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DEVELOPMENT OF EXPLOSIVE FORMING TECHNIQUES FOR SATURN V COMPONENTS
FINAL REPORT
(June 24, 1964 - January 28, 1966)

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FOREWORD

This report summarizes the technical accomplishments under National Aeronautics and Space Administration Contract NAS8-11616 for the period June 24, 1964 thru January 28, 1966. The program was sponsored by the Manufacturing Engineering Division, George C. Marshall Space Flight Center, Huntsville, Alabama. Mr. Manly Tommie was the technical contract monitor.

Work under this contract was performed in two phases. Phase I consisted of the development of design criteria for a die incorporating positive blank restraint features and subsequent design of a male forming die. Computer techniques were used to define the die contour.

Phase II involved the explosive forming of 2014-0, 2219-0, 2219-T31, and 7039-0 aluminum alloys, 1020 carbon steel, and Ti-6Al-4V into 1/7-scale Saturn V gore segments, using a die manufactured to design drawings developed under Phase I. Subsequent evaluation of metal springback and mechanical properties of explosively formed material completed the Phase II technical effort.

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SUMMARY

An investigation of the development of explosive forming techniques for Saturn V components was conducted in two phases. Phase I involved the design and fabrication of an explosive forming die, clamping rings, tools, and templates. Phase II effort was concerned with the use of the designed hardware to explosively form 2014-0, 2219-0, 2219-T31, and 7039-0 aluminum alloys, 1020 carbon steel, and Ti-6Al-4V sheet and plate.

During Phase I, design criteria were developed in three restraining groove concepts using uniaxial mechanical testing methods. An offset edge clamp design was selected for the design. Using the criteria established during test and computerized data relating to die contour, a female die was designed. Economic and technical reasons caused a redirection of the effort to design a male forming die using all applicable criteria. A male forming die and associated hardware were designed and fabricated. Both 1620 and 7094 computer programs were used in the design phase.

During Phase II, the selected alloys were explosively formed using the die and tooling designed in Phase I. Metal springback, metal stretching, and changes in mechanical properties were evaluated. In general, the 0.125-in.-thick 2014-0 aluminum showed the lowest springback, while incomplete forming caused maximum deviation for 2219-T31 aluminum. Metal stretching in the range of 0 to 6% was typical for all alloys within the part trim line. The maximum property changes occurred with 7039-0 aluminum in which tensile and yield strength approached the properties for 7039-T62 after explosive forming. Only moderate changes occurred for the 1020 steel and other aluminum alloys. Blanks from each of the selected alloys were heat treated and trimmed, and gore segment parts were produced.

I. INTRODUCTION AND BACKGROUND

The most serious technical problem to overcome in forming segments of large domes is springback, since the depth of draw, by necessity, is relatively shallow. An understanding of springback, its prediction, and control is, therefore, most important for proper fabrication.

Springback is generally defined as the tendency for a material to return to its original shape after forming. It is most severe when only a shallow draw depth is required and when the blank material has a high yield strength.

Springback must be controlled by clearly understanding the underlying variables and distinguishing between the two contributing factors. One is rebound, resulting when the moving metal blank and the die surface collide. The other contributing factor is the proportion of elastic strain present in the total deformation.

The amount of rebound is proportional to the terminal velocity at which the blank strikes the die surface and the coefficient of restitution between the blank and the die materials. The restitution coefficient is measured by the ratio of the rebound velocity to the impact velocity and depends on the material of the striker and the surface material struck. For example, the restitution coefficient between aluminum and steel would be larger than that between aluminum and concrete. Decreasing the restitution coefficient by changing the material used for the inside liner of a die surface would decrease the rebound. Similarly, decreasing the velocity with which the blank strikes the surface of the die cavity will decrease rebound. Thus, if springback is present, an increased explosive charge will not only fail to reduce springback but could cause an opposite effect by increasing the velocity with which the blank strikes the die surface.

The nature of the explosive-forming process helps reduce the amount of rebound. As the explosive shock wave passes through the water it imparts forward momentum to the water. The shock wave then strikes the blank, forcing it into the die. When the blank tries to rebound eleastically on impact with the walls of the die cavity, its reverse motion is resisted by the forward momentum of the water following the shock wave.

The contribution of elastic strain to springback is more difficult to control. The basic principle underlying any control method is to increase, as much as possible, the proportion of plastic strain required to produce the desired deformation.

To illustrate this principle, a typical stress-strain curve is shown in Fig. I-1.

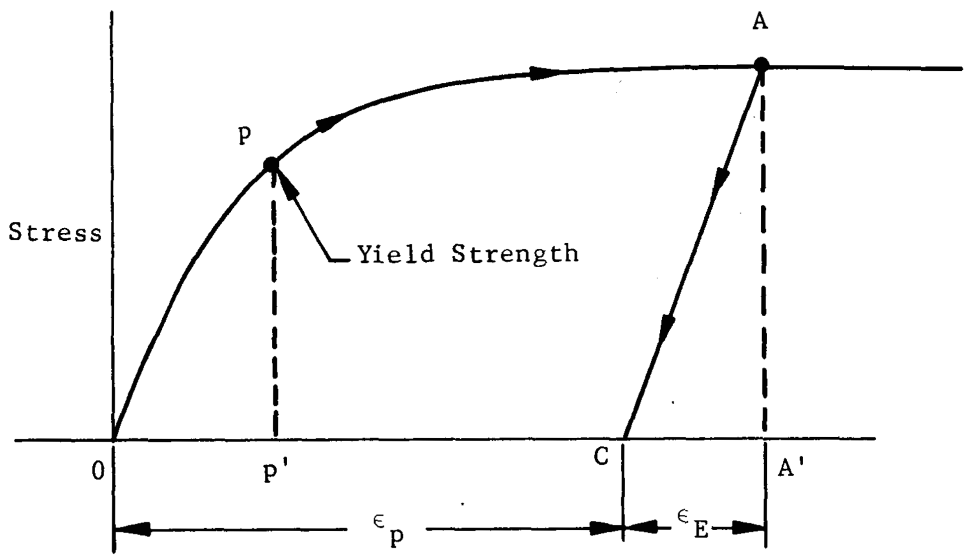


Fig. I-1 Springback due to Elastic Strain

The direction of loading is from O to A and the direction of unloading is from A to C. Point P represents the elastic limit of the material, and OP' represents the corresponding maximum elastic strain.

If the strain in the deformed blank at any location is less than the maximum elastic strain OP', the material at this location will not be permanently deformed, tending to spring back completely. This makes it necessary to deform the material beyond the elastic limit to, for example, Point A in Fig. I-1, which has a total strain of OA'. When the forming pressure is released, the material will unload elastically along the line AC toward Point C. If there is no restraint from adjoining material, the permanent strain remaining is OC. Of the total strain OA', the amount CA' will be elastic and the amount OC will be plastic.

The amount CA' will contribute to springback and the ratio CA'/OA' represents the proportion of elastic strain present that contributes to springback. The farther Point A is from Point P (the elastic limit), the larger the proportion of plastic strain or permanent deformation. Therefore, to reduce springback the plastic deformation must be maximized without exceeding the ultimate value.

It follows, then that the stretching mode of deformation of the blank must be maximized to reduce springback. The most direct method is to provide complete restraint around the perimeter of the blank outside the die cavity. This will prevent the blank material from flowing into the die so it has to be stretched to achieve its desired shape. Considerable force is required to restrain the flange material (that part of the blank remaining outside the die cavity). The restraining force per unit length of perimeter must be equal to or larger than the product of the yield stress of the blank material and the blank thickness. Blank materials having a high yield stress would require holding mechanisms similar to the jaws of a stretch press.

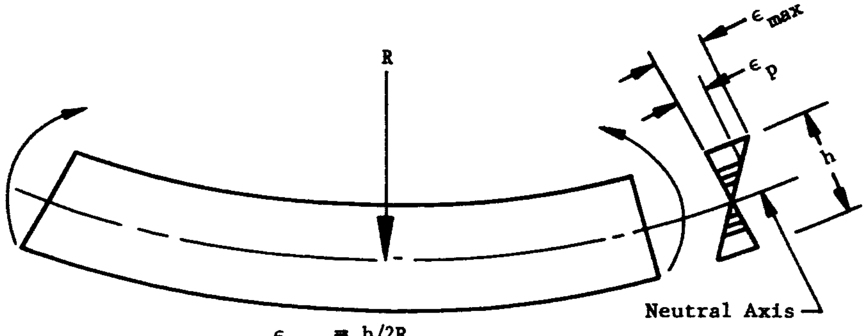
The amount of plastic strain caused by bending a blank to a given curvature can be directly increased by increasing the thickness of the blank. Consider the strip of blank material shown in Fig. I-2 that has been bent from flat to the radius of curvature R. The maximum strain at the outer fiber ϵ_{max}, by geometrical considerations, is

$$\epsilon_{max} = h/2R,$$

where

h = thickness of strip,

R = local radius of curvature of formed shape.



$\epsilon_{max} = h/2R$

ϵ_p = Yield Strain

Fig. I-2 Bending Strains

It can be seen that the larger the radius of curvature R, the smaller the strain will be and, therefore, the larger the springback. For a fixed value of R, ϵ_{max} may be increased well into the plastic range by increasing the thickness, h, sufficiently. For the purpose of scale modeling, it should be noted that the amount of strain is determined by the ratio of a blank thickness to the radius of curvature. For example, if a 1/7-scale model is used to investigate springback, a blank thickness 1/7 of the full scale will be required to make the strain the same for both the model and the full-scale article.

Increasing the blank thickness, however, is not a complete solution. The material in the neighborhood of the neutral axis of the cross section is never strained above the elastic limit because the strain at the neutral axis is zero. The elastically strained portion of the cross section (shaded area in Fig. I-2) where the strain is less than ϵ_{max} will, therefore, always contribute to springback.

If this elastically strained area is not present; i.e., if the whole cross section can be strained above the elastic limit, a substantial contribution to springback can be eliminated. The general principle underlying this approach is to shift the neutral axis (where strain is zero) a sufficient distance above the surface of the blank so the entire blank thickness can be plastically deformed. This can be done in one of two ways -- by providing blank restraint around the perimeter, or by using an integral blanket (a Martin proprietary process).

If the blank stretches because of edge restraint, uniform tensile stress is superimposed across the cross section of the blank (on top of the bending stresses shown in Fig. I-2). This raises the neutral axis above the surface of the blank as shown in Fig. I-3.

If the superimposed tensile stress due to stretching is large enough, it can raise the neutral axis of the blank enough that the strain is well above the elastic limit throughout the entire thickness of the blank. The amount of stretching will increase with the depth of draw so that springback will decrease with the increasing draw depth.

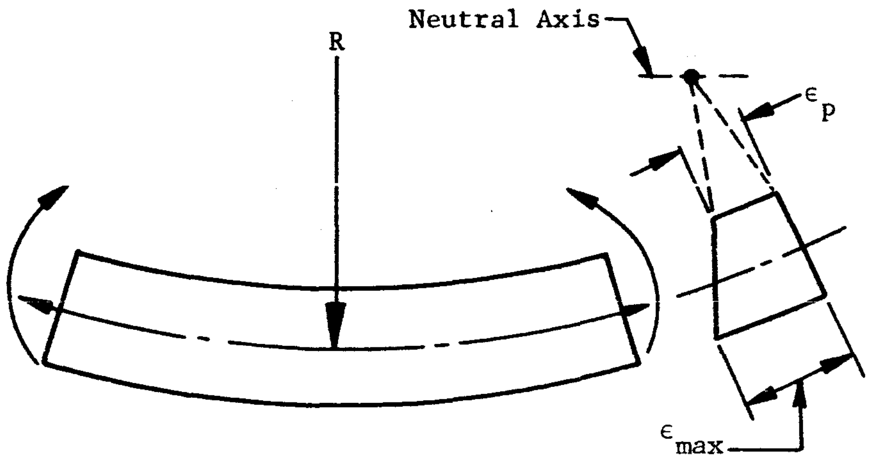


Fig. I-3 Reduction of Springback due to Elastic Strain by Shift of Neutral Axis

There will always be a small irreducible springback caused by elastic strain, regardless of the techniques used. If the irreducible minimum is larger than the required tolerances, the die must be made that much deeper to compensate for it.

Many attempts have been made to theoretically describe the forming process to permit the accurate prediction of springback for a variety of materials and forming conditions. However, no accurate theoretical description has been developed to permit the prediction of the elastic recovery for a given formed shape. It has been found that a completely elastic residual stress state does occur in sheet bending, in contrast to the conditions observed in most other plastic flow analyses (Ref 1).

To estimate springback, one must know several facts:

1) The radius of simple or compound curve that corresponds to the desired final contour;

2) The elements of the cross section of the member including the area, moment of inertia, and the location of the neutral axis;

3) The stress-strain curve of the material for the temperature of forming (Ref 2).

In general, two types of equations can be generated for springback prediction -- a simple equation giving approximate answers for a specific shape and material and an equation applicable to all shapes and amounts of forming. Gardiner (Ref 3) developed theoretical curves for prediction and correction of springback. Rather significant deviations of empirical data from theoretical predictions occurred when general forming cases were considered.

Empirical results illustrate the fact that the accurate prediction of springback is very difficult because of inherent variations in metal behavior and forming conditions for any given process (Ref 4). Experience has shown, however, that springback depends on a number of things (Ref 5 thru 8):

1) Kind of material formed;

2) Temper of material formed;

3) Sheet thickness;

4) Size of the inner bend radius;

5) Clearances and alignment used;

6) Friction between die and part;

7) Pressure exerted during forming;

8) Contour of part;

9) Forming parameters used.

Shaffer and Unger (Ref 1) have established the significant influence of material properties on the resulting springback. It has been shown that less springback occurs with materials of lower yield strength than with materials of higher yield strength. For the same yield strength, a material possessing a high modulus of elasticity will plastically deform to a greater extent than a material having a lower modulus of elasticity. If the ratio of the shear modulus for the material to the yield stress in shear remains constant, these parameters can be varied without any change in springback. Chapman (Ref 5), Strasser (Ref 6), and several others have verified the above observations. Alexander (Ref 8) determined that moderate stretching of the material in the same direction as that in which residual stresses lie will reduce them to insignificant values. This technique for stress reduction, and thus minimum springback, is generally not possible, however, since stress systems arising from heat treatment and quenching usually result in complex stress systems involving all three principal dimensions of the sheet.

Several papers (Ref 4, 9, and 10) have been directed to the problem of compensating for springback. In general, the standard procedure is to overbend or restrike the material to minimize springback by compensating for elastic metal movement. Die design has also been found to be important, and configurations incorporating enlarged cavities and modified entrant radii have been used to control the contour of the finished part.

In explosive forming, several authors have reported reduced and sometimes nonexistent springback (Ref 11 thru 15). Beyer (Ref 14) indicates that proper placement of the explosive charge has large influence on the reduction of springback. A possible explanation for the reduction in springback when explosive techniques were used was posed by Wood et al. (Ref 16) where it was found that initial pressures existed for different materials below which an increase in springback was observed. The pressures, depending on the material being formed, were on the order of 40,000 to 50,000 psi.

Dynamic stress-strain conditions are produced during explosive forming (Ref 17). The deformation is completed within 100 μsec, of which the elastic phase persists for about 25 μsec. During the elastic phase the limit of proportionality for some materials can be extended to about two and one-half times its normal value. According to Sheffield University researchers (Ref 18), springback decreases as the tension increases. Therefore, it is important to maximize in-plane tensile strains in the metal blank during explosive forming by proper blank restraint and placement of explosive charge. Die design becomes important here since it has been found by Henriksen (Ref 19) that significant residual stresses are present during explosive forming that are maximized at regions where large variations of curvature exist, i.e., flanges. Flange stresses of 8,000 to 10,000 psi and 25,000 to 30,000 psi for AISI 1020 and 4335 steels, respectively, have been measured.

As discussed above, it is important to maximize tensile plastic strains in a blank during forming to minimize springback. For shallow shapes such as dome gore segments, plastic strain due to bending alone is small. Stretching must somehow be enhanced to maximize plastic deformation and reduce springback. In this study, a technique for positive blank edge restraint was used in an effort to maximize tensile strains by pretensioning the blank before explosive deformation, and by completely restraining the edges, thus forcing the blank to stretch as well as bend. A male die form of double curvature was used to shape the desired 1/7 scale Saturn V gore segments.

II. EXPERIMENTAL PROCEDURE

A. MATERIALS

To more fully understand the effects of positive blank restraint on the response of alloys to elastic recovery, metals were selected from three different crystal lattice systems for study. Representative alloys from these systems were as follows:

1) Body centered cubic - 1020 low carbon steel;

2) Hexagonal close packed - Ti-6Al-4V;

3) Face centered cubic - 2014, 2219, and 7039 aluminum.

All of the alloys except the 1020 low carbon steel obtain their maximum mechanical properties through thermal treatments. To permit enhancement of plastic deformation, all but one of the alloys were formed in their lowest strength form. Since 2219 aluminum can be strain hardened in addition to age hardening, two different tempers were selected for explosive deformation. One temper, 2219-0, was the lowest strength form, while the other temper, 2219-T31, was a form in which controlled stretching from 1 to 3% was accomplished at the point of manufacture. It was hoped that by explosively forming 2219-T31 one might achieve enough plastic deformation in the metal during forming to convert the alloy to the -T37 temper. Thus, subsequent heat treatment would effect maximum design properties to the alloy, i.e., 2219-T87.

Table II-1 lists pertinent information regarding each alloy. The chemical compositions listed in Table II-2 are those reported by the supplier; the chemistry of each alloy was not verified by independent analysis. However, as shown in Table II-1, all mechanical properties were verified by tests conducted at the Martin Company. All of the alloys exhibited properties stipulated by applicable specifications or manufacturers' claims.

Table II-1 Typical Mechanical Properties of Materials Used in Contract NAS8-11616

Alloy	Ultimate Tensile Strength (psi)	0.2% Offset Yield Strength (psi)	Elongation (%)
2014-0 (L)*	17,100	7,200	30.2
2014-0 (T)†	17,200	6,900	31.0
2014-T62 (L)	61,800	66,800	9.0
2014-T62 (T)	61,400	65,900	9.3
2219-0 (L)	21,600	9,300	28.5
2219-0 (T)	21,200	8,900	27.8
2219-T62 (L)	54,000	36,000	6.0
2219-T62 (T)	55,200	37,100	6.0
2219-T31 (L)	52,900	35,000	26.3
2219-T31 (T)	55,900	31,500	21.2
2219-T81 (L)	62,300	47,400	7.5
2219-T81 (T)	63,100	47,600	7.0
7039-0 (L)	53,100	37,300	26.5
7039-0 (T)	55,800	32,400	21.2
7039-T61 (L)	59,100	49,700	15.5
7039-T61 (T)	58,900	49,200	16.0
1020 (L)	45,500	32,500	35.7
1020 (T)	43,300	29,800	37.2
Ti-6Al-4V (L)	138,200	130,000	12.0
Ti-6Al-4V (T)	137,600	128,600	12.5
Ti-6Al-4V (L)[H‡]	169,500	155,700	7.2
Ti-6Al-4V (T)[H]	168,700	155,200	8.1

Note: Results are for duplicate samples in each condition.

*L = Longitudinal grain direction.

†T = Transverse to grain direction.

‡H = Heat treated (1650°F for 1 hr; age at 950°F for 4 hr).

Table II-2 Typical Chemical Compositions for Alloys Investigated

Alloy	Composition in Weight (%)										
	Si	Fe	Cu	Mn	Mg	V	Zn	Ti	Zr	C	Al
1020	0.05 Max	Bal	--	0.45	--	--	--	--	--	0.20	--
Ti-6Al-4V	--	0.10	H_2 0.010	O_2 0.11	N_2 0.014	4.0	--	Bal	--	0.025	5.8
2014	0.8	--	4.4	0.8	0.5	--	--	--	--	--	Bal
2219	0.20	0.30	6.3	0.30	0.02	0.10	0.10	0.06	0.18	--	Bal
7039	0.3 Max	0.4 Max	0.1 Max	0.25	2.8	CR 0.3	4.0	0.1 Max	--	--	Bal

The strain hardening exponents for each alloy were established. Table II-3 lists the strain hardening exponents as determined by the expression

$$n = \frac{\log S_2/S_1}{\log \epsilon_2/\epsilon_1},$$

which assumes a logarithmic stress-strain relation,

where

n = strain hardening exponent,

S_1 = stress in pounds per square inch, at Point 1 on the stress-strain curve,

S_2 = stress in pounds per square inch, at Point 2 on the stress-strain curve,

ϵ_1 = plastic strain in inches per inch, corresponding to S_1,

ϵ_2 = plastic strain in inches per inch, corresponding to S_2.

Table II-3 Strain Hardening Exponents for Several Different Alloys

Material	ϵ_1 (in./in.)	ϵ_2 (in./in.)	S_1 (lb/in.^{2})	S_2 (lb/in.^{2})	n
2219-T31	0.0072	0.020	40,000	42,000	0.0478
1020	0.011	0.020	44,000	47,000	0.1130
2014-0	0.0084	0.0135	15,000	17,500	0.3180
2219-0	0.0084	0.016	15,000	18,500	0.3230
7039-0	0.02	0.18	18,700	34,300	0.2760
Ti-6Al-4V	0.02	0.18	132,000	138,800	0.0222

Based on the ultimate tensile strength, the maximum restraining force that can be withstood by a 2219-T31 blank is approximately 13,000 lb/in., where $F = \sigma t$ (σ = tensile ultimate strength in pounds per square inch and t = blank thickness in inches). Thus, the restraining force for this alloy and temper dictates the holddown boundary conditions for the forming die since the product of σt is a maximum for all the materials and thicknesses to be studied.

Uniaxial testing was accomplished using the fixtures shown in Fig. III-1. For the knurled grips, maximum loads necessary to produce slippage were established along with holddown pressures required to restrain the specimens. From the data it was possible to calculate the overall coefficients of friction. The groove recess and offset edge clamp concepts were studied with respect to pressures required to seat the male clamp portion into the female portion, clamping force necessary to prevent specimen slippage, and maximum loads at specimen failure or at the point of initial specimen slippage. Table II-4 presents the restraint data obtained using unscaled thicknesses of each material.

Table II-4 Test Data for Blank Restraint Devices

Restraining Device	Material	Thickness (in.)	Seating Load (lb)	Holddown Load (lb)	Maximum Load at Failure (lb)	Ultimate Strength (psi)	C_f
Knurled Grips	2014-0	0.130	8,000	8,000	2700	30,600	0.34
	7039-0	0.127	16,000	16,000	3040	34,400	0.19
	2219-0	0.242	16,000	16,000	5180	30,650	0.32
	2219-T31	0.242	16,000	16,000	8900	52,050	0.56
	6Al-4V	0.061	9,000	9,000	5900	138,000	0.65
	1020	0.118	4,000	4,000	4200	50,700	1.05
Groove Recess	2014-0	0.130	3,200	6,000	2650	29,150	0.44
	7039-0	0.127	3,500	6,000	3070	34,600	0.51
	2219-0	0.242	12,500	4,000	4820	28,550	1.20
	2219-0	0.100	1,200	7,000	1490	19,600	0.201
	2219-T31	0.242	20,000	4,000	9100	53,200	2.27
	6Al-4V	0.061	2,500	6,000	5730	138,000	0.95
	1020	0.118	5,000	4,000	4210	50,450	1.05
Edge Clamp	2014-0	0.130	2,500	4,000	2620	28,750	0.66
	7039-0	0.127	3,000	4,000	3040	33,960	0.76
	2219-0	0.242	10,800	5,000	5120	29,000	1.02
	2219-0	0.100	1,200	4,000	1770	23,350	0.44
	2219-T31	0.242	17,500	4,000	9120	53,350	2.28
	6Al-4V	0.061	2,500	5,000	5900	137,900	1.20
	1020	0.118	5,000	3,800	4140	49,300	1.09

B. DIES AND HOLDDOWN CLAMPS

At the inception of this program, it was intended that a female die and specially designed clamps would be required to completely restrain the blank during explosive forming. In addition, groove recess and offset groove concepts were studied in an effort to establish criteria for effectively restraining metal blanks by edge seating. After a female die had been designed together with a special C clamp design and quotations had been received from prospective contractors, it was obvious that contract funds were not sufficient to permit the fabrication of the necessary tooling. Technical interchange between NASA and the Martin Company led to the decision to design a male die that would have all of the essential features of complete edge restraint and would yield important forming data using male tooling not generally employed in high-energy processes. One important change in design techniques incorporated in the male-die concept was the use of a digital computer program for the definition of die contour and detail.

Further analysis of manual clamping methods revealed that standard clamps could be obtained with a minimum load capability of 50,000 lb. The clamps have several desirable features:

1) Minimum weight can be achieved through the use of high-strength steel;

2) The forged structure increases clamp integrity when compared with cast steel generally used;

3) Greater clamp toughness and ductility permits the application of both clamping and blast loads without concern for brittle fracture.

With the above information, a male die, holddown bars, and C clamps were designed and fabricated for use in explosive deformation of metal blanks. The details of the design and computer program used in the study are presented in Chapter III. Figure II-1 illustrates a typical C clamp and assembled holddown ring used in forming. The portion visible is the matching male form used in seating blanks in a female recess groove on the periphery of the forming die. Figure II-2 shows the male forming die and recess groove. Vacuum manifolding allows evacuation of the four corners of the die before metal deformation. The die is elevated and has web stiffeners on the periphery. This allows clearance for the large forged C clamps needed for blank seating and restraint.

Fig. II-1 Typical C Clamp and Assembled Holddown Bar Used in Explosive Forming

Fig. II-2 Male Forming Die Showing Peripheral Recess Groove

C. BLANK DETAILS AND CONTOUR TEMPLATES

Several blank sizes were studied for the various materials used in the program. Generally, the optimum blank size allowed seating of the blank in the peripheral recess groove with the rim of the blank at or slightly outside the groove centerline when complete seating was effected. Figure II-3 illustrates optimum blank dimensions necessary to facilitate complete seating and to permit a vacuum seal. Note that the blank corners are rounded. This prevents edge cracks, sometimes formed during the seating operation, from progressing into the die cavity. In addition to corner rounding, it is desirable to cut generous notches at the four corners of the blank to prevent folding of metal during the seating sequence. Folds formed from compression forces during blank deformation into the groove often lead to cracks that make evacuation of the region under the seated blank difficult.

The major technical objective of the program was the reduction of metal springback using positive edge restraint. Therefore, suitable methods of measuring blank contour deviations were required. Female sheet-metal templates were fabricated using computer-generated data for contour definition. Figures II-4 and II-5 show the templates used throughout the program. Measurements of the machined die surface revealed contour deviations from the computer-defined templates. Thus, it was necessary to measure contour differences between the templates and the machined-die surface to develop a correction profile. In all subsequent contour measurements, therefore, suitable corrections were used to compensate for die deviations. A balanced template technique was used to make measurements in which the center of the template rested on the apex of the part, and equal edge distances were maintained from the template corners to the formed part. Contour deviations were obtained by using wire feeler gages.

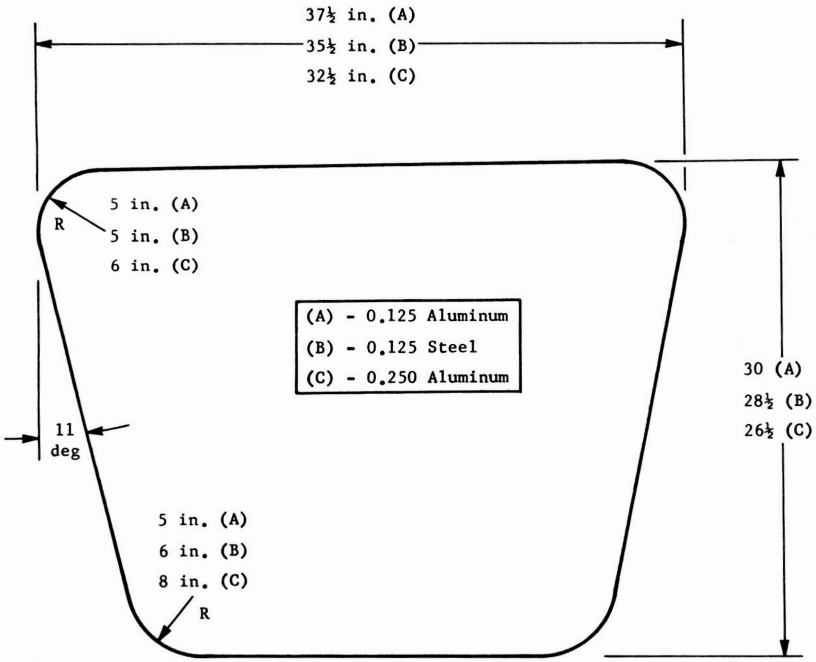


Fig. II-3 Optimum Blank Dimensions for Male Explosive-Forming Technique

Fig. II-4 Contour Templates Used for Springback Measurements

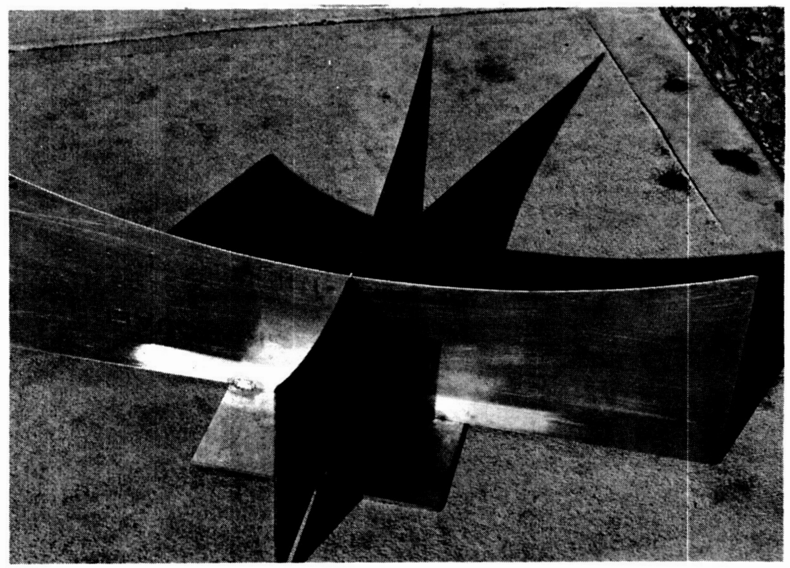


Fig. II-5 Contour Templates

D. FORMING PROCEDURE

The explosive forming of parts over a male forming die involves eight steps:

1) Blank and holddown bar alignment;

2) Blank seating;

3) Charge installation;

4) Explosive forming;

5) Contour measurements;

6) Disassembly;

7) Heat treatment (when required);

8) In-process contour measurements.

The blank and holddown bar alignment is extremely important to successful blank seating and subsequent vacuum sealing. Since the blank literally balances on the top die surface, it is necessary that two people perform the alignment details. Figure II-6 shows the die and clamping components before alignment. Once the blank is positioned over the center of the die with the blank edges directly over the peripheral recess groove, the holddown bar is lowered by crane over the blank and is placed precisely over the recess groove. A wire rope and turnbuckle are generally used to hold the segmented clamping bar together during alignment and subsequent clamping. Figure II-7 shows the balanced blank with the holddown bar properly aligned.

After the alignment procedures are completed, the C clamps are positioned at the ends of each side, and clamping pressure is applied to begin deformation of the blank into the groove. Torque is applied systemically, moving clockwise around the die until the blank material is about 50% into the recess groove. The remaining C clamps are positioned and tightened in sequence until equal force has been applied to all clamps. Clamping pressure is then increased, using the clockwise sequence, until little clamp screw movement can be accomplished with an air-driven impact wrench. The remaining clamping force is applied manually

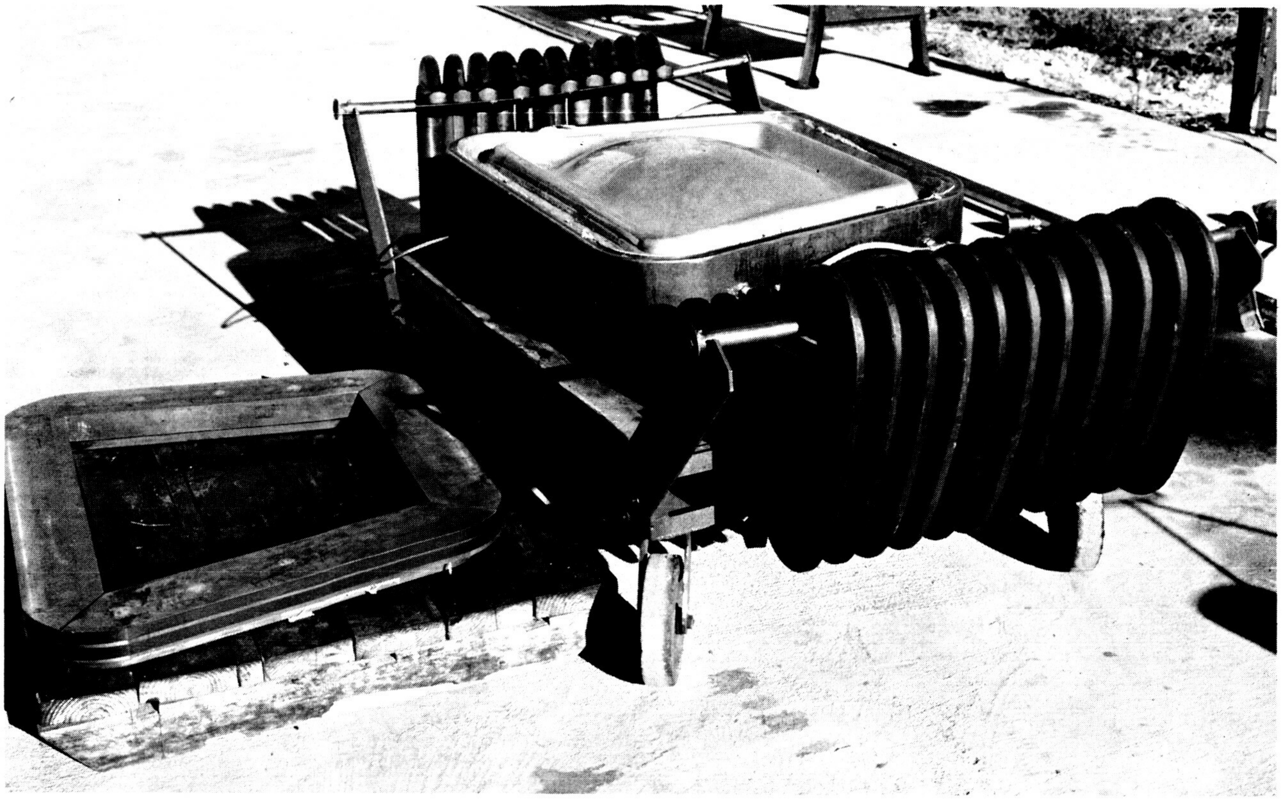


Fig. II-6 Die and Clamping Components before Blank Alignment

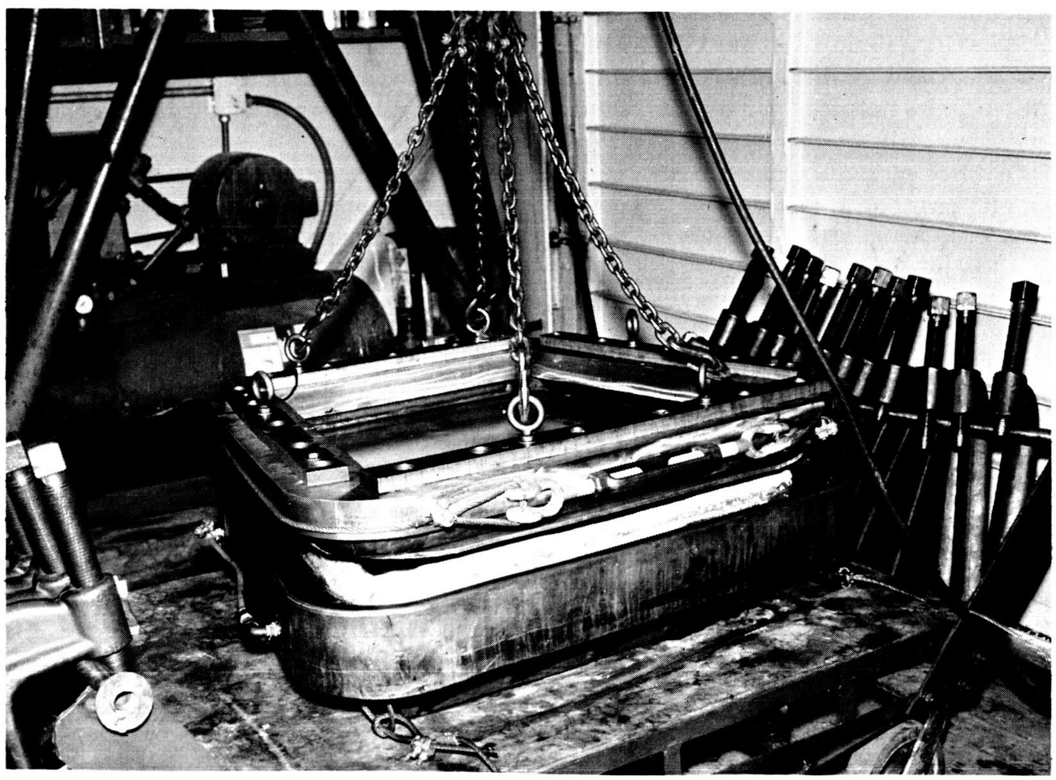


Fig. II-7 Blank and Holddown Bar Alignment using a calibrated torque wrench. A maximum torque of 450 ft-lb/bolt is applied to each clamp. This results in a seating force of 6850 lb/in.* The seating operation takes from 15 to 20 minutes to complete. Figure II-8 shows a typical seating operation using the air-driven impact wrench.

After the blank has been seated, the explosive charge is attached to suitable waterproofed cardboard standoff tubes. With the thinner sheets, a central charge was found most effective while the thicker materials seemed to respond better to a prima-cord ring charge. The two types of charge placements are shown in Fig. II-9 and II-10.

Once the charges have been placed and electric blasting caps attached, the die is lowered into a 7-ft-diameter pool, and explosive detonation is effected. The die is then removed from the pool with the formed part. Figure II-11 shows the die emerging from the pool after forming.

Before the formed part is removed from the die, template measurements are made to establish any apparent contour deviations. The clamps are then removed and the part is removed from the die. Contour measurements are made on the formed part after removal from the die, after heat treatment, and after trimming.

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*It was necessary to use two shims on each side of the die during the final stages of blank seating to prevent the holddown bar from rocking. Misalignment caused by holddown bar rocking prevents edge sealing and necessary die evacuation.

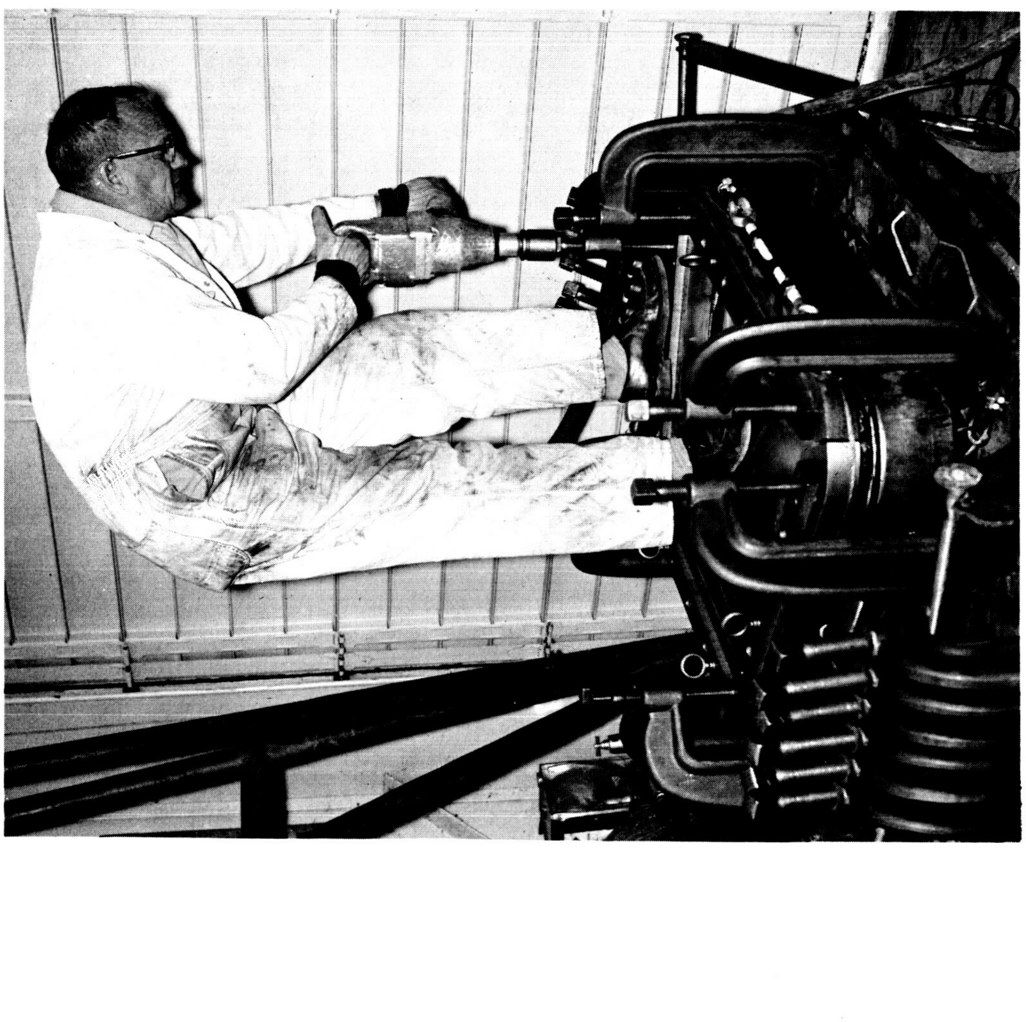


Fig. II-8 Blank Seating Using an Air-Driven Impact Wrench

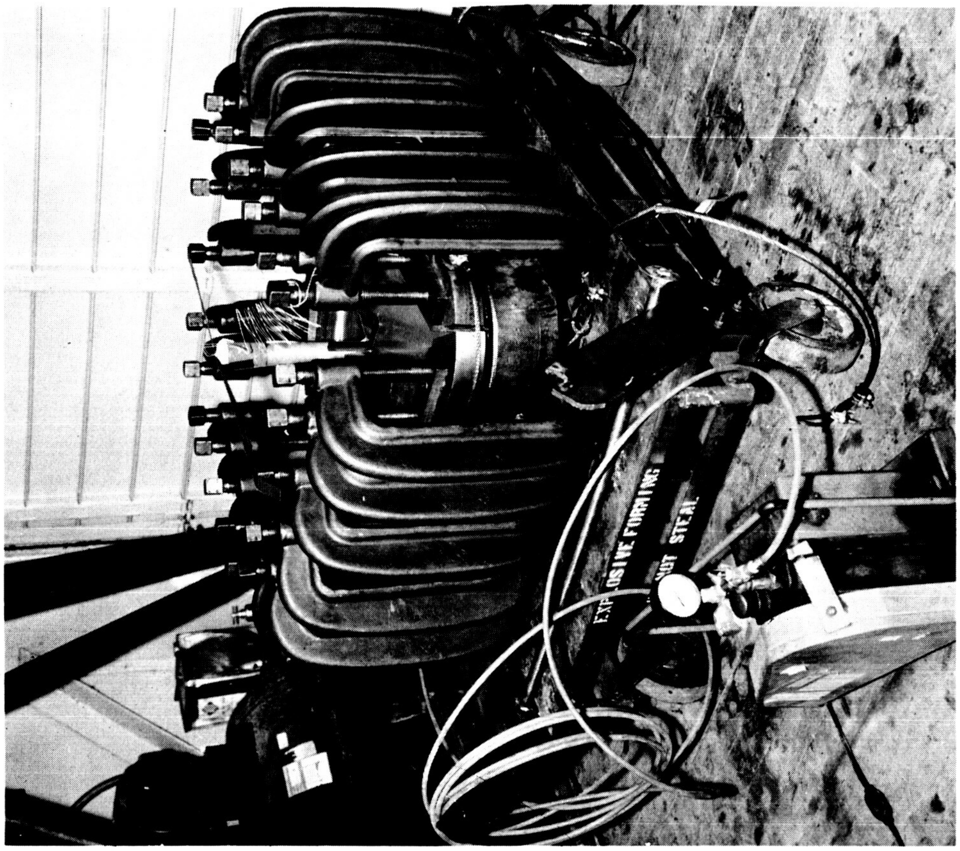


Fig. II-9 Central Charge Placement for Explosive Forming of Thin Gage Alloys

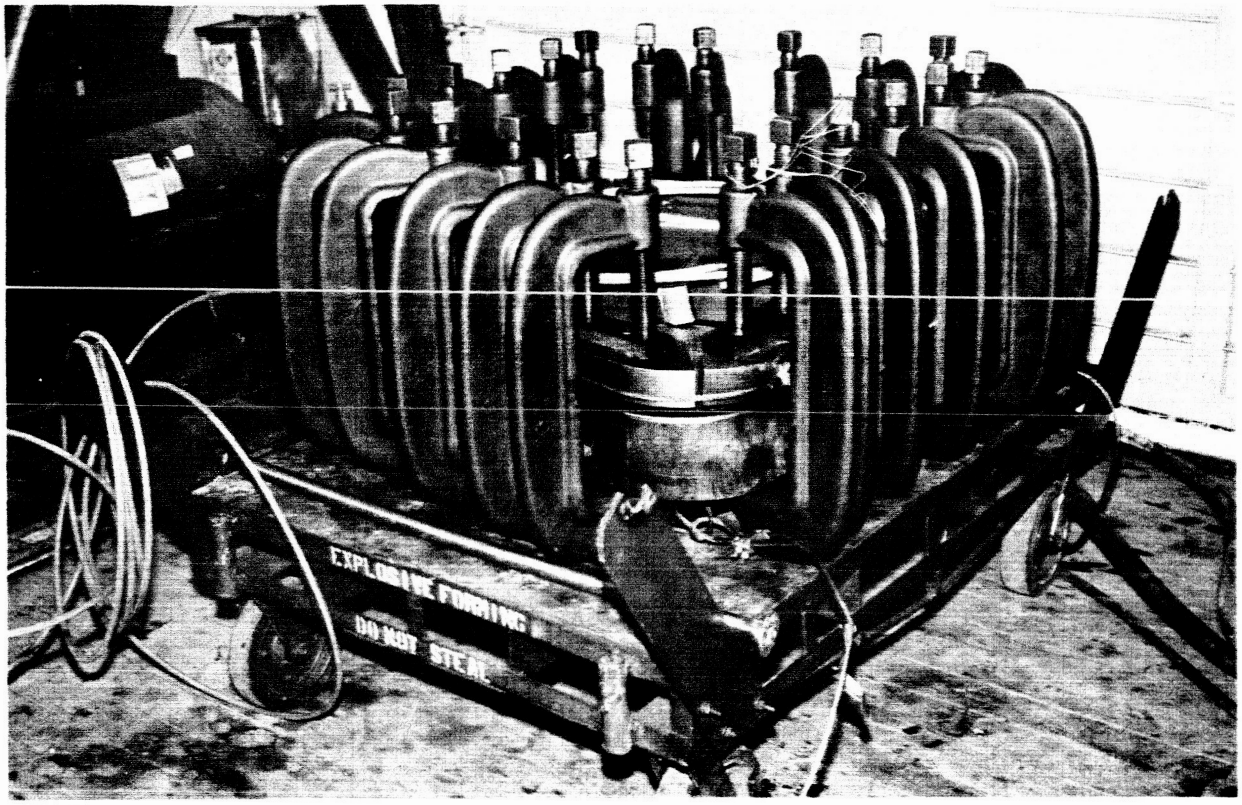


Fig. II-10 Ring Charge Placement for Explosive Forming of Aluminum Plate

Fig. II-11 Die Assembly Emerging from 7-ft-Diameter Forming Pool

E. HEAT TREATMENT

Although all of the alloys used in this program were formed in the softest condition, i.e., annealed or normalized, several of the alloys require thermal treatment after forming to achieve maximum design properties. There was neither time nor money available during this program to optimize heat-treatment cycles for explosively deformed material. However, maximum use of previous experience and knowledge permitted the selection of heat-treating conditions that yielded material properties above specification minimums after forming. Table II-5 presents the heat-treating cycles recommended for each alloy and the thermal treatments used after forming. All of the alloys except Ti-6Al-4V were heat treated in air using an electrically heated furnace shown in Fig. II-12. Temperature control was maintained at ±10°F up to 1000°F and ±20°F from 1000 to 1700°F. The Ti-6Al-4V components are heat treated in an inert atmosphere of argon.

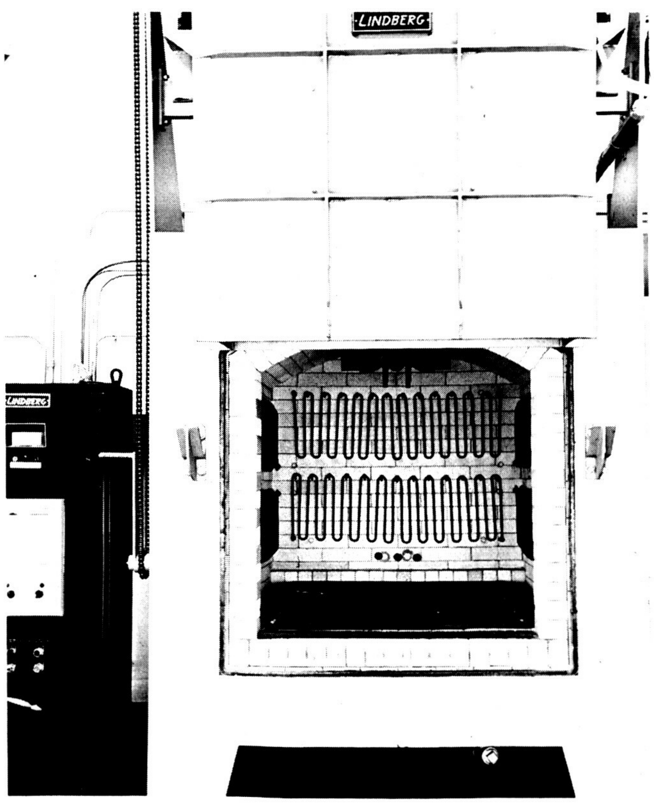


Fig. II-12 Heat-Treating Furnace Used to Process Explosively Formed Components

Table II-5 Heat-Treating Cycles for Explosively Deformed High-Strength Alloys

Alloy	Recommended Cycle for Undeformed Material			Recommended Cycle for Explosively Deformed Material		
	Anneal	Solution Treatment	Age	Anneal	Solution Treatment	Age
2014	750 ± 10°F for 1 hr	950 ± 10°F for 1 hr	350 ± 10°F for 8 hr	750 ± 10°F for 1 hr	950 ± 10°F for 1 hr	350 ± 10°F for 8 hr
7039	775 ± 10°F for 2 hr	750 ± 20°F for 2 hr	Proprietary	775 ± 10°F for 2 hr	750 ± 20°F for 2 hr	Proprietray
2219	775 ± 25°F for 3 hr	995 ± 10°F for 1 hr	375 ± 10°F for 36 hr	775 ± 25°F for 3 hr	995 ± 10°F for 1 hr	375 ± 10°F for 36 hr
1020		Not Heat Treatable			Not Heat Treatable	
Ti-6Al-4V	1350 ± 25°F 4 hr FC to 1050°F	1660 to 1700°F 5 to 10 min WQ	1000 ± 10°F 4 hr AC	1350 ± 25°F 4 hr FC to 1050°F	1660 to 1700°F 5 to 10 min WQ	1000 ± 10°F 4 hr AC
2219-T31	775 ± 25°F* for 3 hr	995 ± 10°F* for 1 hr	325 ± 10°F 24 hr	775 ± 25°F for 3 hr	995 ± 10°F for 1 hr	325 ± 10°F 12 hr
2219-T37	775 ± 25°F* for 3 hr	995 ± 10°F for 1 hr	325 ± 10°F 24 hr	775 ± 25°F for 3 hr	995 ± 10°F for 1 hr	325 ± 10°F 12 hr

*Annealing or solution heat treatment destroys the controlled stretching produced at the mill.

Note: AC, air cooled; WC, water quench; and FC, furnace cooled.

III. TEST RESULTS AND DISCUSSION

A. PHASE I

The technical effort in Phase I consisted of several separate studies to:

1) Develop necessary design criteria for a female and a male forming die;

2) Provide data to establish optimum clamping techniques;

3) Develop computerized methods for the definition of die contour;

4) Fabricate a male explosive-forming die.

The accomplishments under each segment of Phase I follow.

1. Development of Restraint Techniques

The reduction of springback for high-strength alloys depends largely on the amount of plastic deformation induced in the part during explosive forming. In the fabrication of shallow gore shapes, one is not concerned about excessive stretching. Therefore, techniques that permit complete restraint of the periphery of the blank can be considered since maximized metal stretching is desired. In this program three concepts were evaluated -- a knurled, flat grip, a groove recess, and an offset edge clamp. To permit the development of suitable criteria for die design, fixtures of each type were fabricated from heat treated 4130 alloy steel. The fixtures were then used for uniaxial mechanical testing to establish seating loads and slippage loads. Figure III-1 illustrates the test fixtures. The philosophy behind the selection of the three concepts is discussed in the following paragraphs.

Knurled Flat Grip - Figure III-2 depicts a concept utilizing knurled gripping surfaces. Under optimum conditions, the knurled clamping device will, by virtue of frictional forces, completely resist the tension force developed in the blank during the forming operation. Thus $F = C_f P$, where F = blank tension force per inch

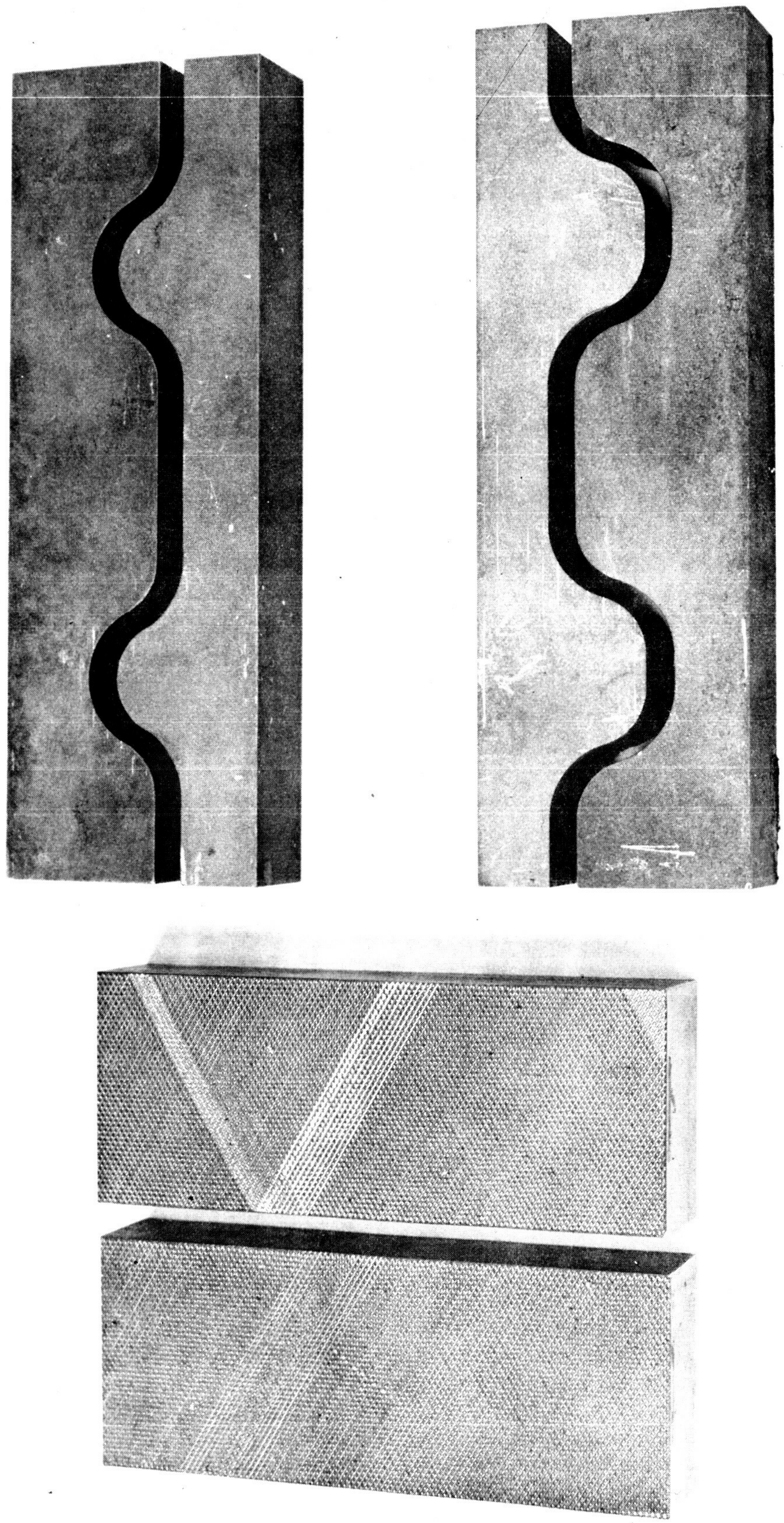


Fig. III-1 Edge Restraint Fixtures for Uniaxial Mechanical Testing of blank perimeter, C_f = coefficient of friction, and P = pressure force per inch of blank perimeter. The coefficient of friction resulting from a knurled surface is dependent on many different variables. The most important variables are: (1) clamping force; (2) blank strength and hardness; (3) draw ring and die plate hardness; and (4) knurl profile geometry. With C_f a function of so many variables, specific values can only be obtained experimentally.

Knurls have a decided influence on the ability of a blank to withstand tension forces. A uniform cross-sectional stress is produced throughout the blank during deformation except at the knurl edges. Here points of stress concentration may effectively reduce the cross-section and subsequently cause tearing or fracture of the blank. Empirical data are required to establish boundary conditions for an optimum knurled clamp.

Groove Recess Grip - The groove recess concept takes advantage of both frictional forces and changes in curvature to effect positive restraint. Figure III-3a illustrates the principal employed. Frictional resistance to the motion of a blank over a curved surface can be visualized as in Figure III-3b. The force, F_1, applied at one end of a curved segment of radius, R, is resisted by the reaction force, F_2, the developed surface, P_n, and the frictional force, q_n. The pressure, P, which varies with the angle, φ, and the frictional force, q, can be expressed by

$$P_n = \frac{F_1}{R\left(1 + C_f\varphi\right)}$$

and

$$q = C_f P_n = \frac{F_1 \; C_f}{R\left(1 + C_f\varphi\right)}$$

The summation of forces over the entire angle φ gives

$$F_2 = F_1 \left[1 - \ln\left(1 + C_f\varphi_B\right)\right]$$

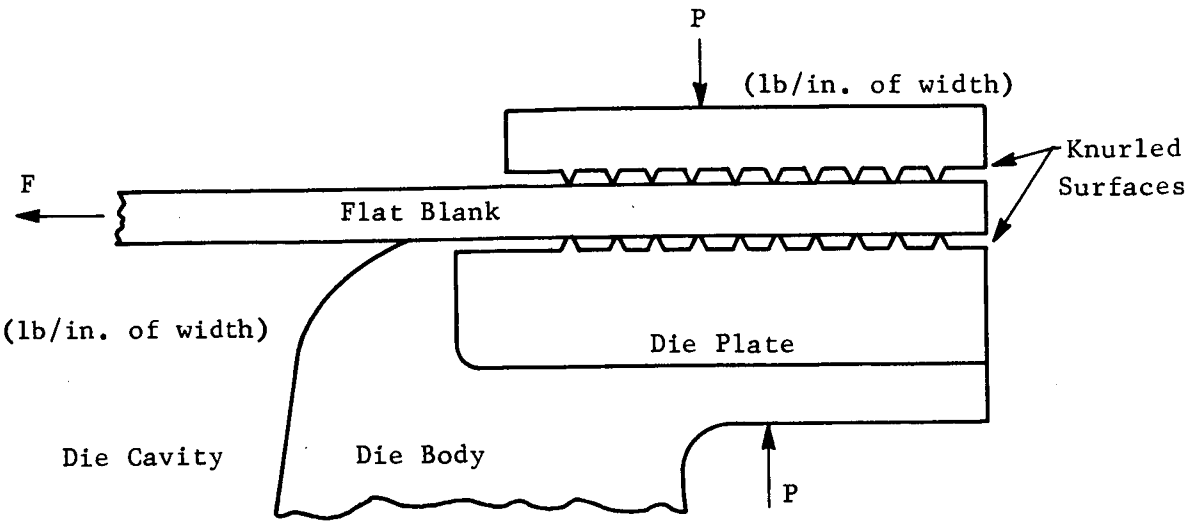


Fig. III-2 Knurled Grip Principle

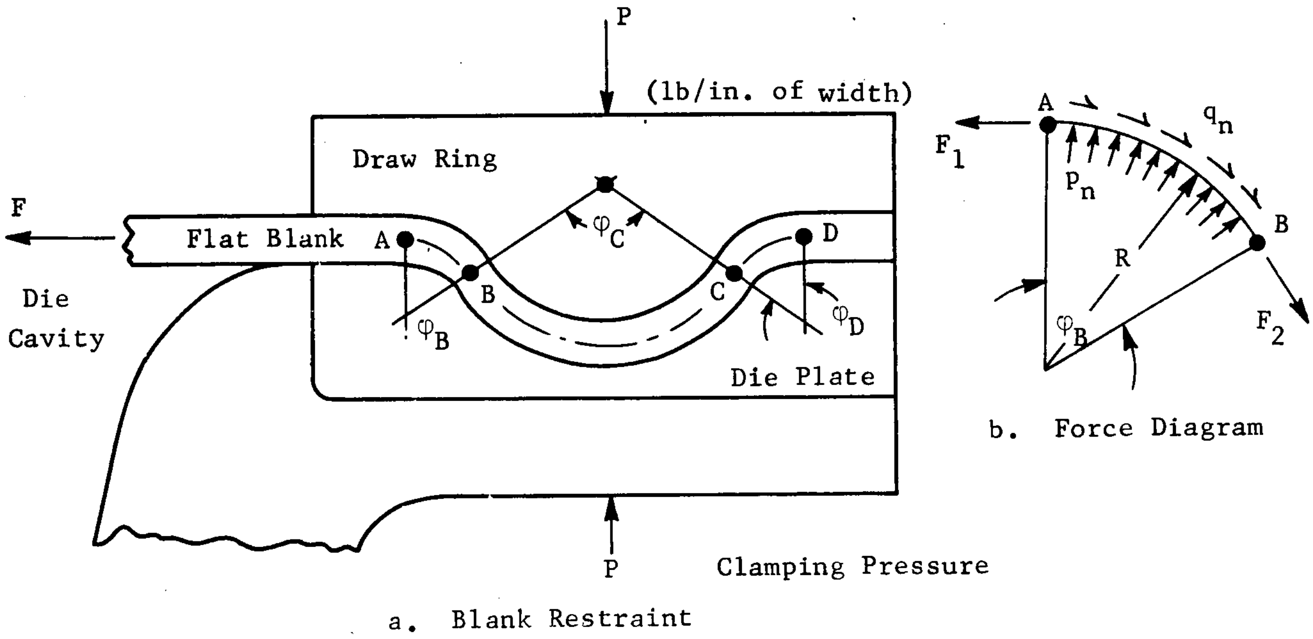


Fig. III-3 Groove Recess Concept

The changes in radius of curvature depicted by points A, B, C, and D, introduce another component of friction in Fig. III-3. If an element of the blank is subjected to a bending moment, M, to produce flattening, and if the bending moment were entirely elastic in nature, the moment can be expressed by

$$M = \frac{Eh^3}{12R}$$

where E = modulus of elasticity, h = material thickness, and R = radius of curvature. If R is kept small (about 4h), plastic deformation would result to aid in seating the blank in the groove. It is known that if R < 4h, cutting of the blank occurs as the metal is forced into the groove.

<u>Offset Edge Clamp</u> - A variation of the recess groove concept is shown in Fig. III-4. A wedge is forced into a recess deforming the blank and creating pressure against the die plate to restrict blank movement.

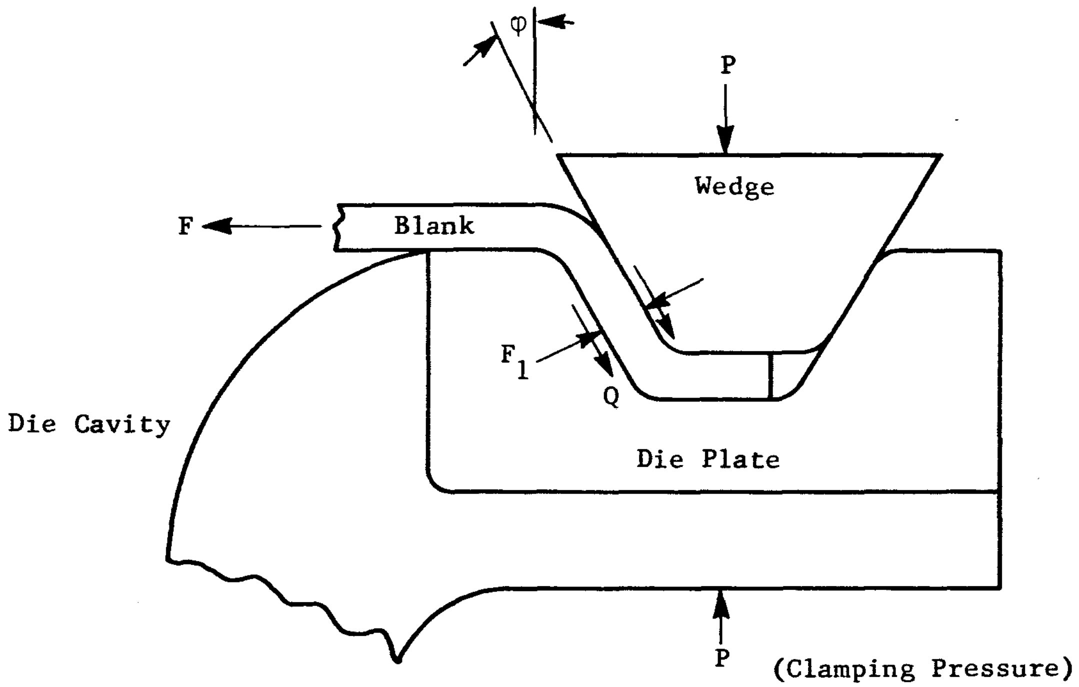


Fig. III-4 Offset Edge Clamp

From Table II-4 it is readily apparent that the edge clamp restraining device yields, in general, the lowest seating loads, lowest holddown loads and maximum calculated coefficient of friction for all alloys. Figures III-5 thru III-7 illustrate a typical seating operation, while Fig. III-8 depicts a test setup using the edge clamp fixture.

2. Die Design and Fabrication

Based on the criteria established above, a female die was designed using an edge clamp restraining concept. A plan view of the female die concept is shown in Fig. III-9. Although the theoretical study had shown the most uniform strains result from the use of a shallow ellipsoidal die rather than a reverse surface (male) die, considerations of blank sizes, die costs, material wastage, and handling, as well as lack of data using male forming dies led to a redesign effort in which a male forming die was designed and fabricated. The die, after fabrication, is shown in Fig. II-2. The double curvature surface of the die was defined using a 7094 digital program computer method. Die templates were defined in the same manner.

Originally projected seating and holddown loads suggested that loads over 100,000 lb/clamp might be required. Therefore special clamps were designed to withstand these loads. However, after complete data were developed and the male die concept defined, it was found that 50,000-lb clamping loads would be adequate. Nondestructive testing of each clamp by the vendor assured maximum clamp integrity. Actual testing in our laboratory also confirmed the serviceability of the clamps by yielding maximum loads near 60,000 lb. The clamp screw rather than the frame proved to be the limiting factor due to columnar failure.

Thus the Phase I technical effort yielded adequate design criteria whereby a serviceable die, clamping rings, and holddown clamps were designed and fabricated. The tools designed under this program have met all of the required loads necessary to effect blank seating and subsequent blast loads during explosive forming.

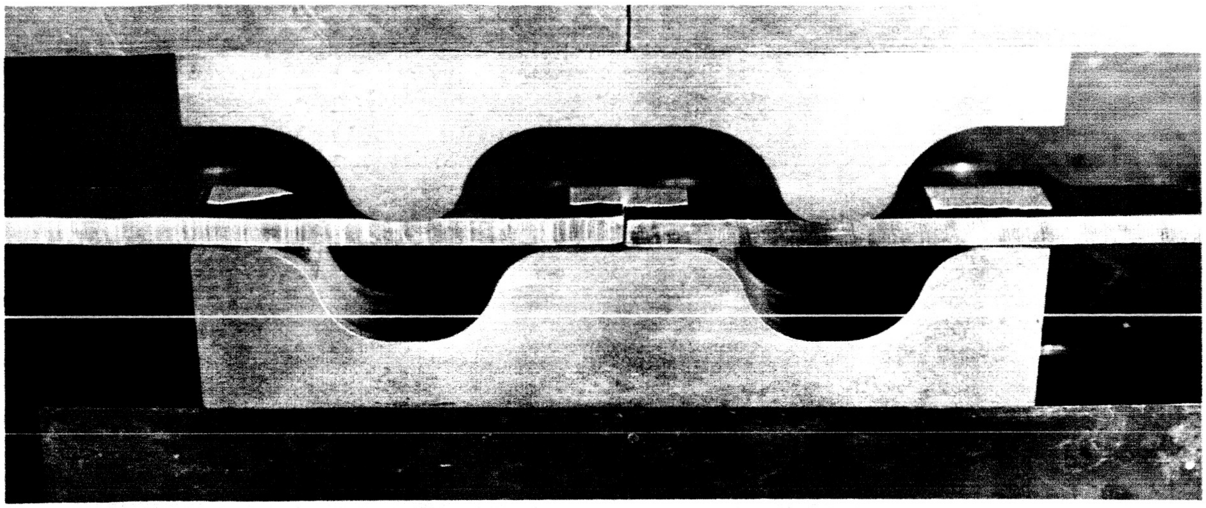


Fig. III-5 Holding Blanks and Test Specimen before Seating in Edge Clamp Fixture

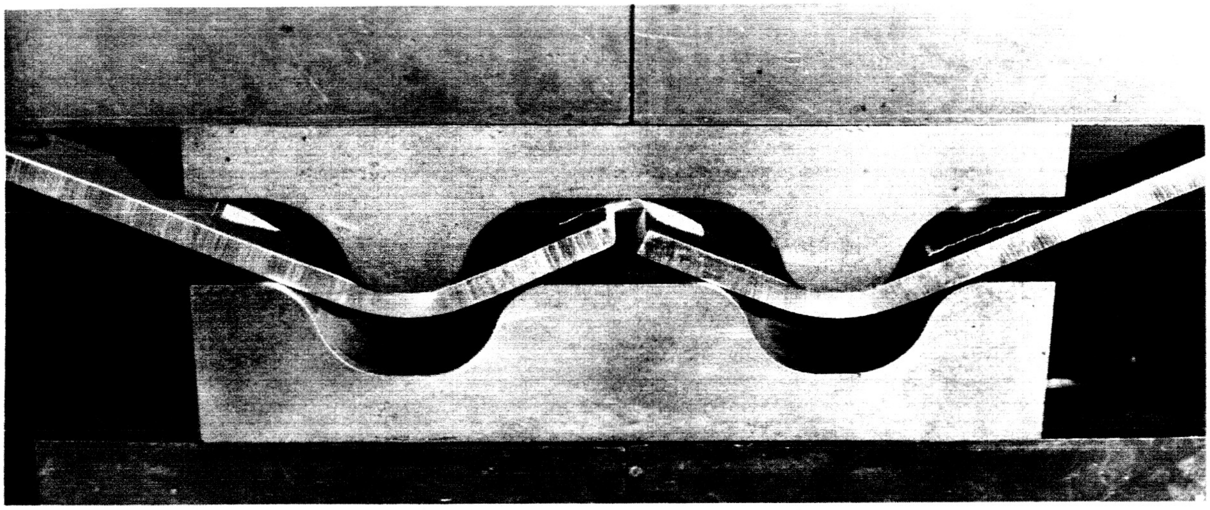


Fig. III-6 Seating 2219-0 Aluminum in Edge Clamp Fixture

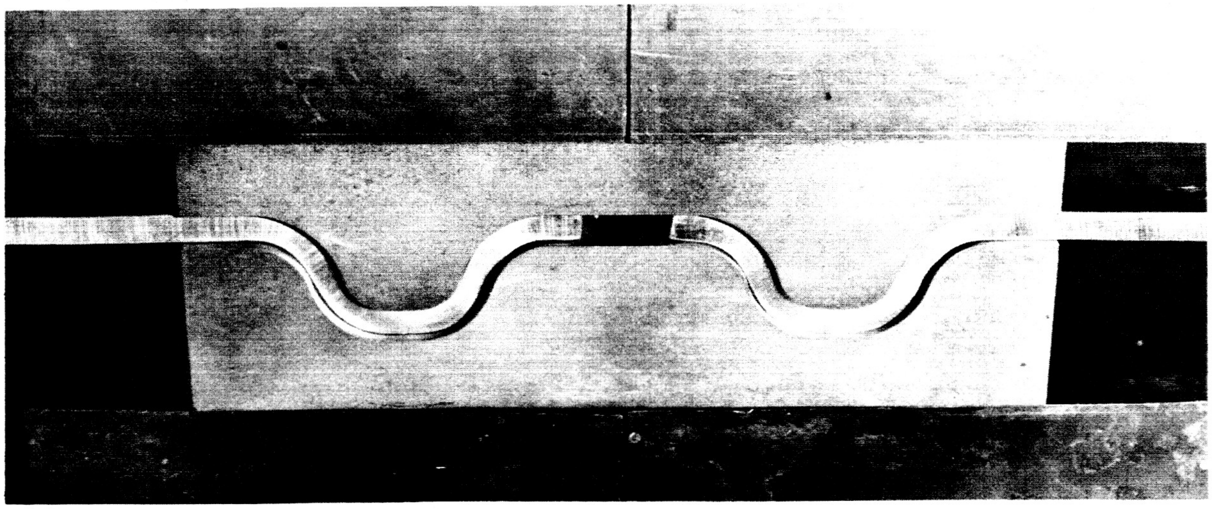


Fig. III-7 Fully Seated 2219-0 Aluminum Test Specimen in Edge Clamp Fixture

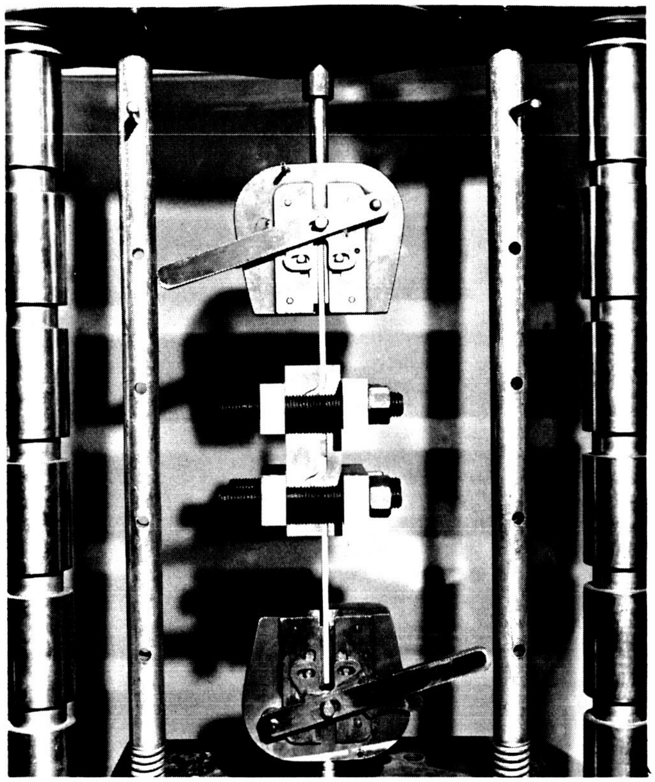


Fig. III-8 Test Setup for Blank Restraint Experiments

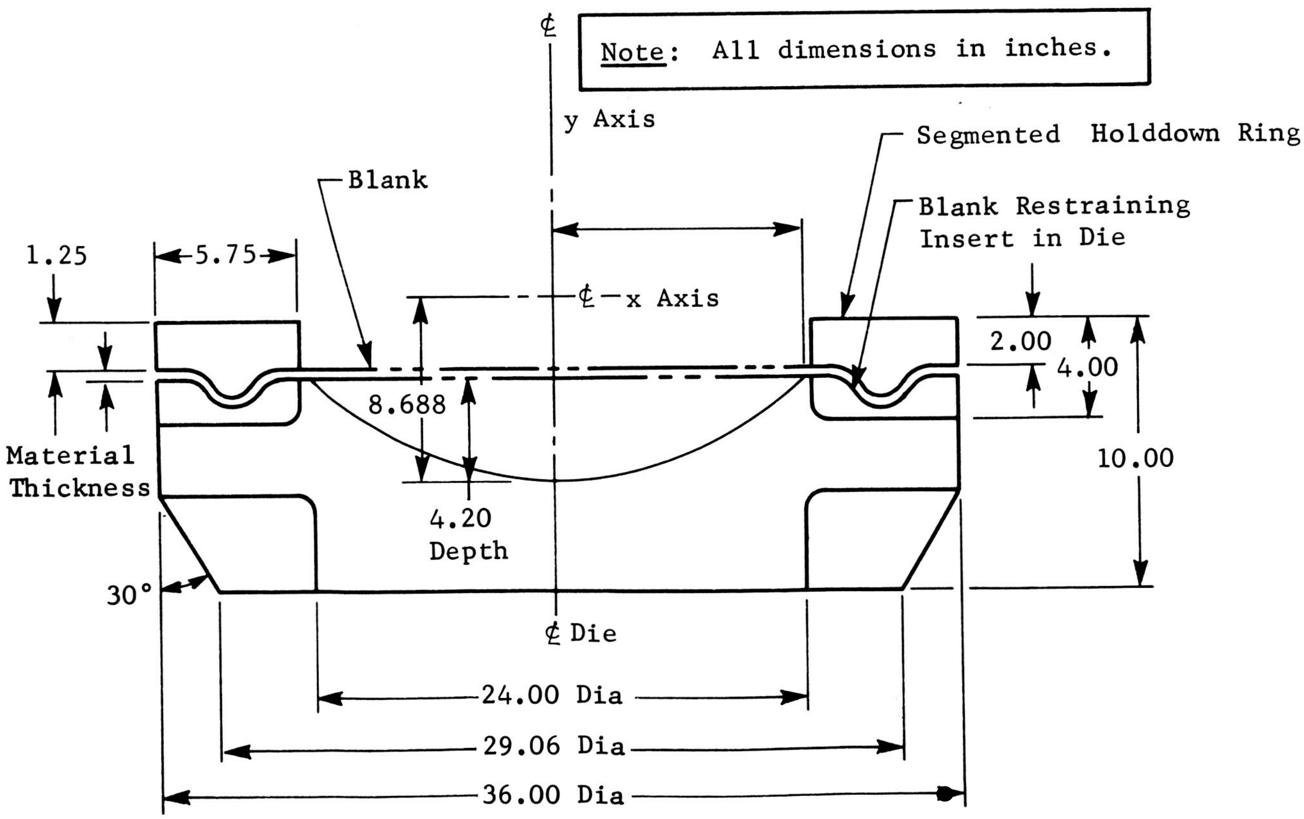


Fig. III-9 Female Forming Die Designed in Phase I

B. PHASE II

1. 2014 Aluminum Sheet

Annealed 2014 aluminum sheet, 0.125-in. thick was selected for explosive forming studies. Blanks of the shape and dimensions shown in Fig. II-3 were used. Seating of the blank in the peripheral groove was accomplished using the procedure described previously. No difficulties were encountered during the operation except that evacuation of the die corners was difficult if insufficient seating pressure was used. In general, bolt torque of 450 ft-lb, resulting in clamping force of 6850 lb/in., was sufficient to prevent air leakage into the die cavity. Bolt torque of 350 to 400 ft-lb could be used if zinc chromate paste was placed at the periphery of the recess groove on the side nearest the die cavity. Since low torque values are desirable to permit minimum full-scale clamping pressures, the use of zinc chromate sealer was desirable for all forming operations. Installed vacuum sealer material is shown in Fig. III-10. Experiments showed that a 48% nitroglycerine equivalent dynamite (Cyadyn 3) centrally placed 6 in. above the blank surface yielded excellent results. A typical part after explosive forming with an explosive charge of 1000 grains of Cyadyn 3 is shown in Fig. III-11. Note the excellent definition of die contour obtained. The forming was accomplished in a 7-ft-diameter pool with about 6 ft of water head over the die. A single forming shot effected satisfactory draw into the die corners.

Mechanical Properties - The properties of the material used for forming averaged 17,200-psi ultimate tensile strength, 7,100-psi tensile yield strength, and 30.6% elongation in a 2-in. section. Heat-treated properties using the thermal cycles shown in Table II-4 were 66,800-psi ultimate tensile strength, 61,800-psi tensile yield strength, and 9% elongation.

After explosive forming, the annealed properties were significantly improved, especially in the central portion of the blank where significant explosive hardening occurred. Properties near the trim line of the part were little affected by the explosive forming process. Average tensile values for as-formed 2014-0 aluminum are as follows:

Fig. III-10 Blank Vacuum Sealing with Zinc Chromate Tape

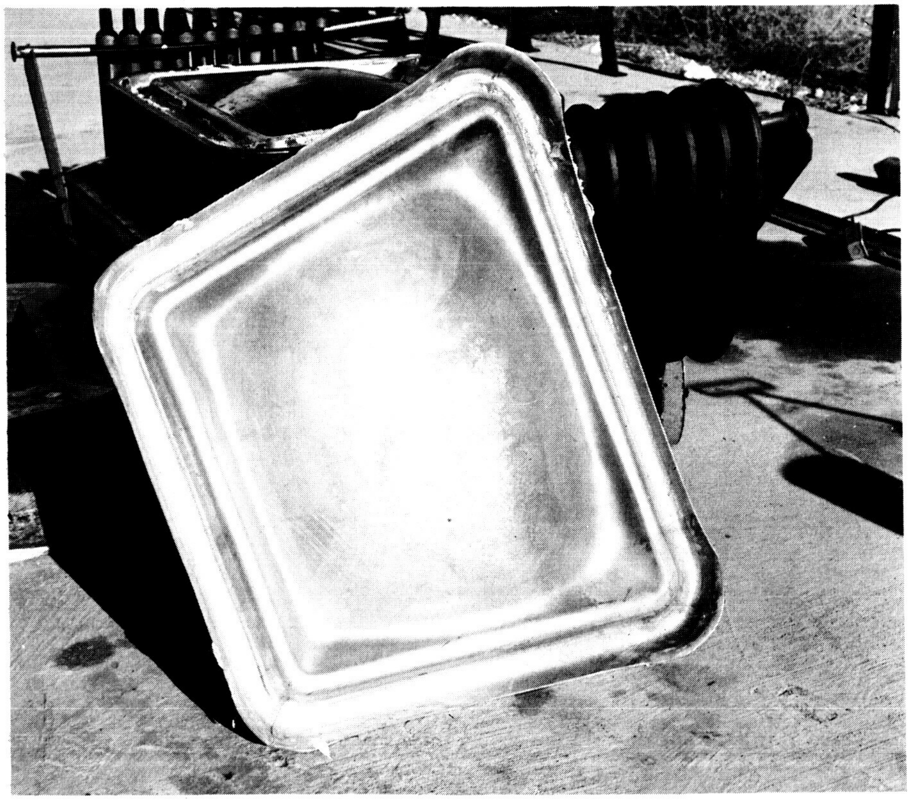


Fig. III-11 Typical 0.125-in.-Thick 2014-0 Aluminum Part Explosively Formed on Male Die

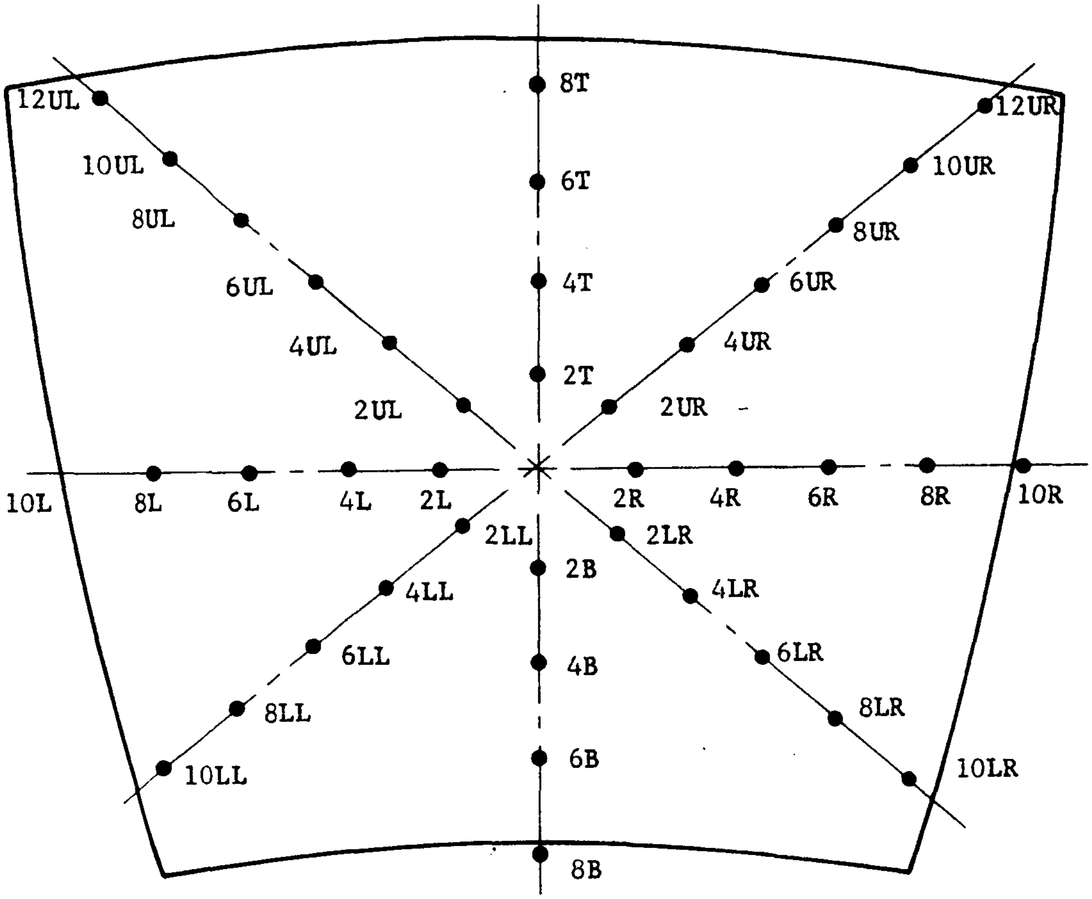
	Blank Center	Blank Edge
Ultimate Strength (psi)	17,800	18,500
0.2% Offset Yield Strength (psi)	16,300	9,900
Elongation in 2 in. (%)	28.0	12.0

Solution heat-treatment of the formed blank specimens with subsequent artificial aging at 350 $\pm$ 10°F for 8 hr resulted in material having properties above listed specification properties. These results were entirely expected since solution treatment of the 2014 alloy removes structural effects induced by the explosive deformation. Proper solution heat treatment, therefore, results in full alloy response. Properties of fully heat treated material after explosive deformation were as follows:

	Blank Center	Blank Edge
Ultimate Tensile Strength (psi)	67,600	66,900
0.2% Offset Yield Strength (psi)	63,200	63,100
Elongation in 2 in. (%)	8.0	8.0

It is possible that improved properties after forming might be obtained by explosively forming material immediately after solution heat treatment; however, this line of investigation was not pursued.

Blank Stretching - Of interest in the explosive forming of gore segment parts is the production of uniform stretching over the blank surface. Blank stretching is relatively uniform using the optimum centrally positioned explosive charge until the sections of the blank near the die corners are reached. Here the strains become quite significant and in some cases approach the ultimate elongation for the alloy. In fact, two blanks failed outside of the trim line in the highly stretched blank corners. Figure III-12 shows typical strain distribution for explosively formed 2014-0 aluminum. Although high strains produced from excessive stretching cannot be avoided, full heat treatment of the alloy after forming permits full recover of alloy properties.



Position	Stretch (%)	Position	Stretch (%)	Position	Stretch (%)
10T		4R	1	12LR	
8T	2.5	6R	1	14LL	
6T	2	8R	1	12LL	
4T	0.5	10R	2.5	10LL	10.5
2T	0.5	14UL/16UL		8LL	3
2B	1.5	12UL	17	6LL	2.5
4B	3.5	10UL	7	4LL	1.5
6B	4.5	8UL	2.5	2LL	0.5
8B	8	6UL	3	2UR	2
10B		4UL	1	4UR	1
10L	3	2UL	0	6UR	3
8L	1	2LR	3	8UR	3
6L	1	4LR	1.5	10UR	7
4L	1	6LR	3	12UR	18
2L	1.5	8LR	5	14UR	
2R	0.5	10LR	9		

Fig. III-12 Stretching of 2014-0 Aluminum after Explosive Deformation

Metal Springback - One of the prime objectives of the contract was the minimization of springback using the positive edge restraint technique developed. This objective has been met for as-formed material. As shown in Fig. III-13, the maximum springback obtained after explosive forming was 0.007-in. This would result in a maximum springback on a full scale component of only 0.049 in. Thus the benefit of positive edge restraint is obvious. The subsequent solution treatment and aging of the deformed alloy destroys the benefits derived from explosive processing. Therefore, for the best results in the forming of 2014 aluminum, it is suggested that freshly quenched material be formed to permit subsequent aging with a minimum of blank distortion. Figure III-13 illustrates the serious distortion of the previously undistorted component caused by the thermal processing.

2 2219-0 Aluminum Plate

The properties of 2219-0 aluminum plate are similar to those for annealed 2014 aluminum. However, the workability of the alloy is slightly less than that of 2014. Centrally placed charges of Cyadyn 3 dynamite did not sufficiently form the blank. Larger charges could not be used at the existing facility, therefore, experiments were conducted using 2-ft-diameter coils of 100 grain/ft primacord at a standoff distance of 2 in. A total of 1200 grains of PETN charge resulted in good metal deformation. Because of the greater stiffness of the 0.250-in.-thick 2219-0, it was possible to obtain blank seating and vacuum sealing with 300 ft-lb of torque (5140 lb/in.). No specific problems were encountered during the seating, forming or disassembly procedures.

Mechanical Properties - The mechanical properties of 0.250-in. thick 2219-0 aluminum plate used in this program averaged 21,400-psi ultimate tensile strength, 9,000-psi tensile yield stress (0.2% offset), and 28% elongation for a 2-in. section. Heat treatment of the material according to recommended procedures resulted in values of 54,000-psi ultimate tensile strength, 36,000-psi tensile yield strength, and 6% elongation for a similar section. After explosive deformation of the alloy in the male forming die there was little change in ultimate strength, but the yield strength was improved by about 65% with only a slight drop in elongation. Properties of explosively formed material are shown in the following tabulation.

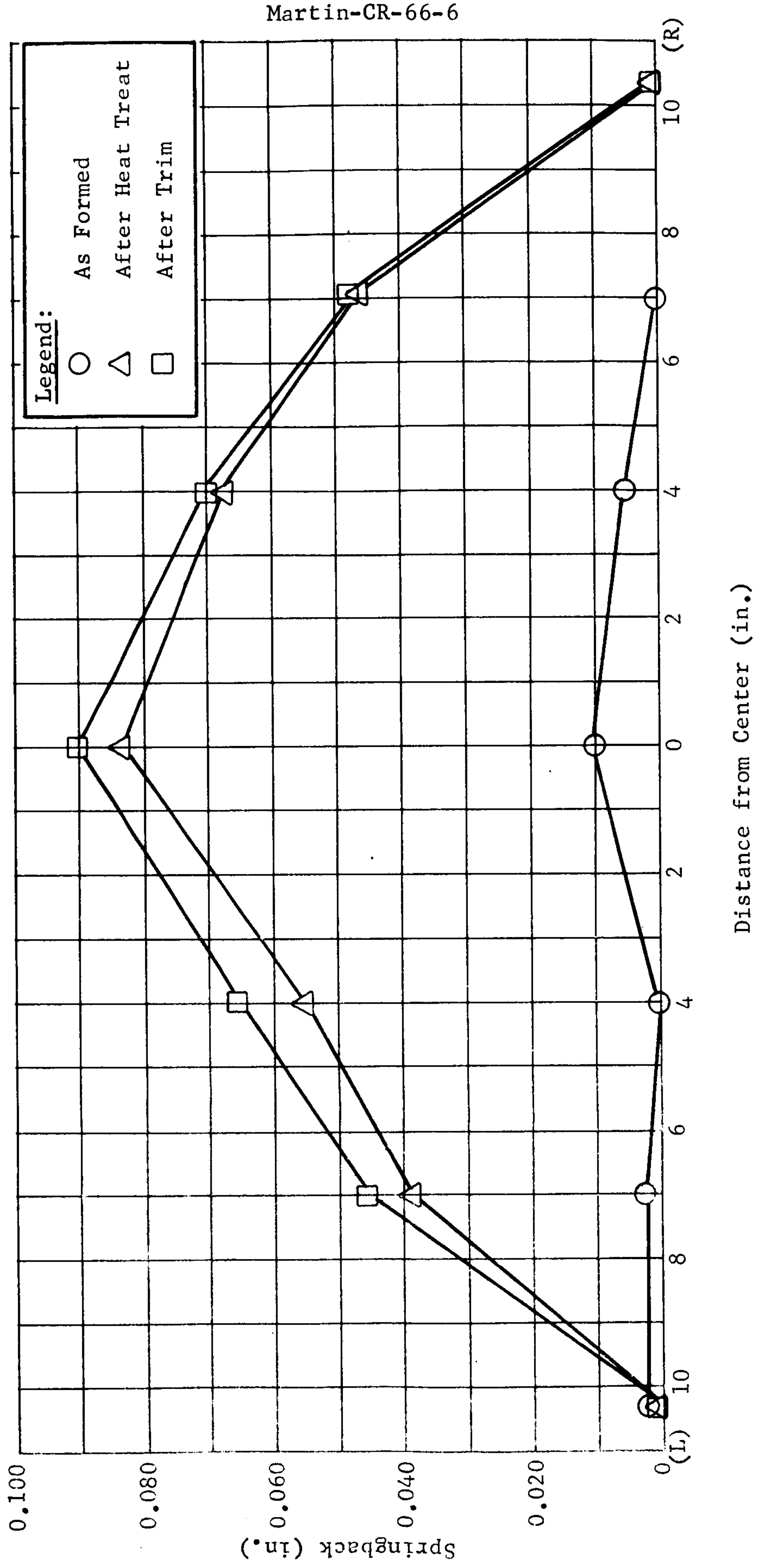


Fig. III-13 Contour Deviation after Explosive Forming of 2014-0 Aluminum

Ultimate Tensile Strength (psi)	22,100
0.2% Offset Yield Strength (psi)	15,000
Elongation in 2 in. (%)	25.2

As with the 2014 material, 2219 material properties responded well to heat treatment after forming since the high temperature solution process removes the effects of explosive straining. Properties shown below are typical for the alloy after forming:

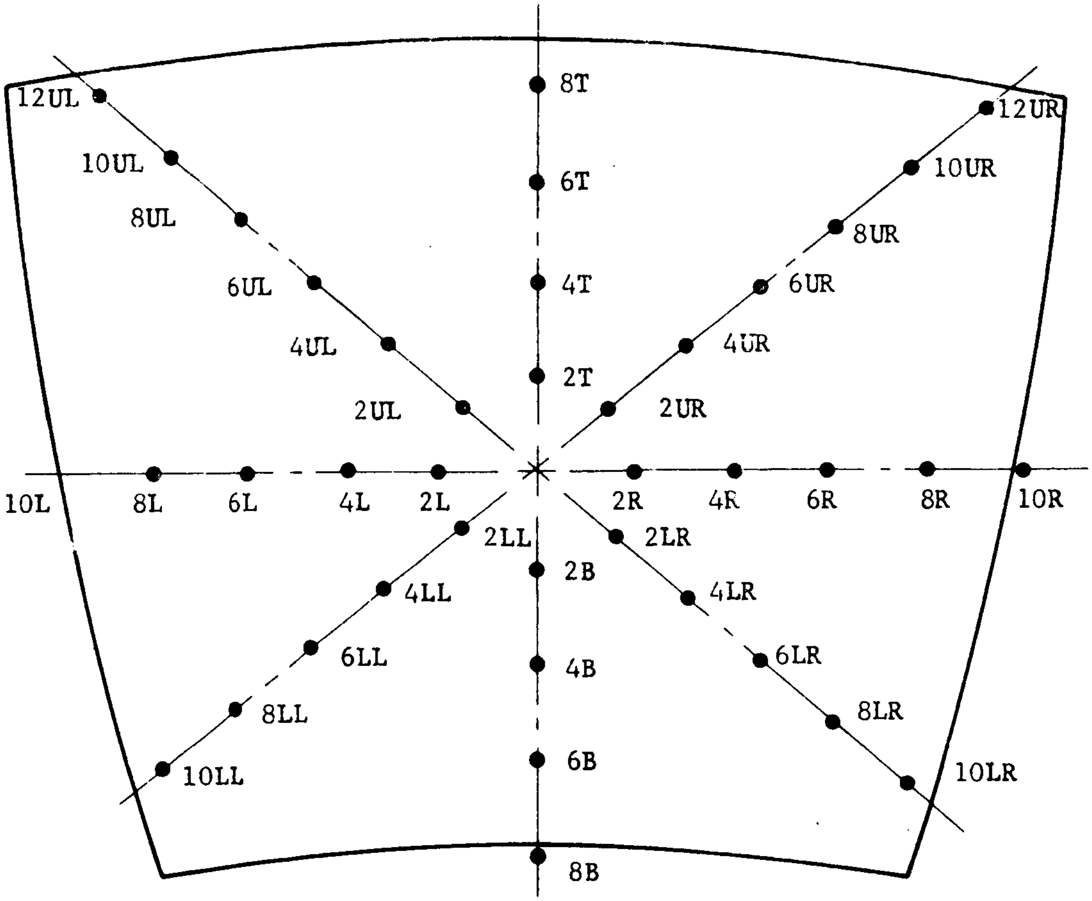
Ultimate Tensile Strength (psi)	55,400
0.2% Offset Yield Strength (psi)	38,300
Elongation in 2 in. (%)	6

Again greater benefits might be realized by forming the alloy in the solution-treated condition immediately after heat treatment.

Blank Stretching - The strain distribution across the 2219-0 blanks was more uniform than for 2014-0 material. In general, strains of from 1 to 5% were prevalent over most of the component surface. Figure III-14 shows a typical blank in plan view with strain measurements indicated. Blank tearing accompanied forming in one case but the tears occurred in the die corners outside of the part trim line, therefore, the breaks were of no consequence to the fabrication of successful parts.

Metal Springback - The springback was low for the explosively formed 2219-0 plate. However, the values were not quite as good as for the 2014-0 or 1020 steel. Figure III-15 shows the contour deviations measured across the formed blank.

Heat treatment of the formed part resulted in little part distortion with an actual decrease in contour deviation. Figure III-15 illustrates the springback observed after thermal processing. Lower springback values were achieved (0.015 in.), however, limited specimens prevented statistical values from being developed. The alloy was solution heat-treated and aged before trimming. The rather stiff panel resulting from the convoluted edges aided in blank restraint and prevented serious distortion from quenching stresses. Trimming of the blank did not seriously affect the measured contour deviations as shown in Fig. III-15. All of the blanks in the program requiring heat treatment were processed in the above manner.



Position	Stretch (%)	Position	Stretch (%)	Position	Stretch (%)
10T		4R	0	12LR	
8T	3.5	6R	0.5	14LL	
6T	0.5	8R	1	12LL	
4T	1.5	10R	2	10LL	13
2T	2	14UL/16UL		8LL	8.5
2B	2	12UL	18	6LL	6.5
4B	2	10UL	7	4LL	3
6B	5	8UL	5	2LL	3
8B	14	6UL	2.5	2UR	0
10B		4UL	0	4UR	1.5
10L	2.5	2UL	1.5	6UR	2
8L	1.5	2LR	0	8UR	4.5
6L	0	4LR	2	10UR	7
4L	1	6LR	4	12UR	10
2L	1	8LR	8.5	14UR	
2R	1	10LR	14		

Fig. III-14 Stretching of 2219-0 Aluminum after Explosive Deformation

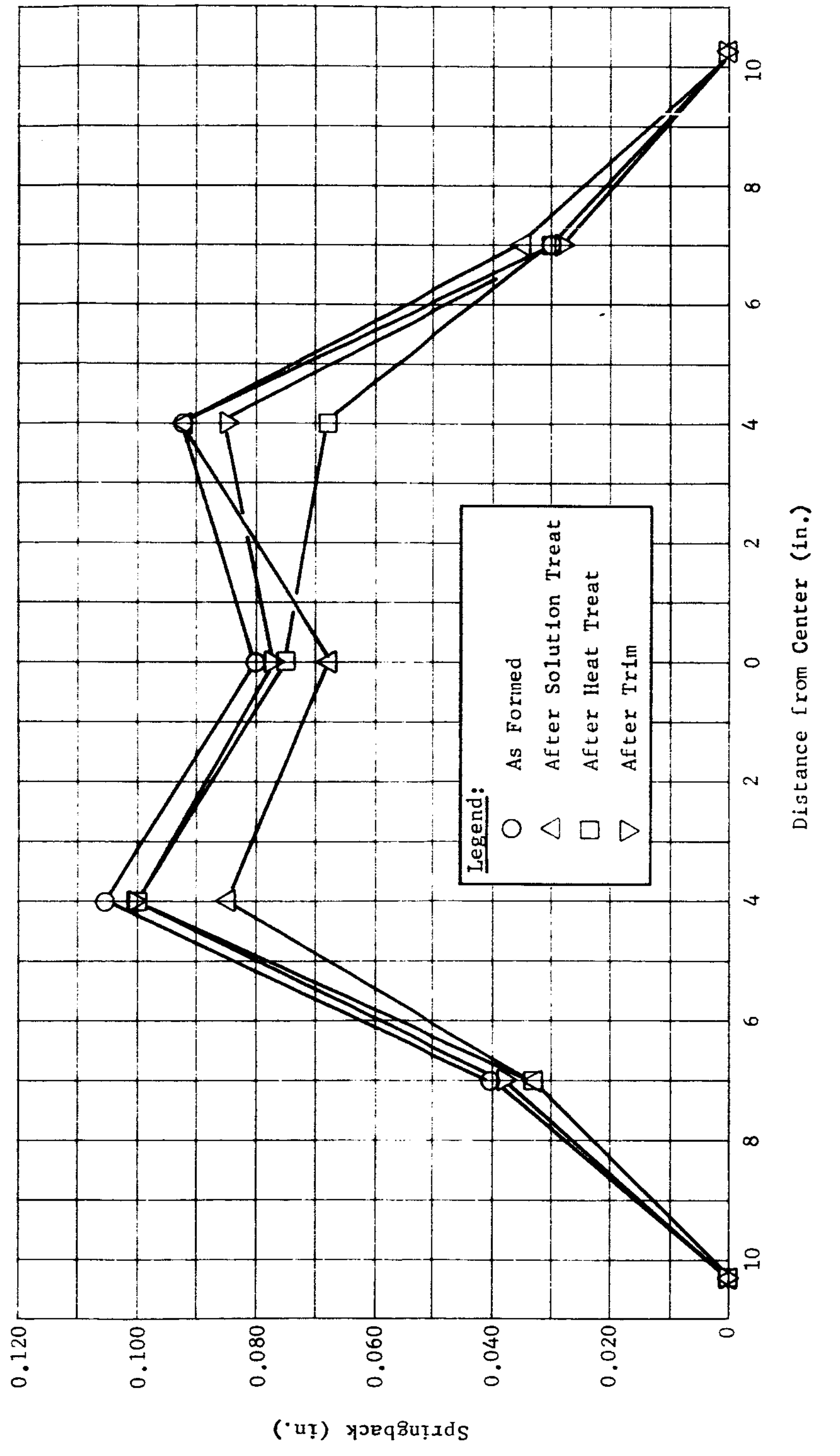


Fig. III-15 Contour Deviation for Explosively Deformed 2219-0 Aluminum

3. 2219-T31 Aluminum Plate

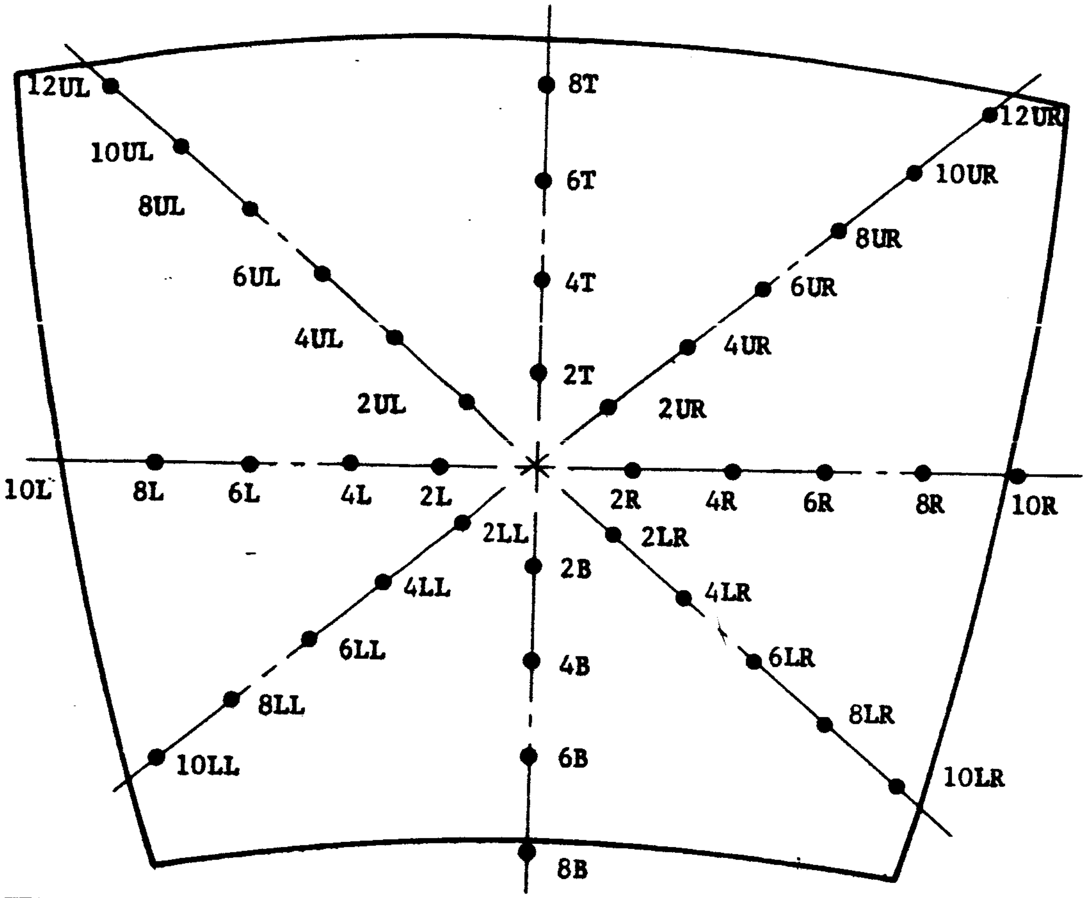
Using complete edge restraint of the 2219-T31 aluminum plate resulted in failure to effect any appreciable forming. Charges varying from central placement to annular location in sizes up to 5950 grains of pressed RDX failed to effect necessary blank stretching. Ring charges consisting of two strands of 400 grain/ft PETN primacord on a 21-in.-diameter caused the clamping bar and holddown clamps to disengage on one side. This caused release of clamping pressure along one side of the part. In addition three clamp screws were deformed by the blast wave. Very little corner deformation occurred using a 3-in. explosive standoff. A pressed charge of RDX weighing 5950 grains located centrally at a 6-in. standoff caused more blank deformation, but still did not effect necessary corner stretching.

A significant amount of difficulty was encountered in trying to seat the blank into the peripheral groove in the die. Corner cracking was present in some cases and the high strength of the alloy prevented routine seating. Bending the edges of the panel into the groove was particularly difficult. Torch heating of the blank periphery was tried in one case to attempt to soften the material enough so that seating might be accomplished more easily. The heating had little noticeable effect on blank behavior.

Because no acceptable parts were produced from this alloy temper, mechanical properties and springback measurements are not presented. Springback measurements were made but the results had little useful meaning. Therefore, their inclusion in the report was not believed to be appropriate. Stretching measurements are shown in Fig. III-16. The partially formed part is presented in Fig. III-17.

4. 7039-0 Aluminum Plate

Several different forming sequences were tried on the 0.250-in. thick 7039 aluminum blanks to effect forming. Sequences included the use of four 500-grain Cyadyn 3 corner shots fired simultaneously, a 10x20x0.025-in. central charge of sheet explosive, and 1200 grains of PETN primacord located in a 2-ft-diameter ring at a 2-in. standoff. The corner charges and sheet explosive were located 6 in. above the blank surface. Of the three charge arrangements the primacord ring gave the best results. It was necessary to use a two-shot forming sequence involving the use of primacord rings containing 1200 and 1500 grains of explosive, respectively.



Position	Stretch (%)	Position	Stretch (%)	Position	Stretch (%)
10T		4R	2	12LR	
8T	3	6R	1	14LL	
6T	2	8R	1.5	12LL	0
4T	2	10R	5	10LL	6.5
2T	1	14UL/16UL		8LL	4
2B	2	12UL	4.5	6LL	4
4B	5	10UL	6	4LL	4
6B	11	8UL	3	2LL	3
8B		6UL	1.5		
10B				2UR	0.5
10L	2.5	4UL	2.5	2UR	0.5
8L	1	2UL	0.5	4UR	2
6L	1.5	2LR	1	6UR	2.5
4L	0	4LR	2	8UR	2.5
2L	1	6LR	6	10UR	
2R	0.5	8LR	4.5	12UR	
		10LR	0	14UR	

Fig. III-16 Stretching of 2219-T31 Aluminum after Explosive Deformation

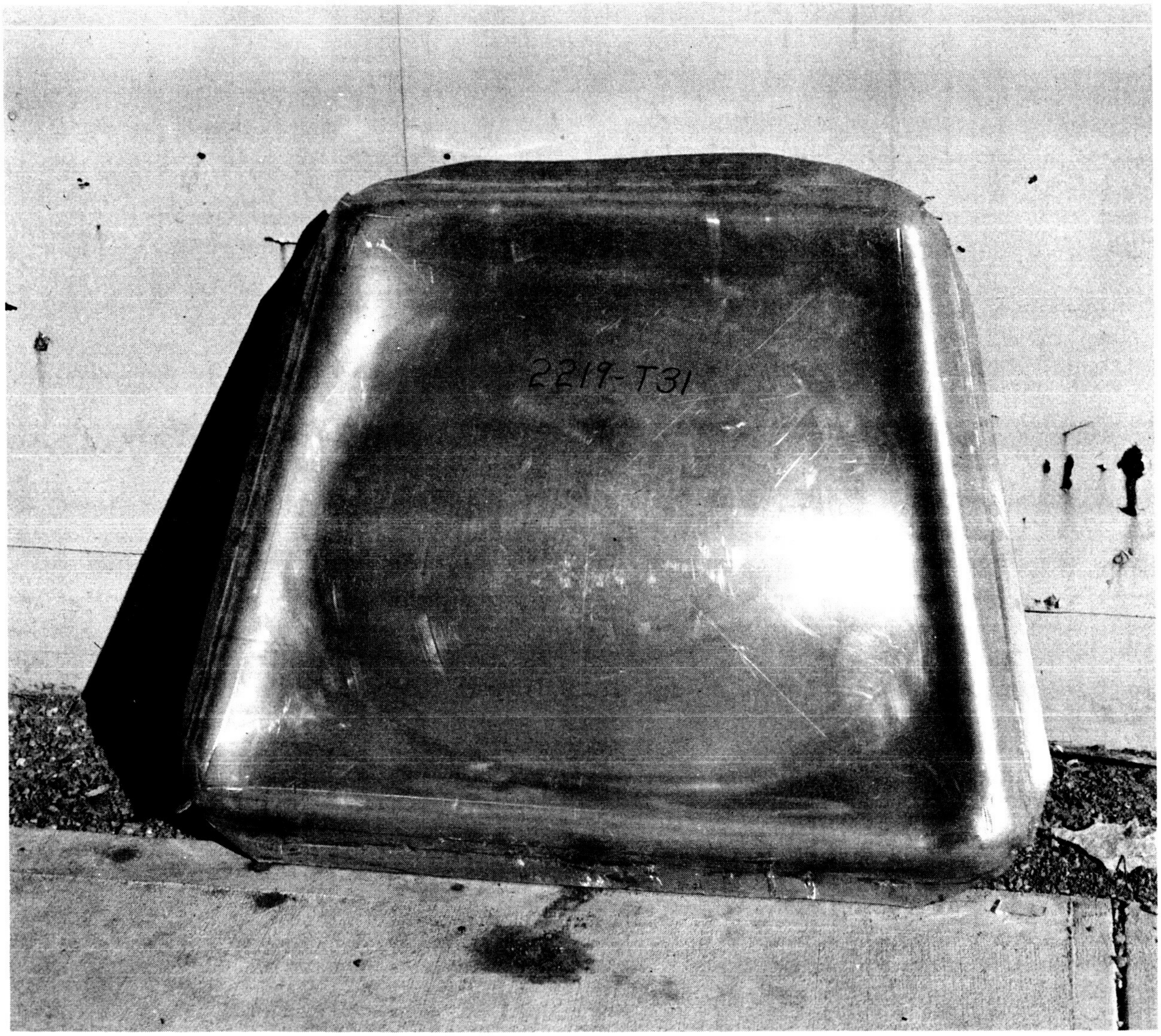


Fig. III-17 Partially Formed 2219-T31 Part

The 7039-0 blank did not create any problems during the seating operation and there was little tendency toward tearing at the blank corners. It was possible to use clamping force as low as 5140 lb/in. to effect blank seating and sealing against air leakage.

Mechanical Properties - The properties of 7039-0 are very similar to 2219-T31 according to test data obtained during the study. The as-received material properties for the 7039 alloy are shown below:

Ultimate Strength (psi)	53,100
0.2% Offset Yield Strength (psi)	37,300
Elongation in 2 in. (%)	26.5

The properties after heat treatment are also similar with the exception that 7039 possesses much higher elongation. The heat treated properties of the alloy are as follows:

Ultimate Tensile Strength (psi)	59,100
0.2% Offset Yield Strength (psi)	49,700
Elongation in 2 in. (%)	15.5

Even though the properties of 7039-0 are similar to those of 2219-T31 the formability of 7039-0 is much superior to that of 2219-T31. It was established in a previous study* that significant strengthening of 2219-T31 occurs from explosive deformation. In fact, by a modified aging cycle (see Table II-4), a full alloy response to achieve 2219-T81 properties can be obtained. In the case of 7039 aluminum, significant strengthening occurs from explosive deformation. The ultimate strength increases by about 11,000 psi, the yield strength by about 5,000 psi, while there is a rather drastic reduction in elongation. The typical values obtained for 7039 after forming are:

Ultimate Strength (psi)	64,100
0.2% Offset Yield Strength (psi)	42,600
Elongation in 2 in. (%)	10.3

*NASA Contract NAS8-11794.

Thus it appears that it may be possible to form 7039-0 material and obtain design properties very near those for aged material since the above mechanical properties are averages for material removed from the center and edges of the formed blank. Because the aging cycle for 7039 aluminum is a rather complex and lengthy process, use of explosively formed, annealed material has many advantages.

Blank Stretching - Using primacord rings on a 2-ft-diameter circle, the most consistent blank stretching was obtained. Figure III-18 shows the strain distribution over the blank surface. Note that a maximum strain of only 9% occurs near the blank corner while the remainder of the blank had indicated strains in the range of 1 to 3% for the major portion of the surface. Thus the uniform mechanical properties obtained from deformed material should be expected. It is very difficult to obtain completely uniform strain over the entire component surface, however, it appears quite feasible to achieve uniformity to within 2 to 3% over the greater portion of the part. If adequate stretching is to be achieved during forming, corner recesses are necessary to preclude low strains near the part trim lines.

Metal Springback - The contour deviations found for explosively formed 7039-0 aluminum were greater than for 2014-0 material. Figure III-19 shows the springback curves for as-formed; as-formed and heat-treated; and as-formed, heat treated, and trimmed material. Note that contour deviations are reduced after the untrimmed part is subjected to the solution treating cycle. Subsequent aging and trimming tend to reduce the extent of contour deviations within the limits desired, i.e., 0.025 to 0.030 in. Slightly higher charges could possibly be used to effect more deformation at the die corners to reduce springback. In addition, the additional work induced in the blank may yield mechanical properties in the region of fully heat-treated material that would preclude the necessity for heat-treatment and thus maintain the low contour deviations. More work is required to develop optimum conditions for minimum springback.

5. 1020 Carbon Steel

No difficulties were encountered during the blank seating operation. Bolt torque of 400 ft-lb, corresponding to clamping force of 6550 lb/in., was necessary to prevent air leakage into the evacuated die corners and completely seat the blank in the peripheral groove. The 1020 steel material is very difficult to deform once an initial forming operation has been accomplished. Central charges of 2000 grains of Cyadyn 3 dynamite at a 6-in. standoff appeared to yield the best results. Die corner charges of 600 grains of Cyadyn 3 each fired simultaneously at the same standoff distance did not result in anywhere near the same deformation. Two strands of 100 grain/ft PETN primacord coiled on a 2-ft-diameter circle at a 2-in. standoff distance resulted in greater metal deformation but the central charges produced the greatest draw. Once an initial forming shot was fired very little was gained by subsequent shots of similar size.

Mechanical Properties - The starting material from 0.125-in.-thick stock showed the following properties:

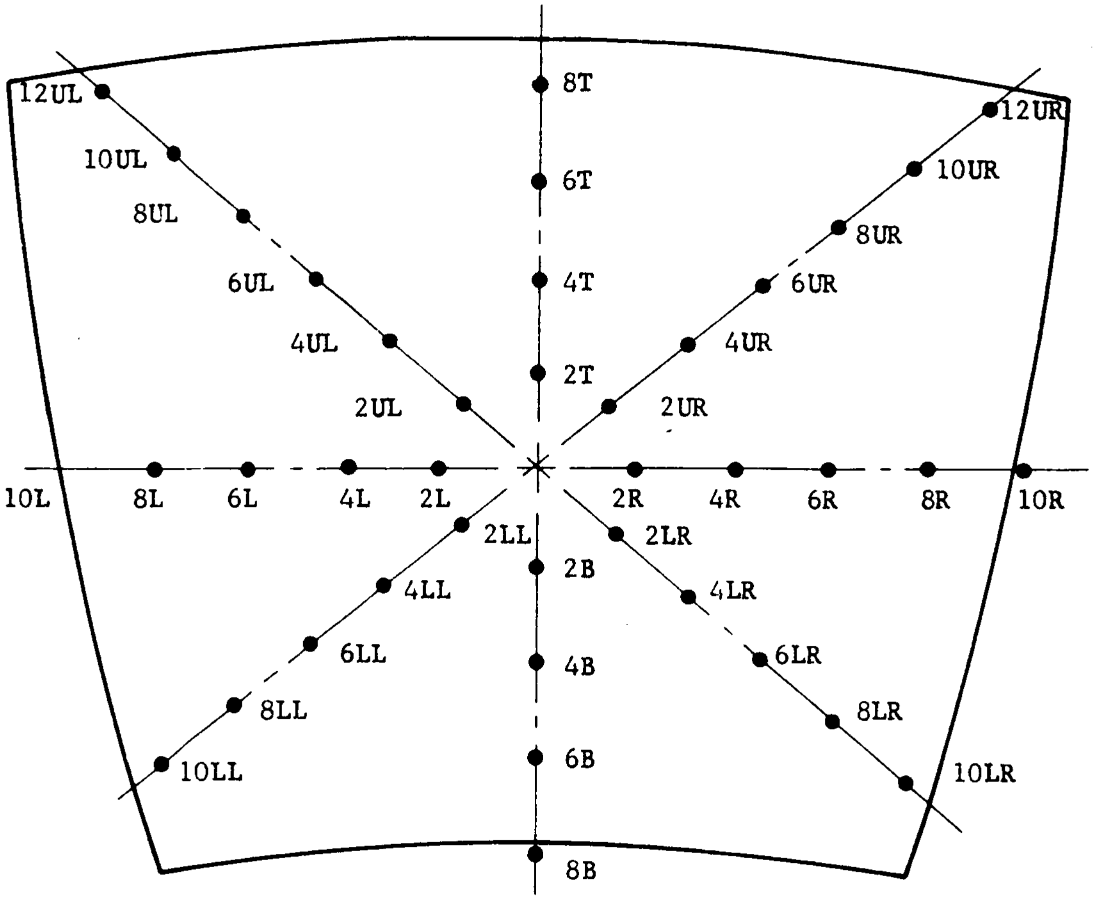
Ultimate Tensile Strength (psi)	45,500
0.2% Offset Yield Strength (psi)	32,300
Elongation in 2 in. (%)	35.6

After explosive forming, there was a gain in both ultimate and yield strengths of about 3,000 and 6,000 psi, respectively, with an attendant loss in elongation. The properties were similar for material removed from the top, left, and bottom of the blank, but were lower on the right side of the blank. Thus property uniformity was not achieved. The more typical blank properties after forming were:

Ultimate Tensile Strength (psi)	48,600
0.2% Offset Yield Strength (psi)	38,800
Elongation in 2 in. (%)	23.0

It does not appear that explosive deformation has an appreciable influence on the properties of 1020 steel when formed in a male die.

Blank Stretching - Figure III-20 shows the blank plan view and attendant metal stretching for specific locations on the blank. In general, strains from 0 to 4.5% were obtained over the entire blank except at the very corners where elongations up to 11.0% were recorded. Most of the deformation occurs in the first shot of a multiple shot forming sequence, and therefore little is gained by using a number of shots to obtain forming.



Position	Stretch (%)	Position	Stretch (%)	Position	Stretch (%)
10T		4R	0	12LR	
8T	1	6R	0.5	14LL	
6T	0	8R	0	12LL	
4T	0	10R	2	10LL	7
2T	0	14UL/16UL		8LL	3
2B	0.5	12UL	8.5	6LL	1
4B	1	10UL	4.5	4LL	2
6B	1.5	8UL	1.5	2LL	0
8B	3.5	6UL	1.5	2UR	0
10B		4UL	0	4UR	0
10L	2	2UL	0	6UR	1
8L	0.5	2LR	0	8UR	1.5
6L	0.5	4LR	1	10UR	4
4L	0	6LR	0.5	12UR	7.5
2L	0	8LR	3	14UR	
2R	0	10LR	6		

Fig. III-16 Stretching of 7039-0 Aluminum after Explosive Deformation

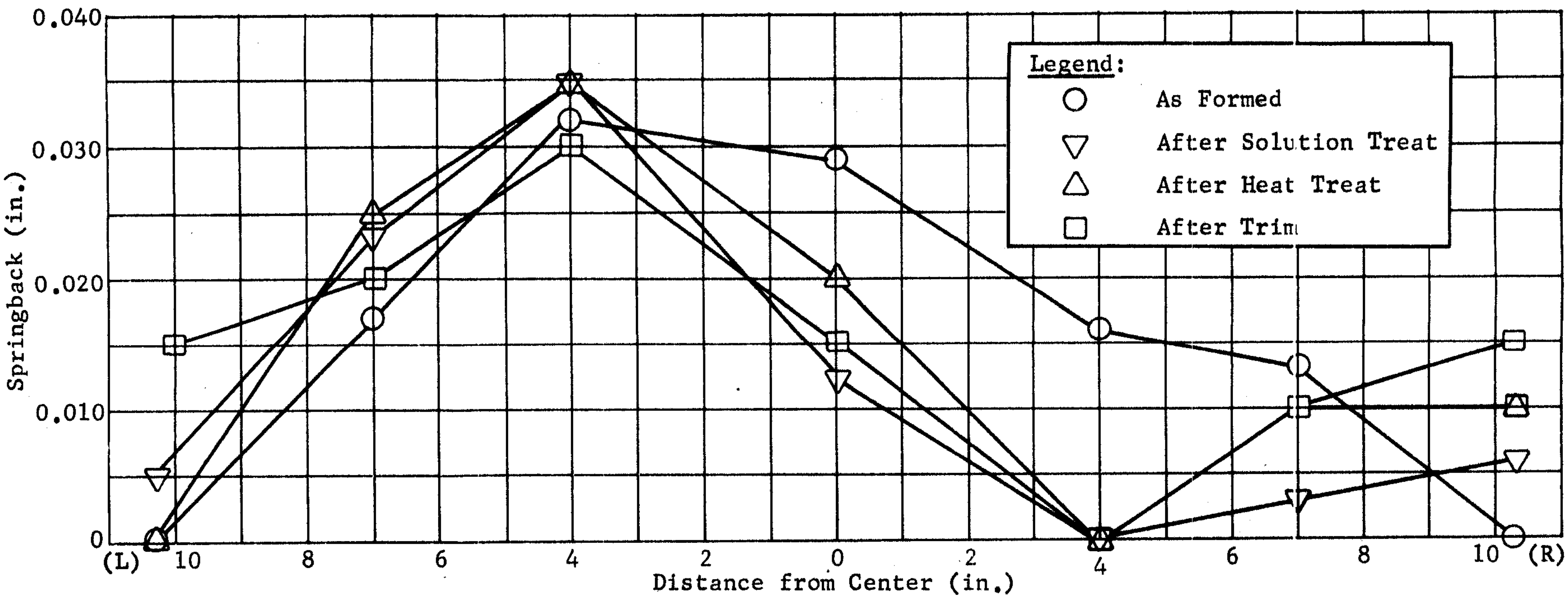
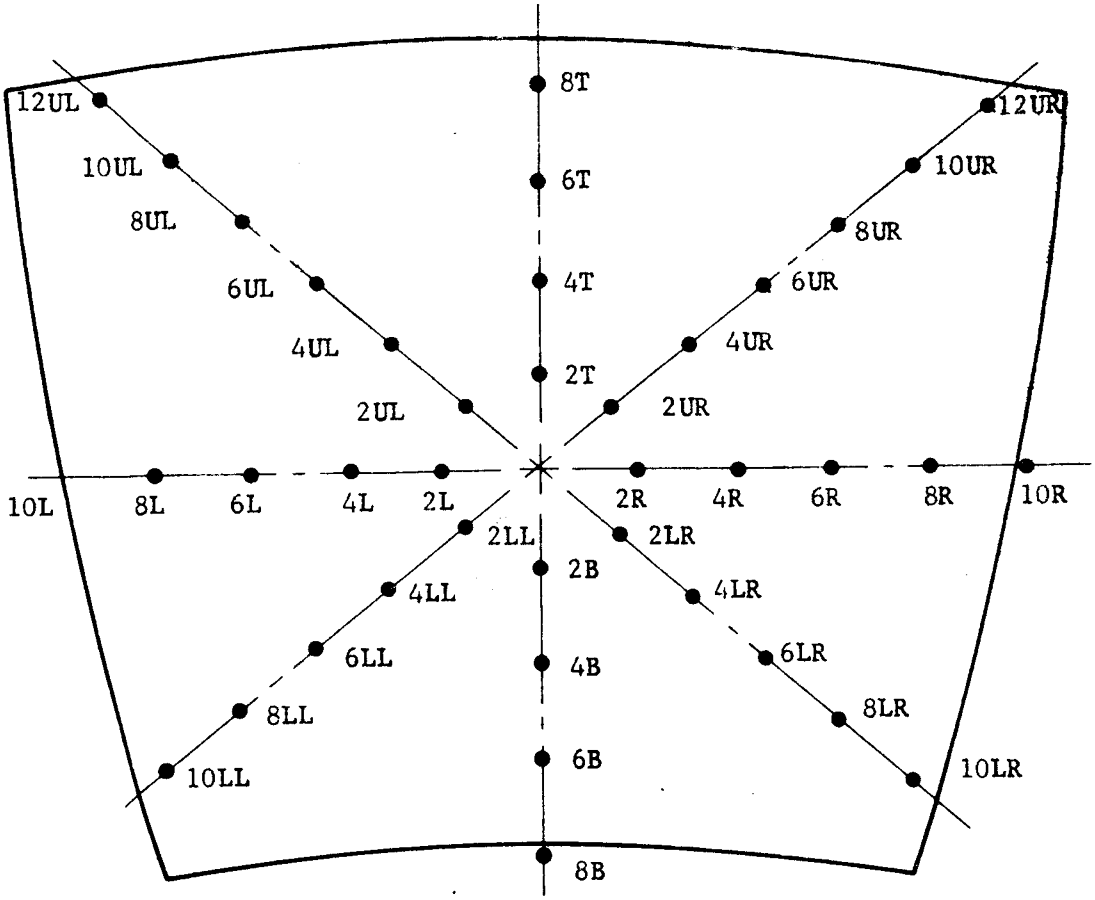


Fig. III-19 Contour Deviation for Explosively Deformed 7039-0 Aluminum



Position	Stretch (%)	Position	Stretch (%)	Position	Stretch (%)
10T		4R	0.5	12LR	
8T	0.5	6R	0.5	14LL	
6T	0.5	8R	0	12LL	7.5
4T	0.5	10R	2	10LL	6
2T	0.5	14UL/16UL		8LL	2.5
2B	0	12UL	11.5	6LL	1
4B	0.5	10UL	4.5	4LL	0.5
6B	2	8UL	2	2LL	0
8B	4.5	6UL	1	2UR	0
10B	5	4UL	0.5	4UR	1
10L	1	2UL	1	6UR	0.5
8L	0.5	2LR	1.5	8UR	1.5
6L	0.5	4LR	0.5	10UR	4.5
4L	0.5	6LR	2.5	12UR	11
2L	0	8LR	2	14UR	
2R	2	10LR	8		

Fig. III-20 Metal Stretching of 1020 Low Carbon Steel after Exposive Deformation

Metal Springback - Part contour deviation from the die was quite low for the 1020 steel as shown in Fig. III-21. In comparison to the aluminum alloys, the steel yielded the lowest contour deviation from the die.

6. Titanium 6Al-4V

A great deal of difficulty was experienced in attempting to form the 0.050-in.-thick Ti-6Al-4V annealed sheet. Attempts were made to form unsandwiched material since the charge requirements are minimal. However, several anticipated problems caused failure when a centrally located charge of 500 grains of Cyadyn 3 dynamite at a 6-in. standoff was used. In general, the primary problem stems from the poor notch toughness of the alloy. When using a blank size of 38½ x 35½-in., metal folding at the die corners caused cracks to form during the seating operation.

In addition, once seated, radial ripples running from the part apex to the die corners form when the die cavity is evacuated. Figure III-22 illustrates the effect which is accentuated after forming. When the explosive is detonated, the cracks which form at the die corners during seating extend and prevent any further forming on the part. The radial ripples enlarge and begin folding, and metal puckering at the inner die draw radius along the sides of the die yield small cracks. There is no appreciable change in blank behavior when using truncated edges, which effectively reduce the blank size. Figure III-23 shows a modified blank form used in experimentation.

Shims had to be used during the seating operation due to the thickness of the material. No particular difficulty was encountered in seating the blank. Evacuation of the die cavity could be achieved even with small corner cracks present.

Since considerable success had been realized in the past using sandwiching techniques for the deep drawing of Ti-6Al-4V, this technique was used in this program. The 0.050-in.-thick Ti-6Al-4V blank was sandwiched between two sheets of 0.075-in.-thick carbon steel. The composite blank was seated without undue difficulty to full groove depth. Clamping force of about 5140 lb/in. was necessary to seat the composite and prevent air leakage into the die. During the seating operation and subsequent die evacuation there was little evidence of the radial ripples seen when unsandwiched material was formed. In addition, minor corner cracking was experienced even after an initial forming operation.

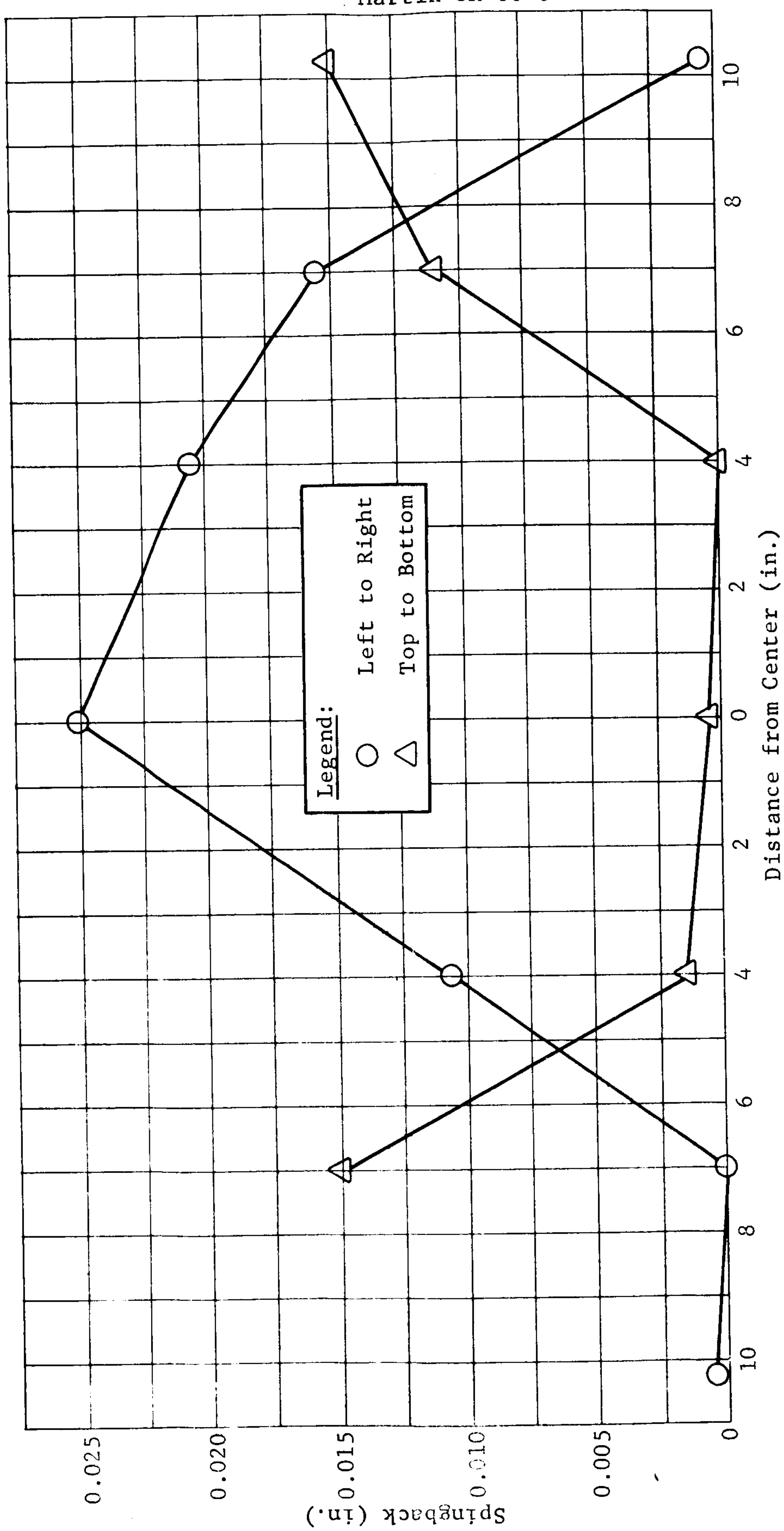


Fig. III-21 Contour Deviation for Explosively Deformed 1020 Steel

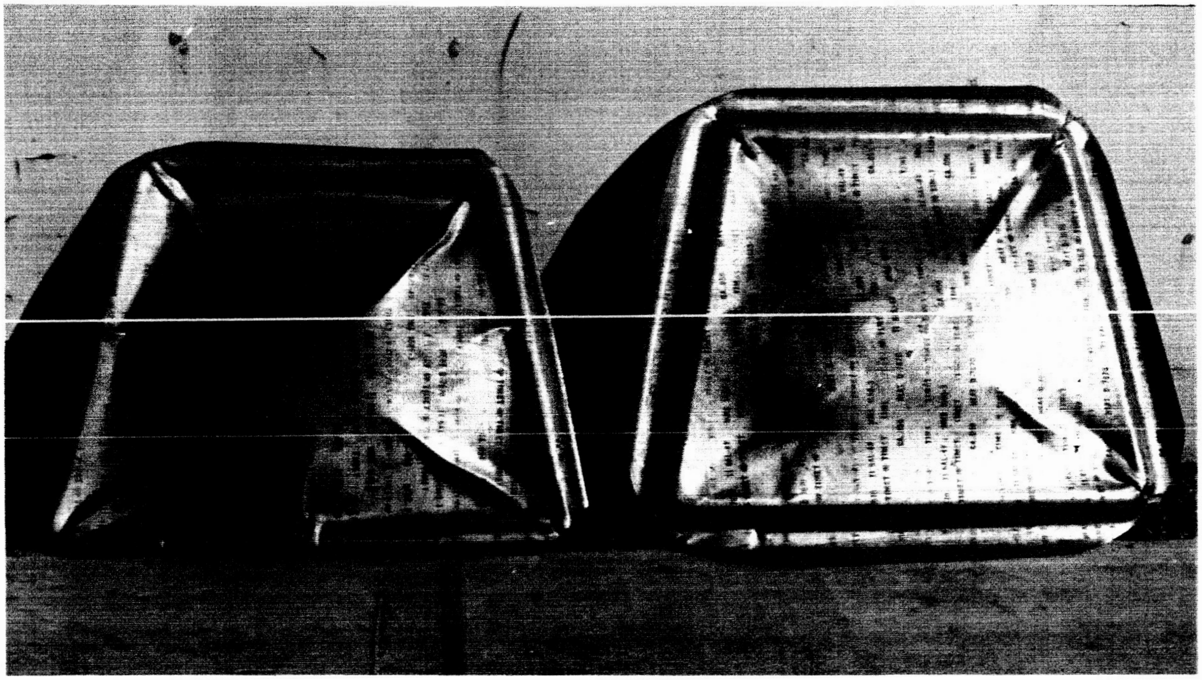


Fig. III-22 Wrinkling of Ti-6Al-4V Alloy after Explosive Forming

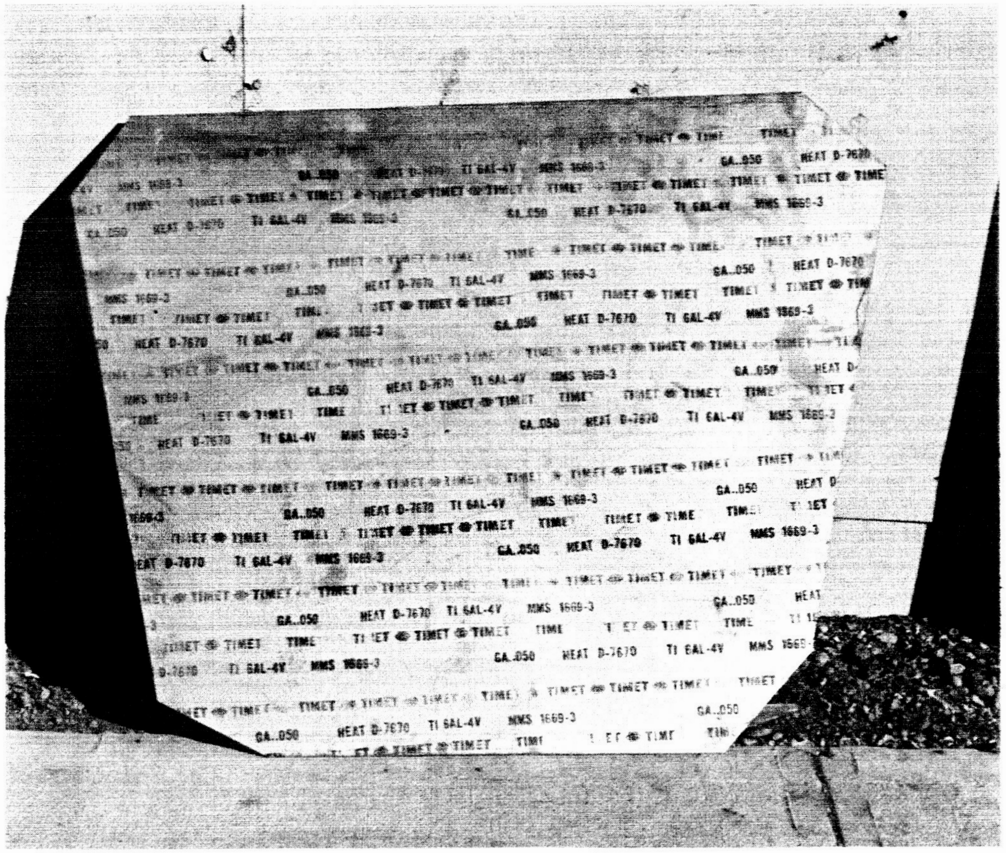


Fig. III-23 Modified Blank Form

The radial ripples were flattened considerably using an X pattern of PETN primacord of 1200 grains total at 3-in. standoff. If there were more time we would have removed the lower 0.075-in. steel sheet and formed it completely, but perhaps with a couple of tears, such as those already begun at two corners, the additional deformation may have caused failure. Figure III-24 depicts the part deviation from true contour, both as-formed and and trimmed.

In summary, it was possible to explosively form 2014-0, 2219-0, and 1020 steel, and 7039-0 alloys to produce gore segment parts (Fig. III-25 and III-26). Summary curves of as-formed material allow suitable comparisons to be made. Figures III-27 and III-28 present the contour data obtained during the program. The 2219-T31 material could not be formed to acceptable tolerances using charge sizes within the capability of the tooling used. In addition the very large charge requirement on the 1/7-scale die would result in charge sizes on the full-scale beyond the capability of any existing facility in the United States.

Note that the contour measurements obtained on the blank from top to bottom (Fig. III-27) were in general somewhat lower than measurements obtained from left to right (Fig. III-28). This was a result of greater blank stretching in the top to bottom direction. However, even for the worst case, the deviations were 0.060-in., which would result in springback of about 0.420-in. on the full scale.

Metal thin-out measurements were made using a Vidigage thickness tester shown in Fig. III-29. However, the amount of thinout recorded within the confines of the trim line was so low that complete measurements for all alloys were not necessary. Thickness deviations of only 0.002 in. were measured, which is well within the tolerance for sheet or plate thickness used. Thus for all practical purposes thin-out was nonexistent.

The properties of 7039-0 alloy underwent the most modification of any of the alloys. Explosive deformation has only a moderate influence on the properties of 2014-0, 2219-0, and 1020 steel. From past experience it is known that the properties of 2219-T31 are significantly influenced by explosive deformation while there is little change in properties for Ti-6Al-4V even for draws comparable to a $\sqrt{2}$:1 ellipsoid shape.

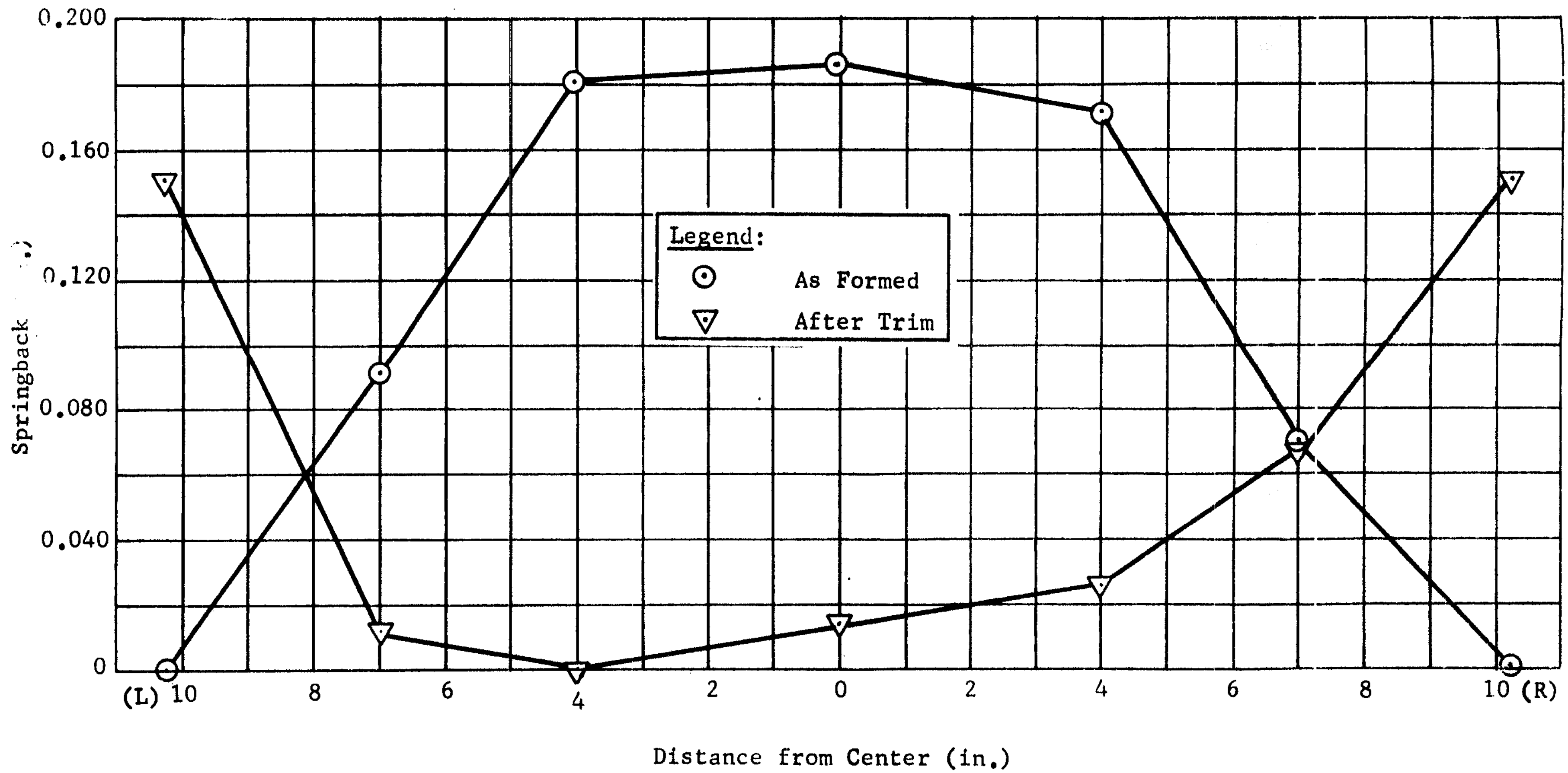


Fig. III-24 Contour Deviation for Explosively Deformed Ti-6Al-4V

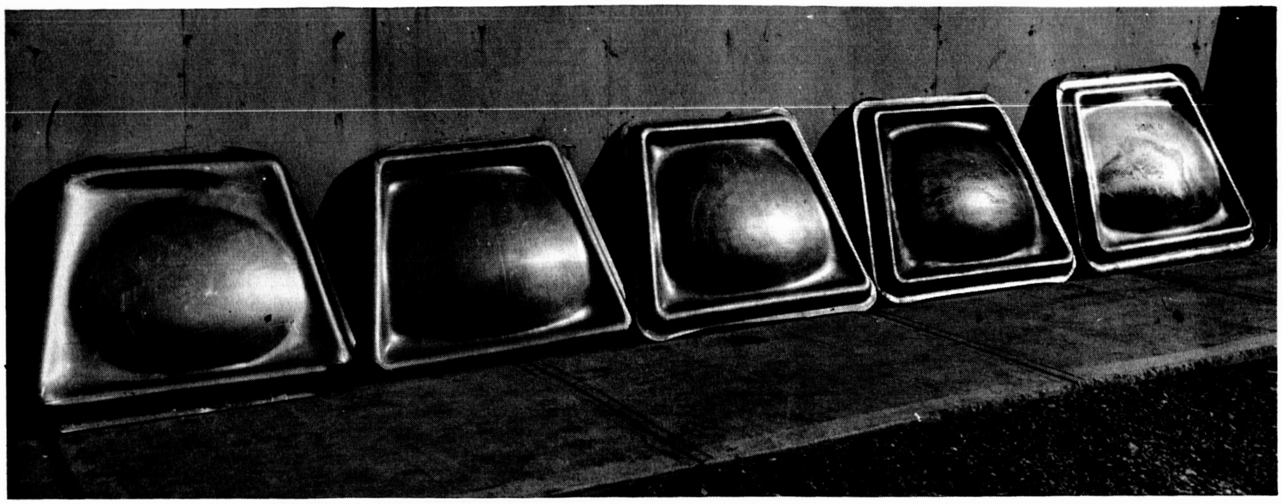


Fig. III-25 Five Segment Parts Explosively Formed

Fig. III-26 Three Segment Parts Explosively Formed

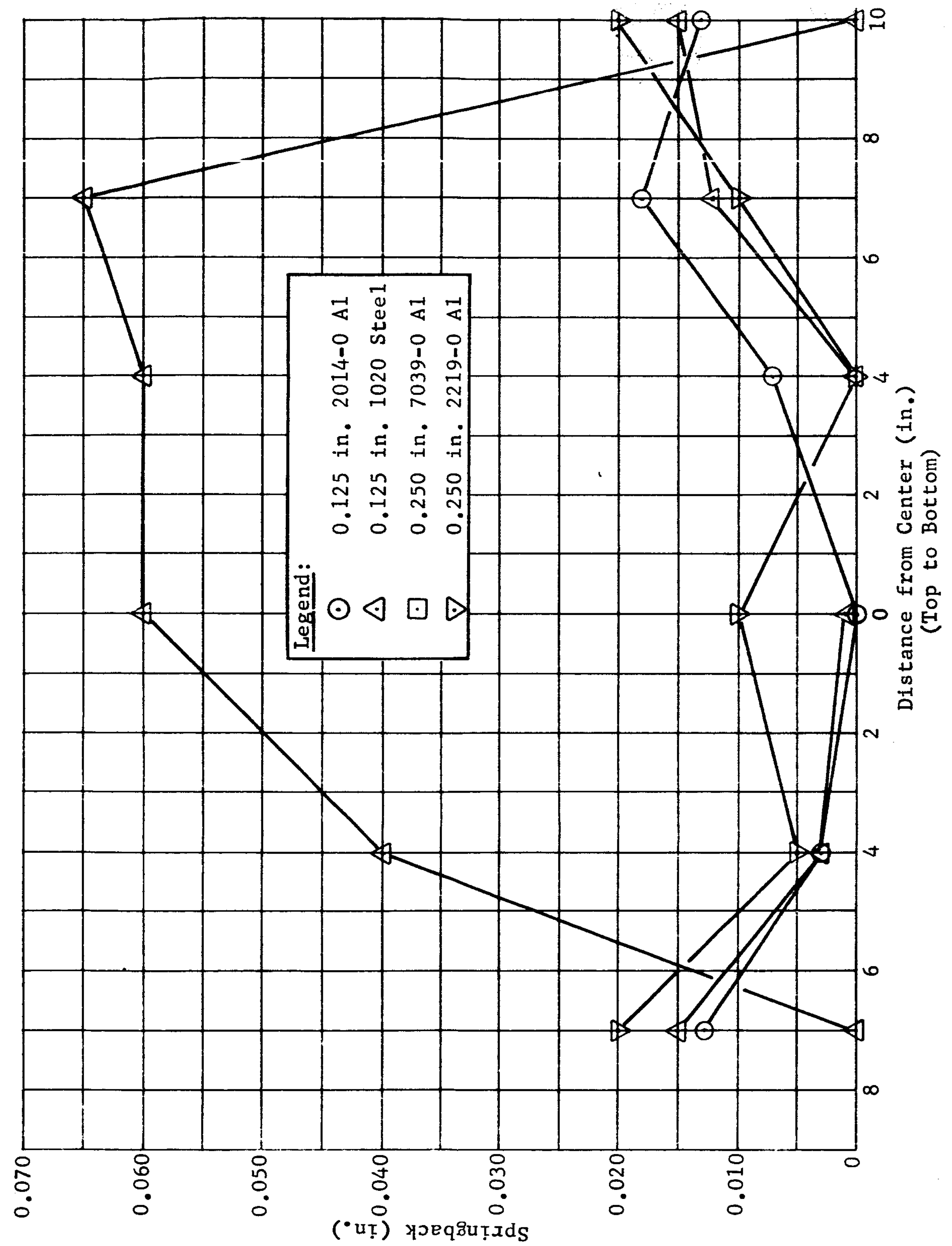


Fig. III-27 Summary Curves for Contour Measurements Made During the Program (As Formed)

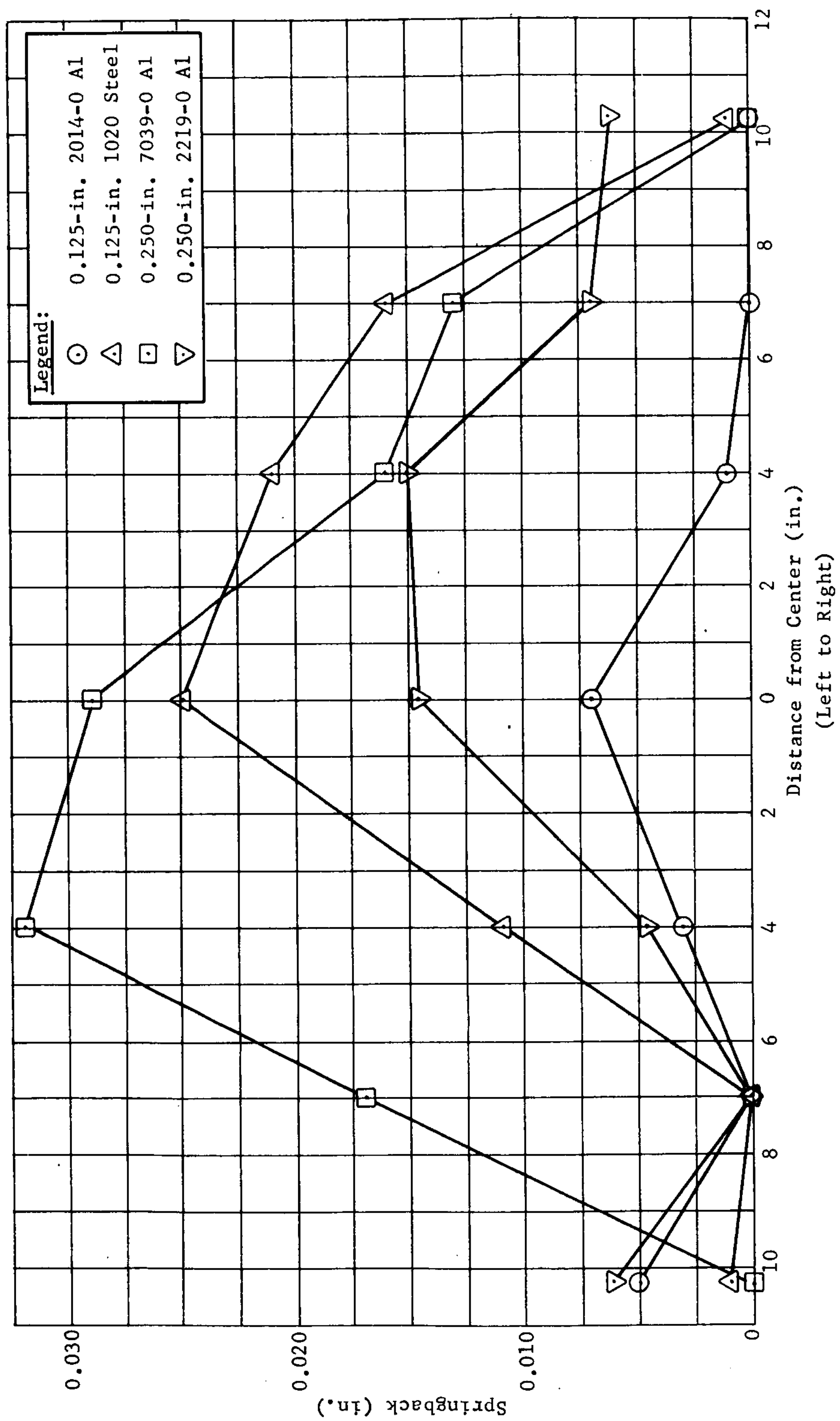


Fig. III-28 Summary Curves for Contour Measurements Made During the Program (As Formed)

Fig. III-29 Vidigage Thickness Measurements of Explosively Formed Components

IV. SCALING CRITERIA

Based on the results of this program, Table IV-1 presents the criteria necessary to explosively form gore segment parts on a male forming die from each of the materials studied.

Table IV-1 Scaling Criteria for Explosive Forming of Full-Scale Gore Segments

Alloy	Blank Size (in.)	Hold-down Force (lb/in.)	Blank Thickness (in.)	Explosive (lb)	Explosive Standoff (in.)
2014					
1/7 Scale	30 x 37.5	6850	0.125	0.143	6.0
Full Scale	210 x 262.5	4790	0.875	49.0	42.0
2219-0					
1/7 Scale	26.5 x 32.5	5140	0.250	0.172*	2.0
Full Scale	185.5 x 227.5	3600	1.750	59.0	14.0
2219-T31					
1/7 Scale	26.5 x 32.5	6550	0.250	0.572*	3.0
Full Scale	185.5 x 227.5	4580	1.750	196.0	21.0
7039-0					
1/7 Scale	26.5 x 32.5	5140	0.250	0.428*	2.0
Full Scale	185.5 x 227.5	3600	1.750	147.0	14.0
Ti-6Al-4V†					
1/7 Scale	25.5 x 32.5	5140	0.050	0.500	6.0
Full Scale	178.5 x 227.5	3600	0.350	171.5	42.0
1020					
1/7 Scale	28.5 x 35.5	6550	0.125	0.172*	2.0
Full Scale	199.5 x 248.5	4580	0.875	59.0	14.0

*PETN primacord, 2-ft-diameter ring.
†Carbon steel cover sheets needed -
1/7 scale: 0.075 in. thick;
Full scale: 0.525 in. thick.

V. CONCLUSIONS AND RECOMMENDATIONS

The results of this investigation have led to the following conclusions:

1) Positive edge restraint of blanks explosively formed on a male forming die greatly reduces springback when compared to techniques allowing free edge pull-in;

2) Rather uniform stretching can be achieved within the confines of the part trim line using the male die concept;

3) The 7039-0 aluminum appears amenable to explosive strengthening to the extent that subsequent heat treatment may be unnecessary;

4) Blank thinout after explosive forming is practically nonexistent (on the order of 0.002 in.);

5) The thickest materials studied all responded well to primacord ring charges while the thinner metals were better formed with central charges;

6) Heat treatment of parts after forming, which includes a solution heat treat step, destroys the low springback achieved on annealed material;

7) Design criteria for dies, holddown rings, and clamps developed under Phase I proved to be quite satisfactory based on die performance;

8) Within the time and money limitations of this contract, suitable explosive forming techniques could not be developed for 2219-T31 and Ti-6Al-4V alloys.

Several areas of additional work are suggested from this study. Recommendations for future work are listed as follows:

1) Studies of solution-treated material should be conducted to eliminate problems of distortion due to quenching stresses;

2) Further research is necessary to explosively form gore segments out of 2219-T31 and Ti-6Al-4V alloys;

3) Subscale studies should be conducted on scaled thicknesses to permit the development of criteria suitable for design thicknesses used on the full scale;

4) Better techniques for blank seating, alignment, and contour measurement should be developed;

5) Improvements in charge size and placement are necessary to reduce charge requirements and improve metal deformation;

6) Subscale test domes fabricated from explosively formed gores would prove the value of reduced springback parts.

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