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ASSESSMENT OF FABRICATION METHODS FOR 70 MM LAWT WARHEAD BODIES

C. T. Olofson, et al

Battelle Columbus Laboratories

Prepared for:

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FINAL TECHNICAL REPORT

on

ASSESSMENT OF FABRICATION METHODS
FOR 70 MM LAWT WARHEAD BODIES

to

GROUND EQUIPMENT AND MATERIALS DIRECTORATE
U.S. ARMY MISSILE COMMAND
REDSTONE ARSENAL, ALABAMA 35809

by

C. T. Olofson and A. L. Hoffmanner

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ABSTRACT

This is the final report for the program "Assessments of Fabrication Methods for 70 mm LAWT Warhead Bodies", for The Ground Equipment and Materials Directorate, U. S. Army Missile Command, Redstone Arsenal, Alabama. This program was performed by Battelle's Columbus Laboratories on U. S. Army Contract DAAH01-73-C-0142 during the period from April 15 through July 15, 1974. This work was performed in the Metalworking Section, Mr. T. G. Byrer, Section Manager. Mr. C. T. Olofson was the project engineer and program management was provided by Dr. A. L. Hoffmanner, Associate Manager, Metalworking Section.

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SUMMARY

The results of this program have shown that metalworking processes can be used to achieve a cost reduction in excess of 60 percent when compared with conventional machining of either solid rounds or tubes. The most significant cost reduction arises from efficient utilization of material achieved by precision metalworking. The following processes appeared most promising for providing low-cost production of the LAWT missile body.

- ° Extrusion of the finished shape followed by finishing machining, and
- ° Precision radial forging of either a rough extruded or rough drawn preform to provide a finished shape.

Regardless of the forming method, significant machining would be required to finish the product. In principle, radial forging possesses the greatest capability for producing a precision shape. However, this precision has not been demonstrated on structures similar to the LAWT. This demonstration would require the use of some novel tooling designs which are described in the text in terms of their utility and potential risk.

The process exhibiting the least risk and one of the lowest costs was combined forward-backward extrusion. The extrusion sequence, starting from a round billet, is described in the text. This process would involve a sequence of operations incorporating upsetting, back extrusion, piercing and blanking, and combine forward-backward extrusion to produce a semi-finished product from rod. The most significant features of this process are its low cost, the several production demonstrations on parts similar to the LAWT, and its adaptability to automated production.

The two processes selected as being most promising provided the lowest cost estimates for producing the target LAWT shape. The costs were in the range of \$3.50 to \$4.00 per piece. These costs include: material, forming, and machining cost to produce the semi-finished target shape. These costs do not represent the total finished cost for the LAWT missile

body which would also include drilling radial holes, milling, and finishing of radii to the specified tolerances. These additional costs were not specifically considered in the cost analyses because they were common to all finishing operations, independent of the forming process which was used.

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INTRODUCTION

The program conducted for the U. S. Army Missile Command from April 15 through July 15, 1974, investigated alternative manufacturing methods for producing the 70-mm LAWT warhead body. The objective was to determine the technical feasibilities, production potentials, and unit costs involved for each method when based on a production quota of 40,000 units per month to produce the warhead body from the aluminum alloy 7075 heat treated to the T6 condition (yield stress range 30,000 to 85,000 psi). This report presents the findings of this study.

The aluminum alloy 7075 is not considered to be a readily formable alloy(1) in either the T6 or TO condition. However, recent work has been performed(2,3) to improve formability by melting practice and thermal-mechanical treatment. This work led to the current development

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* References listed at end of report.

of production forming of aluminum alloy cartridge cases[4]. The major problem in this product development was poor transverse properties leading to longitudinal splitting during forming and service. Although significant improvements were incorporated into the cold forming process for cartridge cases, several (four) intermediate annealing treatments are required. Warm forming could be used to avert the annealing treatments as indicated by the tensile test results in Table 1[5]. These data show that the yield stress drops and ductility increases significantly above 300 degrees F. Holding time at temperature has a significant effect on the temperature dependence of the mechanical properties. Therefore, to achieve improved formability in a realistic time, forming above 500 degrees F is recommended. Moderate working temperatures will produce significant improvements in the formability of this alloy independent of heat treatment. Working temperatures below 800 degrees F can be easily maintained during high production forming with an insignificant effect on life of conventional die steels.

Heat treatment to the T6 temper is performed under the following conditions.

° Solution heat treat - 860 to 930 degrees F for 10 minutes to 1 hour, in general, the low temperature end of the temperature range is preferred for wrought products to avoid grain growth

° Aging - 245 to 255 degrees F for 24 to 28 hours.

Warm working will require final heat treatment, however, the aging time and residual stresses can be minimized by performing a finishing deformation pass in the temperature range of 200 to 240 degrees F.

The manufacturing methods considered for producing the warhead body design, shown in Figure 1, were

(a) Extrusion

(b) Radial forging

(c) Shear forming

(d) Drawing

(e) Machining.

The machining was used as a base for productivity, quality, and cost comparisons between the alternative methods.

TABLE 1. TYPICAL TENSILE PROPERTIES OF THE 7075 ALLOY AT VARIOUS TEMPERATURES WHEN HEATED FOR 1000 HOURS AT TEMPERATURE (Strain Rate 0.01 in/min.)

Testing Temperature, F	Tensile Strength, psi	Yield Strength, psi	Elongation, percent
	BARE PRODUCTS O Temper		
75	33,000	15,000	16
300	19,000	13,000	40
400	14,000	11,000	60
500	11,000	9,000	65
600	8,500	6,500	75
700	6,500	5,000	70
	T6 Temper		
75	83,000	73,000	11
300	25,000	21,000	30
400	14,000	12,000	60
500	11,000	9,000	65
600	8,500	6,500	75
700	6,500	5,000	70

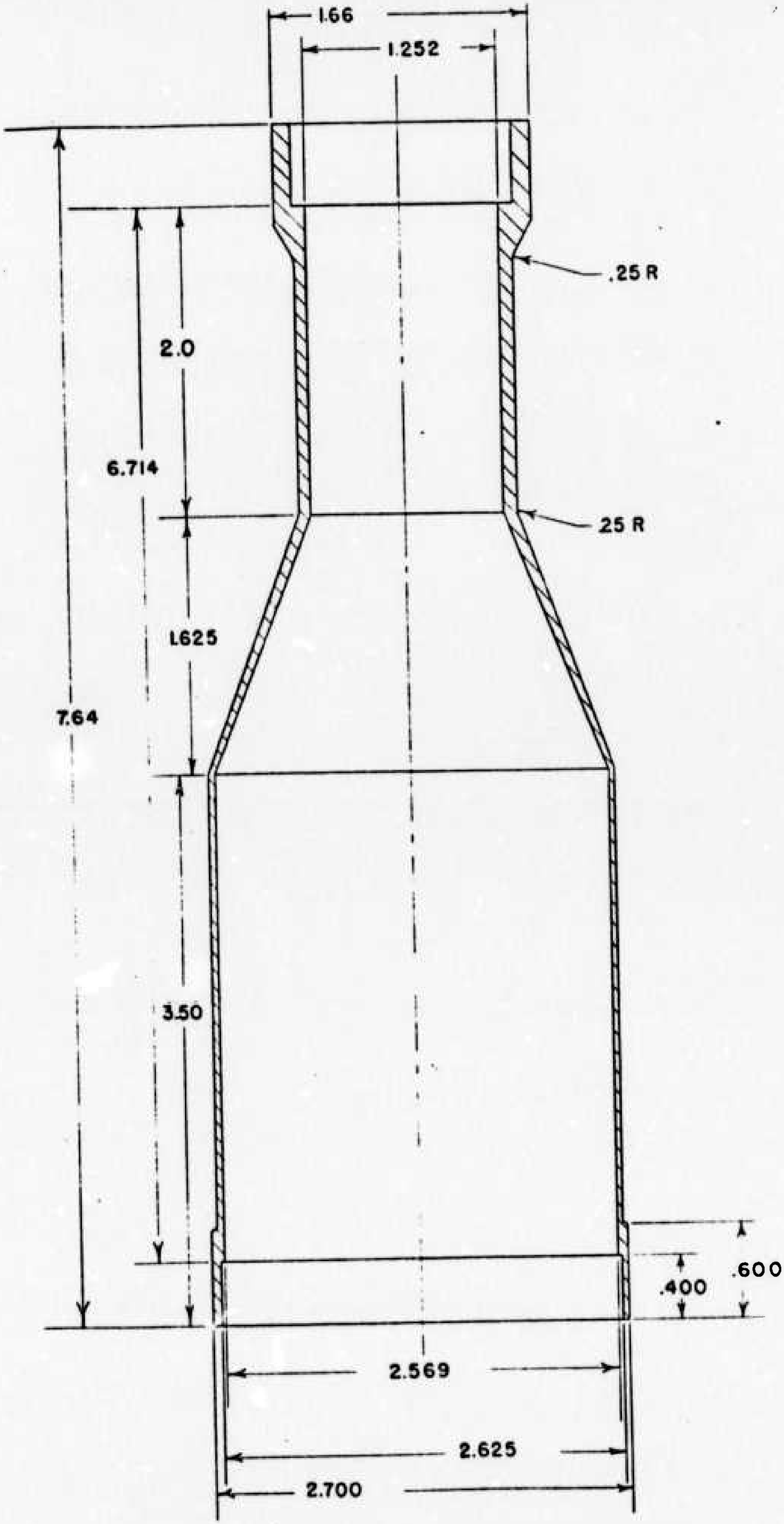


FIGURE 1. LAWT TARGET SHAPE USED FOR THE PROCESS ANALYSES

APPROACH AND ASSUMPTIONS

Precision metalworking processes are usually the most economical high-volume production methods because of their capabilities for producing a precision final shape with low material consumption, low manpower and/or handling requirements,through the easily justified expenditure for automatic machinery,and minimal finishing costs. The major problems with these methods are high-initial investment, high start-up costs and the need for rigid stock and product inspection and quality control, and process control. Without these controls, the actual product cost can vary widely. Stock and process control factors which would affect the cost and quality of the LAWT body in production fabrication are the following.

° Residual Stress
  (1) Stock
  (2) Product
° Heat Treatment - Dimensional Control
  (1) Stress relief
  (2) For final properties
° Consistency of Metalworking Process Performance
° Tool Wear

The finished dimensions of the LAWT body require special fixtures to maintain dimensional control during final heat treatment and final finishing operations. These additional costs were not specifically considered because they are common to all the fabrication routes considered.

A problem associated with all metalworking processes is residual stress which becomes more significant as the surface-to-volume ratio of the part increases. This problem will be significant with LAWT and would necessitate stress relief and sizing procedures before finishing. Recent work has demonstrated that negligible residual stress can be achieved in worked products through die design[6] and by mechanical means[7,8]. However, these techniques have not been sufficiently developed to apply directly to an arbitrary product shape without process development. Because the level of residual stress in the final worked product is not known and the dimensions of LAWT make its dimensional stability particularly sensitive to residual stress during machining, it was assumed that stress relief would be required for all processes before finishing.

The LAWT shape can be produced from preforms of three general shapes: plate, solid cylinders and thick-wall tubes. Quotations were obtained for the aluminum alloy 7075 in these shapes and cost estimates were obtained for producing tubes from cylinders in processes amenable to tube fabrication. With these preforms, the technological feasibility and costs were evaluated for producing a nearly-finished product by the following methods.

- Extrusion
- Radial forging
- Shear forming or spinning
- Drawing
- Machining

Where the success of a particular process was thought to be questionable, machine manufacturer's recommendations or published data were used to justify the deduction.

These general considerations apply to the Cost Analyses and are reviewed for specific processes in the following section on Production Processes.

PRODUCTION PROCESSES

The following is a brief description of production processes which are candidates for forming the LAWT body. Some of the processes are particularly useful for preforming, whereas others are primarily finishing operations. A few are amenable to the entire production sequence, but may not have sufficient production data to unequivocably attest to their production feasibility for LAWT. For these reasons, the potential applications of each process are reviewed followed by examples, typical tolerances and problems.

Extrusion

Extrusion is a metal-deformation process performed on billet confined in a cylindrical cavity created by a surrounding container, an advancing ram, and a die. The billet is forced by the ram to deform under predominantly compressive stresses through the shaped opening of the die to form a new, elongated shape. There are two basic extrusion techniques: forward or direct extrusion in which the billet, ram and product move in the ram direction, and backward or indirect extrusion in which the ram moves in the opposite direction of the newly forming product and the remaining, undeformed portion of the billet is stationary. In backward extrusion, a die is usually attached to the ram. These two processes may be combined in one operation[9] of combined forward and backward extrusion. Either technique can be used to produce rod and, with a mandrel, cans or tubes. Examples of these extrusion techniques are shown in Figure 2.

Forward extrusion in horizontal presses is not being considered here, except as a method for producing heavy-wall extruded tubes. These tubes would be used as starting blanks in other forming operations, and conceivably, this material would be available from a commercial mill. Forward-stepped extrusion is a relatively new concept with potential application to LAWT. In this process, extrusions with two or more deforming cross sections are made by interrupting the extrusion process to transfer the part to another set of dies to complete the remainder of the part with a different contour. The advantage of stepped extrusions lies principally in the elimination of excess metal from sections which otherwise would require major metal removal operations[10].

Backward extrusion in vertical presses, with or without forward extrusion, is a principal candidate manufacturing method for producing the LAWT warhead. Backward extrusion could be used to produce an intermediate cup-like part for final forming and/or machining. However,

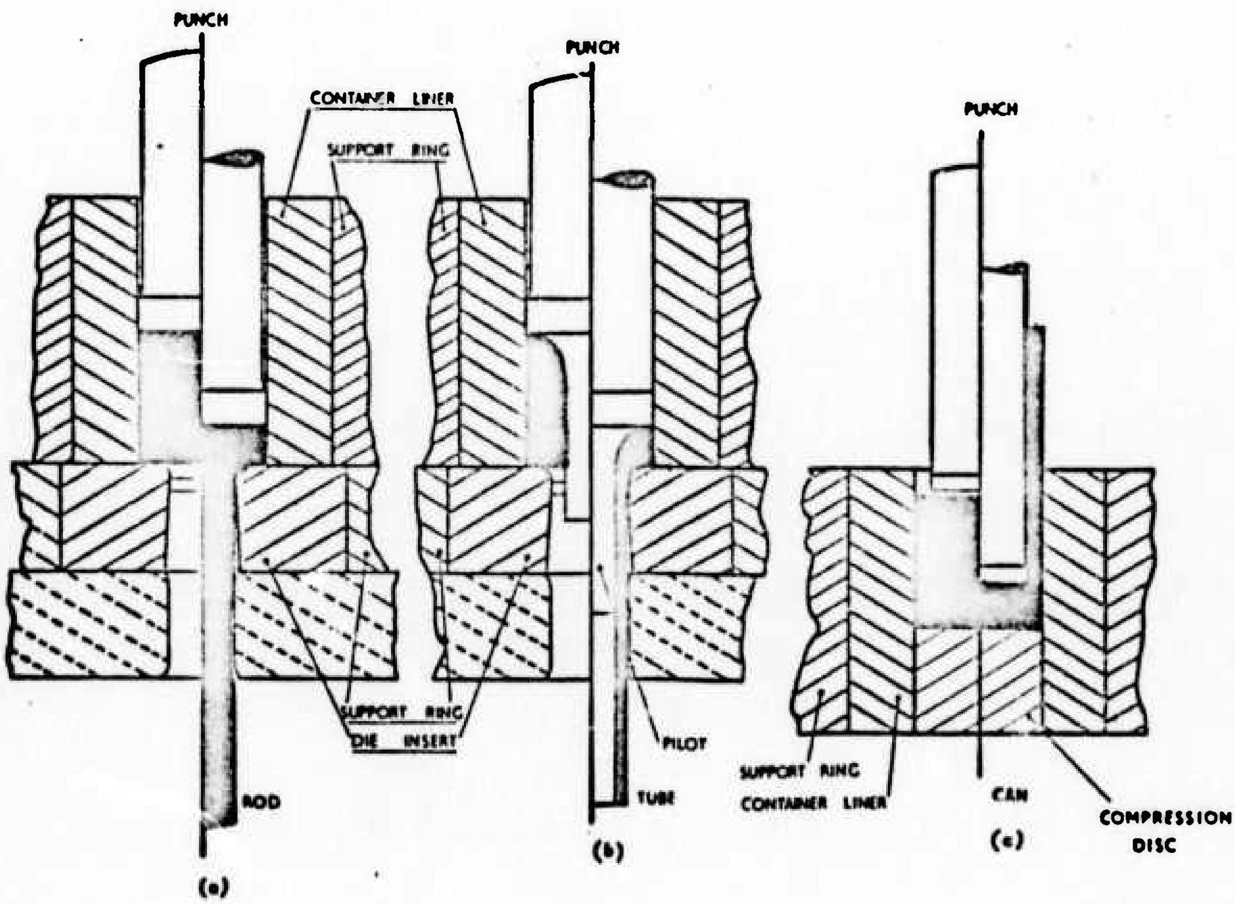


FIGURE 2. BASIC TOOLING ARRANGEMENTS FOR EXTRUSION

incorporating the simultaneous forward and backward extrusion of a billet into "can-can" and "can-tube" shapes appears most applicable to LAWT. A schematic description of this combined process is shown in Figure 3, using a rod. A tubular preform could produce surface finish problems at the ID from wrinkling during upsetting to achieve the LAWT shape. This extrusion sequence is readily amenable to production, but because of the OD flanges on the LAWT, only the ID of the missile body could be precision extruded.

The lower strength, more ductile aluminum alloys (1100 and 3003) can be cold extruded[11]. When higher mechanical properties are required in the final product, the heat treatable grades (6061 and 7075) are used. The higher-strength alloys, however, are more susceptible to defects, such as laps or cracks, than the lower strength alloys and, in general, for these reasons, are not as amenable to cold working to large reductions. Recent work at Battelle[12] has shown that 7075-T0 can be hydrostatically extruded at room temperature to reduction ratios in excess of 100:1 at safe working pressures (below 180,000 psi ram pressure). Hydrostatic extrusion[13] of 7075-T6 could be performed as an alternate to warm extrusion or cold extrusion with intermediate anneals using the sequence in Figure 3.

Typical Parts and Tolerances

Three different parts typical of a flare case, a hydraulic cylinder body and a splined housing[11] are shown in Figure 4 . These cold-extruded parts, which are similar in size and shape to the LAWT body, were produced from the aluminum alloys 1100-T0 and 3003-T0 which are significantly more workable than 7075-T0 at room temperature. Production and tolerance data for these parts are summarized in Table 2.

The flare case was produced by backward-forward extrusion using two hits. The first hit formed a 2-inch diameter tubular section as a preform. The second hit formed a 1.45-inch diameter can. A step,rather than a taper, joined the two diameters. The part had a total length of 13 inches. The operations was done on a mechanical press at a production rate of 1500 pieces per hour.

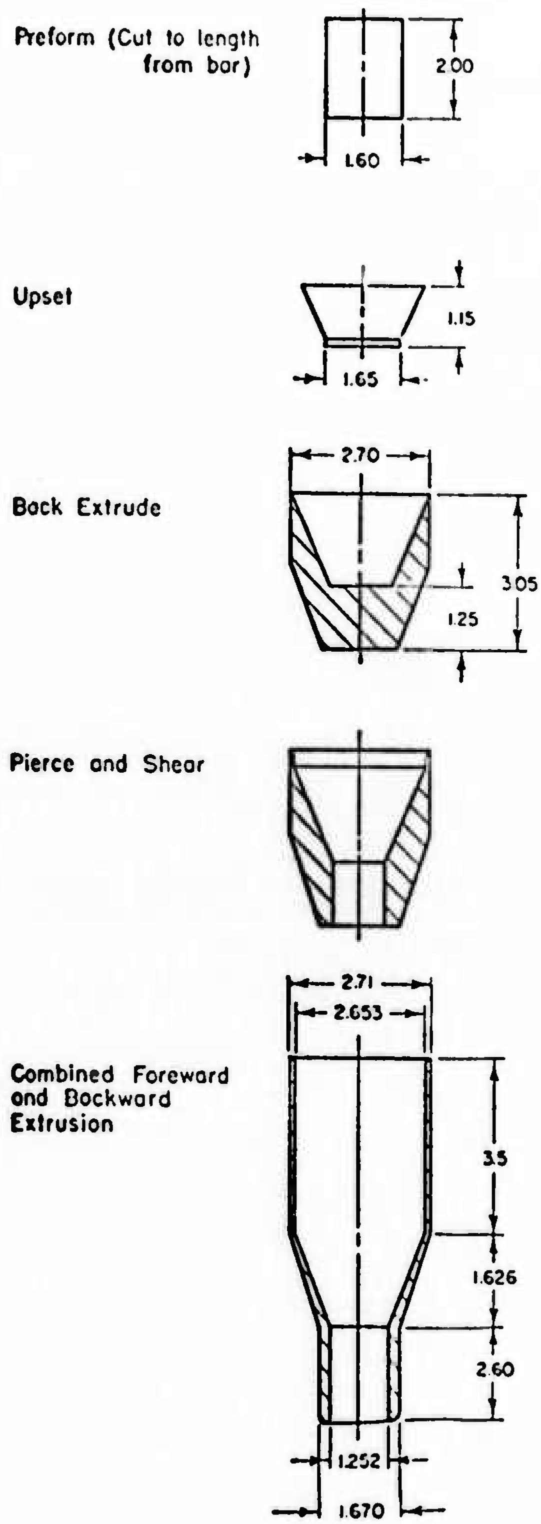
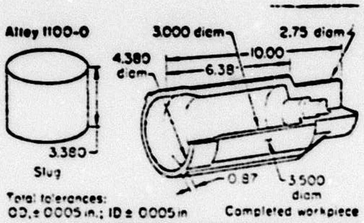


FIGURE 3. SCHEMATIC DESCRIPTION OF A CANDIDATE EXTRUSION PROCESS FOR THE LAWT MISSILE BODY



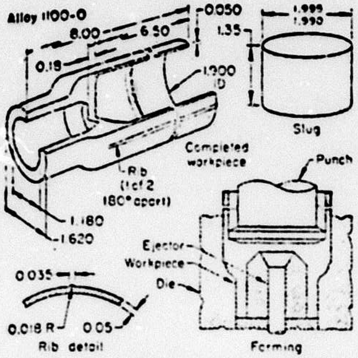
Total tolerances: OD, ± 0.005 in.; ID ± 0.005 in

Press	Hydraulic, 800-ton (set at 500 tons)
Die	Single-station
Type of slug	Sawed from bar, and annealed
Lubricant	Zinc stearate
Production rate	300 pieces per hour
Tool life, minimum	70,000 pieces

MAXIMUM EXTRUDABILITY FOR A COMPLEX SHAPE

This hydraulic cylinder body was extruded from a solid slug in one hit. Alloy 1100, which has maximum extrudability, was required for this part because of the abrupt changes in section of the cylinder body. Surface cracks and laps resulted when more difficult-to-extrude alloys were used. The different wall thicknesses and steps in this design represent near-maximum severity for extruding in one hit, even with the most extrudable alloy. During development of this part, it was necessary to change the face angles, shorten the steps, and blend the outside ribs more gradually to insure complete fillout.

Note: Hydraulic cylinder body extruded in one hit. Complexity of configuration is about the maximum producible by one-hit extrusion of alloy 1100-0.



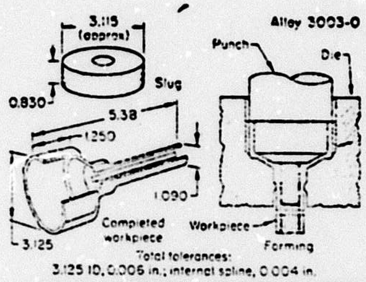
Total tolerances: OD, 0.004 in.; wall thickness, 0.005 in.

Press	Mechanical, crank-type, 190-ton
Die	Single-station
Type of slug	Sawed from bar, and annealed
Lubricant	Zinc stearate
Production rate	1500 pieces per hour
Tool life, minimum	75,000 pieces

ONE-HIT EXTRUSION OF A CASING WITH OUTSIDE RIBS

This flare casing with two longitudinal locating ribs on its outside diameter was produced in one hit by backward-forward extrusion.

Note: Flare casing with two outside ribs that was produced in one hit by backward-forward extrusion.



Total tolerances: 3.125 ID, 0.006 in.; internal spline, 0.004 in.

Press	Mechanical, horizontal, 1000-ton(a)
Die	Single-station
Type of slug	Sawed from bar(b)
Lubricant	Liquid wax (dip)
Production rate	1500 pieces per hour
Tool life, minimum	200,000 pieces

(a) 375 tons required. (b) Hole was drilled or pierced; slugs were then annealed.

USE OF A DOUGHNUT SLUG IN BACKWARD-FORWARD EXTRUSION IN ONE HIT

This splined housing was extruded by the backward-forward technique in a single hit from a drilled (or pierced) slug. The eight splines were formed in the small diameter by forward extrusion, using the serrated portion of the punch. At the same time, the ribbed cup portion of the workpiece was formed by backward extrusion with the intermediate diameter of the punch. Length of the cup section was controlled by a step in the punch that confined the metal in the die.

Note: Splined housing extruded in one hit from a doughnut slug.

FIGURE 4. ALUMINUM ALLOY SHAPES PRODUCED BY EXTRUSION[11]

TABLE 2. PRODUCTION AND TOLERANCE DATA FOR COLD-EXTRUDED ALUMINUM PARTS

Part	Flare Case	Cylinder Body	Housing
lloy	1100 - TO	1100 - TO	3003 - TO
ress	Mechanical (190 ton)	Hydraulic (800 tons)	Mechanical (1000 tons)
ie	Two Station	Single Station	Single Station
lug	Round bar, Annealed	Round bar, Annealed	Round bar, Annealed
ubricant	Zinc Stearate	Zinc Stearate	Liquid Wax
roduction Rate (pieces/hr.)	1500	300	1500
ool Life, (Parts)	250,000	70,000	200,000
olerances, (inch)	2 O.D. ± 0.010	OD ± 0.005	3-1/8 O.D. ± 0.006
	1.45 I.D. ± 0.005	ID ± 0.005	-
	Wall ± 0.005	-	-

The hydraulic cylinder body was back extruded from a solid slug. The shape and dimensions of this part correspond to those of the LAWT warhead except that the small and large diameters were about 1.6 times larger than the corresponding diameters of the warhead. The cylinder body is also about 1.3 times longer. Aluminum alloy 1100, which has maximum extrudability, was required for this part because of abrupt changes in section. Surface cracks and laps occurred when more difficult-to-extrude alloys were used.

The housing was extruded by the backward-forward technique in a single hit using a drilled slug. The larger cylindrical portion of this part was 3-1/8-inches diameter x 1-1/8-inches long. The smaller section was 1.090 inches in diameter x 4-1/8-inches long.

Advantages and Limitations

The major advantages of extrusion for the LAWT missile body are high-production rates, moderately precise dimensional control, the capability to achieve large reductions by either cold or hot extrusion (at moderate temperatures), efficient utilization of stock and good surface finishes.

The major limitations of this process achieve particular significance when reviewed with the requirements of the LAWT shape. These limitations are as follows.

(1) Dimensional control on the OD and ID is at best marginal for the LAWT requirements (see Table 2).

(2) The large surface-to-volume ratio of the product requires a good finish on the billet and good lubrication practice to avoid scuffing[11] or galling.

(3) The large reductions required for LAWT will necessitate precise considerations of ram speed, extrusion temperature and intermediate anneals to produce a good quality product.

(4) Tooling costs will be high, but tool life should be large with aluminum alloys if good extrusion practices are established.

The aluminum alloy 7075-TO has relatively poor extrudability when compared with other aluminum alloys. This condition is demonstrated by the results in Table 3 on the cold extrusion of annealed slugs[11,14] of various aluminum alloys. However, at typical hot-working temperatures (500 to 850 F) tool life is excellent and this alloy has low strength and excellent ductility. However, hot working, in general, does not provide good dimensional control on thin structures.

Difficulties

External and internal defects are the principal difficulties with extruded parts. Such defects may arise from the starting material or from the deformation process itself. Surface defects in extruded products may result from the billet, from a deficiency (or excess) of lubricant, or from scuffing[15]. High-quality billets free of surface defects are needed to produce high-quality extrusions. Large reductions can cause lubricant breakdown and poor quality surfaces. Scuffing is a mechanical problem which can be solved by polished dies and properly aligned tooling.

Internal cracks can arise from a variety of causes, including heat treatment before extrusion, or flow conditions during extrusion. These dificiencies can be corrected by modifying the extrusion temperature, the lubrication system, changing the extrusion speed, warming the billet, or by any combination of the foregoing.

In general, dimensional problems in thin structures arise from temperature gradients either during final heat treatment or during handling of heated extrusions. Cold extrusion of 7075 would avoid the handling problems, but the large required reductions would probably produce cracking. Furthermore, time consuming interstage annealing would be required. Because the hot working temperatures for 7075 are moderate (approximately 850 degrees F ± 100) tool life will be excellent, interstage annealing could be avoided and large reductions could be taken. However, handling, dimensional control and surface quality would not be as good as cold extrusion.

TABLE 3. TENSILE PROPERTIES AND RELATIVE PRESSURE REQUIREMENTS FOR COLD EXTRUDING ANNEALED SLUGS[11,14]

Alloy	Tensile Stress, ksi[a] Ultimate	Yield	Elongation percent[b]	Relative Extrusion Pressure[c]
1100-TO	13	5	35	1.0
3003-TO	16	6	30	1.2
6063-TO	13	7	--	1.2
6061-TO	17	7	25	1.6
2014-TO	25	10	21	1.8
7075-TO	33	15	17	2.3

(a) Nominal values
(b) 2-inch gage lengths
(c) Based on alloy 1100-0 as 1.0

Radial Forging

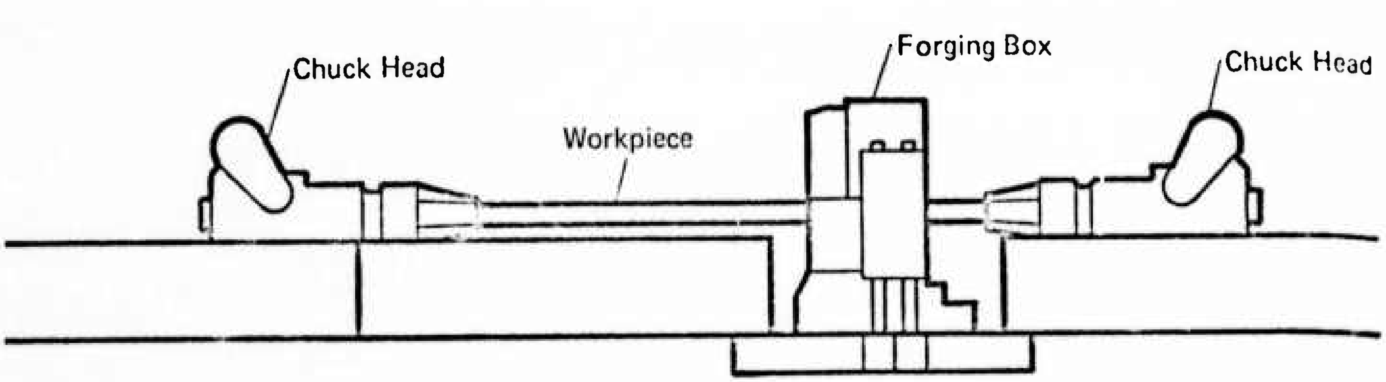
Radial forging[16] is a precision metalworking process for producing solid and tubular products with OD and ID contours (for tubes) which are symmetric about the axis of the product (e.g., cylinders, squares, rectangules, hexagons, and octagons which can have circular, contoured inner diameters). These shapes are achieved by feeding a rotating prefo: between the dies or hammers of the machine which oscillate through a preset amplitude, but their actual minimum radial position can be automatically adjusted by either cam or numerical control. The basic elements of the machine are shown in Figure 5.

Precision radial forging machines are usually 4-die machines, but may also be 2- or 6-die machines. The piece is fed into the dies and rotated by the chuckhead (headstock). The workpiece is held on centers between the chuckhead and the counterholder (tailstock) on opposite sides of the dies. The component on the chuckhead which grips the part is called a "plunger" which is connected to a hydraulic ram at a preset, controlled pressure which can be automatically changed to preset pressures (e.g., high pressure and low pressure to achieve a decired type of metal flow to control dimensional precision). The counterholder operates during the forging cycle at one set pressure.

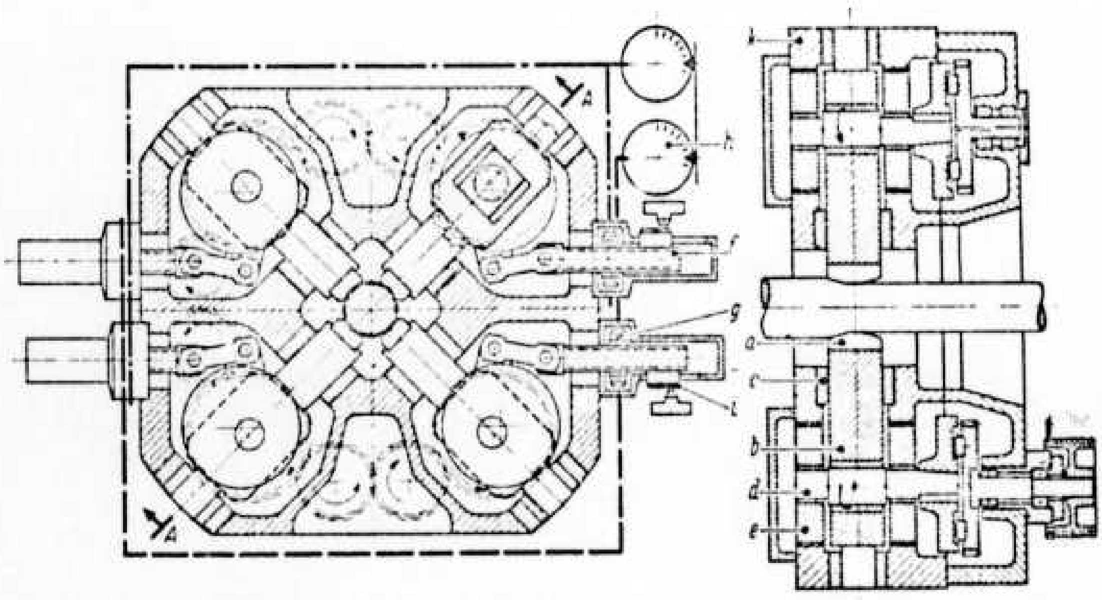
The most common and highly developed machines are the GFM radial forging machines which are fully automatic and capable of accurate repetition of the forging cycle. A portion of a typical production cycle for producing a contoured tubular product, such as LAWT, is shown in Figure 6. The complete cycle would consist of the following steps.

(1) Automatic pickup and transfer of the preform from the feed table and location in front of the dies

(2) Rapid traverse of the counterholder and chuckhead-plunger assembly to near-contact with the preform with simultaneous positioning of the mandrel inside the part and between the dies, and into an induction coil (for hot or warm forging) in front of the dies



SCHEMATIC OF A GFM RADIAL PRECISION FORGING MACHINE WITH TWO CHUCK HEADS (For small workpieces, one chuck head would be used with a counterholder).



FORGING BOX OF A RADIAL PRECISION FORGING MACHINE ILLUSTRATING THE TOOL FUNCTION AND ADJUSTMENT

- **a .. dies**
- **b .. pitman arm**
- **c .. guides**
- **d .. eccentric shaft**
- **e .. adjustment housing**
- **f .. adjustment screw**
- **g .. worm gear drive**
- **h .. adjustment input**
- **i .. adjustable cam**
- **k .. forging box.**

FIGURE 5. SCHEMATIC DIAGRAM OF A GFM RADIAL FORGING MACHINE

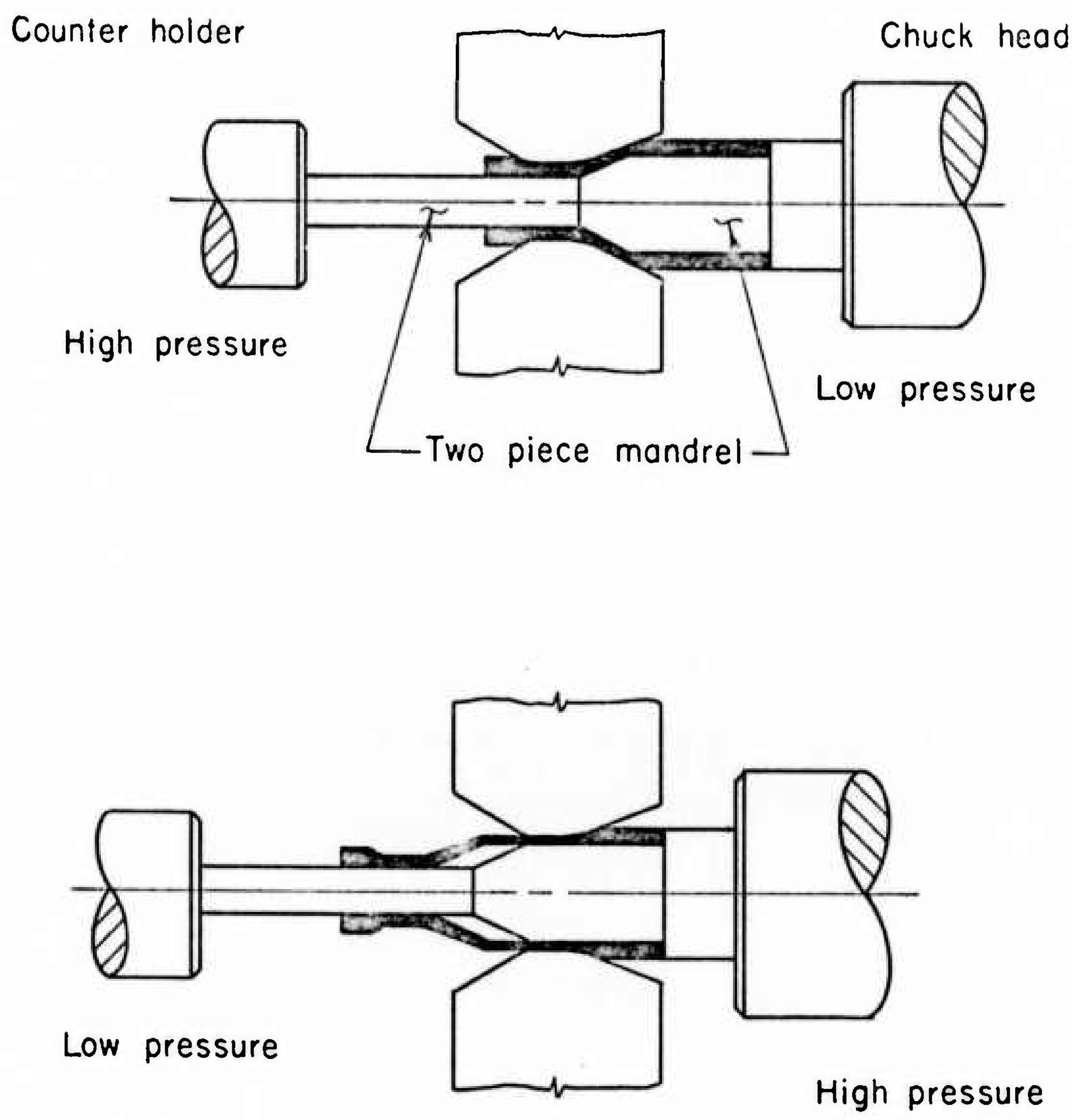


FIGURE 6. POTENTIAL PRODUCTION SEQUENCE FOR RADIAL FORGING THE LAWT SHAPE

(3) Initiation of the feed cycle:

(a) Programmed power cycle may be initiation in the induction coil to heat the part

(b) Chuckhead begins traverse at prescribed feed rate

(c) Preform is completely engaged by the plunger and counterholder and transfer mechanism retracts

(d) Plunger rotation is initiated and counterholder and plunger are pressurized to the prescribed pressures.

(4) The feed cycle consists of the motion of the chuckhead at the prescribed feed rate and the corresponding opening and closing of the dies relative to the chuckhead position to achieve the contoured part. The relative pressures of the counterholder and plunger may also be set to change at precise locations to achieve accurate ID contours.

(5) Completion of the feed cycle may involve water cooling of the product before retraction of the chuckhead and part to the removal position.

(6) Automatic gripping of the product by the transfer mechanism and subsequent further retraction of the chuckhead to release the product.

(7) Discharge of the product onto the discharge table.

(8) Reinitiation of the forging cycle.

With this automatic cycling, high production output of a precision product can be achieved with a low manpower requirement. Machine operations require only one operator who is also free to load and remove parts. The following will review typical parts and tolerances made by radial forging.

Typical Parts and Tolerances

The GFM machine recommended for use on parts with the LAWT geometry is the 4-die SHK10, a 4-inch machine. An SHK10 machine has been in use at Rock Island Arsenal for precision forging rifling barrels[17]. Typical tolerances for simultaneous rifling and chambering are stated by GFM to be ± 0.002 inches on the OD and ± 0.0002 inches on the ID. Figure 7 shows typical tubular products produced on a larger machine and Figure 8 shows parts and cycle times for solid products.

Advantages and Limitations

The major advantages of radial forging are:

- Exceptional precision
- Repeatibility
- Automatic operation
- Excellent surface finishes
- High production rates
- OD and ID contouring capability
- Enhanced workability.

Recent work[17] performed on the Rock Island machine demonstrated that completely heat treated nickel-base superalloys and tool steels could be precision cold forged to rifle barrels. This is the only known demonstration in which a manufacturing process was established with materials which are known to be very difficult to even hot work. In addition, tooling design practices have been established to produce a cold forged product[6] free of residual stress.

The major limitation of the GFM machine for precision fabrication of the LAWT body is the thickness of the structure. Although it is anticipated that a minimum of 20 percent cold reduction could be achieved with 7075-T6, the thickness of the structure is not expected to be sufficient to avoid distortion and subsequent wrinkling during forging unless special fixturing is used. This problem is demonstrated in Figure 9.

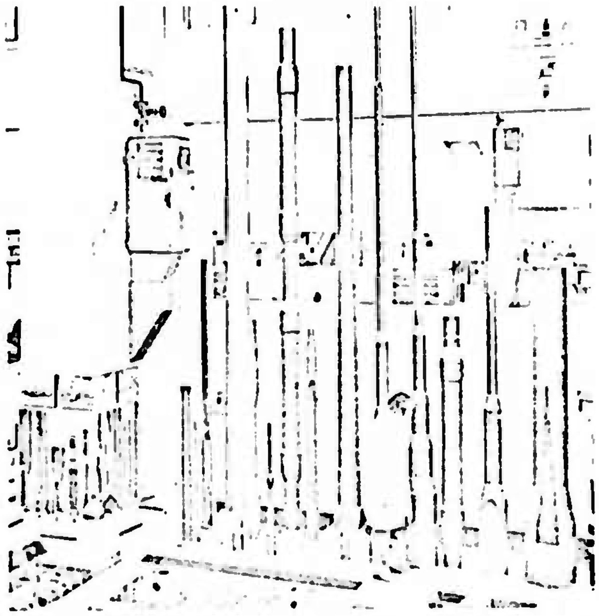


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FIGURE 7. TUBULAR PRODUCTS PRODUCED BY RADIAL FORGING

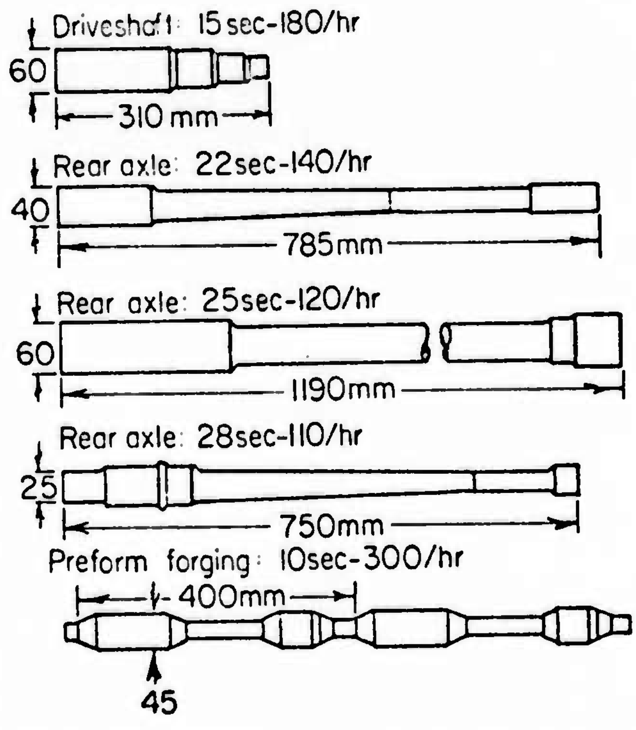
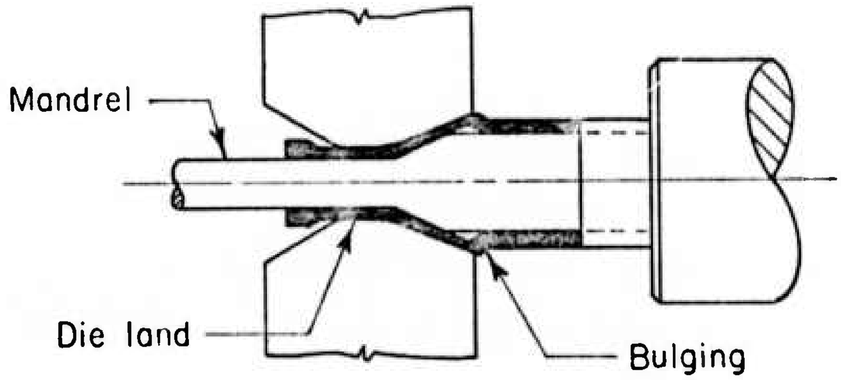
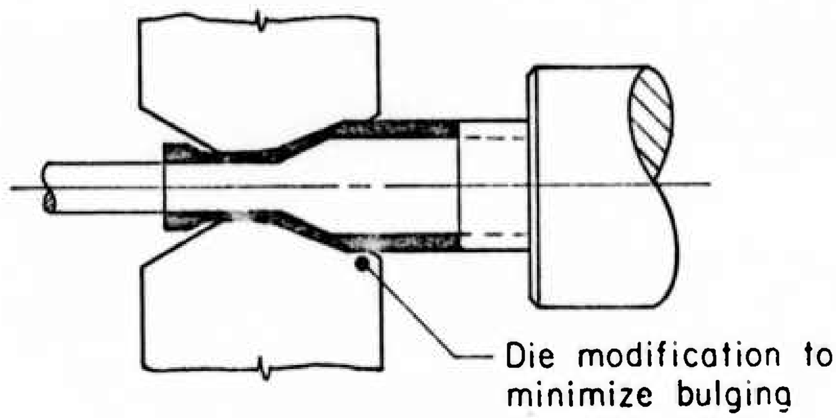


FIGURE 8. PARTS AND CYCLE TIMES FOR RADIALLY FORGED PARTS



9a



9b

FIGURE 9. POTENTIAL WRINKLING (9a) AND DESIGN TO AVOID WRINKLING (9b) DURING RADIAL FORGING OF THIN WALL STRUCTURES

Because of the wall thickness required in the blanks or preform, the preform mass probably cannot be used to avoid bulging as shown in Figure 9. To accurately reproduce the shoulder, a significant fraction of the metal flow must occur against the shoulder. This condition is achieved during gun barrel forging by dropping the plunger force to a value less than the counterholder force, while still maintaining a net forward feed rate. The condition shown in Figure 9 has been observed with thin-wall tubes[18]. The thick wall tubes used for gun barrels do not exhibit this behavior because

(1) The inner (chamber) and outer tapers are small when compared to the tube thickness, and

(2) The massive tube walls constrain the bulging.

An additional problem encountered with large shoulders, such as the LAWT is severe "hammering" of the machine resulting from the large shoulder area and the shoulder angle which produce a large resultant component of the die force opposing feeding of the part. Therefore, during each die closure, a significant force is generated opposing the feeding of the part which produces the hammering and resulting chatter marks on the OD and ID of the part. This hammering has been evaluated in swaging[6] and has been shown to become large at angles in excess of 6 degrees. Although the GFM radial forging machines have been designed with hydraulic, motor-driven feed mechanisms to provide some shock absorbing capability, hammering can still be severe in these machines under the conditions described in Figure 9.

GFM-Austria reported[18] experimental trials on a shape similar to the LAWT, although the exact details of the shape were not communicated. Hammering was recalled as not being a serious problem, although a machine was used with a much larger size capacity than the part. A split cylindrical sleeve was bolted about the large diameter portion of the body to avoid bulging. During this process development, two problems were encountered.

(1) Dimensional control on shoulder thickness of ± 0.010 inch was observed. Improvements in this control would require more rigid positioning of the mandrel relative to the die.

(2) The use of a sleeve involved a significant portion of the cycle time and was thought to be sufficient for demonstration purposes but not for production fabrication.

Accurate mandrel positioning would require a minor machine modification, and bulging could be avoided by fixturing and/or tooling design to fully utilize the automatic cycling of the machine. Although no attempts were made to evaluate the following techniques, bulging could be avoided by either:

(1) Feeding the preform through a close-fitting, stationary sleeve located in front of the dies, or

(2) Contouring the dies to forge simultaneously the shoulder and segments of the LAWT adjacent to the shoulder as shown in Figure 9b.

Radial forging of the finished LAWT body has a great potential for providing a precision product cold forged from fully heat treated 7075-T6. However, preforms with precise radial dimensions would be required. This preform could be produced from tubes on the radial forging machine, but might be more accurately formed by another process. These other processes are reviewed with radial forging in this discussion on production processes.

Shear Forming

Shear forming[19,20,21], shear spinning, or spinning refer to the method of forging sheet metal or tubing into seamless hollow cylinders, cones, hemispheres or other circular shapes by a combination of rotation and force. Spinning is performed with manual or power tool control, but in both cases the basic machinery is the same. Spinning is performed on converted lathes (manual spinning) or on similar but specially designed machines. These machines include a headstock containing a mandrel, a tailstock for support and concentricity and a tool post or rest containing a roller or the tool. During power spinning, multiple tools, usually 2 or 3, are used to provide better part support and improved dimensional control. Rotation of the preform is produced by the power to the headstock and the shape is produced by the motion of the tool or roller over the part. Spinning has had widespread use in missile case fabrication.

A distinction is usually made between tube spinning and cone spinning based on process design considerations. The reduction per pass in tube spinning is determined by the force applied to the tool. However, when forming other shapes (e.g., cones, domes, hemispheres, etc.), optimum dimensional control is achieved by process design based on a sine law relationship between the preform thickness (t_i) and product wall thickness (t_f) using the angle, α, between the mandrel centerline and the tangent to the mandrel surface where the product is being formed. This relationship is given by

$$t_f = t_i \sin\alpha \quad .$$

For an overreduction, $t_f > t_i \sin\alpha$, back extrusion will occur resulting in loss of dimensional control in the previously formed portion of the product. Underreduction, $t_f < t_i \sin\alpha$, will promote wrinkling.

Tube spinning can be performed with either forward or backward spinning. In forward spinning (the only practice for cone spinning) of tubes, the roller moves away from the fixed end of the preform and metal flows in the same direction, usually toward the headstock. The major advantage of forward spinning is form-length control. The major disadvantages are (a) the need for a closed end or collar on the preform for fixturing to the mandrel, and (b) machine size and production rates are increased because the roller must transverse the full finished length of the part.

In backward spinning, the preform fits against a stop or shoulder on the mandrel and the roller transverses from the opened end of the preform toward the fixed end. The major advantage of backward spinning are (a) a simpler preform with less material because an internal collar or closed end is not required for clamping, and (b) increased production with less required machine capacity because the roller only tranverses the portion of the preform to be deformed and not the larger finished part length.

Spinning can be used to form most metals and alloys, either cold or hot in a variety of sizes, as shown by the results in Table 4. The results in Figure 10[29] show the relation between maximum reduction in spinning and the reduction in area in a tensile test (the true fracture strain in a tension test equals the natural logarithm of the ratio of the cross sectional areas of the tensile specimen before and after testing).

Typical Parts and Tolerances

The size of the part that can be shear formed is determined by the size of the available equipment. One of the most obviously successful production applications of shear forming has been the manufacture of rocket-motor cases[23,24]. Typically, these cylinders are approximately 65 inches in diameter and 94 inches long with a wall thickness of 0.16 inch. Other parts successfully shear formed include straight-wall and tapered-wall cones up to 21 inches in diameter and 30 inches high, and cylindrical-conical combinations made from two shear-formed pieces.

The tolerances achieved with the above parts are shown in the following tabulation.

Dimension	Measurement, inch	Tolerance, inch
Thickness	0.040	+ 0.010 - 0.006
Thickness	0.060	+ 0.010 - 0.006
Thickness	0.125	± 0.006
Thickness	0.197	± 0.006
Diameter	under 1.5	± 0.010
Diameter	1.5 to 5.0	± 0.015

TABLE 4. TYPICAL SPINNING MACHINE SIZES AND PRODUCTION RATES[13]

Manufacturer	Part Diameter, inches	Part Length, inches	Production Rate, piece/hr.
Lodge and Shipley, (Floturn)	12	15	75 to 100
	12	15	90 to 125
	24	30	30 to 80
	40	50	8 to 30
	60	70	1 to 15
	70	84	1 to 15
Cincinnati Milling Machine Company (Hydrospin)	42	50	--
	42	50	--
	62	50	--
	70	72	--
Hufford, (Spin Forge)	60	60	--
	60	120	--

Power forming machines are available in a variety of sizes. Typical machine capacities and production rates are shown in Table 4. Fundamental equipment differences usually occur in the roller-control mechanisms. Typically rotational speeds vary with machine size from about 60 rpm for the larger equipment to over 360 rpm for the smaller. Feed rates generally range from 1 to 4 inches per minute (0.01 to 0.1 inch/revolution).

It is impractical and, in some cases, impossible to produce some shapes by spinning. For example, the LAWT shape cannot be formed directly from either a plate or tubular preform. The limiting factor is wrinkling of the type described for radial forging in Figure 9. This wrinkling will not permit the forming of the shoulder from a rough preform (such as shown in Figure 3). However, the shoulder itself could be used as a collar to form the LAWT shape by the following methods:

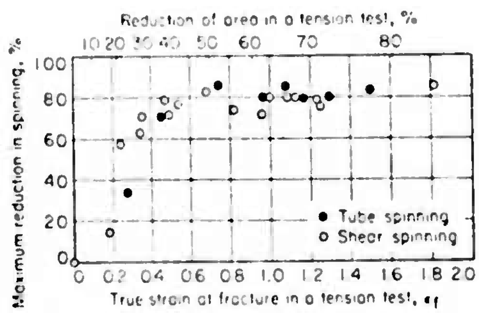


FIGURE 10. CORRELATION OF MAXIMUM REDUCTION IN SPINNING WITH REDUCTION OF AREA IN A TENSILE TEST

(1) Backward tube spinning of the neck and neck-flange areas, and

(2) Forward tube spinning of the body and body flange areas.

A potential spinning sequence employing these operations is shown in Figure 11 using a forward-back extruded preform. The nominal dimensions shown were calculated for single-pass spinning which appears feasible based on the results in Table 4 and Figure 10. However, in actual practice, it may be more desirable to rough spin, solution treat, cold finish by spinning and then age. This procedure eliminates distortions occurring during solution treatment and, in general, distortion during aging of 7075 should be small.

Spinning has been an important process for aerospace structures and particularly rocket-motor bodies. For large volume production, spinning is generally considered slow, but low setup costs make this forming method particularly amenable to small-to-moderate production lot sizes. Both cam and numerical control increase the flexibility of spinning machines. The advantages and limitations are briefly reviewed in the following.

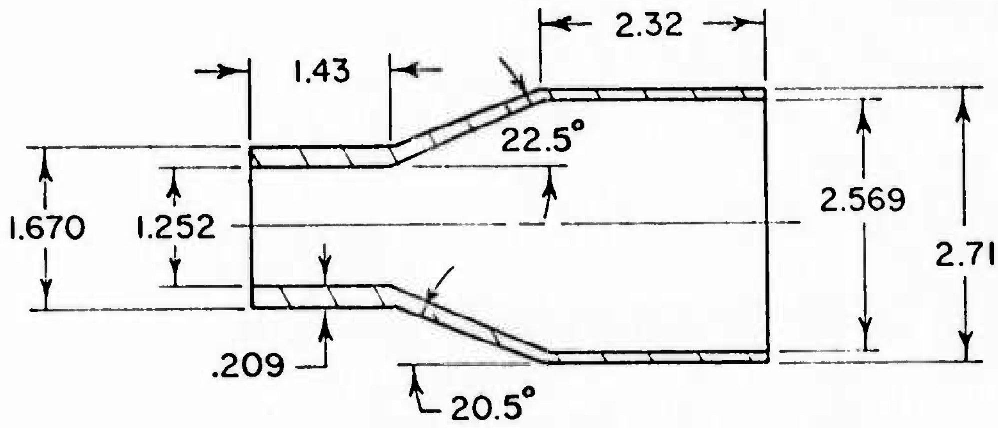
Advantages and Limitations

The major advantages of spinning are:

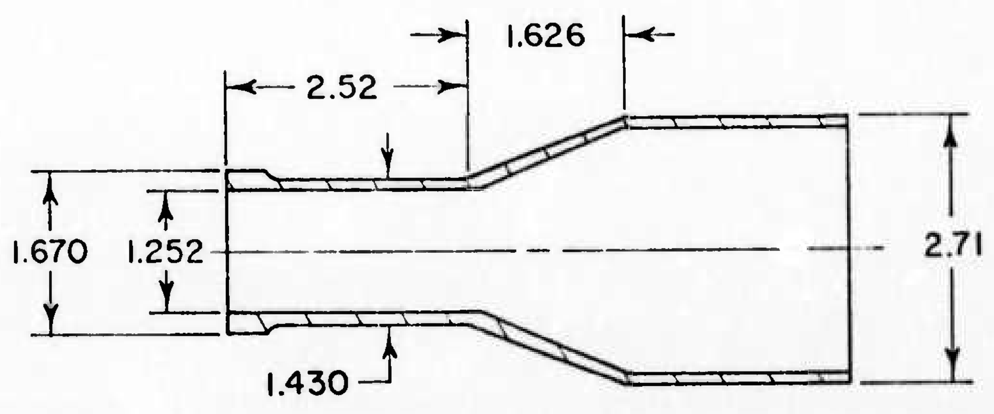
° Low setup costs
° Moderate precision
° Process flexibility for use in forming a wide variety of parts
° Improve material utilization
° Good surface finish.

The major limitations are:

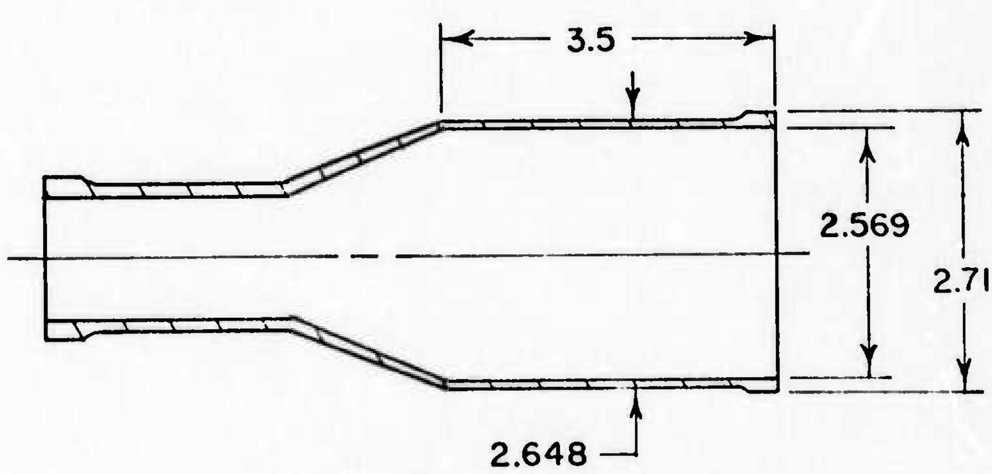
° Production rates are moderate to low when compared with competitive processes
° Spinning is applicable to forming sheet or tubular preforms in a limited class of shapes
° Intermediate annealing treatments are usually required to produce a finished shape
° Moderate precision.



Preform



Backward Tube Spin Neck and Neck-Flange Areas



Forward Spin Body and Body-Flange Areas

FIGURE 11. TUBE SPINNING SEQUENCE FOR SEMI-FINISHING A PREFORM

Although there is little published information on defects caused or exaggerated by shear forming, tears, laminations, and orange peel are sometimes found on finished parts. Metal failure can occur as inside diameter or circumferential tears, through-wall tears, and axial tears. Laminations are internal defects observable only by nondestructive testing. Orange peel is a roughened surface characteristic of heavily-formed parts[21].

Inside-diameter tear defects are usually short and may not be visible until the part is removed from the mandrel. Some are extremely small and difficult to find. These tears are commonly associated with a rough surface or with tool marks. They can also be caused by nonmetallics on the blank surface, or by poor lubrication. The solutions to these defect problems are obvious: good surface finish on the blank and correct lubrication during shear forming.

Through-wall tears occur on both the inside and outside surfaces. They are usually caused by heavy-wall reductions, or when using roller radii that are too sharp. Depending on the material, solutions might lie in heat treatment (anneal, temper, etc.) to soften the starting blanks to permit greater reductions. Application of heat and/or intermediate annealing treatments are other alternatives.

Axial tears occur when a gap forms between the mandrel and workpiece. Prevention lies in maintaining continuous contact, and a blank with an inside diameter close to the diameter of the finished part.

Laminations can occur when small planishing reductions (up to about 8 percent) are used during cylindrical shear forming. The effects are like the "fish-mouth" defects occurring during the cold rolling of strip using small reductions. The solution, obviously, lies in continually taking reductions larger than about 10 percent.

Orange-peel, usually the result of heavy forming, is often traceable to excessively coarse grain size in the starting blank. The best solution is to use only fine-grain material, although intermediate annealing steps can sometimes be used to refine grain size. Polishing after the first pass will also help to minimize the orange-peel effect.

The defects associated with spinning are not uncommon to other sheet forming operations. In these processes, the following practices are used to avoid their occurrence.

- ° Establish the proper melting practice[2,3]
- ° Establish the proper rolling and thermal-mechanical processing sequence[2,3]
- ° Utilize intermediate annealing treatments
- ° Standardize processing conditions[4]
- ° Use appropriate statistical inspection procedures for process control[3,4,23].

Considerable metallurgical evaluations were performed in the development of the aluminum-alloy cartridge case[2,3,4]. This work was performed on 7075 and similar alloys and is relevant to the LAWT production by any or all of the potential processes.

Drawing

Drawing is a metalworking process for forming sheet metal by forcing a sheet through a die (die ring) with a punch to produce a cup, cone, box or shell-like product. Drawing usually implies deep drawing, which is an arbitrary term. Usually deep drawing is applied to products in which their depth is greater than one-half their average diameter. Other press operations have become associated with drawing because these operations are commonly used with drawn products to produce a specific final shape[25]. These operations and the reasons for their use are as follows.

- ° Redrawing - A partial or complete diameter reduction and length increase of a previously drawn product
- ° Reducing - A form of sinking, used to reduce the mouth of a shell. Reducing is also referred to as necking, closing, tapering or closing.
- ° Bulging or expanding - A process used to produce complex shapes of revolution on a cylindrical shell by the use of a wedge-action punch or die, a fluid or rubber punch

° Sizing - A final, usually light reduction pass, to achieve final dimensions

° Ironing - A stretching operation used to intentionally thin the walls of a drawn shell by forcing the part through dies with a die-punch clearance less than the preform wall thickness. Ironing of a cup produces a longer, thin-wall cup with a thick-wall bottom. In general, ironing produces a cup wall less susceptible to distortion and cracking than a drawn cup without ironing.

During deep drawing and redrawing, size control is provided by the punch, the holddown pressure on the blank and lubrication. Die-punch clearance is usually large and dimensional control is best at the ID. Subsequent bulging, sizing and ironing passes provide OD control, in addition to ID dimensional control.

In recent years, there has been a rapid growth in the understanding of drawing(26,27). This work has demonstrated that material factors promoting good drawability can be classified as follows.

° Uniform deformation (factors tending to avert localization of deformation)

(1) Homogeneous microstructures with fine grain and particle sizes and low volume of percipitate

(2) Large strain rate sensitivity and work hardening coefficient

(3) Normal (cystallographic or yield stress) anisotropy (28) i.e., a higher yield stress in the through-thickness direction than in the plane of the sheet

° Large strains to fracture.

Currently, the aluminum alloys commonly formed are 1100 and 3003 because of their excellent workability and low cost. These low-strength alloys are particularly amenable to forming. In general, higher strength (lower work hardening coefficient) and more complex alloys (greater inhomogenity of the microstructure) are more difficult to form. Alloys such as 7075 are either formed in the TO condition or immediately after solution treating and quenching. Considerable process developments, melting and thermal-mechanical processing, have been performed to improve the formability of 7075[2,3]. This work has been performed mainly to improve the micro-structural uniformity and fracture strain (e.g., splitting tendency). The development of normal anisotropy to improve drawability of the aluminum alloys is not particularly significant (i.e., similar to steel and other alloys with cubic crystal structures)[26,28]. This condition results in limiting draw ratio (LDR) of about 2, where LDR is the largest ratio of the blank-to-cup diameters which can be drawn before failure. Planar anisotropy, e.g., anisotropy within the plane of the sheet, appears to be sufficiently well understood[25] in alloys to be avoided. If significant planar anisotropy exists, the drawn cup and subsequent redrawn products will exhibit earing[25,28].

The drawing process is very complex because small changes of the process variables can produce a significant improvement in the success of the process. The significant process variables and their associated effects are as follows.

- Punch and die radii - decreasing radii below a maximum of about 10 times the sheet thickness reduce the LDR and increase the punch force
- Punch-die clearance - decreasing clearance below about 20 percent of the sheet thickness increases punch load, reduces the LDR,and results in cup burnishing
- Holdown pressure on the blankholder - required holdown pressure depends on sheet thickness. For thick blanks no holdown is required but as the sheet thickness decreases:
  (1) Low holdown pressure produces wrinkles
  (2) Large holdown pressure reduces the LDR by promoting fracture of the cup bottom
- Lubrication - poor lubrication limits LDR in the same manner as increased holdown pressure, but can be offset by using lighter holdown pressures.
- Press speed - increased press speed above a maximum, depending on the alloy, can promote fracture.

The process design parameters, with the exception of press speed, can be easily adjusted or modified in a particular operation to avoid failure. Nominal press speeds for drawing are typically in the range of 20 to 55 feet per minute for single action presses and 35 to 50 for double action presses However, the actual speed will depend on the material and the equipment (mechanical or hydraulic press) being used. Table 5 shows nominal speeds for drawing various alloys. The nominal press speeds of 35 feet per minute for drawing and 20 feet per minute for ironing[25] will be used in the cost analysis of the drawing process. In general, a slower press speed is used for ironing because of the severity (stretching) of the operation. These general considerations will be reviewed in the following discussion on fabricating the LAWT by drawing.

Typical Parts and Tolerances

Several parts similar to the LAWT missile body have been fabricated. However, most of these parts have been designed to be amenable to drawing. The features of the LAWT limiting fabrication by drawing are:

(1) The tapered thickness of the shoulder

(2) The OD flange on the neck

(3) The OD and ID radii at junctions between elements of the body contour

(4) The tolerances on thickness and diameter dimensions.

These geometrical features make complete fabrication of the LAWT impossible by drawing. However, as with extrusion and other processes, an approximate form can be produced.

During the last few years, considerable work has been performed with 7075 and similar aluminum alloys to produce cartridge cases in the 5.56 mm to 30 mm range[4,29,30]. The sequence of operations for aluminum and brass cartridge cases are similar. For 7075, these operations would involve the following starting with 7075-TO material.

TABLE 5. NOMINAL SPEEDS FOR DRAWING OF VARIOUS METALS

Metal	Speed, Feet Per Minute: Single-Action Press	Speed, Feet Per Minute: Double-Action Press
Aluminum	175	100
High-strength aluminum	--	30 to 40
Brass	200	100
Copper	150	85
Steel	55	35 to 50
Steel (with carbide dies)	--	60
Stainless steel	--	20 to 30
Zinc	150	40

(1) Cold cup (or backward extrusion)
(2) Wash (4)
(3) Anneal (680 degrees F for 30 minutes and air cool)[4]
(4) First Draw
(5) Wash
(6) Anneal
(7) Wash
(8) Second Draw
(9) Wash
(10) Anneal
(11) Wash
(12) Third Draw
(13) Wash
(14) Anneal
(15) Fourth Draw
(16) Wash
(17) Trim
(18) Wash
(19) Head
(20) Wash
(21) Pierce
(22) Wash
(23) Anneal
(24) Wash
(25) Reduce (neck)
(26) Wash
(27) Solution and Age
(28) Head Turn
(29) Final Trim
(30) Clean
(31) Inspect.

Reductions during drawing were maintained between a minimum of 23 percent to avoid exaggerated grain growth during heat treatment, and a maximum of 48 percent, which is the approximate maximum for a limiting draw ratio of 2[4]. During the solution and aging treatment a reproducible shrinkage of 0.2 percent was observed and subsequently accomodated in the processing sequence. For the 5.56 mm cartridge case a wall thickness variation of 0.004 inch (requiring polishing and alignment of tooling) and an OD gage diameter of ± 0.0005 inch were maintained.

The processing sequence for cartridge cases is complex. However, manufacture of this product has been so highly developed that production rates of 1200 per minute are being produced in 5.56 and 7.62 mm with special-purpose transfer systems.

The development of aluminum alloy cartridge cases has demonstrated that casting practice, thermal-mechanical processing, and intermediate annealing treatments are critical[2,3]. In general, aluminum alloys do not have the drawability possessed by steels[26] and, therefore, greater precautions must be taken. In general, this requires anneals between each drawing pass. A drawing sequence for the LAWT body is shown in Figure 12. This sequence involves starting with a blank in the TO condition followed by three drawing and three ironing passes with intermediate anneals. The drawing and ironing passes have been designed to satisfy safe drawing practices and represent a near-optimum sequence. It is conceivable that the last ironing pass could be preceded by a solution anneal and warm-ironing-aging to maintain dimensional stability. After this final ironing pass, the nose on the contoured cup would be blanked.

The blank thickness in Figure 12 was determined by the maximum LAWT neck thickness (i.e., the wall thickness at the neck flange). It is impossible to include forming of this neck contour in a drawing sequence. Therefore, another operation, such as spinning, must be included. The flange at the extremity of the missile body can be produced by ironing. However, because the ironing die closely fits the product ID (contrary to a drawing die for which there is clearance), ejection of the finished product from the die would produce galling and, therefore, is not practical.

Gas bottle production also is similar to potential processes for the LAWT. Drawing combined with either spinning or reducing (necking) is used to manufacture gas bottles[25]. Figures 13 and 14 are examples of gas-bottle manufacture using either a blank or a back-extruded cup as the starting configuration for subsequent drawing. The bottle shown in Figure 13 was closed by spinning. This technique is used on bottles with a spherical or radiused closure, unlike the LAWT. The gas-bottle in Figure 14 was drawn in 6 passes and necked, after annealing, in 5 necking or reducing passes on a mechanical press at 3200 pieces per hour.

The necking operation is usually performed with a necking die containing a mandrel to maintain both OD and ID form during each necking pass. This assembly is shown schematically in Figure 15. The necking operation produces an increase of the wall thickness. A recent analysis of this process[31], which showed excellent agreement with experiment, indicated that a tube with an OD of 2.70 inch and a wall thickness of

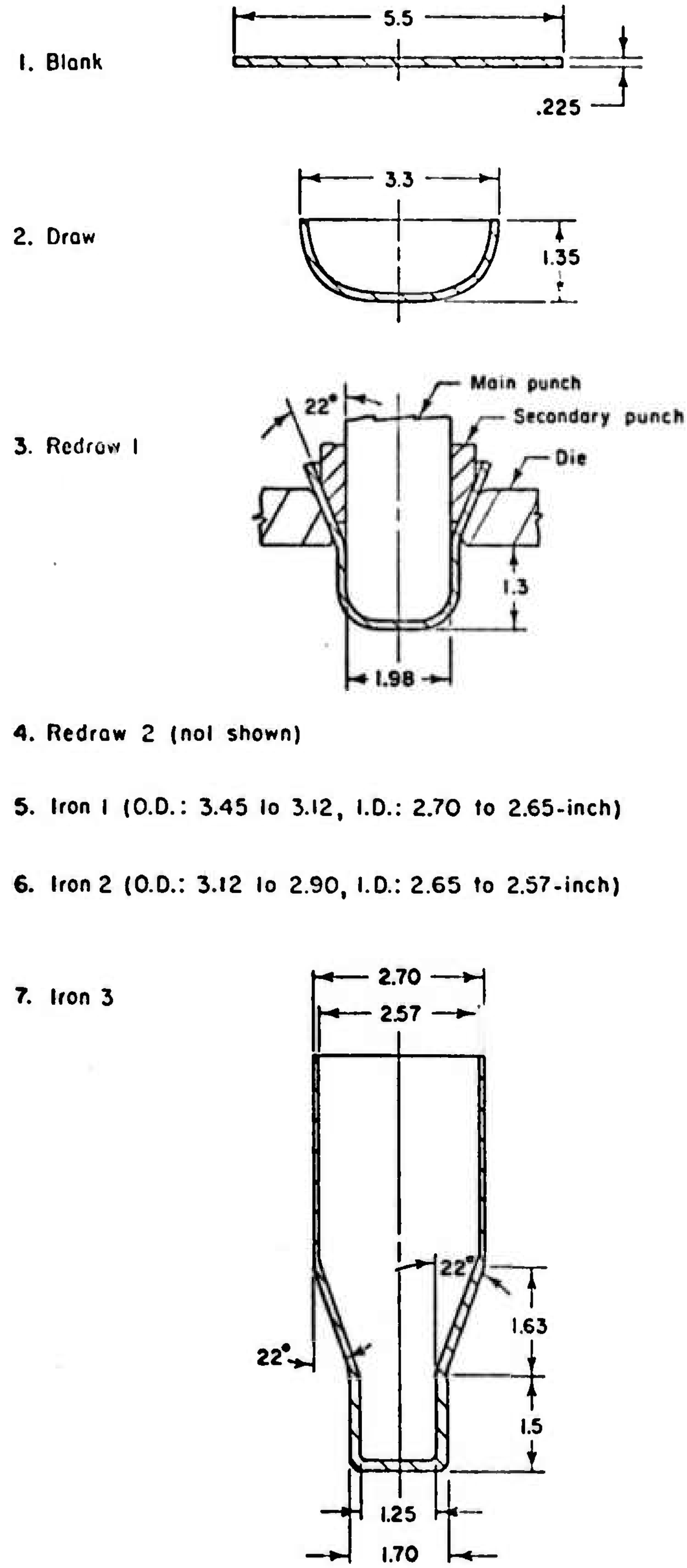


FIGURE 12. DRAWING SEQUENCE FOR THE LAWT

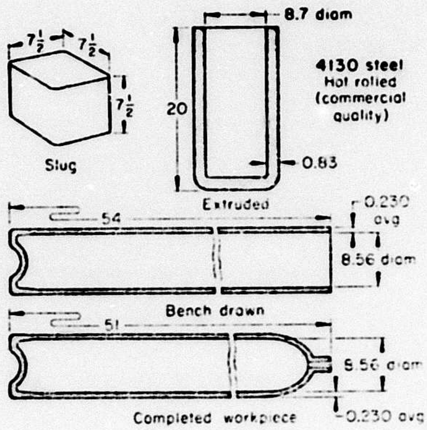


FIGURE 13. HIGH-STRENGTH CYLINDER (FOR COMPRESSED OXYGEN) THAT WAS DRAWN FROM A HOT EXTRUDED SHELL

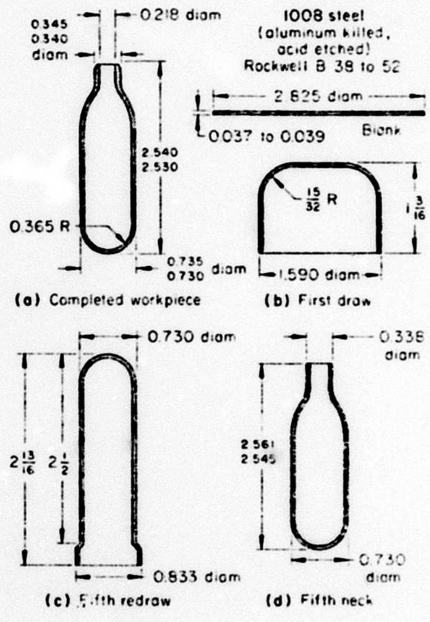


FIGURE 14. DRAWING AND NECKING A BOTTLE FOR CARBON DIOXIDE GAS

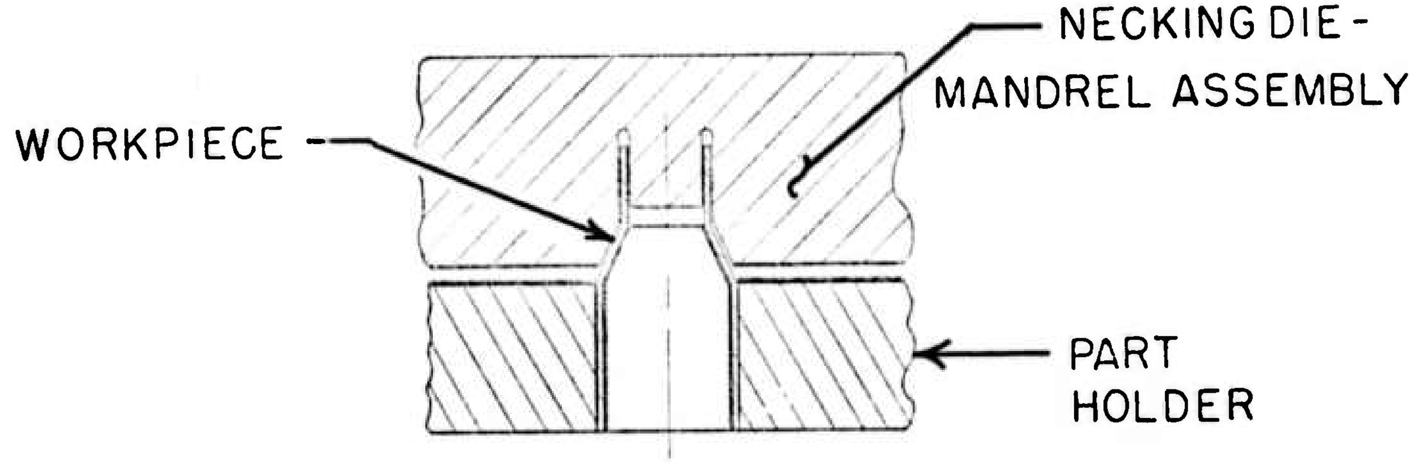


FIGURE 15. SCHEMATIC DIAGRAM OF NECKING OPERATION

0.16 inch could be necked with 38.5 percent OD reduction to produce a tube neck with an OD of 1.66 inch with a 0.21 inch wall thickness. This necking operation could be performed with tubing in four operations and without intermediate annealing treatments if the operations was performed at about 600 degrees F.

This review of the important and complex metal forming operation, drawing, discussed typical parts and tolerances applicable to LAWT fabrication. Some problems were discussed with the examples. However, the advantages and limitations will be briefly reviewed in the following.

Advantages and Limitations

Drawing is a well-developed metalforming technique which has been automated to produce a great variety of products[25]. Knowledge of the source of production defects is known and established procedures can be used to avert their occurrence. Although dimensions control on the order of ± 2 to 5 percent of the wall thickness is typical in deep drawing, ironing, and/or sizing passes can be used to obtain dimensional control to within ± 0.0005 inch for small parts.

The major limitations in applying automated, high volume production techniques for the LAWT body are as follows.

- The use of the high-strength aluminum alloy 7075, which is susceptible to splitting unless frequent annealing treatments are used; and
- The shape of the missile body (external flanges at its extremities).

Both of these factors limit the efficient use of drawing for producing this structure.

The cartridge-case forming sequence[4] requires anneals between each drawing pass. These anneals were established for 7075 and similar alloys tc avoid case splitting both during forming and in service. These annealing treatments are necessary for drawing high-strength aluminum alloys and should significantly affect production costs. However, as in cartridge-case fabrication, these treatments can be automated.

The drawing sequence can be calculated from established principles[25,26]. These calculations show that the blank thickness must not be less than about the maximum thickness of the drawn product. Therefore, the nose-flange thickness (0.204 inch) stipulates the minimum blank thickness. In general, the tendency for wrinkling will be reduced as the thickness increases; however, because the drawing forces will increase, galling and/or scoring of the product will become more prevalent. This problem can be reduced with improved lubrication.

The blank thickness (0.204 inch for drawing and ironing, and 0.160 inch for drawing and sinking) required to achieve the final flange thickness will result in considerably more scrap than a similar structure without the flanges. This additional scrap will result from the part thickness and extra-lengths required for fixturing and dimensional control during subsequent ironing or sinking.

The nose flange thickness seriously limits the applicability of drawing for fabrication of the LAWT body. Drawing can only be used to make a preform for subsequent finishing by machining or by an additional forming method, such as radial forging or tube spinning, before finish machining.

COST ANALYSES

The cost analyses are based on speeds and feeds of contemporary equipment. However, it should be recognized that special-purpose equipment may be constructed for the LAWT. This special equipment might include simultaneous, multiple operations, thereby reducing fabrication cost and time. These potential cost reductions will be discussed when appropriate.

The cost analysis are presented in four parts:

- Material Cost
- Metalworking Costs

- Finishing Costs
- Ancillary Costs
  - (a) heat treatment
  - (b) in-plant transportation cost
- Total Cost.

No attempt was made to provide a complete cost analysis which would include testing, inspection and other operations common to each process. Therefore, the cost analyses, are presented for the fabrication practices which are involved with each process for the purpose of selecting the process providing the least product cost less the cost of operations common to all processes. Because it was found that no metalworking process could produce the holes and slots required for the LAWT shape (per U. S. Army Missile Command Drawing No. 11499604), the product shape considered for the cost analyses is shown in Figure 1. The discussions of tolerances and process limitations described the capability of each process for achieving the shape in Figure 1. Some processes were capable of producing only a rough or preform shape, whereas others were most suitable for finishing. To arrive at the most desirable processing sequence, the shaping capabilities and product cost for each process were considered separately, and, subsequently, were included within a total processing sequence to arrive at the cost for the Figure 1 shape usually by multiple operations.

The general process-flow sequence is described in Figure 16. This sequence shows a processing alternative, complete heat treatment before the final forming pass, which could be beneficial for obtaining dimensional control and reduced processing costs. Specific consideration will be given to the alternatives and costs involved in the sequence from Material (e.g., material shape and condition) through Heat Treatment (C). In addition, since a particular process may involve a large amount of handling, in-plant transportation and/or handling costs were also considered. These costs are developed in the following.

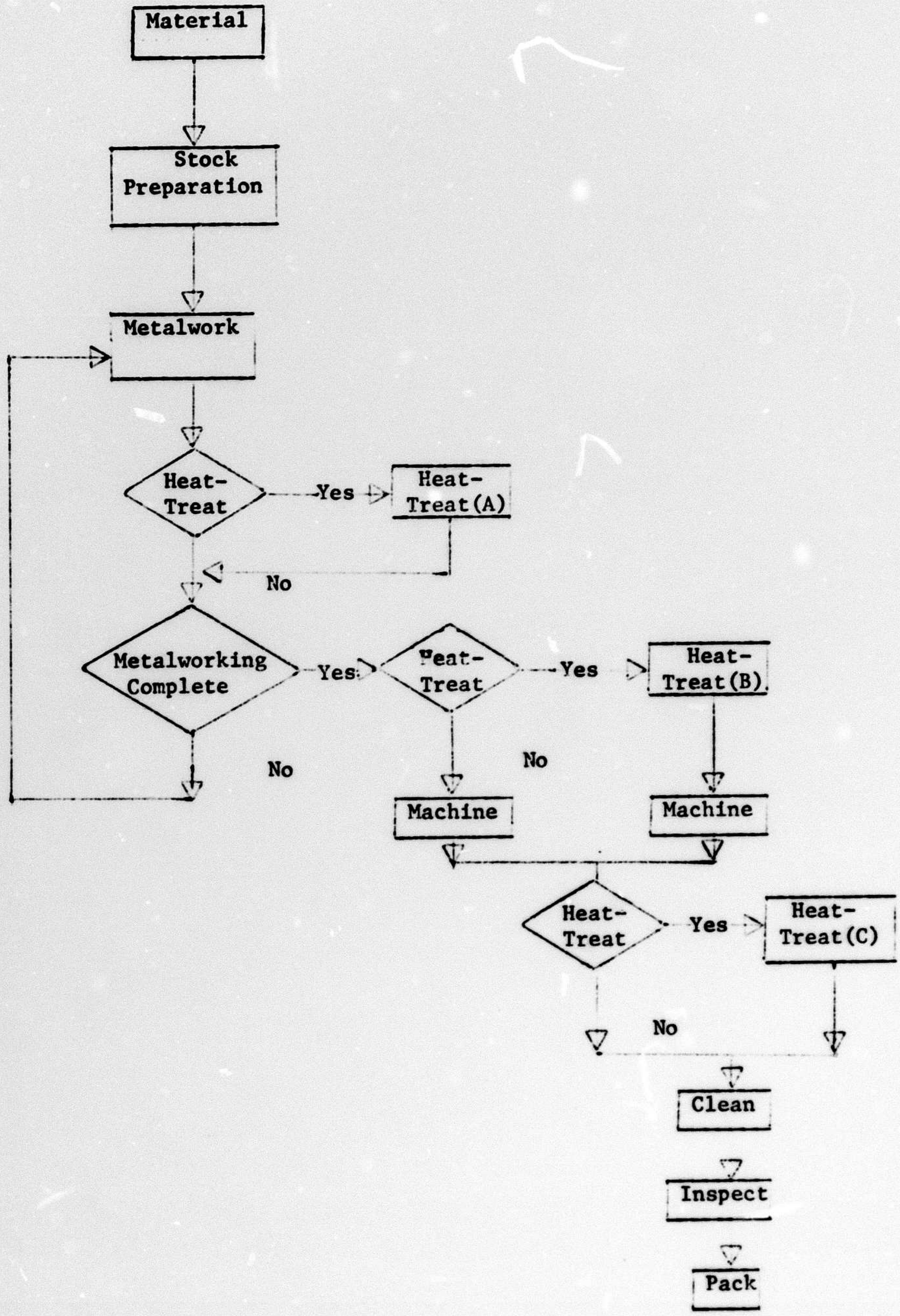


FIGURE 16. GENERAL PROCESS-FLOW SEQUENCE FOR THE LAWT MISSILE BODY

Material

The following prices for 7075-T0 were obtained on the assumption of delivery of a minimum quantity of 30,000 pounds and represent current costs as of June 30, 1974.

Bar Stock	- 1.60 inch diameter	\$1.005/pound
Tube	- 2.75 inch diameter x 1.25 inch diameter	\$1.335/pound
Sheet	- 0.160 inch thick	\$0.80 /pound

These costs will be used in the following analyses of fabrication costs.

Processes

Extrusion

Extrusion costs were estimated for semi-finishing and rough-forming using the sequence shown in Figure 3. The same sequence was used for finish and rough forming except no heat treatments were used with the rough formed-warm worked product. This sequence is based on starting from cylindrical billets 1.60 inch diameter x 2.00 inch long. Shear-cut billets should be adequate for this sequence because the initial operation, upsetting, should not be seriously effected if the ends of the short billets are not square. Because of the short press stroke required for each operation in the extrusion sequence, a mechanical press would be most desirable for this method.

Figure 17 shows the process flow diagram and alternatives to arrive at the costs shown in Table 6. It was assumed that heating was automated, but press operation and loading was manual. This latter assumptions may be overly conservative because the extrusion sequence does appear readily amenable to automation. The tool life data were obtained from published results at similar production rates[11]. The labor costs are based on typical production times involved with tooling change and repair, heat treatment, etc., using \$15.00 per hour for skilled labor and \$12.00 per hour for semi-skilled. These costs

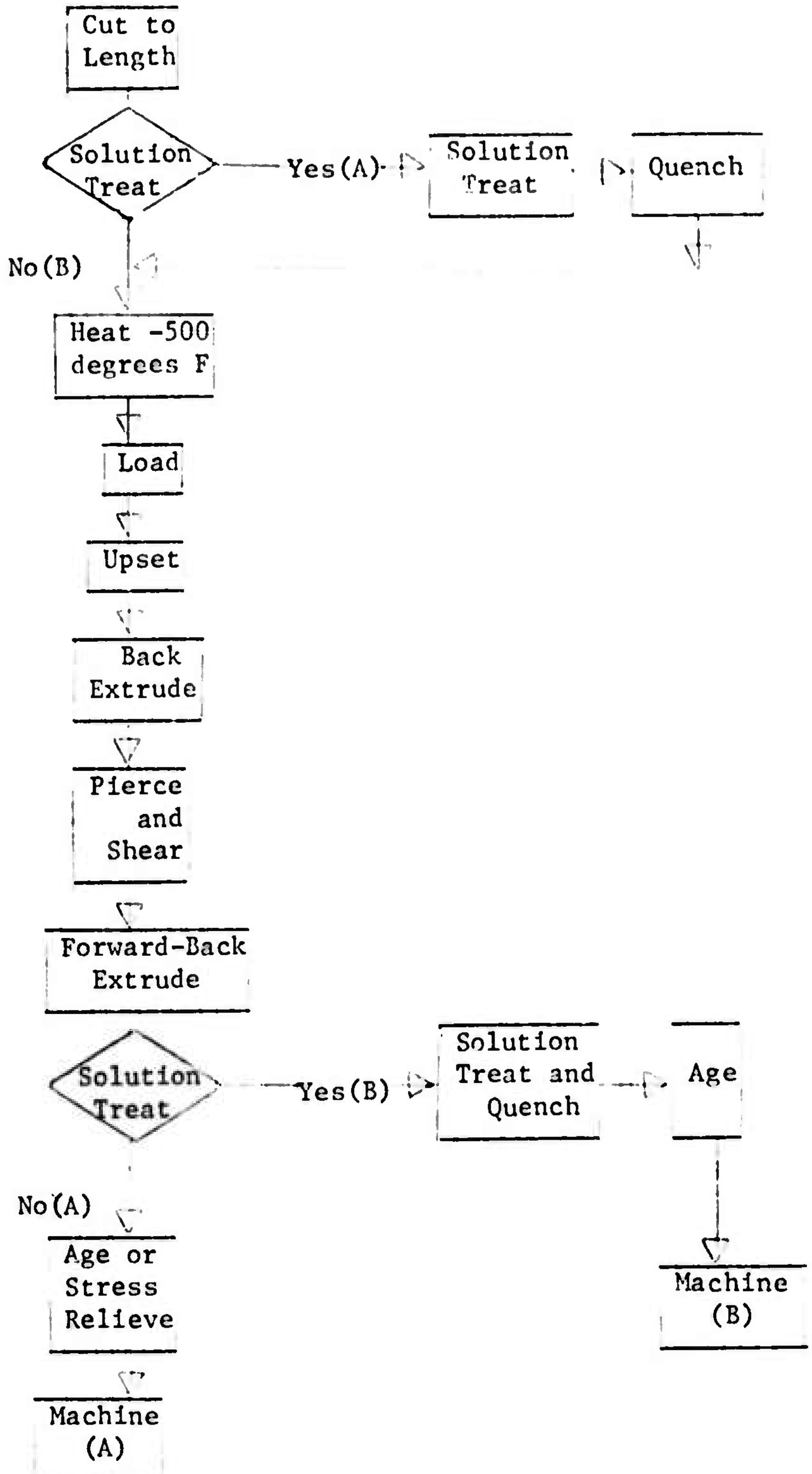


FIGURE 17. PROCESS FLOW DIAGRAM FOR ROUGH-FORMING BY EXTRUSION

TABLE 6. ESTIMATED EXTRUSION COSTS FOR A SEMI-FINISHED SHAPE (Figure 8)

Operation	Cycling Rate on One Machine, pcs/hour	Expendable Tool Cost/Life, dollars (pcs)(1)	Tool Change Cost, $/pc.	Equipment	Labor, $/piece
Cut to Length	286	0.011	0.008	Automatic-Bar Cut-off (2/man)	0.021(2a)
Heat-Treat (A)	5200				0.017(2a)
Transport					
(A)					0.0014(2a)
(B)					0.0007
Extrude					
1. Load/Heat	240				0.05(2a)
2. Upset	240	$3000/80,000 (0.038)	0.001	Mechanical Press	0.031(2b)
3. Back Extrusion	240	$5000/80,000 (0.063)	0.001	Mechanical Press	0.031(2b)
4. Pierce	240	$4000/60,000 (0.067)	0.003	Mechanical Press	0.031(2b)
5. Forward and Backward Extrusion	240	$12,000/50,000 (0.24)	0.003	Mechanical Press	0.031(2b)
Transport					0.007(2b)
Heat-Treat (A)	400				0.03(2a)
Heat-Treat (B)	108				0.111(2a)
Transport					
(A)					0.0007
(B)					0.0007
TOTAL					
(A)		0.419	0.016	0.699	0.264
(B)		0.419	0.016	0.779	0.344

Material Cost: (A) = $0.485
(B) = $0.485

Total Cost: (A) = $1.184 (1.136 as rough formed)
(B) = $1.264

(1) Includes repair and regrinding
(2) Labor
(a) $12.00/hour (semi-skilled or helper)
(b) $15.00/hour (skilled or operator).

include direct labor, general overhead, G and A, etc., but may not be appropriate for the operation of special-purpose equipment where a particular overhead or use rate would be imposed.

Radial Forging

Radial forging possesses the precision contouring capability, in principle, to produce the LAWT body. The questionable points regarding the applicability of this process are as follows.

- Rough forming from a tubular preform, and
- Finishing on and about the shoulder area.

Any committment to this process should be preceded by a process feasibility study. The major advantage of this process is its automatic loading and cycling and the capability to obtain and reproducibly maintain metalforming tolerances equal or superior to production machining tolerances.

Rough forming from a tubular preform would be performed in one operation in two forming cycles from a 3.05 inch OD x 2.58 inch ID x 4.1 inch long preform. The two forming cycles, as described in Figure 16, would involve the following.

(1) Free sink and form 1.70 inch OD x 1.27 inch ID x 1.7 inch long neck and rough-form shoulder

(2) Reduce body thickness to 2.82 inch OD x 2.58 inch ID x 1.75 inch length.

Potential problems involved with rough forming could arise from surface wrinkling during sinking, leading to laps, and the die force imparted to the feed mechanism during forming of the shoulder. The latter could also be a precision-limiting problem during finishing. This problem could be averted by a machine-design, modification to provide a stronger, more shock-resistant feed mechanism. It is anticipated that this cost would be insignificant when compared with the installed price of the machine (about $450,000).

The costs for roughing and finishing by radial forging were estimated separately using standard production rates at a feed rate of 15 inches/minute and radial die closure of 8 inches/minute. These costs are shown in Tables 7 and 8. The process flow diagram for finish forging by radial forging is shown in Figure 18.

Shear Forming

Shear forming (tube spinning) can be used as a semi-finishing operation for the LAWT body. This forming would necessitate a shaped preform as shown in Figure 11. Forming would be performed to obtain the neck and body detail but could not be performed at the shoulder. Furthermore, the use of a tubular preform is not recommended because spinning rates would be very slow to avoid collapse of the tube during attempts to form the shoulder and neck.

The cost estimate was based on the assumptions that the preform, however made, wculd not require machining either for dimensional control or surface preparation. With the reduction anticipated (e.g., in excess of 30 percent) dimensional control on the preform diameter to within ± 0.004 inch should not produce problems with eccentric deformation. The actual machining cost is treated separately in the section on Machining. The following are the assumptions used for the cost estimate.

(1) Machine: Staggered, two-roller machine with template control and compensation

(2) Roller life: 40,000 pcs

(3) Mandrel life: 10,000 pcs, until loss of dimensions, but 100 pcs, between on-machine polishing and cleaning

(4) Tooling cost:

  (a) Rollers - $ 800

  (b) Mandrel - $3000

  (c) Template - $ 150

(5) Speed: 800 SFM

TABLE 7. ESTIMATED COSTS FOR ROUGH FORMING BY RADIAL FORGING

Operation	Cycling Rate on One Machine, pcs/hour	Expendable Tool Cost, $/life in pcs[1]	Tool Change Cost, $/pc.	Equipment	Labor, $/pc.
Transport					0.0007[2a]
Radial Forge					
1. Neck	75	0.215	0.0027	Radial Forging Machine	0.200[2b]
2. Body					
Transport					0.0007[2a]
Heat-Treat (anneal)	800				0.015[2a]
TOTAL		0.215	0.0027		0.2227

Material Cost: $1.1489
Forging Cost: $0.4341
TOTAL COST: $1.583

(1) Includes repair and regrinding
(2) Labor
(a) $12.00/hour (semi-skilled or helper)
(b) $15.00/hour (skilled or operator)

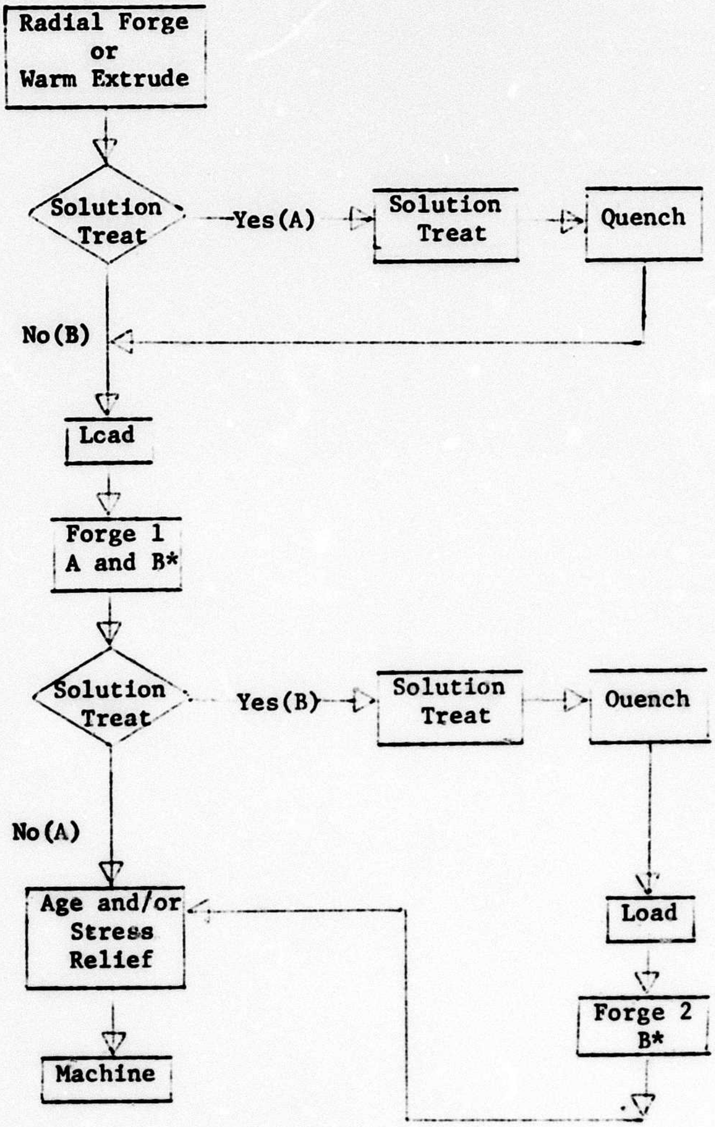
TABLE 8. ESTIMATED COSTS FOR FINISHING BY RADIAL FORGING

Operation	Cycling Rate on One Machine, pcs/hour	Expendable Tool Cost, \$/life in pcs[1]	Tool Change Cost, \$/pc.	Equipment	Labor, \$/pc.
Heat-Treat (A)	5200				0.017[2a]
Transport					0.014[2a]
Forge				GFM Radial Forging Machine	
1. Load					
(A)	240				0.050[2a]
(B)	360/220				0.0879[2a]
2. Forge 1					
(A)	240	0.095	0.00222		0.0625[2b]
(B)	360	0.0475	0.00111		0.0417[2b]
3. Forge 2B	220	0.095	0.00222		0.0682[2b]
Transport (A)					0.007[2a]
Transport (B)					0.021[2a]
TOTAL					
(A)		0.095	0.00222		0.1505
(B)		0.1425	0.00333		0.2498

Preform Cost: Extrude - \$1.136 (rough, warm formed and not heat-treated)
Radial Forged - \$1.583

Total Cost:	Extruded Preform	Radially Forged Preform
(A)-	\$1.384	\$1.831
(B)-	\$1.532	\$1.979

(1) Includes repair and regrinding
(2) Labor
(a) \$12.00/hour
(b) \$15.00/hou-



* A = 60 percent reduction in neck in one pass
B = 60 percent reduction in neck in two passes.

FIGURE 18. PROCESS FLOW DI GRAM FOR FINISH-FORGE BY RADIAL FORGING

(6) Feed:

(a) Rough - 0.040 inch/revolution

(b) Finish - 0.020 inch/revolution

(7) No requirement for neck and body length and squareness is necessitated because location of the preform and part loading will be on the shoulder.

With these assumptions, and the process-flow diagram in Figure 19, the costs were developed in Table 9.

Drawing

Drawing of the LAWT shape can be performed by the processing sequence shown in Figure 20. This sequence includes blanking a disk 5.5 inch diameter by 0.225 inch thick from sheet stock; a drawing step to form a cup; two redraws; and three ironing passes. The flow diagram in Figure 20 was developed for the calculated sequence design in Figure 12. This calculation was based on the following.

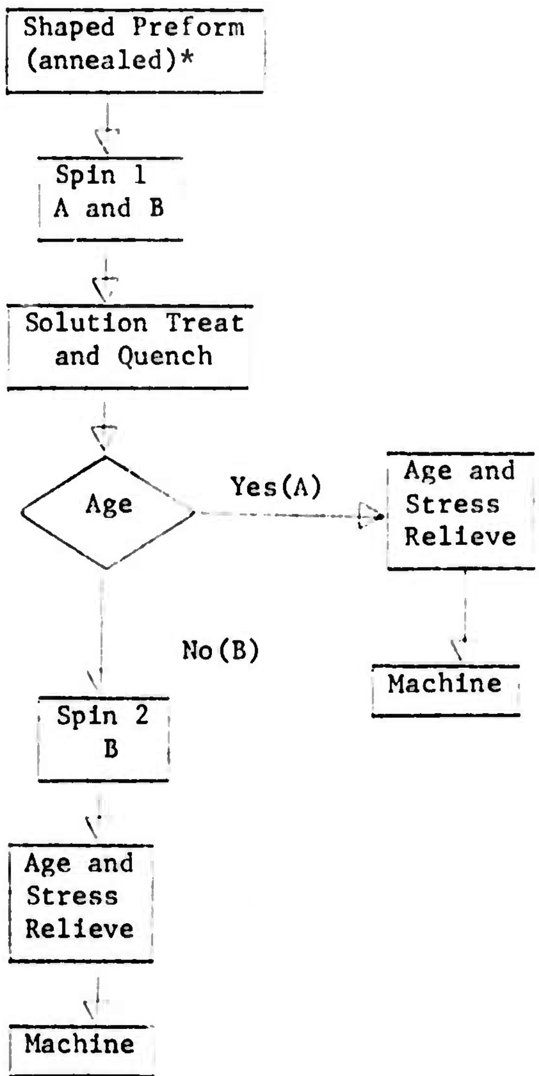
(1) Blank dimensions - based on achieving neck - wall thickness equal to approximately the neck-flange thickness by drawing (i.e., no stretching), and

(2) Drawing-iron sequence - based on conventional design practices (i.e., not exceeding 50 percent reduction per pass and a blank-to-cup diameter ratio less than 2).

The possibility of using a drawn preform with subsequent finish-forming: and sinking and sizing of a tubular preform were considered separately for producing the preform shape in Figure 11. For pure sinking of a tube with a 2.70 inch OD to a 1.60 inch OD x 1.252 inch ID, the wall thickness of the preform must exceed 0.148 inch. Therefore, the following preform dimensions were determined for producing the LAWT shape.

(1) Drawing a preform - sheet preform: 6.60 inch diameter x 0.155 inch thick

(2) Sinking a tube - tubular preform: 3.01 inch OD x 2.60 inch ID x 4.00 inch length.



* Annealed or hot worked.

FIGURE 19. PROCESS FLOW DIAGRAM FOR PARTIAL FINISHING BY TUBE SPINNING

TABLE 9. ESTIMATED COSTS FOR SHEAR FORMING

Operation	Cycling Rate on One Machine, pcs/hour	Expendable Tool Cost, \$/life in pcs[1]	Tool Change Cost, \$/pc.	Equipment	Labor, \$/pc.
Transport					0.0007[2a]
Spin 1				Tube Spinner Machine	
(A)	90	0.32	0.30		0.233[2b]
(B)	112	0.24	0.30		0.1875[2b]
Heat-Treat					
(A)	108				0.111[2a]
(B)	5200				0.017[2a]
Transport					
(A)					0.0007[2a]
(B)					0.0014[2a]
Spin 2 (B)	90	0.30			0.233[2b]
Transport B					0.0014[2a]
Age B	400				0.030[2a]
TOTAL					
(A)		0.32	0.30		0.3454
(B)		0.56	0.60		0.471

Preform Cost: \$1.184 - (Extrusion)

	A	B
Fabrication Cost:	\$0.965	\$1.631
TOTAL COST:	\$2.149	\$2.815

(1) Includes repair and regrinding
(2) Labor
(a) \$12.00/hour
(b) \$15.00/hour

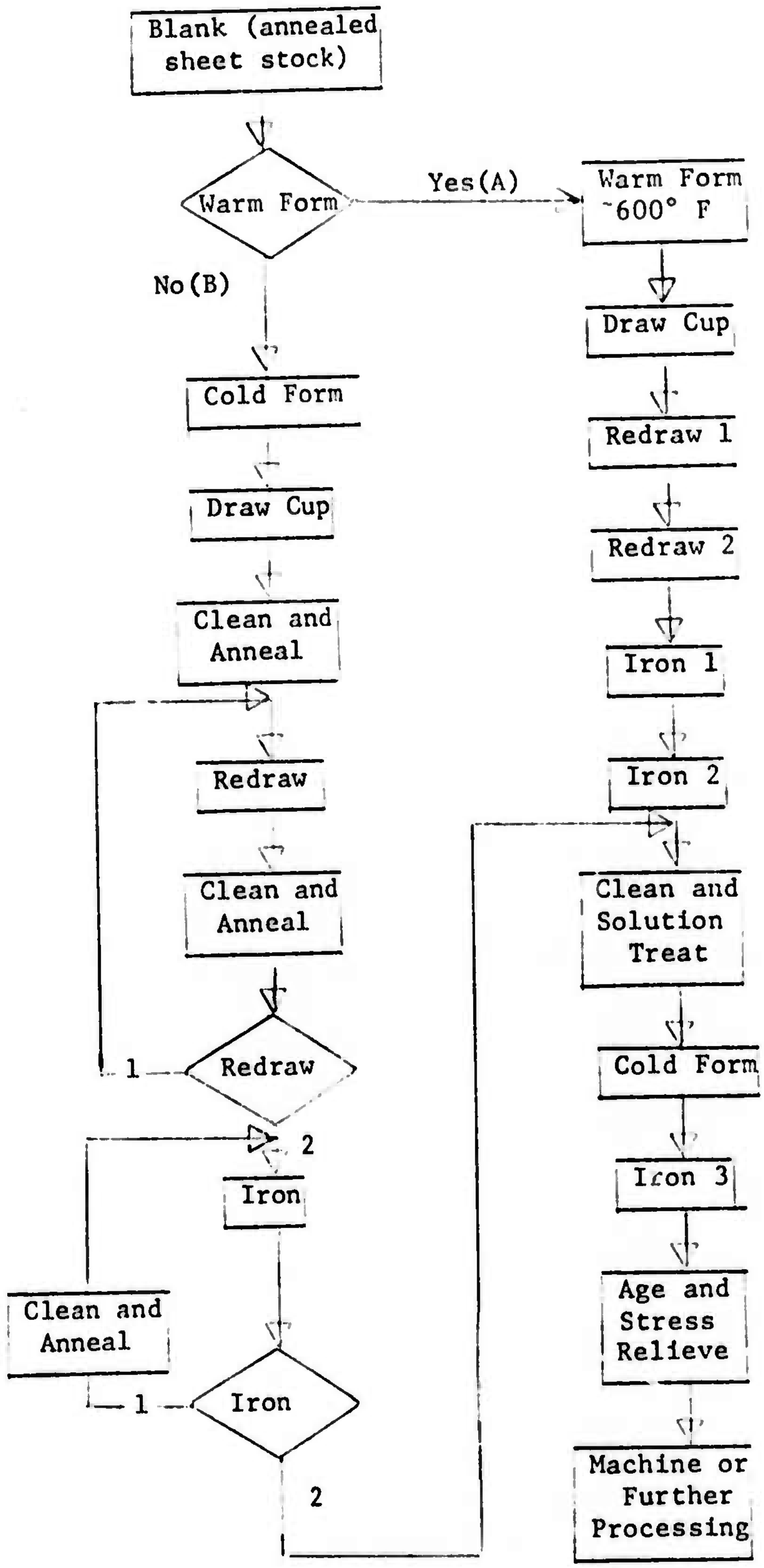


FIGURE 20. PROCESS FLOW DIAGRAM FOR ROUGH FORMING BY DRAWING

Extra volume, beyond that of the formed part, is required for both preforms. The sheet preform includes an additional volume of 0.9 cubic inches because of the disk which must be blanked from the straight cup before sinking. The tubular preform requires an excess volume 2.9 cubic inches, about equal to the product volume, for the following reasons.

(1) Metal flow during tube sinking is sufficiently quantitative to calculate the preform dimensions required to make a particular final shape

(2) The thickness of the neck flange must be equal to or greater than the thickness of the neck on the product after sinking

(3) All wall thickness increase upon sinking

(4) Some length of the body (2.70 inch OD) must exist on the preform (1.0 inch length was assumed necessary) for proper fixturing.

The length dimensions required on the tube are approximately:

(1) 1.00 inch length on the body portion for location during sinking and for stock during subsequent forming of the body

(2) 1.63 inch length for the shoulder area to accept a mandrel for size control during final sizing

(3) 1.37 inch length for the volume necessary in the neck after sinking.

The material costs for providing a rough shape similar to the preform in Figure 11 are as follows.

(1) Drawing a preform - \$0.685

(2) Sinking of a tube - \$1.040

For the contoured shape in Figure 12, the cost is:

(3) Drawing of semi-finished shape - \$0.691.

These material costs are comparatively high when compared with the total cost for a semi-finished shape produced by extrusion. Therefore, the forming costs must be comparatively low if these processes are to be competitive. The costs for drawing are reviewed in the following Tables 10 and 11 and discussion.

TABLE 10. ESTIMATED COSTS FOR DRAWING (Shape in Figure 12)

Operation	Cycling Rate on One Machine, pcs/hour	Expendable Tool Cost, $/life in pcs[1]	Tool Change Cost, $/pc.	Equipment	Labor, $/pc.
Transport					0.0007[2a]
Blank	1440	0.040	0.018	Automatic Blanking Machine	0.015[2b]
Draw					
(A)	360	0.180	0.0097	Mechanical Press	0.063[2b]
(B)	360	0.150	0.0081	Mechanical Press	0.166[2b]
Clean and Heat-Treat					
(A)	400			Automatic/On-Line	0.027[2a]
(B)	400				0.090[2a]
Iron					
(A)	360	0.170	0.0092	Mechanical Press	0.103[2b]
(B)	360	0.150	0.0081	Mechanical Press	0.125[2b]
Transport					
(A)					0.0007[2a]
(B)					0.0021[2a]
Clean and Heat-Treat					
(A)	400				0.027[2a]
(B)	400				0.067[2a]
Age	400				0.030[2a] 0.030[2a]
TOTAL					
(A) - warm work		0.390	0.021		0.266
(B) - cold work		0.340	0.018		0.496

Material Cost: $0.691
Total Cost: (A) = $1.37
(B) = $1.54

(1) Includes Repair and regrinding
(2) Labor
(a) $12.00 per hour
(b) $15.00 per hour

TABLE 11. ESTIMATED COSTS FOR SINKING AND SIZING A TUBE TO PRODUCE A ROUGH PREFORM (See Figure 11)

Operation	Cycling Rate on One Machine, pcs/hour	Expendable Tool Cost, \$/life in pcs[1]	Tool Change Cost, \$/pc.	Equipment	Labor, \$/pc.
Transport					0.0007
Sink					
(A)	600	0.168	0.00243	Mechanical Press	0.060
(B)	600	0.168	0.00243		0.10
Clean and Anneal					
(A)	400			Automatic/On-Line	--
(B)	400				0.12
Size					
(A)	600	0.095	0.00246	Mechanical Press	0.015
(B)	600	0.095	0.00246		0.025
Clean and Anneal					
(A)	400				0.017
(B)	400				0.03
Transport					
(A)					0.0007
(B)					0.0035
TOTAL					
(A) - warm work		0.263	0.00489		0.0934
(B) - cold work		0.263	0.00489		0.2792

Material Cost: \$1.040
Fabrication Cost:
(A) - warm work = \$0.361
(B) - cold work = \$0.547
Total Cost:
(A) - warm work = \$1.401
(B) - cold work = \$1.587
(1) Includes repair and regrinding
(2) Labor
(a) \$12.00 per hour (semi-skilled or helper)
(b) \$15.00 per hour (skilled or operator)

The costs for drawing the preform shape in Figure 11 are nearly the same as the drawing costs (excluding ironing) in Table 10. However, because this shape is rough (i.e., for subsequent processing), the final condition of heat treatment could be either as warm worked or as annealed. The costs for this shape are:

Material Cost:	\$0.685
Fabrication Costs:	
A (warm worked)	\$0.344
B (cold worked)	\$0.470
Total Costs:	
A (warm worked)	\$1.029
B (cold worked)	\$1.155

The costs for sinking and sizing a tubular preform by both warm (600 degrees F), Sequence A, and cold working Sequence B, are presented in Table 11. It is anticipated that four sinking and one sizing pass will be required to produce this shape. Because of the stock and product shapes and the simplicity of the operation, it is anticipated that this operation could be easily automated at a nominal cost to provide a production rate of 10 pieces per minute.

All of the structures produced by the metalworking processes require machining for finishing the form as well as cutting to length and producing holes and slots. The costs for machining the LAWT shape are reviewed in the following.

Machining

Machining operations are usually required on most rocket motor and warhead components to obtain the final shape within the desired tolerance. The type of machining operation employed depends on the part configuration. Machining of cylindrical or concentric shapes is normally carried out on a lathe. Drilling and boring can be performed on a lathe, drill press, jig bore, or boring mill.

The machining operations which would be used on the LAWT warhead include turning, drilling, boring, and threading. Turning is used to finish the outside surface, and is the only machining operation which is affected time-wise by the previous forming operation performed. The various forming tolerances, and associated amounts of metal removed for the different forming methods will directly affect machining time. Drilling is used mostly to make fastner holes. Boring is used to make concentric openings which are larger than those practical by drilling. The boring operation is normally preceded by a drilling operation to start the hole.

Machining is one of the most expensive operations to be performed on warheads and cases because it involves (1) expensive equipment, (2) considerable time, (3) skilled labor, and (4) comparatively high-scrap losses. The time required to remove a volume of material depends on the machining behavior of the material and its hardness. Some materials such as aluminum alloys have very high metal removal rates, while others, such as titanium, have low metal removal rates resulting in high machining costs.

A literature survey was made in another program[32] to determine machining cost methodology. This review provided three significant references[33,34,35] which were used throughout this study to arrive at suitable cost formulas and parameters for machining-cost estimations.

The cost of machining the LAWT warhead involves Running Costs (C_R), Setup Costs (C_S), Tooling Costs (C_T), and Material Cost (C_M). Formulas have been derived to represent these expenses for producing the semi-finished shape shown in Figure 1. The machinability data in Table 12 are considered good industrial practice and were the basis for these calculations.

Running Time

The overall running cost per part, C_R, is determined by the product of the accumulated run times, T_R, of the machining operations performed for a part, and the overall cost per hour, C_H. This relationship can be expressed as

$$C_R = T_R \, C_H \quad .$$

Run time, T_R, in the above expression is the sum of the productive, nonproductive, and inspection times per part, or

$$T_R = T_P + T_{NP} + T_T \quad .$$

Production time, T_P, means metal removal time per operation per part, and can be determined as a quotient of the volume of metal removed (VMR) and the metal removal rate (MRR). Thus, T_P = VMR/MRR.

The metal removal rate for turning is determined from

$MRR = 12d \, f_r \, V_c$, where

d = depth of cut, inch

f_r = feed, inch per revolution

V_c = peripheral speed of workpiece, feet per minute.

The metal removal rate for drilling can be calculated from the formula:

$$MRR = \frac{\pi D^2}{4} f_m ,$$

where D = drill diameter

f_m = in-feed of drill, inch per minute.

TABLE 12. MACHINABILITY DATA FOR ALUMINUM ALLOYS

Operation	Speed, feet per minute	Feed, inch per revolution	Tool Life, inches
Turning			
Roughing	1100	0.020	1200
Finishing	1400	0.010	1000
Drilling	275	0.020	1000
Boring			
Roughing	550	0.010	1200
Finishing	1000	0.015	1000

The in-feed, f_m, is determined by the formula

$$f_m = f_r \times rpm,$$

where $rpm = \frac{V_c}{(0.262)\ (D)}$

f_r = drill feed, inch per revolution

V_c = peripheral speed of the drill, feet per minute.

Nonproductive time, T_{NP}, has been determined from specific formulas suited to the machining operation involved. Thus, for drilling operations, a multiple of the productive time, T_P, is used if time study data are not available. The specific formula used is

$$T_{NP} = \frac{2T_P}{Y},$$

where Y = reciprocal of the machinability rating, or 0.333 for aluminum alloys.

Nonproductive time for turning and boring can be expressed in terms of the part diameter, or

$$T_{NP} = 0.01\ 3335\ D.$$

The amount of inspection time per part, T_I, to charge to a given setup can be difficult to assess. Based on operations at missile manufacturing, it appears that 0.10 hours every part is a reasonable value to use.

The preceding formulas were used to calculate the run times involved in machining a LAWT warhead as a semi-finished shape. The results are shown in Table 13.

Running Cost, C_R

The running cost per part (C_R) is determined from the total run time shown in Table 13 and the overall cost per hour. The running cost for semi-finish machining the LAWT warhead from solid rounds was determined using a rate of $15 per hour for labor and overhead and a total run time, T_R, of 0.331 hours per part. This provided a cost of

$$C_R = (T_R)\ (C_H) = 4.965/\text{part}.$$

TABLE 13. PROCESS TIMES REQUIRED FOR MACHINING AN LAWT WARHEAD FROM A SOLID 7075 ALUMINUM ALLOY ROUND*

			Dimensions, inch				Process Time, hrs/part			
Setup	Where Machined	Machining Operation	Original	New	VMR, cu in.	MRR cu in. min	T_P	T_{NP}	T_I	Run Time, T_R
1	Small end	Turn OD	2.875	1.75	11.44	29.7	0.007	0.038	0.02	0.065
1	Small end	Drill ID	--	1.20	4.665	10.7	0.007	0.042	0.02	0.069
2	Large end	Turn OD	2.875	2.870	0.128	0.294	0.007	0.038	0.02	0.065
2	Large end	Drill ID	--	1.20	4.665	10.7	0.007	0.042	0.02	0.069
2	Large end	Bore ID	1.2	2.50	14.36	23.76	0.01	0.033	0.02	0.063
					TOTAL RUN TIME, T_R, HOURS/PART					0.331

Semi-Finished Part Volume = 14.151 cu inches
Semi-Finished Part Weight = 1.42 pounds
* Parametric data used was obtained from 6061

Set-Up Cost

Cost of a given setup depends on the time required to prepare a machine tool for a particular machining operation (or operations) undertaken on that setup. It can be expressed as

$$C_{SU} = (T_{SU})\ (L_2) \quad ,$$

where T_{SU} = setup time, hour

L_2 = Labor + overhead rate, dollars per hour.

The setup cost per part, C_S, can be determined from the formula

$$C_S = \frac{C_{SU}}{Q} \quad ,$$

where Q is the number parts machined in the setup, which is very large in this study. The time required for setting up necessary tooling for turning and subsequent drilling or boring operations on the same setup can be expressed as

$$T_{SU} = 1.74 + 0.066D - 0.0009D^2 \quad ,$$

where D = blueprint diameter of the part. If D = 2.875 inches, the setup time calculates to 1.92 hours for the two setups involved. The cost per part becomes \$0.006 for 5000 parts, and for large volume production could be considered negligible because a single machine would be dedicated to each operation.

Tooling Cost

Tooling costs are determined by tool life and costs which depend on the tool, tool material and operating conditions. The data in Table 12 were used to obtain the combined tool cost per piece, which may include regrinding, and the cost of the time for replacement. These costs are presented in Table 14 as tool replacement costs.

TABLE 14. TOOL REPLACEMENT COSTS

Operation	Stock Shape Round	Tube
Drilling	0.160	0.092
Boring	0.029	0.029
Turning	0.0247	0.0247
TOTAL	\$0.214	\$0.146

Material Cost, C_M

The material cost, when using solid tubular workpieces, can be determined from the volumes of the workpieces needed. The result of such calculations are shown below.

7075-T6, Solid Rod, 2.875 inches OD

Volume = 53.6 cubic inches per piece

Weight = 5.36 pounds per piece

Cost per pound = \$1.005 (approximate)

Workpiece Cost = \$5.39 per part.

7075-T6, Heavy-Wall Tube (2.875 inch OD, 1.20 inch ID)

Volume = 44.2 cubic inches per piece

Weight = 4.42 pounds per piece

Cost per pound = \$1.335 (approximate)

Workpiece Cost = \$5.90 per part.

Total Machined-Part Cost

Table 15 shows a cost summary for a LAWT warhead ready for final machining. It summarizes the results obtained when a solid workpiece was used, as well as the results obtained for a tubular workpiece. Table 16 shows the glossary of terms used in the cost estimate equations.

TABLE 15. TOTAL COST PER PART FOR LAWT WARHEAD WHEN PRODUCED BY CONVENTIONAL MACHINING

	Solid Workpiece	Tubular Workpiece
Running Cost, C_R, \$/part	4.965	4.39
Setup Cost, C_S, \$/part	0.006	0.006
Tool Cost, C_T, \$/part	0.214	0.146
Total Machining Cost, \$/part	5.185	4.542
Material Cost, \$/part	5.39	5.90
Total Cost Per Part (excluding finish machining)	10.58	10.44

Summary of Manufacturing Costs

Metalworking Processes and the associated costs were determined for preform fabrication (rough forming),rough semi-finishing (Figure 3) and semi-finishing (an approximate Figure 1 shape). The preforming methods were evaluated to determine their cost-reduction potential as input shapes for subsequent semi-finishing by either radial forging or shear forming. These semi-finished metalworked shapes would require a small amount of machining to achieve the target shape in Figure 1 which was the basis for the machining cost analysis. The rough, semi-finished shape would require significant machining, but could provide a low-cost route for producing a finished product by machining if the costs for finishing semi-finished shapes are high. To provide a cost comparison for the various metalworking methods, the total costs required to produce the target Figure 1 shape were developed for the rough semi-finished and semi-finished shapes. These costs are presented in Table 17.

TABLE 16. GLOSSARY OF TERMS USED IN THE COST ESTIMATE EQUATIONS

D = Blueprint, outside diameter, inches

H = Length, inches

Q = Quantity, number

t = Maximum blueprint thickness, inches

C = Cost, each, dollars

C_P = Material preparation cost, dollars/part

C_T = Tooling or fixture cost, dollars

C_M = Material cost, dollars per part

C_F = Forming cost, dollars per part

C_S = Setup costs, dollars

C_R = Run time cost, dollars per part

C_1 = Inspection cost, dollars per part

L_1 = Labor, unskilled, + overhead + G and A + profit, dollars per hour

L_2 = Labor skilled, + overhead + G and A + profit, dollars per hour

W = Weight of finished component, pounds

q = Learning curve factor, dimensionaless; $q = Q^{-0.2340}$

X = Material factor in forming, dimensionless

Y = Reciprocal of machinability rating, dimensionless

m_2 = Material cost per pound, dollars per pound, billet

e = Density of materials, pounds per cubic inch

TABLE 17. SUMMARY OF MANUFACTURING COSTS (Dollars per Piece)

Process	Fabrication	Machining	Total
Extrusion (Figure 3)	$1.184	$2.50	$3.68
Semi-Finished			
(A) warm work	$1.184	$2.50	$3.68
(B) cold work	$1.264	$2.50	$3.76
Rough Formed	$1.136	--	
Radial Forging (Figure 6)			
Rough-Forged	$1.583	--	
Finish-Forged			
(A) warm work			
Extruded Preform	$1.384	$2.12	$3.50
Rough Drawn Preform	$1.277	$2.12	$3.40
(B) cold work			
Extruded Preform	$1.532	$2.12	$3.65
Rough Drawn Preform (A)	$1.425	$2.12	$3.56
Shear Forming (Extruded Preform) (Figure 11)			
Partially Finished Form			
(A) warm work	$2.149	$2.50	$4.65
(B) cold work	$2.815	$2.50	$5.32
Drawing			
Draw and Iron (Figure 12)			
Semi-Finished Form			
(A) warm work	$1.37	$2.76	$4.13
(B) cold work	$1.54	$2.76	$4.30
Rough Drawn Preform (Figure 11)			
(A) warm work	$1.029	$2.76	$4.13
(B) cold work	$1.155	--	$4.30
Rough Preforming by Sinking (Figure 11)			
(A) warm work	$1.401	--	
(B) cold work	$1.587	--	
Machining			
From Round Bar			$10.58
From Tube			$10.44

CONCLUSION

The results of this program have shown that metalworking processes can be used to achieve a cost reduction in excess of 60 percent when compared with conventional machining. The most significant cost reduction arises from the efficient utilization of material achieved by precision metalworking. Although the costs were presented to 3 and sometimes 4 significant figures for comparative purposes, it is doubtful that their accuracy exceeds 20 percent. In recognition of this fact, the following processes appear most promising for providing low-cost production of the LAWT missile body.

- Extrusion of a semi-finished shape
- Precision radial forging of either a rough-extruded or a rough-drawn preform to provide a semi-finished shape.

Regardless of the forming method, significant machining would be required to finish the product. In principal, radial forging possesses the greatest capability for producing a precision shape. However, this precision has not been demonstrated on structures similar to the LAWT. This demonstration would require the use of some novel tooling designs which were described in the text in terms of their utility and potential risk.

The process exhibiting the least risk and one of the lowest costs was extrusion. This process would involve a sequence of operations incorporating upsetting, back extrusion, piercing and blanking and combined forward-back extrusion to produce a semi-finished product from rod. The significant features of this process are its low cost, the several production demonstrations on parts similar to the LAWT, and adaptibility to automated production.

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