal levels without adverse effects remaining. In a survey of aluminum alloys only, Orava et al (19) disclosed that an appropriate heat treatment would restore the original properties to a deformed metal. Upon considering, however, that for the 2000 series alloys, forming rate was found not to contribute significantly to as-formed mechanical behavior, the above statement is of lesser import.

Explosively formed metals exhibit a high concentration of vacancies with the result that the aging process is normally accelerated (59). Precipitation is a diffusion-controlled mechanism and the presence of vacancies substantially increases diffusion rates, thereby lowering the aging time of explosively formed metals. A higher hardness was obtained in A-286 Stainless Steel in less aging time due to explosive forming effects (60). Thurston (61) studied the heat treatment response

of 250 Grade Maraging Steel explosively loaded to a pressure of 2,600 ksi. The recommended aging temperature of 900^{o}F was used and the time to reach optimum mechanical properties was reduced to thirty minutes. This clearly depicts the tendency of HERF to lower aging time. Another effect on aging behavior, as a result of explosive forming, is a higher ultimate strength before aging than after for some metals, notably 17-7 PH Steel and 6 Al-4 V Titanium (62). Such observations indicate the possibility of over-aging following dynamic straining.

2.5 Summary and Conclusions of Literature Survey

Scientists and engineers are always searching for new metal-forming techniques, and, as a result, a great deal of interest has been shown in the research and development of explosive forming. However, large gaps still remain in the understanding of forming-rate effects. Rowden, in his investigation (37) into metal behavior subsequent to dynamic straining said, "a critical evaluation of the terminal characteristics of metallic materials formed by high energy rate techniques is sorely needed at present".

Explosive forming and HERF have become almost synonymous; however, any forming operation in which deformation is completed in micro- or milliseconds is referred to as HERF. With HERF, the material properties which have shown greatest reliability are strength, hardness, ductility and fatigue. Since there has been such variation in the amounts these properties are enhanced by HERF, using different metals and forming conditions, it is thought that discussing the adverse effects would furnish insight

into the shortcomings of this metalworking technique. The most salient reductions have been in:

i) the strength of 17-7 PH Steel

ii) the ductility of 5052-0, 2219-T87, 7089 Aluminum Alloys

iii) the stress-corrosion life of Cr-Ni Stainless Steel

iv) the fatigue life of commercially pure aluminum and 5052-0 Aluminum Alloy.

The principal mechanisms of plastic deformation are slip and twinning. Both mechanisms are affected by similar parameters, namely material, temperature, strain and strain rate. There are twelve slip planes in BCC and four in FCC structures, but the relative formability of the metal is not determined by the number of slip planes, since with HERF rates, normally only FCC materials exhibit an increase in formability. By treating thermal response separately, an attempt has been made to avoid unnecessary ambiguity. Also, to focus attention on a few mechanisms, and thereby permit the mechanical behavior of as-formed metals to be more clearly understood, heat treatment for optimum behavior is frequently omitted from explosive forming tests. The role of forming rate in causing overaging effects with precipitation-hardenable alloys is not yet clear. The literature indicates a distinct dependence of mechanical twins on forming rate, but, as yet, terminal properties have not been correlated satisfactorily with these microstructural changes.

Effective comparisons among researchers in explosive forming are often difficult due to incongruence in deformation techniques and heat treatments. A greater degree of standardization is continually being sought, with the predominance of cylinders and domes as test specimens.

Conflicting opinions exist regarding the advantages and disadvantages of explosive forming, but those most agreed upon include:

(a) Advantages

1. The current knowledge of welded blanks permits no limit to the part size that can be formed.
2. Lead time is much lower than that of most conventional processes, hence the application with the manufacture of prototypes.
3. Springback is more predictable since it is reduced and may, in many cases, be virtually eliminated with closer tolerances resulting.
4. Capital investment is lower since tooling is less costly with the need for only one-half a die.
5. A reduction in the number of manufacturing operations is frequently possible with the accompanying reductions in labor and material costs.
6. Metals which are difficult or impossible to form by conventional processes may be readily formed by explosives.
7. Ductility is improved as some metals can be explosively formed beyond their normal, slow-rate limits of deformation.
8. The strength, hardness and metallurgical properties of many alloys are improved by explosive action.

(b) Disadvantages

1. Skill and experience requirements are greater than those necessary for the operation of conventional forming equipment.
2. The production rate is slow due to the necessity of having a single setup and blast operation.
3. Remote locations are required for the safe use of explosives.
4. The fatigue life of explosively formed metal is reduced in most cases.
5. The stress-corrosion life of many metals is detrimentally affected by explosive forming.

The explosive forming process has been described as "an excellent means of producing contamination-free, close tolerance parts at competitive prices" (41). Although deleterious effects are present in some metal properties, these are seldom significant and, once they are understood, may be compensated for in design. In order for industry to accept the process completely, explanations must be provided for the property changes that follow HERF. Recently, in a review of the effects of HERF on terminal metal behavior, the current situation was clearly stated to be one in which "there is little question that a great deal of work is still needed to satisfy designers and fabricators that material properties, especially fracture toughness, fatigue, creep, stress corrosion, and ductility will conform to acceptable standards after high energy rate forming relative to more conventional processes" (42).

CHAPTER III

Experimental Study

3.1 Introduction

Statically and explosively deforming a metal has frequently been used to determine the relative effect of forming rate on the fatigue life of an alloy. However, due to the incompleteness of such comparisons and the nonuniformity of testing procedures, data thus obtained cannot always be satisfactorily correlated with similar experimental investigations. Therefore, in an effort to make an independently valid investigation into the effects of forming rate, metal in the "as-received" condition has been compared with that of the statically and explosively deformed metals.

Preliminary investigations are all that have been reported to date on the effects of explosively forming AMS 6520 (18% Ni Maraging Steel) (11), and no data has been reported for similar comparisons using AMS 6435 sheet metal. It was considered, therefore, that by endeavoring to compare the fatigue life for both metals in each of these three conditions, a valuable contribution would be made to our fund of engineering knowledge.

The comparison of fatigue life was made at four stress levels, maintaining throughout a constant ratio of static prestress to dynamic stress. Strain and hardness tests were made in an attempt to explain the lower fatigue life in the explosively formed specimens.

3.2 Materials and Specimens

The materials investigated were AMS 6520, commonly called 250 Grade 18% Ni Maraging Steel, and AMS 6435. Both metals are currently being used in the aerospace industry for rocket motor casings. Two cylinders, sixty-two inches in length, with a mean diameter of ten inches were rolled and welded from 0.056 inch sheet metal. Each cylinder thus fabricated was cut into five, eleven-inch test cylinders. Thus, for each metal tested, all specimens came from the same pour of sheet metal. The approximate chemical compositions for AMS 6520 and AMS 6435 are given in Tables 3.1 and 3.3 respectively. The mechanical properties prior to heat treatment are given for AMS 6520 in Table 3.2 and for AMS 6435 in Table 3.4.

3.3 Specimen Forming

(a) Explosive Forming

A diagram of the explosive forming arrangement is shown in Figure 3.1. A cylindrical die and centering lids were machined as shown in Figures 3.1 and 3.2. The charge was 200 gr/ft Primacord coiled around a one-half inch solid steel centre rod. The weight of charge used in forming AMS 6520 and AMS 6435 cylinders was determined experimentally to be 62.85 grams and 42.18 grams respectively. Number six electric blasting caps were used to detonate the high explosive Primacord with a standard wall outlet as the power source. The charge and cap were positioned with a 4½ inch standoff distance, determined jointly by the diameters of the test cylinder and centre rod. A plastic bag was inserted into the test cylinder and filled with water to within one-half inch from the top lid.

TABLE 3.1

Approximate Chemical Composition of AMS 6520 (250) Grade Maraging Steel)

Nickel	18.00%
Cobalt	7.80%
Molybdenum	4.90%
Titanium	0.40%
Aluminum	0.10%
Manganese	0.10%
Silicon	0.10%
Others	0.05%

TABLE 3.2

Mechanical Properties of AMS 6520*

Ultimate tensile strength	136,500 psi
Tensile yield strength (at 0.2% offset)	131,000 psi
Elongation, in 10 mm gauge length	2.5%
Modulus of elasticity	27×10^6 psi

*Tested in the solution heat-treated condition in the direction of rolling before optimum strength heat treatment.

TABLE 3.3

Approximate Chemical Composition of AMS 6435

Nickel	1.80%
Chromium	0.80%
Manganese	0.75%
Silicon	0.50%
Molybdenum	0.35%
Carbon	0.35%
Copper	0.35%
Vanadium	0.20%
Others	0.02%

TABLE 3.4

Mechanical Properties of AMS 6435*

Ultimate tensile strength	92,500 psi
Tensile yield strength (at 0.2% offset)	81,000 psi
Elongation, in 1-inch gauge length	11.0%
Modulus of elasticity	29×10^6 psi

*Tested in the solution heat-treated condition in the direction of rolling before optimum strength heat treatment.

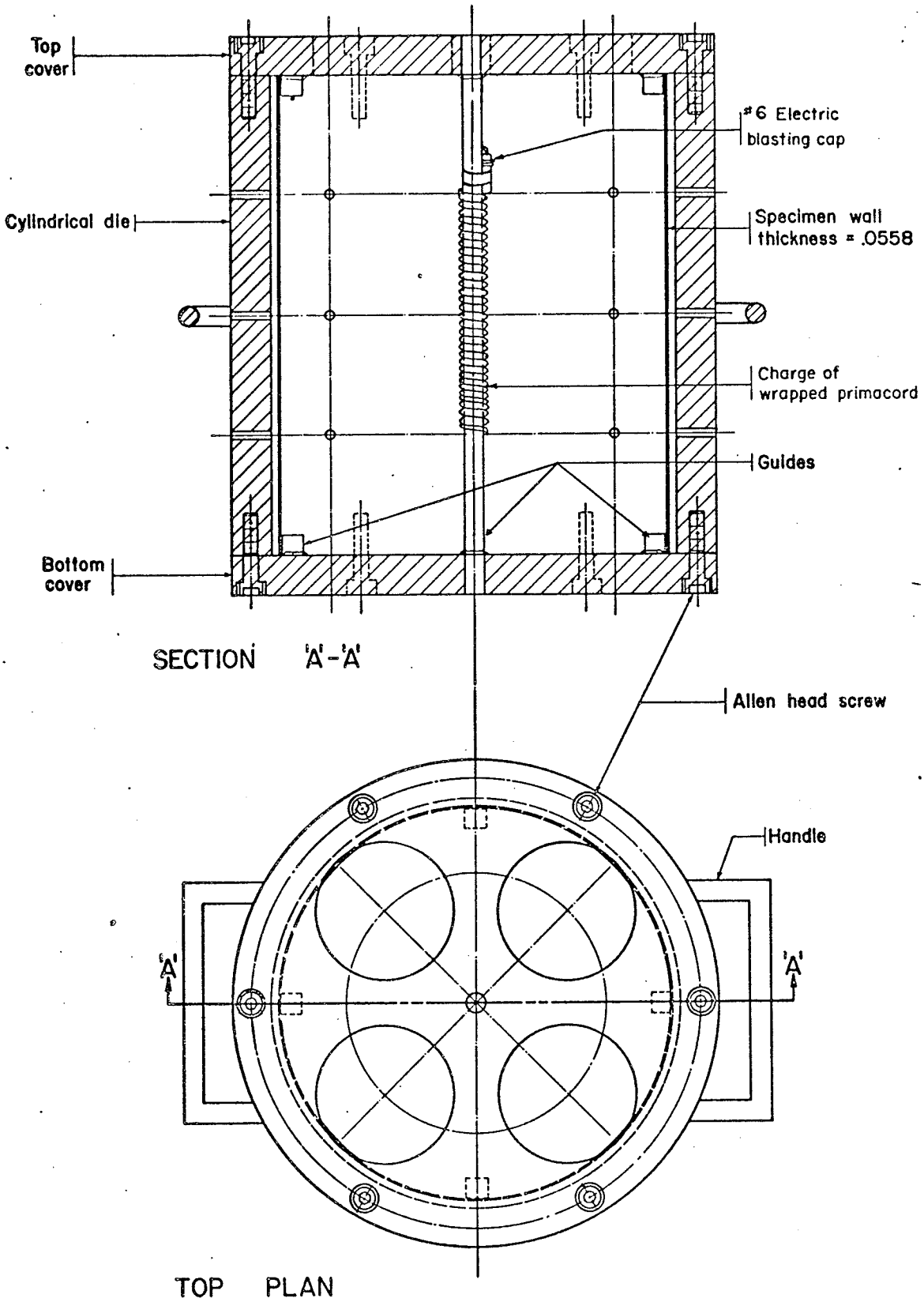


FIGURE 3.1 ARRANGEMENT FOR EXPLOSIVE FORMING

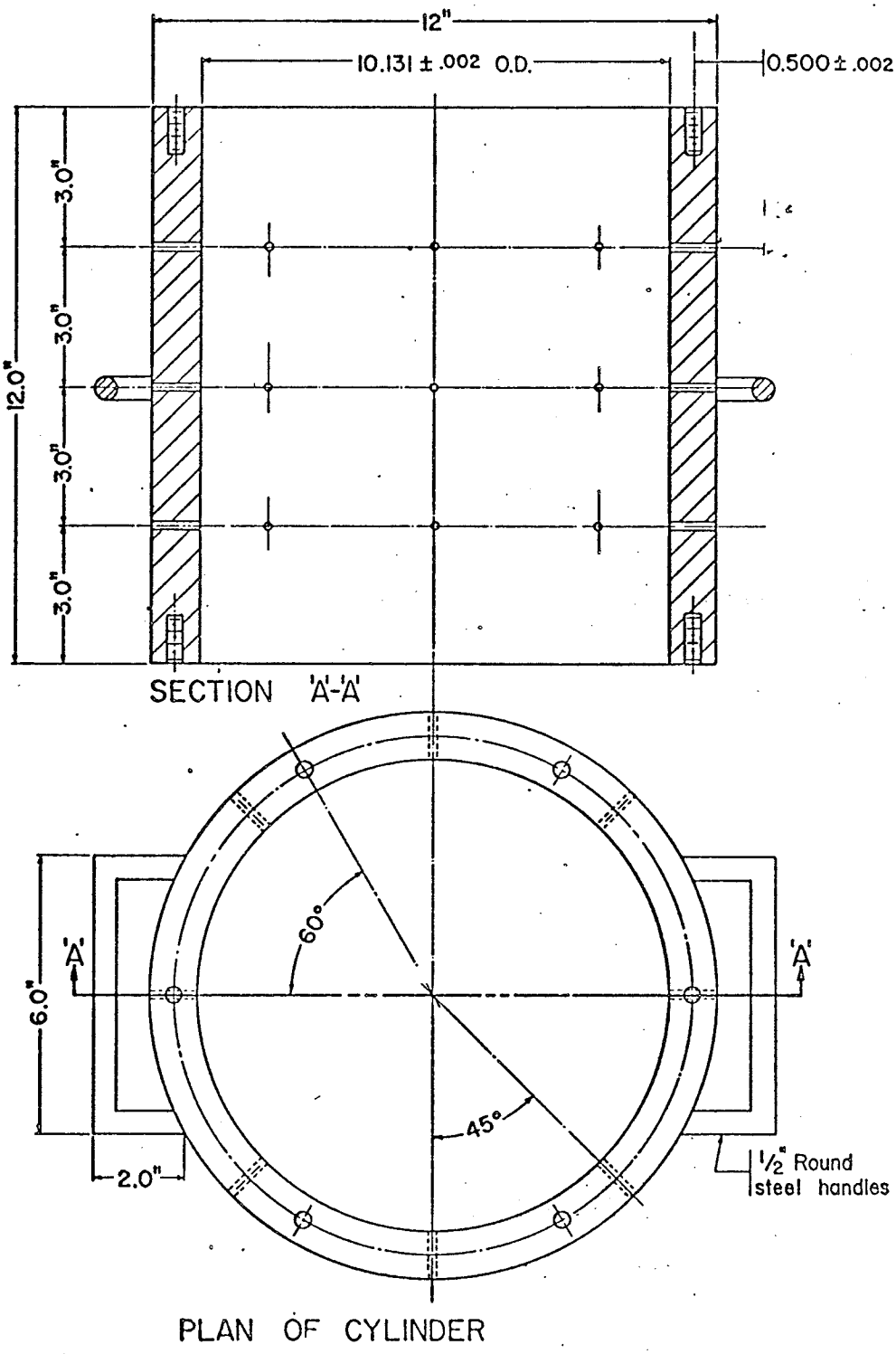


FIGURE 3.2 CYLINDRICAL DIE

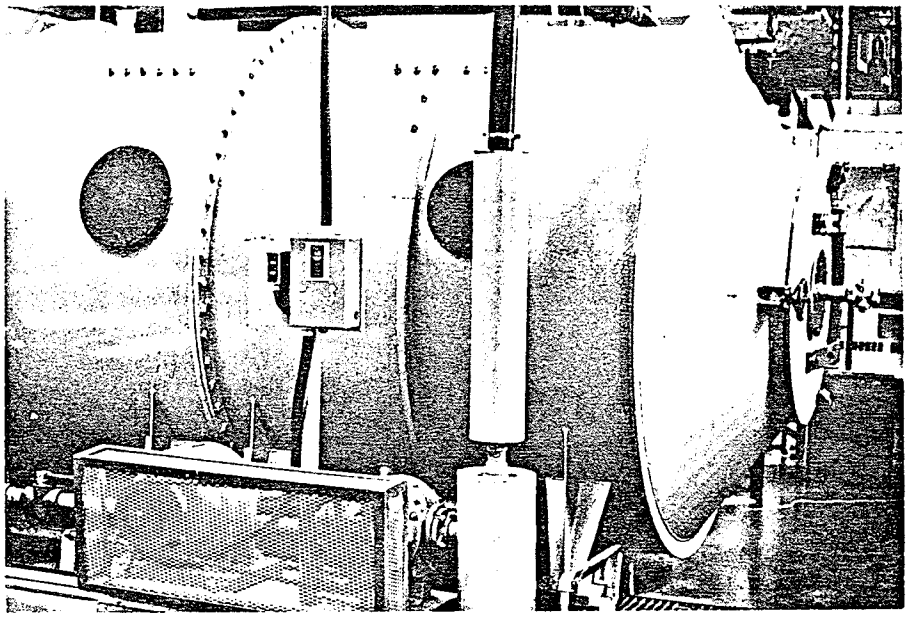
With the entire assembly placed in a vacuum chamber, Figure 3.3, and the space between the walls of the die and test cylinder evacuated to 26 inches of mercury, the charge was detonated. Setup time was approximately 20 minutes.

Evacuating the entire explosion chamber of air served a two-fold purpose; firstly, of permitting the testing to occur indoors, and secondly, of enabling the test cylinder to be formed completely against the inner die wall.

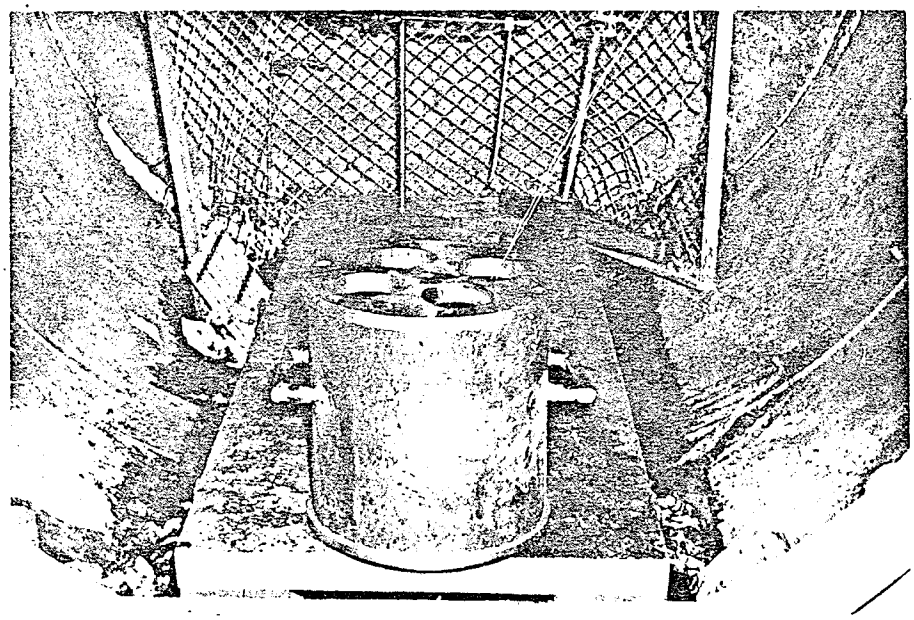
The cylinder diameter was different for each of the two metals tested: AMS 6520 was 10.025 inches and AMS 6435 was 9.900 inches, and for this reason, the lids used in centering the specimens in the die were machined to fit each test series, Figure 3.4. Removal of the test cylinder from the die was facilitated by cutting through a groove in the inner die wall, as shown in Figure 3.5. The bulged cylinder was then the source from which material was cut and straightened in preparation for fatigue testing.

(b) Static Prestraining

For a valid comparison of the fatigue life of statically and explosively deformed metals, accurate prestraining is essential for both metals to have the same strain history. Wherever possible, the same or a similar die would be used for both forming operations. Rather than straining the cylinder hydraulically at extremely high hydrostatic pressure statically strained specimens were obtained by stretching coupons in uni-axial tension.



(a) Chamber exterior with vacuum pump and control panel



(b) Chamber interior with die assembly

FIGURE 3.3 VACUUM CHAMBER

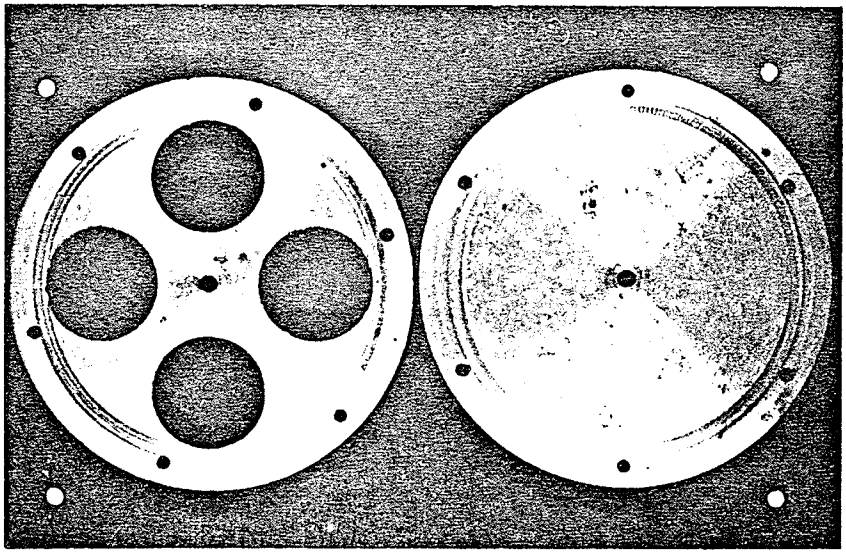


FIGURE 3.4 TOP AND BOTTOM DIE LIDS

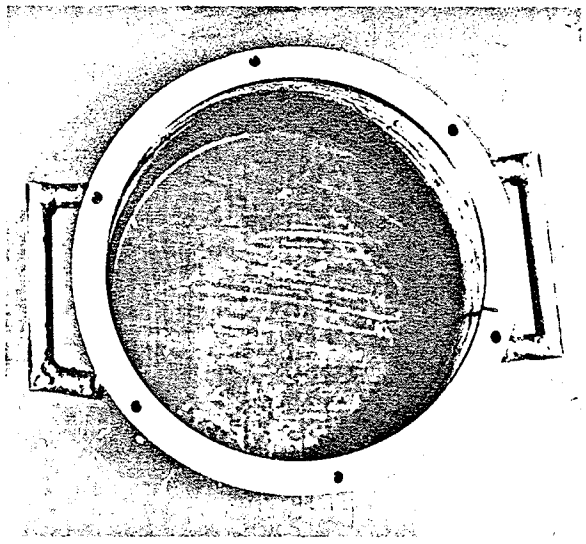


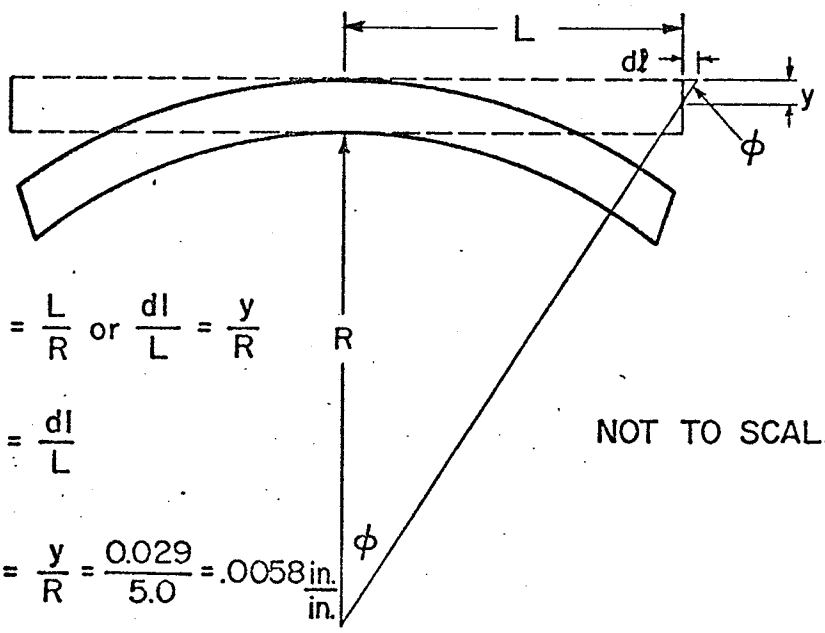
FIGURE 3.5 EXPLOSIVE FORMING CYLINDRICAL DIE

One undeformed cylinder for each material was the source of the "as-received" and statically prestrained specimens. The removal of curvature was accomplished by tapping the specimen in a copper-sleeved vise with a lead mallet. The contribution of this straightening process to strain is shown to be negligible in Figure 3.6

An Instron Tensile Testing Machine was employed in the static prestraining operation, Figure 3.7. A strain rate of 0.05 cm/min was maintained with a constant load on the specimen. The percent elongation sought for comparison was determined by that of the explosively bulged cylinders. Due to failure at the grips with AMS 6520 specimens, the milling of a reduced centre section was required, Figure 3.9(a). All AMS 6435 specimens were prestrained as flat, rectangular strips ½" x 3", Figure 3.9(b). In order to obtain the desired permanent set upon removal of the tensile load, the desired prestrain value was exceeded by an amount determined by trial and error.

3.4 Prestrain Measurements

Prior to explosive bulging, a knife-edge vernier was used to scribe lines in the paint layer sprayed onto each cylinder to facilitate strain visualization. A dividing head enabled the lines to be accurately spaced at one-half inch intervals with each turn of the crank, Figure 3.11. Following the explosive bulging operation, each cylinder was again set up on the dividing head, and, with the aid of a vernier microscope, the spacing of the scribe lines was measured as shown in Figure 3.12. The percent elongation arrived at explosively was, therefore, the determinant of that to be obtained statically with the Instron. These values were

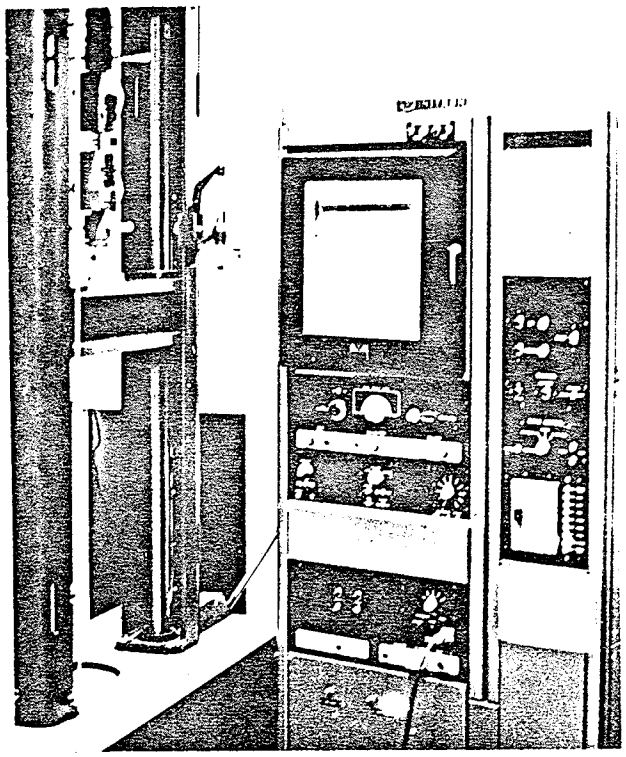


by geometry, $\frac{dL}{y} = \frac{L}{R}$ or $\frac{dl}{L} = \frac{y}{R}$

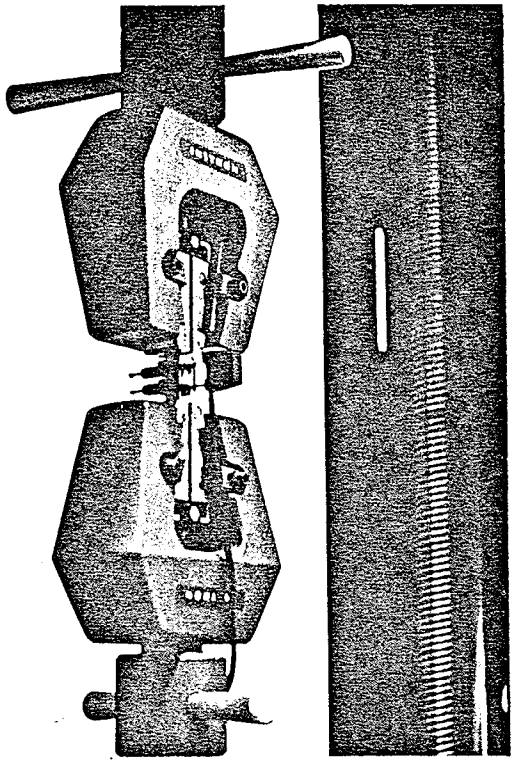
and strain, $\epsilon = \frac{dl}{L}$

$= \frac{y}{R} = \frac{0.029}{5.0} = .0058 \frac{in.}{in.}$

FIGURE 3.6 STRAIN EFFECTED BY THE REMOVAL OF CURVATURE



(a) Instron chart and control cabinet



(b) Extensometer positioned on a specimen

FIGURE 3.7 INSTRON TENSILE TESTER

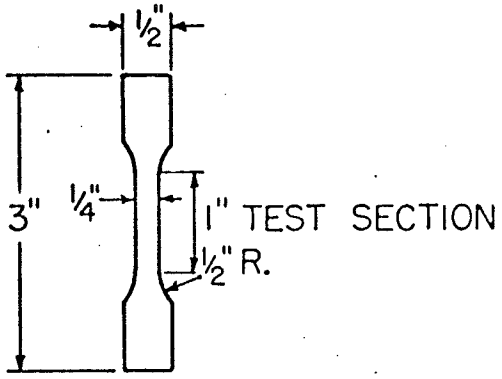


FIGURE 3.8 TENSILE TEST SPECIMEN

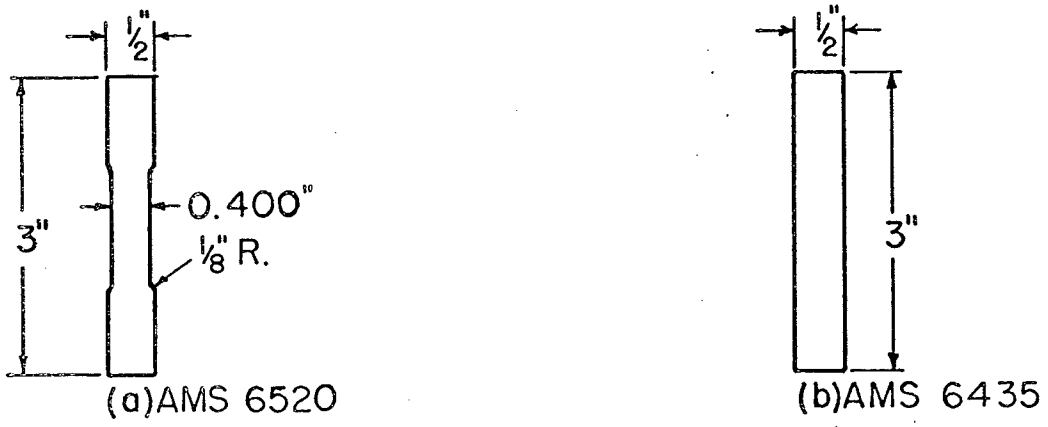


FIGURE 3.9 PRESTRAIN SPECIMENS

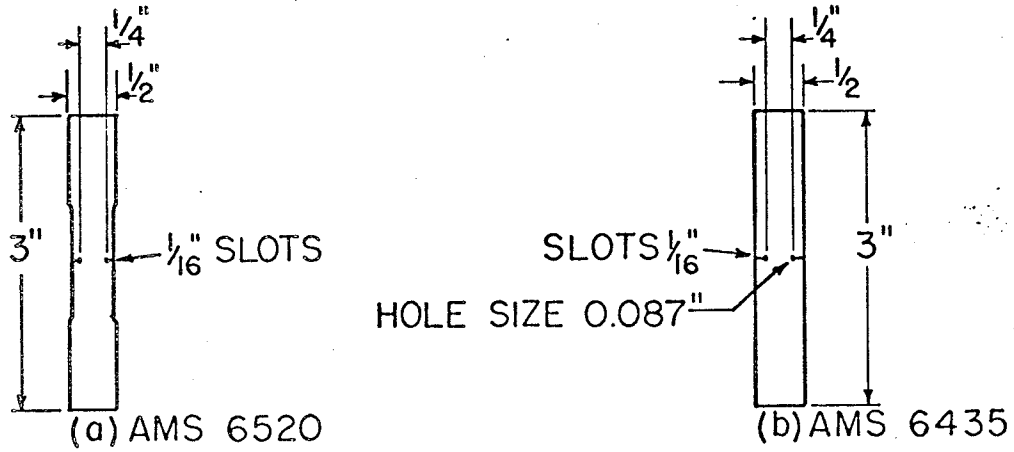


FIGURE 3.10 FATIGUE SPECIMENS

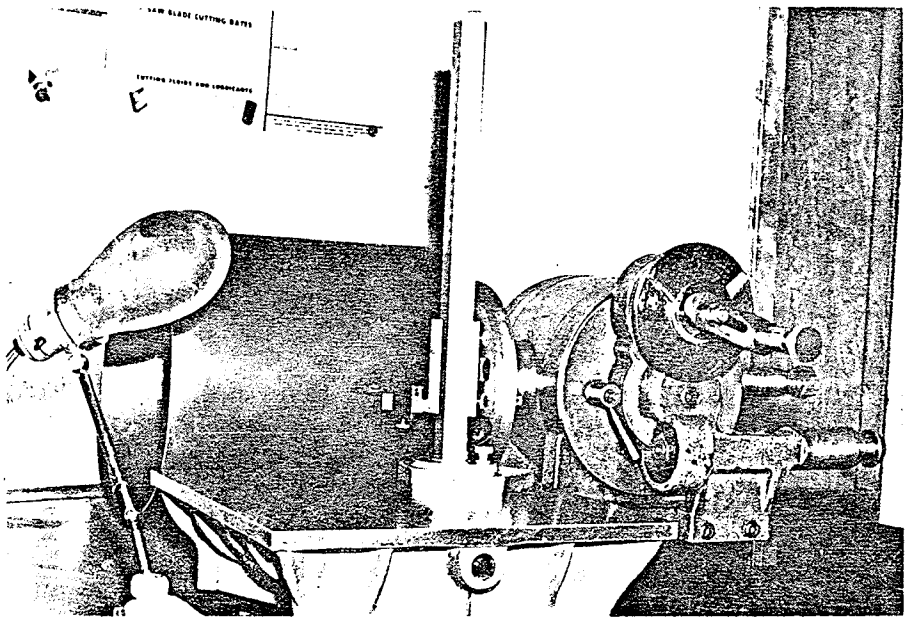


FIGURE 3.11 KNIFE-EDGE VERNIER AND DIVIDING HEAD

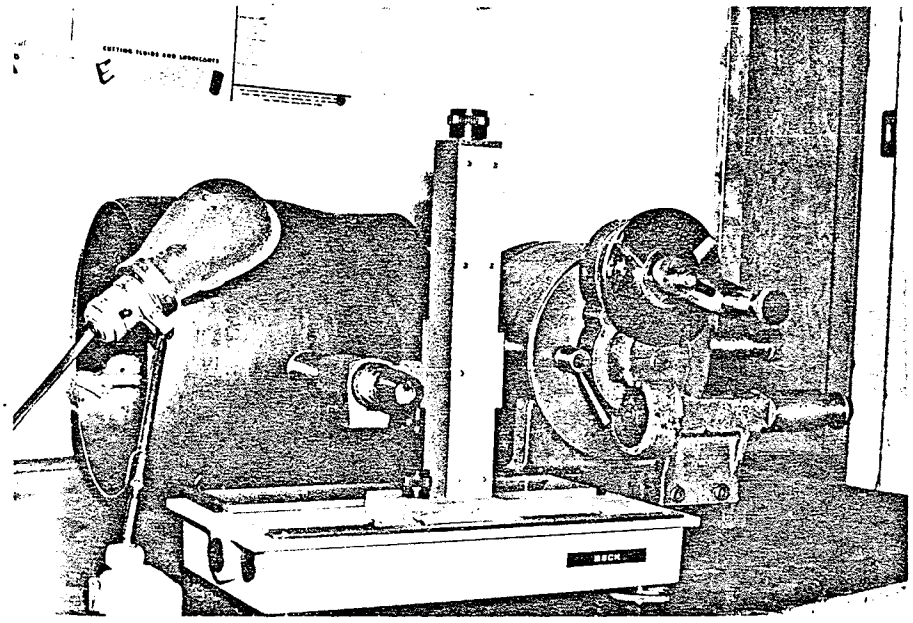


FIGURE 3.12 VERNIER MICROSCOPE AND DIVIDING HEAD

2.0% for AMS 6520 and 5.38% for AMS 6435.

The gauge length of the extensometer was 10 mm and the Instron chart was calibrated to read percent elongation directly. Accuracy of ±0.05% was obtained when 1 cm on the chart represented 0.25% elongation. The amount of overstraining necessary to achieve the desired permanent elongation was found to be 0.32% for AMS 6435 and 0.60% for AMS 6520. These values were in close agreement with those obtained from the relationship $E = \frac{Sy}{\varepsilon}$. (E = 29,000,000 psi).

3.5 Testing Procedures

(a) Strain and Hardness

The study of fatigue behavior requires an understanding of related properties such as unit strain and hardness. Added meaning may be derived from fatigue data if these properties exhibit any changes related to those of fatigue effected by dynamic deformation. In particular, the manner in which hardness varies with strain is felt to contribute greatly towards a better understanding of terminal fatigue behavior.

The scribing of parallel longitudinal lines spaced one-half inch apart enabled an accurate strain profile to be established in the circumferential direction. Preliminary bulge tests, depicting longitudinal strain to be negligible, were made and similar findings were reported by Johnson et al (63). The hardness at intersections of the grid was measured with a Vickers Pyramidal Hardness Tester set at the 30 kilogram weight.

Parent stock materials of AMS 6520 and AMS 6435 were tested for yield strength, ultimate strength and percent elongation in one inch. Specimens of both transverse and longitudinal directions were tested in tension. During forming, strain in the direction transverse to the rolling direction was insignificant; therefore, subsequent property tests were performed with tensile specimens taken in the longitudinal direction. A standard tensile specimen for the longitudinal mechanical property tests performed in this program is shown in Figure 3.8. Strain and hardness profiles were plotted for each metal and the results indicate changes in mechanical properties due to different strain rates.

(b) Stress Concentration

To lessen the effects on fatigue life of machining irregularities and surface finish, a controlled stress raiser was provided. A jig was employed to drill two 0.087-inch holes, one-quarter inch apart in the centre of each fatigue specimen. A slot was then cut from the outer edge to each hole, with care being taken not to mar the test section of the specimen. A standard fatigue specimen appears in Figure 3.10.

(c) Fatigue Tests

The fatigue specimen was designed for testing in a Baldwin Model SF-1-U Sonntag Fatigue Testing Machine, Figure 3.13. The maximum unidirectional load capacity of this machine is 2,000 lbs. The test program was set up to give failure in a range below 200,000 cycles.

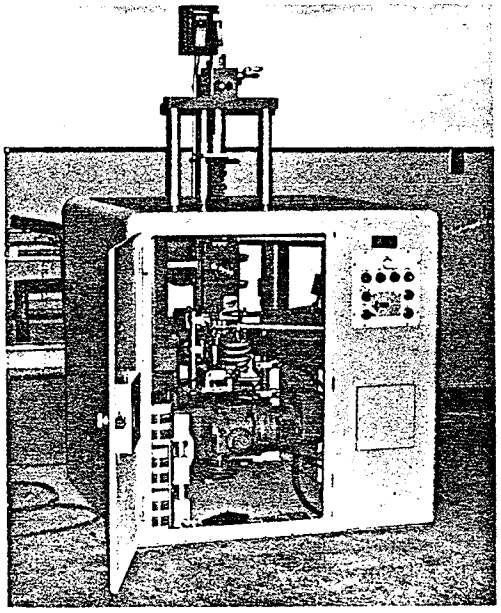


FIGURE 3.13 BALDWIN FATIGUE TESTING MACHINE

Each metal was tested in three conditions of deformation: "as-received" or undeformed, statically, and explosively deformed. Twelve specimens were tested in each condition and four stress levels were employed, with three specimens for each level. A constant stress ratio was maintained throughout the testing. This is the ratio of minimum to maximum stress and a value equal to 0.03 was maintained at each stress level by varying the preload and alternating load.

CHAPTER IV

Test Results - Analysis and Discussion

4.1 Results and Analysis

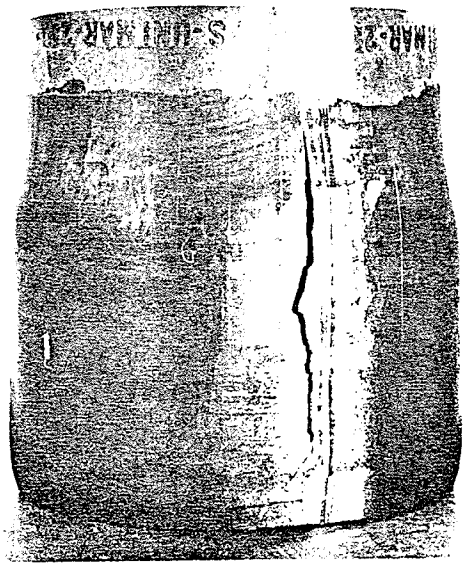
(a) Strain Distribution

In the bulged section of the explosively formed cylinders, the strain distribution in the circumferential direction was uniform, with the exception of the weld region. Here, maximum strain occurred, with fracture resulting in two cases, as shown in Figures 4.1 and 4.2. A successfully bulged cylinder is shown in Figure 4.3

In the preparation of fatigue specimens, the same static and explosive strains were used exclusively. To provide information on the work-hardening characteristics of each metal, strain and hardness readings were taken from zero to maximum strain. Proceeding in the longitudinal direction, hoop strain distribution, as obtained by the scribed grid method, varied from no strain at the free edge to a uniform maximum in the bulged section. Strain results for explosively formed AMS 6435 and AMS 6520 cylinders are given in Table 4.1. The average distribution of hoop strain along four parallel longitudinals 90^{o} apart is shown for both explosively formed metals in Figures 4.4 and 4.5. A representation of the static strain distribution is given also. A tapered specimen had to be used to provide a basis for comparing hardness after straining. Four specimens (0.5 x 0.625 x 3" long) were tested for each metal.

Less uniformity was observed in the strain distribution of the explosively formed specimens than in the statically formed specimens.

(a)



(b)

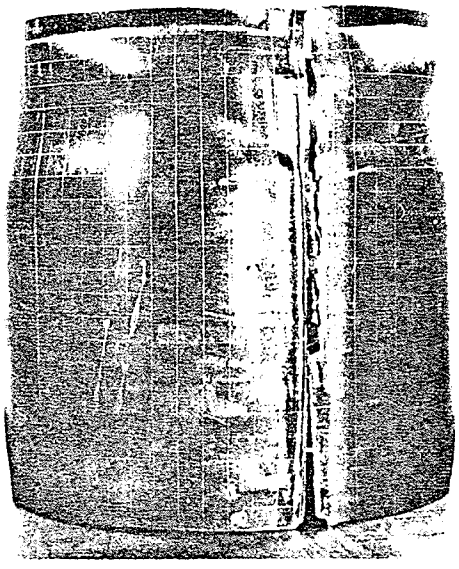


FIGURE 4.1 FRACTURE ADJACENT TO THE WELD SEAM CAUSED BY THE EXPLOSIVE OVERSTRAINING OF TWO AMS 6520 CYLINDERS

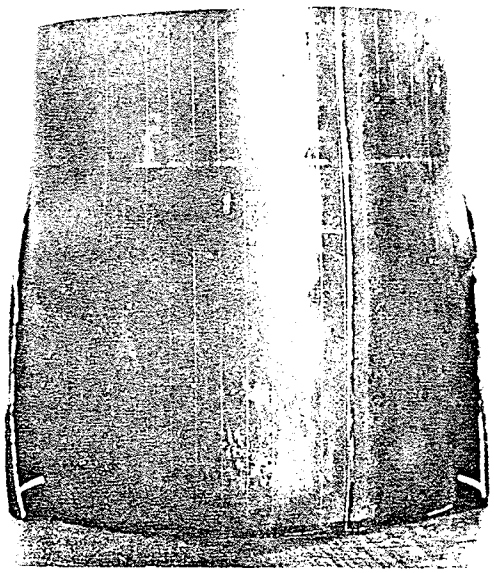


FIGURE 4.2 HERF FRACTURES SITUATED 90° FROM THE WELD REGION OF A STATICALLY PRESTRAINED (1.7%) AMS 6520 CYLINDER

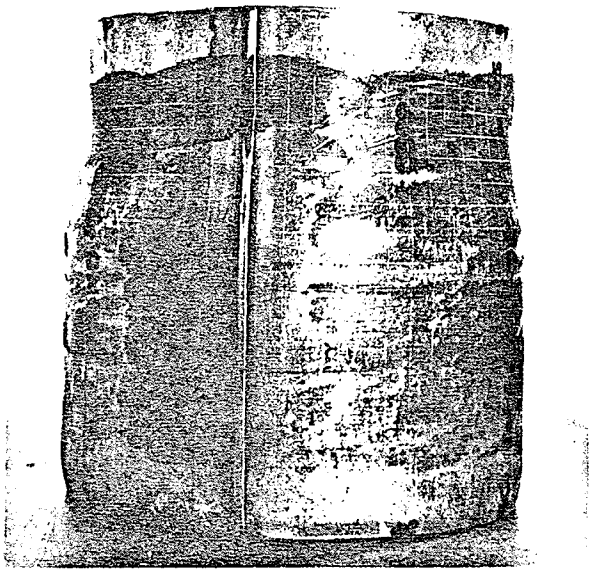


FIGURE 4.3 A TYPICAL EXPLOSIVELY-BULGED CYLINDER

TABLE 4.1

Explosive Forming Strain Results (Percent)

AMS 6435

Longitudinal At:	Hoop Number 1	2	3	4	5
0°	1.58	3.71	5.30	7.12	8.47
90°	2.29	3.71	5.45	7.98	9.25
180°	1.66	3.32	4.90	8.22	9.56
270°	2.69	3.48	5.06	6.64	7.83
MEAN	2.06	3.55	5.18	7.49	8.77

AMS 6520

Longitudinal At:	Hoop Number 1	2	3	4	5
0°	0.40	2.47	4.22	5.90	7.22
90°	1.91	4.70	6.61	7.96	10.20
180°	2.31	4.30	5.97	7.56	9.40
270°	1.11	3.10	5.41	7.33	9.48
MEAN	1.43	3.64	5.55	7.19	9.32

Note: Hoop No. 1 has been selected where visible straining starts.

VALUES PLOTTED ARE THE MEANS FROM FOUR LONGITUDINALS 90° APART

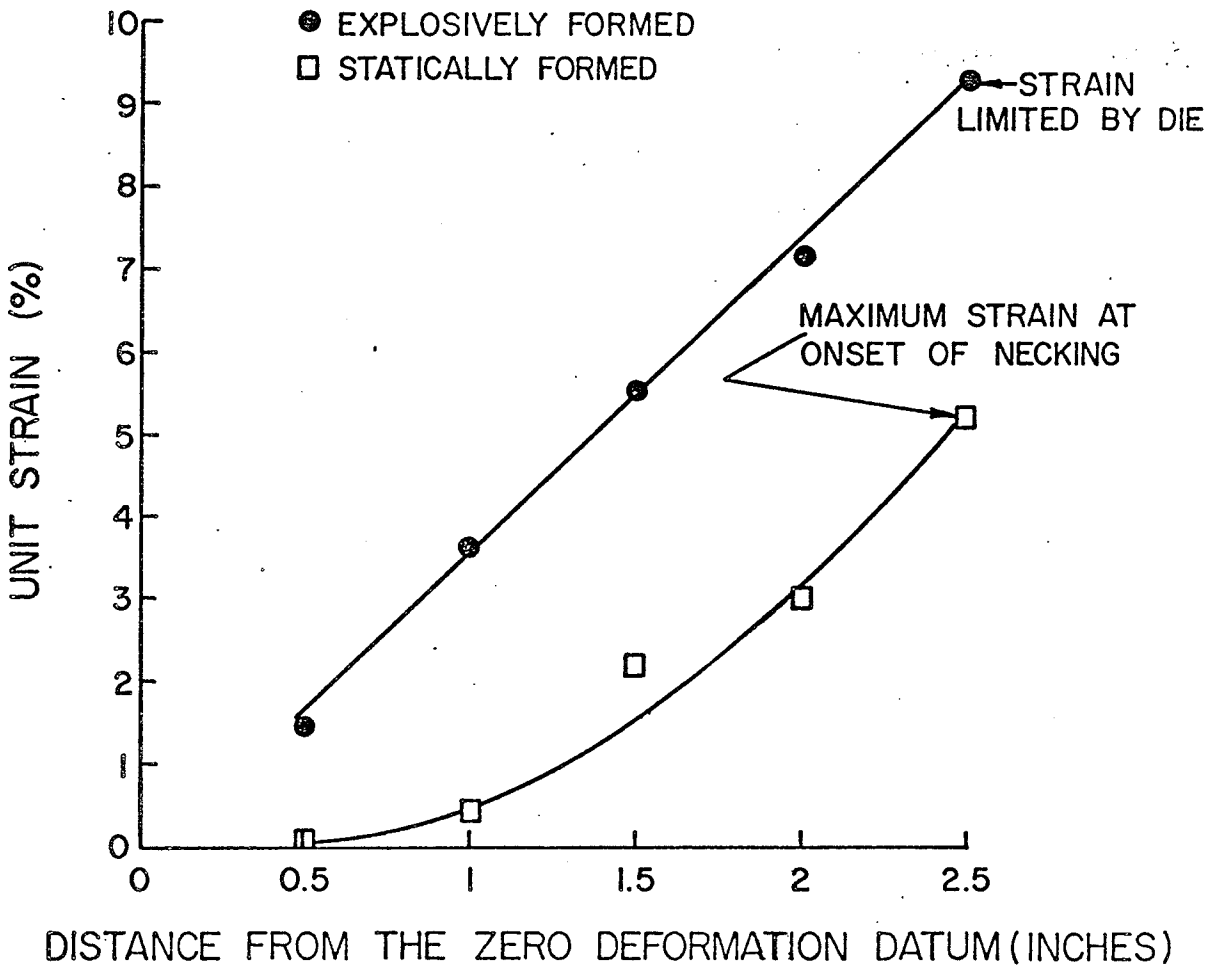


FIGURE 4.4-AMS 6435 STRAIN PROFILES

VALUES PLOTTED ARE THE MEANS FROM FOUR LONGITUDINALS 90° APART

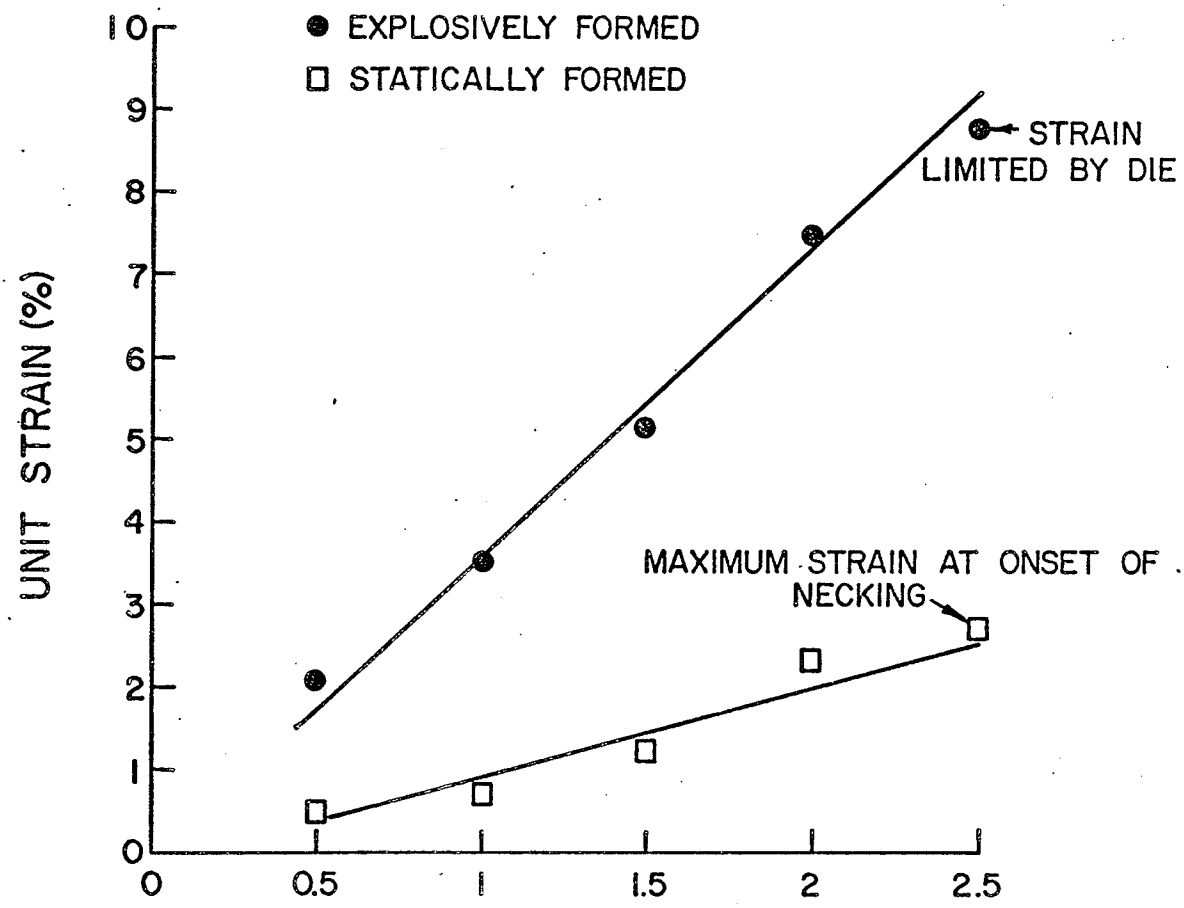


FIGURE 4.5 AMS 6520 STRAIN PROFILES

However, higher magnitudes of strain were evident in the explosively formed cylinders of both metals than were obtainable statically, up to the onset of necking as well as a greater overall ability to absorb plastic deformation.

(b) Hardness

Hardness readings were taken at one-half inch intervals along the same four longitudinals as those used to represent the strain distribution of the explosively formed specimens, and similarly, the same static specimens were used. The comparative hardness profiles are shown in Figures 4.6 and 4.7. The tests for both static and dynamic specimens showed greater hardness in the region of maximum straining. For both AMS 6435 and AMS 6520 metals, explosive specimens gave higher hardness readings in this region. Hardness results are presented in Tables 4.2 and 4.3.

(c) Work-Hardening

Comparing the increase in hardness with the rise in percent strain gave an indication of the relative work hardening effect of the explosive and static forming processes. This comparison is shown in Figure 4.8.

The results showed that explosively formed AMS 6435 hardened more than the statically formed metal for the same increase in percent strain. Explosively formed AMS 6520 exhibited, more substantially, the same trend over its static counterpart. Similar trends have been reported by Williams (38) for stainless steel which had been explosively formed and statically pressed.

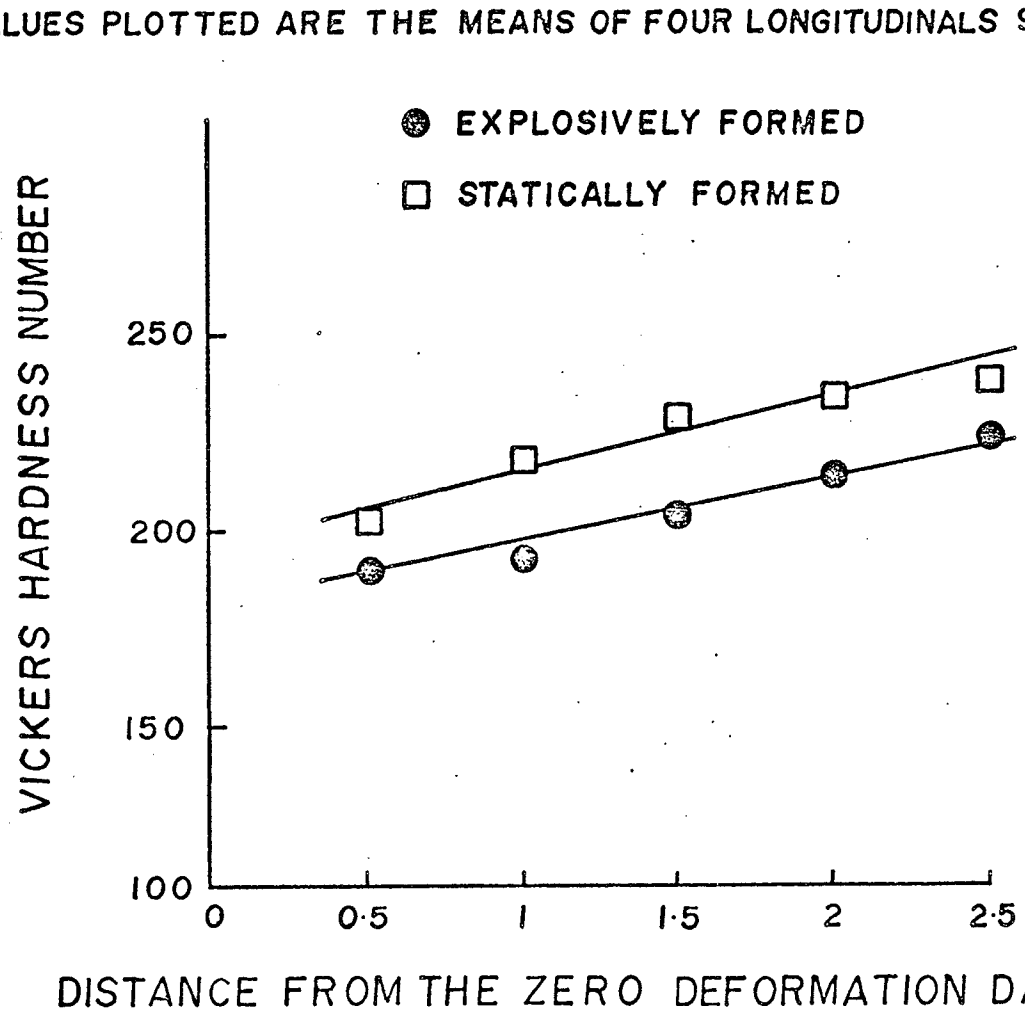


FIGURE 4·6 AMS6435 HARDNESS PROFILES

VALUES PLOTTED ARE THE MEANS OF FOUR LONGITUDINALS 90° APART

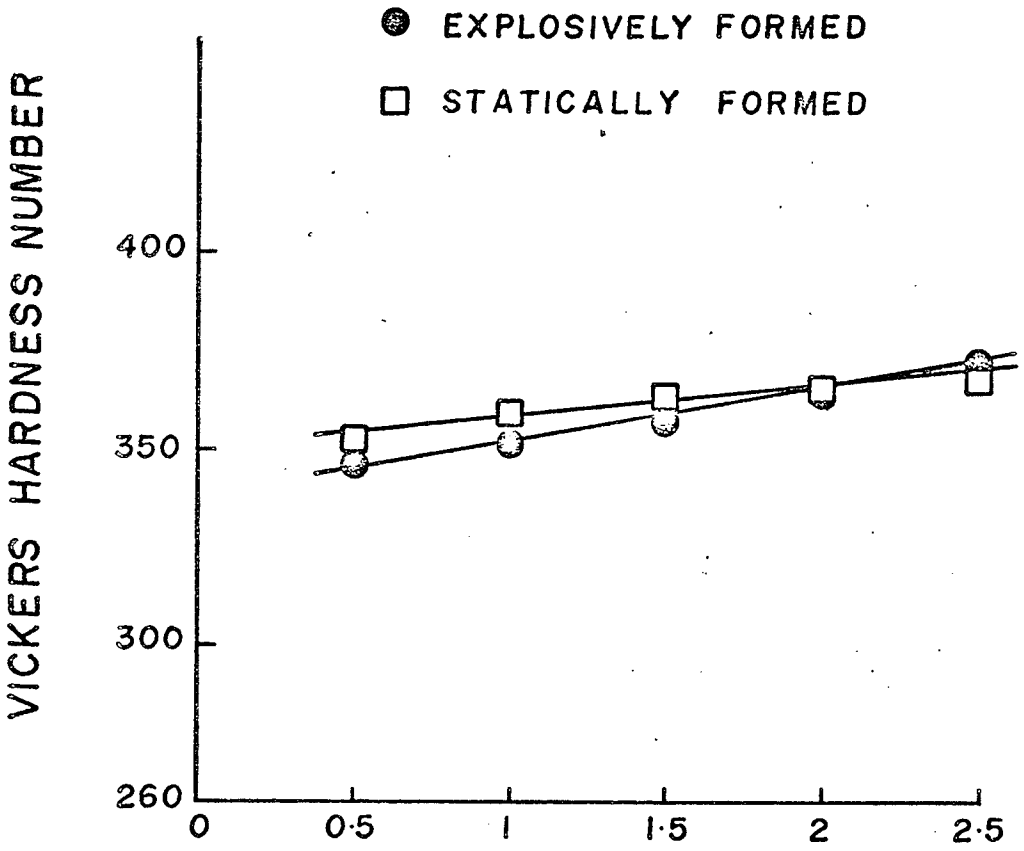


FIGURE 4·7 AMS 6520 HARDNESS PROFILES

TABLE 4.2

AMS 6435 Hardness Results

Longitudinal At:	Explosively Formed					Statically Formed				
	Vickers Pyramidal Hardness Number									
	Hoop Number					Hoop Number				
	1	2	3	4	5	1	2	3	4	5
0°	173	186	199	213	221	204	220	232	236	240
90°	179	193	205	214	220	202	218	229	230	235
180°	174	187	202	210	229	198	216	226	234	239
270°	184	200	205	213	218	199	215	224	233	241
MEAN	178	192	203	213	222	201	217	228	233	239

TABLE 4.3

AMS 6520 Hardness Results

Longitudinal At:	Explosively Formed					Statically Formed				
	Vickers Pyramidal Hardness Number									
	Hoop Number					Hoop Number				
	1	2	3	4	5	1	2	3	4	5
0°	352	360	363	364	366	345	349	357	364	372
90°	351	358	362	363	365	347	351	357	361	363
180°	351	357	364	365	368	346	349	356	361	364
270°	354	362	363	366	369	345	351	354	368	383
MEAN	352	359	363	365	367	346	350	356	364	371

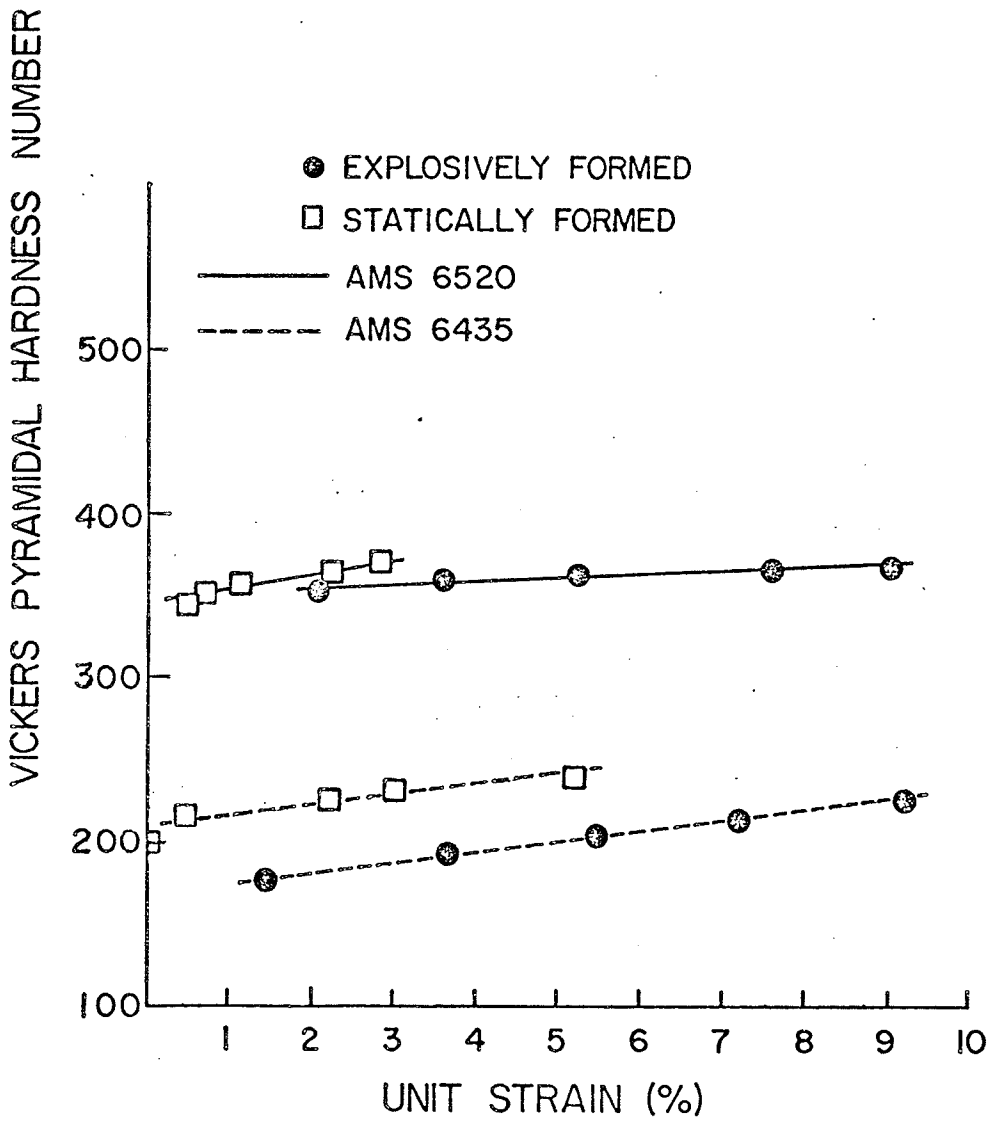


FIGURE 4.8-HARDNESS VS % STRAIN CURVES FOR AMS 6435 AND AMS 6520

(d) Fatigue

A total of seventy-two specimens were tested in the fatigue program. The S-N fatigue curves comparing the fatigue life of the "as-received", statically and explosively formed metals are shown in Figures 4.9 and 4.10. The results of these fatigue tests, comprising cycles to failure of each group, mean cycles to failure, standard-deviation, are presented in Tables 4.4 and 4.5

4.2 Discussion of Results

The purpose of this project was to investigate the possible existance of a cause and effect relationship between strain rate and low cycle fatigue properties in the case of two different materials. The "t" test for the significance in difference between sample means was employed to test this hypothesis by comparing the observed results of both static and explosive treatments (sample calculation p 65). In the case of all four stresses no statistically significant differences were observed between these two treatments. It can only be concluded, therefore, that no peculiar effect is developed by explosive forming on these two materials, AMS 6435 and AMS 6520, in the range of stresses investigated.

Both static and explosively treated groups had the same prestrain history before fatigue testing. There appeared to be no difference between the hardness resulting from these two treatments. Increased hardness is associated with a longer fatigue life unless microcracks are introduced with the higher hardness during forming. Verbraak (30) and Dalebozik (29) allude to the presence of microcracks as a cause of reduced life, but the degree of damage is unknown.

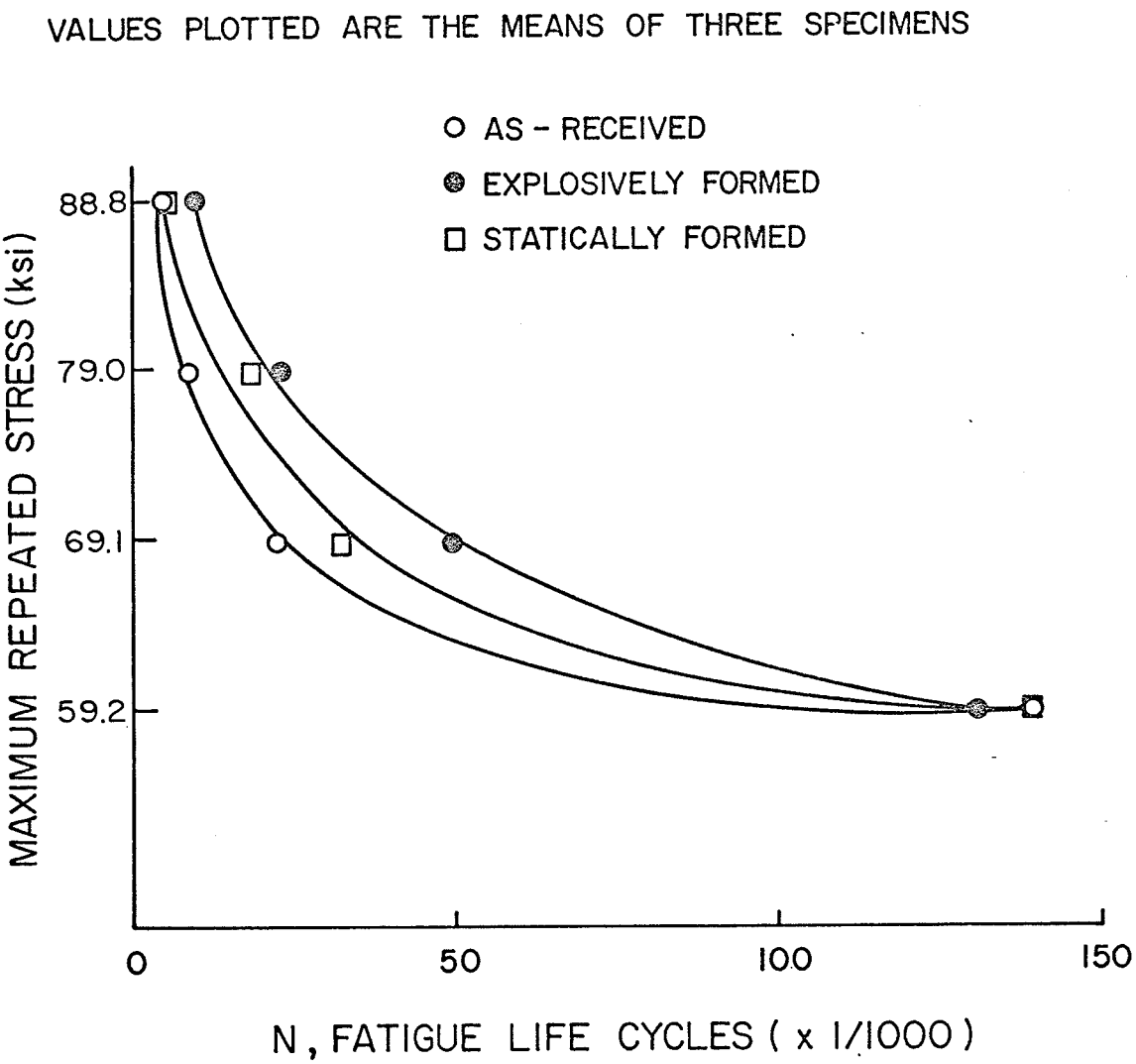


FIGURE 4.9 - FATIGUE LIFE COMPARISONS FOR AMS 6435

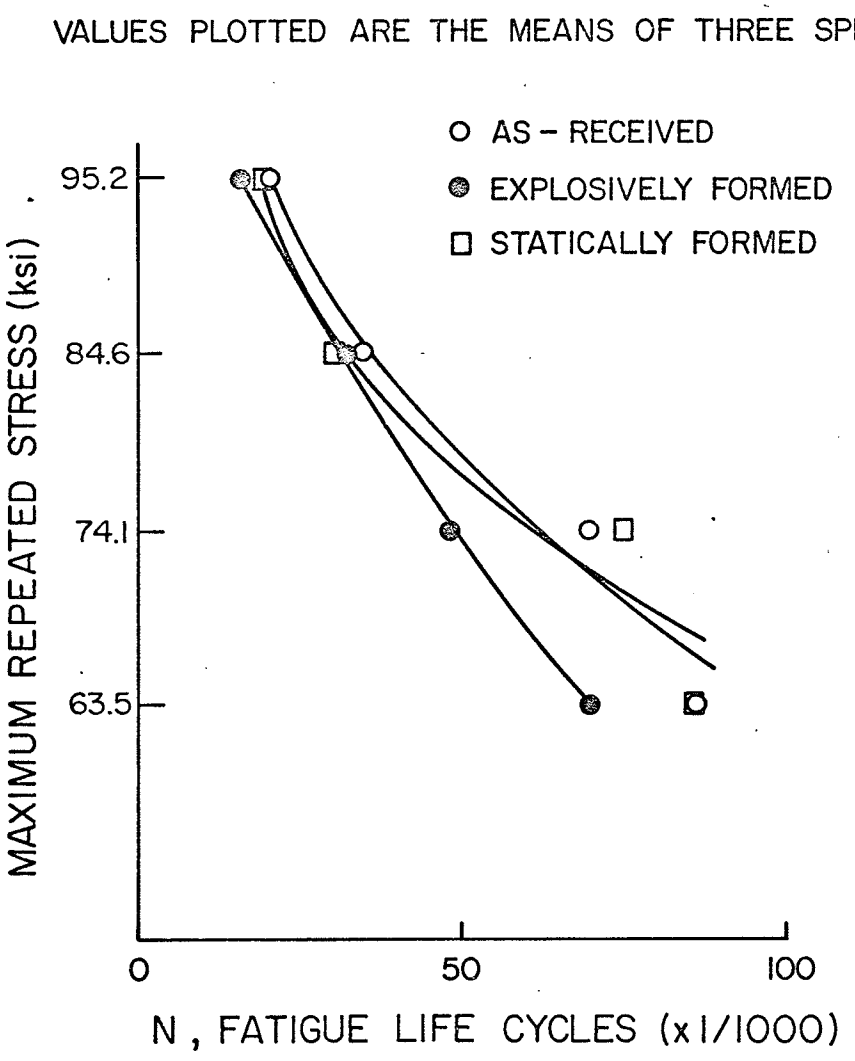


FIGURE 4.10-FATIGUE LIFE COMPARISONS FOR AMS 6520

TABLE 4.4

Fatigue Results - AMS 6435

Max. Repeated Stress (ksi)	As-Received					Explosively Formed (Strained 5.38% Before Testing)					Statically Formed (Strained 5.38% Before Testing)				
	Cycles to Failure x 10^{-3}			Mean	S.D.	Cycles to Failure x 10^{-3}			Mean	S.D.	Cycles to Failure x 10^{-3}			Mean	S.D.
88.8	6	5	4	5.0	1.0	9	10	8	9.0	1.0	8	5	6	6.3	1.5
79.0	10	9	6	8.3	2.2	23	28	17	22.7	5.5	13	25	17	18.3	6.1
69.1	17	24	26	22.3	4.7	40	52	56	49.3	8.3	34	33	29	32.0	2.6
59.2	154	71	192	139.0	61.6	80	125	186	130.3	53.2	90	194	134	139.3	52.2

TABLE 4.5

Fatigue Results - AMS 6520

Max. Repeated Stress (ksi)	As-Received					Explosively Formed (Strained 2.0% Before Testing)					Statically Formed (Strained 2.0% Before Testing)				
	Cycles to Failure x 10^{-3}			Mean	S.D.	Cycles to Failure x 10^{-3}			Mean	S.D.	Cycles to Failure x 10^{-3}			Mean	S.D.
95.2	15	24	23	20.6	4.9	18	16	16	16.7	1.2	21	19	17	19.0	2.0
84.6	42	29	34	35.0	6.5	36	30	32	32.7	3.1	30	34	28	30.7	3.1
74.1	90	69	51	70.0	19.5	63	44	38	48.3	13.1	48	121	46	75.0	40.3
63.5	98	74	87	86.3	14.1	65	75	69	69.7	5.0	104	68	87	86.3	18.0

Although the fatigue life of some metals has been favorably influenced by straining, this did not occur with either metal in this test series.

The effect of explosive forming on notch sensitivity may also be an influencing factor in the apparently reduced fatigue life. Although surface effects were eliminated by the use of semicircular notches as stress concentrations, the higher strain rate encountered in explosive forming may make the AMS 6520 metal more notch sensitive, causing a reduction in fatigue life.

4.3 Sample Calculation to Determine the Statistical Significance of the Sample Results

$$\text{"t"} = \frac{\bar{x}_1 - \bar{x}_2}{\frac{\hat{\sigma}_1}{\sqrt{N_1}} + \frac{\hat{\sigma}_2}{\sqrt{N_2}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

$$\hat{\sigma} = \sqrt{\frac{\Sigma a^2 - \frac{(\Sigma a)^2}{N}}{N - 1}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

$$\bar{x} = \text{Guess} + \frac{\Sigma a}{N} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

Symbol Key:

$\hat{\sigma}$ = Best estimate of population standard deviation.

$\bar{x}$ = Sample mean fatigue life.

a = The difference between an observed fatigue life value and the guessed mean.

N = Number of specimens tested at the same stress.

Where subscripts 1 and 2 refer to the two samples being compared.

For AMS 6520 fatigue tested at repeated stress of 10,000 psi:

Explosively Formed		
x	a	a^2
18	+1	1
16	-1	1
16	-1	1
	-1	3

Statically Formed		
x	a	a^2
21	+2	4
19	0	0
17	-2	4
	0	8

$$\bar{x}_1 = 17 - \frac{1}{3} = 16.67 \qquad \bar{x}_2 = 19 + \frac{0}{3} = 19$$

$$\hat{\sigma}_1 = \sqrt{\frac{3 - \frac{(-1)^2}{3}}{3 - 1}} = 1.155 \qquad \hat{\sigma}_2 = \sqrt{\frac{8 - \frac{(0)^2}{3}}{3 - 1}} = 2$$

$$\text{"t"} = \frac{19 - 16.67}{\frac{1.155}{\sqrt{3}} + \frac{2}{\sqrt{3}}} = 1.88$$

$\eta = N_1 + N_2 - 2 = 4$ degrees of freedom.

From probability table with "t" = 1.88 and $\eta = 4$ the probability of this result is 0.87.

CHAPTER V

Summary and Conclusions

5.1 Summary

A comparison of the fatigue life of statically and dynamically formed AMS 6435 and AMS 6520 metals has been made. The comparison was carried out at four stress levels, maintaining a constant stress ratio throughout the testing at each level. Strain and hardness changes during explosive and static forming were measured.

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 two different treatments appeared to have no discernible effects on the fatigue strengths of either metal tested.

(b) The cylindrical die designed and constructed for the experimental portion of this thesis is quite satisfactory for the investigation of high energy rate forming behavior of high-strength, high-alloy steel cylinders.

(c) Higher percentage strains were obtainable by explosive means than in static, uniaxial tension tests for both metals, notably AMS 6520, which fractured under 3% static elongation.

5.3 Suggestions for Further Study

(a) Completion of S-N curves for AMS 6435 and AMS 6520 to enable the presentation of a more complete comparison of fatigue life.

(b) A metallurgical investigation into the microscopic mechanisms of deformation of these high strength steel alloys with the intention of:

i) explaining the distinct increases in ductility exhibited by explosive forming.

ii) determining the effect of mechanical twins on hardening and terminal cracking characteristics.

(c) Determination of the effects of high strain rate on flow and forming limits of high strength alloys, such as the 18% Ni Maraging Steel, which exhibit marked tendencies to neck.

(d) A series of fatigue tests with specimens of age-hardenable alloys in the three conditions of deformation: "as-received", statically and explosively formed, which had been:

i) statically prestrained prior to explosive bulging,

ii) heat treated after forming to obtain the optimum strength characteristics.

BIBLIOGRAPHY

(1) Suiter, J., "Explosive Forming", The Journal of the Australian Institute of Metals, Vol. 7, No. 3, August 1962.

(2) Rinehart, J.S. and Pearson, J., "Explosive Working of Metals", Pergamon Press Inc., New York, N.Y., Part II, pp 147-281, 1963.

(3) Sheffield, I.K. and Agricola, K.R., "Development of Explosive Forming Techniques for Saturn V Components", NASA CR-70588 (Final Report, Cr 66-6 Martin Co.), January 1966.

(4) "High Velocity Forming of Metals", ASTME Publication, Chapter 2, 1964.

(5) Blazynski, T.Z., "Experimental and Theoretical Development of the High-Energy Rate Forming Processes, Engineer 217, 5657, 1117-24, June 1964.

(6) Ezra, A.A., "Principles and Practices of Explosive Forming", Martin Co. Report R-64-5, April 1964.

(7) Bridgman, P.W., "The Effect of Pressure on the Tensile Properties of Several Metals and Other Materials", Journal of Applied Physics, Vol. 24, pp 560-70, 1953.

(8) Campion, D.J., "The Manufacture of Components from Maraging Sheet Steel", Sheet Metal Industries, pp 733-745, October 1968.

(9) Vernon, R., "The Deep Drawing and Stretchforming Properties of a Maraging Steel of the 18 percent Nickel Type, Report B.48, p 472.

(10) Derricott, R.T., "Assessment of the Pressforming Properties of an 18 percent Nickel Maraging Steel", Met. 33, 1965.

(11) Agricola, K.R. and Tate, F.G., "A Preliminary Investigation of the Feasibility of Explosive Cold Forming Air Melted 18% Nickel Maraging Steel", ASTME SP66-50, 1966.

(12) Edington, J.W., "Behavior of Metals Under Dynamic Loads", ed. U.S. Lindholm, Springer-Verlag, N.Y., p 191, 1968.

(13) Rinehart, J.S., "Explosive Forming of Metals", ASME Mech. Eng., Vol. 81, No. 7, July 1959.

(14) Wood, W.W., "Experimental Mechanics at Velocity Extremes - Very High Strain Rates", Experimental Mechanics, Vol. 7. p 444, October 1967.

(15) Pipher, F.C., Rardin, G.N. and Richter, W.I.: "High Energy Rate Metal Forming", Lockheed Aircraft Corporation, Report No. AMC TR 60-7-588, October 1960.

(16) Strohacker, D.C., North American Aviation Inc., Report NA 61 H 76, 1961.

(17) Schmidtmann, E., Kremer, K. and Schenck, H.: "Model Tests on Explosive Forming of Thin Plates", Arch. Eisenbuttenw 36, 5, pp 333-42, May 1965.

(18) Wood, W.W., "A Critical Review of High Energy Forming Methods", ASTME Vol. 60, Bk. 1, 1960.

(19) Orava, R.N. and Otto, H.E., "Proc. 2nd Int. Conf. of the Center for High Energy Forming", ed. Ezra, A.A., University of Denver, pp 1.2.1-33.

(20) D'Aguanno, P. and Pfanner, G., "Theoretical and Experimental Evaluation of High Energy Forming of Hemispherical Shapes in Metals", Republic Aviation Corp., NASA Phase II Report N66-23706, December 1963.

(21) Beyer, W.K., "Behavior of Metals Under Conditions of Explosive Stressing", General Dynamics Report No. AN61AMR8024, December 1961.

(22) Pearson, I. and Hayes, C.A., "Some Material Behavior Patterns in Explosive Working", ASTME Creative Manufacturing Seminars, SP 62-07, 1962.

(23) Potteiger, L.A., "Explosive Harening of Nickel Maraging and Manganese Steels", U.S. Naval Weapons Laboratory, Report No. 1934, September 1964.

(24) Fowler, E.L., "Design Properties and Fabricating Characteristics of Maraging Steels", Machine Design Vol. 34, pp 192-94, October 1962.

(25) Agricola, K.R., et al., "Advanced Explosive Forming Processes (HERF)", AFML-TR-67-70, 1967.

(26) "Explosives' Double-Barrel Approach: Shaping and Strengthening", Iron Age, Vol. 196, No. 17, October 1965.

(27) Mikesell, R., "Proc. 2nd Int. Conf. of the Center for High Energy Forming", University of Denver, pp 1.3.1-7, 1969.

(28) Williams, C.P., Journal of Metals, Vol. 12, No. 1, pp 33-36, 1960.

(29) Dalebozik, R., "A Comparative Study of the Effect of Static and Dynamic Forming on the Biaxial Notched Fatigue Strength of 1100 SH 14 Aluminum", M.Sc. Thesis in Mechanical Engineering, University of Manitoba, May 1970.

(30) Verbraak, C.A., Metallurgical Progress, Vol. 83, pp 109-12, January 1963.

(31) Verbraak, C.A., C.I.R.P. Annalen, Vol. 11, pp 137-41, 1963.

(32) Bennett, C.P., "The Effect of Explosive Forming on Fatigue Properties", Materials Research and Standards, Vol. 7, No. 7, pp 305-09, July 1967.

(33) Aluminum Standards and Data, Aluminum Association, 1968-69, 1st Ed., p 29, April 1968.

(34) Jacobs, A.J., "The Effect of Explosive Deformation on the Stress Corrosion and Mechanical Properties of 7075 Aluminum Alloy", AIAA 7th Structures and Materials Conference, April 1966.

(35) Agricola, K.R. and Snyder, J.T., Metals Engineering Quarterly, Vol. 7, No. 3, pp 59-63, November 1967.

(36) Orava, R.N. and Whiting, G.S., "Proc. 2nd Int. Conf. of the Center for High Energy Forming", University of Denver, pp 2.4.1-20 1969.

(37) Rowden, G., Metallurgia, Vol. 75. pp 199-201, 1967.

(38) Williams, T., Sheet Metal Industries, Vol. 39, pp 487-94, 1962.

(39) Tardif, H.P. and Erickson, W.H., Trans. Am. Soc. Mech. Eng., Vol. 77, 1958; J. Appl. Mech., Vol. 22, pp 285-7.

(40) Sernka, R.P., "Spin Forge Processing of the 300 ksi Grade of 18% Ni Maraging Steel", DMIC Report 181, October 1963.

(41) Agricola, K.R., ASTME Conf. 1968, Iron Age, Vol. 201, No. 20, May 1968.

(42) Orava, R.N. and Otto, H.E., "The Effect of High Energy Rate Forming on the Terminal Characteristics of Metal", Journal of Metals, pp 17-30, February 1970.

(43) Rinehart, J.S. and Pearson, J., "Behavior of Metals Under Impulsive Loads", Dover Publications, Inc., N.Y., pp 171-90, 1965.

(44) Parker, E.R. and Smith E.A., Transactions of AIME, Vol. 156, pp 142-8, 1944.

(45) Yoshica, S. and Nagata, N., Trans. Japan Inst. Metals, Vol. 8, pp 26-33, 1967.

(46) Hollis, W.S., Aircraft Production, Vol. 22, pp 446-51, 1960; Prod. Eng., Vol. 40, pp 216-25, 1961.

(47) Hollingum, S.W., Journal of Australian Institute of Metals, Vol. 12, pp 199-214, 1967.

(48) Rosenhain, W. and McMinn, J., Proc. Roy. Soc. (London), Vol. A103 pp 231-9, 1925.

(49) Campbell, J.D. and Harding, J., "Response of Metals to High Velocity Deformation", Interscience, pp 51-76, 1961.

(50) Krafft, J.M., Sullivan, A.M. and Tipper, C.F.: Proc. Roy. Soc. (London), Vol. A221, pp 114-27, 1953.

(51) Campbell, J.D., Duby, J. and Puttick, K.E.: Phil. Mag., Vol. 2, pp 548-53, 1957.

(52) Otto, H.E. and Mahajan, S., "Shock Hardening of Metals", First Annual Report, Center for High Energy Forming, Martin Co., Report CR-65-77, p I-1, August 1966.

(53) Smith, C.S., "Metallurgical Studies of Materials After Explosive Shock", Transactions of AIME, Vol. 212, p 570, 1958.

(54) Swann, P.R., "Electron Microscopy and Stength of Crystals", Interscience, pp 131-181, 1963.

(55) "A Discussion of the Physical Metallurgy of the 18% Nickel Maraging Steels", DMIC Report 194, November 1960.

(56) Floreen, S. and Decker, R.F., "Heat Treatment of 18% Nickel Maraging Steel", Transaction of the ASM, Vol. 53, No. 3, pp 518-30, September 1962.

(57) Hamaker, J.C. and Yates, D.H., "New Ultra-High-Strength Steels, The Maraging Grades", Metal Progress, pp 31-34, September 1962.

(58) Campione, A.A. and Colangelo, V.J., "Explosive Forming of Gun Tube Sections", Watervliet Arsenal, Report No. WVT-11-6409, July 1964.

(59) Wilkin, J.F., Henriken, E.F. and Liberman, I.: "Metallurgical Effects of Explosive Strain Rates on Metal Alloys", Aerojet-General Corp., Report No. 0513-10(02)FP, 1963.

(60) Hendriksen, E.K., et al., "Symposium on Dynamic Behavior of Materials", Am. Soc. Test. Mat., Spec. Tech. Pub. 336, pp 104-64, 1964.

(61) Thurston, G.A., "Sixth Quarterly Report of Technical Progress", Center for High Energy Forming, University of Denver, Denver, Colorado, January 1967.

(62) Baron, H.G. and Costello, E., Met. Rev. Vol. 8, pp 369-426, 1963.

(63) Johnson, W., Dodge, E. and Travis, F.W.: "The Explosive Expansion of Unrestrained Tubes", Prov. Instn. Mech. Engrs., 179, Part 1, 7, pp 240-56, 1964-65.