IR 140-8 (I)

MAR 25 1968

PROTOTYPE PRODUCTION PROCESS FOR FABRICATION OF WIRE AND TUBING BY HYDROSTATIC EXTRUSION-DRAWING

R. J. Fiorentino
J. C. Gerdeen
G. E. Meyer
B. D. Richardson
A. M. Sabroff

BATTELLE MEMORIAL INSTITUTE
COLUMBUS LABORATORIES

INTERIM ENGINEERING PROGRESS REPORT

February 1968

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals must be made only with prior approval of the Manufacturing Technology Division

METALLURGICAL PROCESSING BRANCH
MANUFACTURING TECHNOLOGY DIVISION
AIR FORCE MATERIALS LABORATORY
DIRECTORATE OF LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

NOTICES

DDC RELEASE TO OTS NOT AUTHORIZED.

This document may not be reproduced in any form in whole or in part without prior approval of the Research and Technology Division. However, DDC is authorized to reproduce the document for "U.S. Governmental purposes".

Qualified requesters may obtain copies of this report from DDC, Defense Document Service Center, Cameron Station, Alexandria, Virginia, 22134. Orders will be expedited if placed through the librarian or other person designated to request documents from DDC.

Copies of this report should not be returned to the Air Force Materials Laboratory unless return is required by security considerations, contractual obligations, or notice on a specific document.

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval to the Manufacturing Technology Division.

PROTOTYPE PRODUCTION PROCESS FOR FABRICATION OF WIRE AND TUBING BY HYDROSTATIC EXTRUSION-DRAWING

R. J. Fiorentino
J. C. Gerdeen
G. E. Meyer
B. D. Richardson
A. M. Sabroff

ABSTRACT

This report describes the initial steps taken towards ascertaining the production tooling and the proper process sequences for prototype production of beryllium wire and titanium tubing by hydrostatic extrusion-drawing (HYDRAW). Design specifications have been drawn up for a straight-bore container to be used for the HYDRAW of beryllium wire and consideration is being given to the possibility of using a side-bore container for the HYDRAW of titanium tubing. Design analyses are still being conducted on side-bore containers.

Experimental equipment is being constructed which will be used for process parameter studies in sub-scale hydrostatic tooling.

FOREWORD

This Interim Engineering Progress Report covers the work performed under Contract No. F 33615-68-C-1197 from 1 November 1967 through 31 January 1968. It is published for technical information only and does not necessarily represent the recommendations, conclusions, or approval of the Air Force.

This contract with Battelle Memorial Institute of Columbus, Ohio, was initiated under Project No. 140-8, "Prototype Production Process for Fabrication of Wire and Tubing by Hydrostatic Extrusion-Drawing". It is being administered under the direction of Mr. Gerald A. Gegel of the Metallurgical Processing Branch (MATB), Manufacturing Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

The program is being conducted at Battelle by the Metalworking Division with Mr. R. J. Fiorentino, Associate Chief, as Program Manager. Mr. B. D. Richardson, Research Metallurgical Engineer, is Project Engineer of the studies on beryllium wire and rounds and Mr. G. E. Meyer, Research Metallurgical Engineer, is Project Engineer of the titanium tubing portion of the program. Others contributing to the program are Mr. J. R. Douglas, Research Metallurgist, and Mr. A. M. Sabroff, Chief of the Metalworking Division, and Mr. F. W. Boulger, Senior Technical Advisor of the Department of Process and Physical Metallurgy. Dr. J. C. Gerdeen, Senior Research Mechanical Engineer, Advanced Solid Mechanics Division, is contributing to the high-pressure-container design study. Data from which this report has been prepared and recorded are in Battelle Laboratory Record Book No. 24446.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

INTRODUCTION

The purpose of this research program is to ascertain the production tooling and the proper process sequences for prototype production of 0.005-inch-diameter beryllium wire and thin-wall Ti-6Al-4V titanium-alloy tubing in sizes ranging from about 1/4 to 1-inch OD. The production technique to be used will be hydrostatic extrusion-drawing. This Battelle-developed technique*, called HYDRAW, consists of applying a hydrostatic pressure to the unreduced stock while simultaneously applying a controlled drawing stress at a predetermined drawing speed.

Present-day conventional techniques for producing beryllium wire and titanium tubing are quite costly. The results obtained in an earlier program(1)** at Battelle on Air Force Contract No. 33(615)-1390 indicate that the techniques outlined for this program offer the prospect of reducing fabrication costs substantially as well as possibly improving product quality. The current program is divided into three phases, each subdivided for beryllium wire and seamless Ti-alloy tubing with the following general objectives:

Phase I

Part (a). To establish the various parameters which affect the hydrostatic extrusion-drawing of fine beryllium wire and seamless titanium tubing with existing tooling.

Part (b). To design and construct prototype production tooling for extrusion-drawing of beryllium wire and titanium tubing for the Phase II effort.

Part (c). To establish the various die design parameters which influence the hydrostatic extrusion of brittle materials without the use of a fluid counter-pressure system.

Phase II

To ascertain the processing techniques and conditions necessary for producing high-quality, 0.005-inch-diameter beryllium wire and aircraft-quality Ti-6Al-4V tubing with the prototype production tooling.

Phase III

To produce a sufficient quantity of the beryllium wire and titanium tubing to verify the processing sequence and to enable evaluation by users.

---

* U. S. Patent No. 3,328,998, "High Reduction Drawing", A. M. Sabroff and R. J. Fiorentino, Issued July 4, 1967.

** References given at end of report.

The design and construction of tooling for extrusion-drawing of beryllium wire [in Phase I, Part (b)] is being funded independently by Battelle-Columbus. However, in the interest of furthering the tooling design technology developed in the past program(1), complete details of the proposed tooling design are included in this report.

During this first quarter much of the effort was devoted to procuring the equipment, materials, and tooling necessary to conduct the process parameter investigations. In addition, the design specifications for the 7-inch-bore container to be used in the Phases II and III efforts on beryllium wire, have been completed. A preliminary design analysis of the side-bore container which might be used for the Phases II and III efforts on titanium tubing has been conducted.

HYDRAW STUDIES

The Phase I process parameters studies on the HYDRAW of both beryllium wire and titanium alloy tubing are to be conducted in tooling constructed for the Air Force Materials Laboratory on Air Force Program No. AF 33(615)-1390. This tooling, which is described in detail in Reference (1), has a design pressure capacity of 250,000 psi on a bore 2-3/8-inch diameter x 20 inches long. The chamber volume is adequate for handling sufficient quantity of material for the evaluation of the initial process variables. Preliminary details of the design of prototype production containers for the Phases II and III effort are given later in the report.

HYDRAW of Beryllium Wire

Experimental trials on the HYDRAW of beryllium wire are soon to be conducted. In an earlier program(1), beryllium wire was hydrostatically extrusion-drawn from 0.020 to 0.0124-inch diameter (a reduction of 60 percent) at a speed of about 40 fpm. In the forthcoming trials, the following parameters will be evaluated:

(a) Lubrication. In an earlier program only one wire lubricant, PTFE, was evaluated. This was quite satisfactory but several wire lubricants are now to be evaluated with the aim of possibly improving lubrication efficiency and reducing the cost of application and removal. Initially, the selected wire lubricants will be evaluated at a reduction of 60 percent.

(b) Reduction ratio. Dies have been ordered which will enable reduction of 60, 70, 75, and 80 percent. Data obtained in another program have indicated that reductions up to 80 percent are possible within the available pressure capacity, providing efficient lubrication can be obtained.

(c) Temperature. Workpiece temperatures lower than the presently established 500-550 F range will be used to determine their effect on pressure requirements and material properties.

(d) Exit speed. Equipment has been purchased and assembled which will enable a greater flexibility of drawing speed and draw stress than was previously used. Wire exit speeds will be independently controllable from 30 to 600 fpm. Should relatively high exit speeds be possible, it is anticipated that the heat generated during deformation may allow lower environmental preheat temperatures to be used. The unit will also be able to provide controlled drawing loads ranging from about 0.1 to 150 lbs.

Beryllium wire representing both ingot and powder origin has been purchased. The wire is nominally 0.020-inch diameter and is to be reduced in the annealed condition. On the basis of previous experience obtained in the HYDRAW of this material (see Reference (1)), the wire will be pre-coiled by a warm-wrapping technique (at 600 F) and will be paid out from within the hydrostatic container from a free vertical coil. The coil will be loaded in a unit which will also house the die. This unit will facilitate the handling of the wire and die during loading in the hydrostatic container.

Initially, the HYDRAW experiments will be conducted at temperatures up to 550 F. This requires preheating the container, fluid, and the wire and die unit. However, studies are currently being made of techniques for locally heating the wire around the die orifice. This will allow the container and most of the fluid to be maintained at or near room temperature, which should reduce the problems of sealing and materials handling accordingly.

HYDRAW of Titanium Tubing

Contacts have been made with possible vendors of titanium tubing for use in the process parameter studies. Until the available tube sizes are established, the experimental trials cannot be planned in detail – especially in regard to the design of mandrels and dies. Only three out of nine seamless tube manufacturers have expressed an interest in producing the Ti-6Al-4V alloy tubing in the sizes and quantities required. It is anticipated that a working arrangement can be established with at least one of these companies by which the tube manufacturer can participate in the evaluation of the tubes produced by HYDRAW. The use of the manufacturer's test facilities would minimize wasteful duplication of equipment.

The approximate tube stock sizes which will be initially evaluated by HYDRAW are as follows:

OD, inches	ID, inch	Wall Thickness, inch
1.125	0.981	0.072
0.625	0.527	0.049

The HYDRAW trials will be aimed at determining the processing parameters required to reduce both the bore diameter and the wall thickness of the tubing.

To best utilize the capabilities of the HYDRAW process, very high draw loads will be required to provide draw stresses in the order of 150,000 psi. A special hydraulic draw bench is currently being designed with this capacity. The drawing unit will be designed for use on Phases II and III of the program also.

HYDRAW TOOLING FOR PROTOTYPE PRODUCTION

The preliminary design studies have indicated that the container to be used for the HYDRAW of beryllium wire should be of straight-bore multi-ring construction but the container to be used for the HYDRAW of titanium tubing might be of right-angle or side-bore design. These conclusions are based on the design requirements for each application and on the limited amount of design data available on side-bore container design. The fluid pressure level required for the HYDRAW of beryllium wire, at least 200,000 psi, for a long-fatigue-life side-bore container appears to be too high based on the present-day technology for such designs. A side-bore design would have an advantage in paying out wire tangentially from a large coil of wire stock. However, it is anticipated that paying out wire from a straight-bore container will present no problems.

An advantage of the side-bore design for extrusion of tubing is the ability to use vertical hydraulic presses without large vertical "daylight" between platens and without deep pits beneath them to extrude long lengths of product. It is estimated that a side-bore system can be designed to withstand pressures (P) on the order of 150,000 psi. It appears that this level should be sufficient for HYDRAW of titanium alloy tubing, since it will be possible to apply a draw stress (D) of at least 125,000 psi to the tube product (together with the 150,000 psi fluid pressure). This would make the total P + D = 275,000 psi, which is adequate to effect substantial tube reductions in a single pass. A model study of the right-angle system is to be conducted to determine with a greater degree of certainty the feasibility of containing pressures in the order of 150,000 psi and higher. This study will be conducted in the near future.

Design of a Container for the HYDRAW of Beryllium Wire

The straight-bore, multi-ring container for the HYDRAW of beryllium wire has been designed on the basis of the fatigue-strength criterion established in an earlier program(1). In addition to beryllium wire, the container will have the capability of being used for a wide variety of hydrostatic extrusion applications. It has been designed to withstand pressures of 250,000 psi on a bore of 7-inches diameter by 30 inches long. Thus a coil of wire up to at least 6-inches diameter can be accommodated co-axially in the container. To add to the versatility of the tooling, the container has also been designed to withstand up to 350,000 psi on a 4-inch diameter bore, provided that a liner material having suitable properties is available. This pressure capability would be achieved by press fitting a 4-inch bore liner into the 7-inch bore.

The outer dimensions and number of rings of the container were calculated for the 7-inch bore container using optimum design procedures. This was done using the computer code MULTIR developed in an earlier program(1). A summary of the calculations is shown in Table 1. The following generalized fatigue relations, formulated in an earlier program(1), were used in the design:

$$A_n (\sigma_\theta)_r + B_n(\sigma_\theta)_m = \sigma_n \qquad \text{or} \qquad A_n S_r + B_n S_m = \sigma_n \tag{1a, b}$$

TABLE 1. DESIGN DETAILS FOR TWO MULTI-RING HYDROSTATIC EXTRUSION CONTAINERS HAVING 5 RINGS IN COMMON

Ring	Diameter, inches		Material Design Stress(a)	Manufactured Interferences(b)	Stress on ID at Pressure, psi			Residual Stresses on ID, psi		
	OD	ID			Radial	Hoop	Shear	Radial	Hoop	Shear
					7-Inch Bore, 250,000 psi Container					
2	11.9	7.0	300,000	0.0453	-254,000	8,000	131,000	0	-258,000	129,000
3	18.5	11.9	250,000	0.0462	-168,000	37,000	102,000	-84,000	- 59,000	12,000
4	25.7	18.5	170,000	0.0702	-108,000	51,000	80,000	-77,000	8,000	43,000
5	35.8	25.7	170,000	0.0745	- 70,000	95,000	82,000	-56,000	70,000	63,000
6	46.5	35.8	150,000		- 30,000	117,000	74,000	-26,000	101,000	64,000
					4-Inch Bore, 350,000 psi Container					
1	7.0	4.0	350,000	0.0272	-366,000	11,000	188,000	0	-361,000	180,000
2	11.9	7.0	300,000	0.0441	-239,000	1,000	120,000	-121,000	-123,000	1,000
3	18.5	11.9	215,000	0.0462	-161,000	33,000	97,000	-122,000	- 11,000	55,000
4	25.7	18.5	160,000	0.0660	-104,000	51,000	78,000	- 89,000	31,000	60,000
5	35.8	25.7	160,000	0.0687	- 66,000	91,000	79,000	- 60,000	79,000	70,000
6	46.5	35.8	140,000		- 28,000	110,000	69,000	- 26,000	103,000	65,000

(a) The design stress for Rings 1, 2, and 3 was the ultimate tensile strength. The design stress for Rings 4, 5, and 6 was the yield tensile strength. The design stress is the right hand side of the fatigue relations, Equations (1a, b) in the text.

(b) Interferences between each ring before assembly.

where

(a) A_n, B_n are coefficients describing the material of ring number n,

(b) subscript, r, denotes the semi-range stress component,

(c) subscript, m, denotes the mean stress component, and

(d) σ_n is the tensile strength of ring number n.

It is seen in Table 1 that to withstand 250,000 psi on the 7-inch bore (which is the inside diameter of Ring 2) an outside diameter of 46.5 inches and 5 rings are required. This design was influenced by the fact that a liner (Ring 1 in Table 1) is to be press-fitted in the 5-ring assembly to give a container having a 350,000 psi pressure capacity on a 4-inch bore. Details of this design are also given in Table 1.

The fatigue life of the two containers is expected to be 10^5 to 10^6 cycles under ideal conditions. They were designed to be operated at room temperature only.

The computer program was not capable of exactly matching the requirements of the two containers and so the calculated interferences for the 6-ring container differ slightly from those obtained for the 5-ring. However, if Ring 1 is removed from the 6-ring container it is seen in Table 2 that the stresses in the remaining 5 rings compare very closely with the optimum design stresses required to contain 250,000 psi. Thus, the design interferences for the 6-ring container will be adopted for the multi-purpose hydrostatic extrusion container. However, the higher design strengths of the outer four rings of the 5-ring, 250,000 psi container will be used.

TABLE 2. COMPARISON OF STRESSES IN THE OUTER 5 RINGS OF THE 6-RING CONTAINER (LINER REMOVED) WITH THOSE IN THE 5-RING CONTAINER

	Stresses on ID at Pressure, psi			Residual Stresses on ID, psi		
Ring	Radial	Hoop	Shear	Radial	Hoop	Shear
	Stresses in 5 Rings of 6-Ring Container (Liner Removed)					
2	-250,000	12,000	131,000	1,000	-250,000	125,000
3	-164,000	38,000	101,000	-82,000	- 57,000	12,000
4	-105,000	53,000	79,000	-74,000	11,000	43,000
5	- 67,000	92,000	80,000	-54,000	67,000	61,000
6	- 28,000	111,000	70,000	-24,000	95,000	60,000
	Stresses in 5-Ring Container (Optimum Design)					
2	-254,000	8,000	131,000	0	-258,000	129,000
3	-168,000	37,000	102,000	-84,000	- 59,000	12,000
4	-108,000	51,000	80,000	-77,000	8,000	43,000
5	- 70,000	95,000	82,000	-56,000	70,000	63,000
6	- 30,000	117,000	74,000	-26,000	101,000	64,000

On the basis of this design, three industrial companies have been asked to quote on the fabrication of the tooling. As soon as quotations have been received and the exact specification of the tooling has been ascertained, a more detailed design of the auxiliary tooling specifically required for the HYDRAW of wire will be prepared. This will include the wire spooling and paying-out arrangements. These will be based on preliminary model studies of techniques required to pay out axially from a large coil of fine wire. It is anticipated that most of this effort will be conducted in the next quarterly period.

Design of a Container for the HYDRAW of Titanium Tubing

A preliminary design assessment of a right-angle or side-bore container has been conducted because of the possibility of its use for the HYDRAW of titanium tubing.

A monoblock side-bore container is shown in Figure 1. (The term "side-bore" is used here to distinguish it from a "cross-bore" design in which one hole intersects the other in two places.) This design offers advantages to the hydrostatic extrusion process where the billet length plus the stem stroke results in an excessive length for a straight-bore container. If a side-bore container could be used, the required container length would be less and consequently the required working clearance of the press would be less.

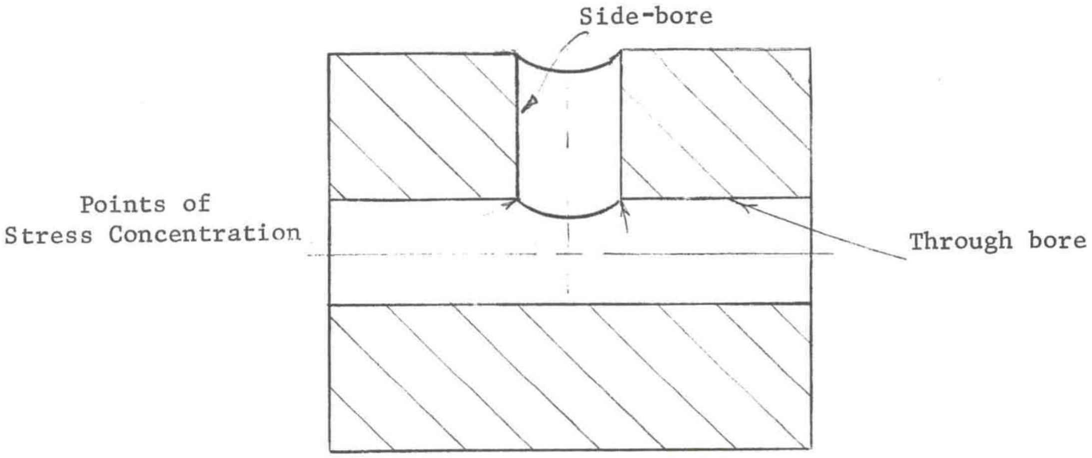

FIGURE 1. CROSS SECTION OF A MONOBLOCK SIDE-BORE CONTAINER

However, a side-bore container suffers from a stress concentration at the critical "tee-section" at points of intersection of the main bore and the side bore as shown in Figure 1. The stress-concentration factor, k_h, on the hoop stress results in a hoop stress of $(\sigma_\theta)_T$ at the tee-intersection of

$$(\sigma_\theta)_T = k_h \sigma_\theta \tag{2}$$

where σ_θ is the nominal hoop stress calculated for a straight cylinder.

The stress-concentration factor, k_h, can be expected to be different for internal pressure and external pressure loadings on the liner. The k_h for these two loadings are denoted as k_{hi} and k_{he} respectively.

In a straight-bore container, the maximum shear stress, S, at the bore is

$$S = \frac{\sigma_\theta - \sigma_r}{2} \quad . \tag{3}$$

At the tee-intersection of a side-bore container for the internal pressure condition, $\sigma_r = -p$, the shear stress is

$$S_T = \frac{k_{hi}\sigma_\theta + p}{2} \tag{4}$$

where p = fluid pressure.

Consequently, the stress-concentration factor, k_{si}, on the shear stress for the internal pressure condition is

$$k_{si} = \frac{S_T}{S} = \frac{k_{hi}\sigma_\theta + p}{\sigma_\theta + p} \quad , \tag{5}$$

whereas at the unloaded condition (residual stress condition with zero-bore pressure), the shear-stress concentration factor is

$$k_{se} = k_{he} \quad . \tag{6}$$

If the stress-concentration factors are known, then the semi-range and mean stresses for a pressure cycle can be calculated as follows:

$$(\sigma_\theta)_r = \frac{k_{hi}\,(\sigma_\theta)_{max} - k_{he}\,(\sigma_\theta)_{min}}{2}$$

$$(\sigma_\theta)_m = \frac{k_{hi}\,(\sigma_\theta)_{max} + k_{he}\,(\sigma_\theta)_{min}}{2} \tag{7a, b}$$

and

$$S_r = \frac{k_{si}\,S_{max} - k_{se}\,S_{min}}{2}$$

$$S_m = \frac{k_{si}\,S_{max} + k_{se}\,S_{min}}{2} \tag{8a, b}$$

where the stresses $(\sigma_\theta)_{max}$, $(\sigma_\theta)_{min}$, S_{max}, and S_{min} for a straight cylinder can be calculated using Equations (1a, b) and:

$$Sr = \frac{k_n^2}{2(k_n^2 - 1)} [\, p_{n-1} - p_n) - (q_{n-1} - q_n)], \text{ at } r = r_{n-1} \tag{9}$$

and

$$S_m = \frac{k_n^2}{2(k_n^2-1)} \left[(p_{n-1} - p_n) + (q_{n-1} - q_n)\right], \text{ at } r = r_{n-1} \tag{10}$$

where

k_n = wall ratio of component n, $k_n = r_n/r_{n-1}$

p_n = pressure acting on component n at r_n where $p \neq 0$, psi

p_{n-1} = pressure acting on component n at r_{n-1} where $p \neq 0$, psi

q_n = residual interface pressure acting on component n at r_n where $p = 0$, psi

q_{n-1} = residual interface pressure acting on component n at r_{n-1} where $p = 0$, psi

r_n = outside radius of component n, inches

r_{n-1} = inside radius of component n, inches.

(Reference (1) gives the derivation of Equations (9) and (10)).

For large-diameter cylinders of large wall ratio (k_1), it has been found (in both theoretical and experimental studies at Battelle) that the minimum k_h, i.e., the optimum geometry, occurs when the side-bore diameter equals the bore diameter. This yet needs to be verified experimentally for smaller wall ratio liners for $k_1 \leq 6$. For $k_1 \geq 6$ it has also been found that $k_{hi} \approx k_{he}$. Thus, assuming $k_{hi} \cong k_{he} \equiv k_h$ and a maximum-tensile-stress fatigue criterion on the hoop stress for a side-bore liner, the pressure capability, p_{sb}, predicted for a side-bore container is

$$p_{sb} = p/k_h \tag{11}$$

where p is the pressure capability for a straight cylinder. If $k_h = 1.5$ and $p = 300,000$ psi, then $p_{sb} = 200,000$ psi.

The corners at the "tee-intersection" can also be rounded off at the points shown in Figure 1 to reduce the stress-concentration factor by a few percent, and thus increase p_{sb} somewhat.

To improve the pressure capacity of a side-bore container, it might be possible to provide some prestress to the liner material by similar techniques to those used in straight-bore containers. The possibilities offered by multi-ring construction are now considered.

Equation (11) would apply to a multi-ring, side-bore container only if the outer rings, which also must have side bores and corresponding stress concentrations, are not stressed too high. If it is necessary that the side-bore diameter of each ring must be equal to the bore diameter as was found for the optimum design of monoblock containers, then the side bore must be larger for each subsequent outer ring as shown in Figure 2. However, the stepwise increase in side-bore diameter results in less and less supporting material. Perhaps a better design would be to use a double set of shrink-rings that are separated longitudinally such as shown in Figure 3. This would avoid stress concentrations in the outer rings, but would result in less compressive stress at the bore of the liner than would be achieved if a continuous ring was shrunk

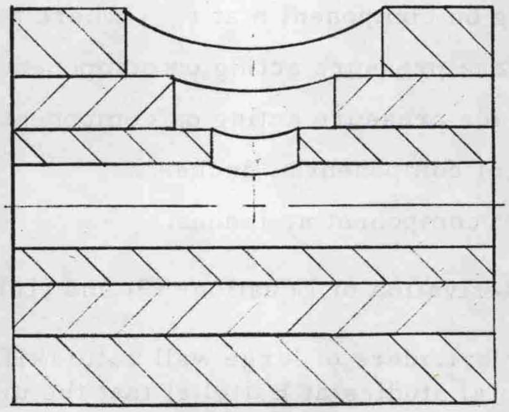

FIGURE 2. CROSS SECTION OF A SHRINK-FIT SIDE-BORE CONTAINER (WITH SIDE-BORE DIAMETERS EQUAL TO BORE DIAMETERS OF EACH RING)

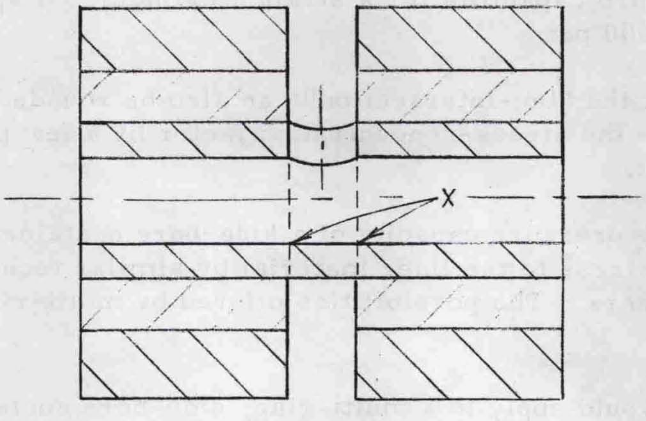

FIGURE 3. CROSS SECTION OF A SIDE-BORE CONTAINER WITH A DOUBLE SET OF SHRINK RINGS

on. For example, it can be shown that the nominal residual hoop stress at the liner bore at Point X in Figure 3 would be 1/2 the value normally achieved entirely under the shrink-ring. (An analysis of this is given in Reference (2)). This is assumed to apply to the type of shrink rings shown in Figure 2 as well. Thus, it is concluded that a side-bore container with such "partial" shring-rings, compared to a straight-bore container with the same number but "whole" shrink-rings, will have a pressure capability less than that given by Equation (11).

To avoid difficulties associated with shrink-rings on a side-bore liner, an autofrettaged monoblock design of a side-bore container is considered. If the wall ratio could be made sufficiently large, and an autofrettage residual stress of sufficient magnitude could be achieved, then Equation (11) may apply for p = pressure capability of an autofrettaged straight cylinder. For example, pressures, p, up to 290,000 psi have been applied many times to a monoblock autofretteged cylinder of 285,000 psi ultimate tensile strength as reported by Thomas, Turner, and Wall(2). The cylinder had an overall wall ratio of K = 7.2.

Before autofrettage can be recommended with confidence for side-bore cylinders, experiments should be conducted to determine if the same benefit is achieved as achieved in straight-bore cylinders. It is well to point out here that autofrettaged cylinders are weaker in fatigue than are shrink-fitted cylinders(2) but an autofrettaged monoblock may be easier to replace than a liner of a shrink-fitted container.

Clearly, there are many unknowns in the design of side-bore containers. Even in the design of straight-bore containers much remains to be learned about such factors as fatigue properties of high-strength steel cylinders under cyclic internal pressures and the autofrettaging capabilities of high-strength steels. However, because relatively low fluid pressures of about 150,000 psi will be required for the HYDRAW of titanium tubing, the use of a side-bore container is a distinct possibility and would be eminently desirable from a materials handling standpoint. Consequently, studies are soon to be conducted on geometrically similar plastic models to determine the stress-concentration factor at the critical tee-intersection. This will be done by measuring the strains under pressure indicated by suitably positioned strain gauges. Pressures of only a few hundred psi would be required. The variation of stress-concentration factor with wall ratio will be investigated. The model will be designed with an optimum side-bore to through-bore diameter ratio of one, and with a tee-intersection-radius to bore-radius ratio of one.

REFERENCES

(1) Fiorentino, R. J., Richardson, B. D., Meyer, G. E., Sabroff, A. M., Boulger, F. W., "Development of the Manufacturing Capabilities of the Hydrostatic Extrusion Process", Technical Report AFML-TR-6, Contract No. AF 33(615)-1390, October 1967.

(2) Meyer,G. E., Simonen, F. A., Gerdeen, J. C., Fiorentino, R. J., Sabroff, A.M., "Design Study of a Production Press for Ultrahigh-Pressure Hydrostatic Extrusion", Final Report, Contract No. F 33615-67-C-1434, to be issued March 1968.

(3) Thomas, S. L. S., Turner, H. S., and Wall, W. F., "Piston-Cylinder High Pressure Apparatus for Use up to 25 kb", Paper No. 11, Institution of Mechanical Engineers, High Pressure Engineering Conference, London, September 11-15, 1967.

DISTRIBUTION LIST

U. S. Government

AFFDL (FDTS)
Wright-Patterson AFB, Ohio 45433

AFML (MAAM)
Attention Library
Wright-Patterson AFB, Ohio 45433

AFML (MAMN/Mr. Tom Cooper)
Wright-Patterson AFB, Ohio 45433

AFML (MAMP/Mr. N. M. Geyer)
Wright-Patterson AFB, Ohio 45433

AFML (MAMP)
Attention Mr. V. DePierre
Wright-Patterson AFB, Ohio 45433

AFML (MAMP)
Attention Mr. K. Kojola
Wright-Patterson AFB, Ohio 45433

AFML (MAMP/K. Elbaum)
Wright-Patterson Air Force Base
Ohio 45433

AFML (MANF/Mr. J. H. Ross)
Wright-Patterson AFB, Ohio 45433

AFML (MAP/Mr. Besancon)
Wright-Patterson AFB, Ohio 45433

AFML (MATB)
Attention Mr. G. A. Gegel (8 copies)
Wright-Patterson AFB, Ohio 45433

AFML (MATF)
Wright-Patterson AFB, Ohio 45433

ASD (ASFE)
Wright-Patterson AFB, Ohio 45433

ASD (SEVS)
Wright-Patterson AFB, Ohio 45433

Defense Documentation Center (DDC)(20)
Cameron Station
5010 Duke Street
Alexandria, Virginia 22134

FTD
Attention TD-E2b
Wright-Patterson AFB, Ohio 45433

FTD (TDEWP)
Wright-Patterson AFB
Ohio 45433

Lewis Research Center
AFSC/STLO
Attention Capt. J. O. Tinius
21000 Brookpark Road
Cleveland, Ohio

Los Alamos Scientific Laboratory
Attention Dr. John E. Hockett
Los Alamos, New Mexico

National Aeronautics & Space
Administration
Lewis Research Center
Attention Mr. C. P. Blankenship
M. S. 105-1
21000 Brookpark Road
Cleveland, Ohio 44135

National Aeronautics & Space
Administration
Lewis Research Center
Attention Mr. George Mandel
Chief, Library
21000 Brookpark Road
Cleveland, Ohio 44125

NASA-Marshall Space Flight Center
Redstone Arsenal
Attention Mr. William A. Wilson, Chief
Methods Development Branch
R-ME-MM Manufacturing
Research Technology Division
Huntsville, Alabama 35812

DISTRIBUTION LIST
(Continued)

Naval Air Systems Command
Department of the Navy
Code AIR 520311
Attention Mr. R. Schmidt
Washington, D.C. 20360

Oak Ridge National Laboratory
Building 4508
Attention Mr. W. R. Martin
Oak Ridge, Tennessee

U. S. Army Missile Command
AMSMR-RKK (Mr. Charles H. Martens)
Redstone Arsenal, Alabama

U. S. Atomic Energy Commission
Technical Information Services Extension
Attention Mr. Hugh Voress
P. O. Box 62
Oak Ridge, Tennessee

U. S. Army Materials Research Agency
Watertown Arsenal Laboratories
Attention Mr. Robert Colton
Chief, Shaping Technology Branch

Director, USAEL
Hq. USAECOM
Attention AMSEL RD-PEE (Mr. Divita)
Ft. Monmouth, New Jersey 07703

Hq USAF (AFSPDI/Mr. W. Martin)
The Pentagon
Washington, D.C. 20330

Commanding Officer
Watertown Arsenal Laboratories
Attention Mr. S. V. Arnold
Associate Director
Watertown 72, Massachusetts

Watervliet Arsenal
Maggs Research Center
Attention Dr. T. A. Davidson
Watervliet, New York 12189

Watervliet Arsenal
Process Engineering Section
Benet Laboratories
Attention Mr. Leonard Liuzzi
Watervliet, New York 12189

Industrial

Aerojet General Corporation
P. O. Box 296
Azusa, California

Allegheny Ludlum Steel Corporation
Research Center
Attention Mr. E. G. Flynn
Supervising Metallurgist
Extruded Products
Brackenridge, Pennsylvania

Allis-Chalmers
Box 512
Attention Dr. Laird C. Towle
Research Physicist
Milwaukee, Wisconsin 53201

Alpha Metals, Inc.
Attention Mr. R. H. Hilsinger
56 Water Street
Jersey City, New Jersey 07304

DISTRIBUTION LIST
(Continued)

Aluminum Company of America
ALCOA Building
Attention Mr. R. W. Andrews
Pittsburgh, Pennsylvania

Babcock & Wilcox Company
Attention Mr. James Barrett
Beaver Falls, Pennsylvania

Baldwin-Lima-Hamilton Corporation
Industrial Equipment Division
Attention Mr. B. Shalomith
Philadelphia, Pennsylvania 19142

Barogenics, Incorporated
Attention Mr. A. Zeitlin
50 MacQuesten Parkway South
Mount Vernon, New York 10550

The Beryllium Corporation
Attention Mr. E. C. Bishop
Reading, Pennsylvania 19603

The Beryllium Corporation
Attention E. A. Smith, Jr.
Assistant to the Vice President
Reading, Pennsylvania 19603

J. Bishop & Co., Platinum Works
Attention Supervisor, Production
Engineering
Malvern, Pennsylvania

The Boeing Company
P. O. Box 3985
Attention Mr. A. E. White, Mgr.
Manufacturing Development
Section
Seattle, Washington

High Pressure Data Center
P. O. Box 60
University Station
Brigham Young University
Provo, Utah 86601

Brunswick Corporation
Corporate Research & Development
Needham Laboratories
Needham, Massachusetts 02192

The Brush Beryllium Company
Attention Mr. John Estess
17876 St. Clair Avenue
Cleveland, Ohio 44110

The Brush Beryllium Company
Attention Mr. R. G. O'Rourke
17876 St. Clair Avenue
Cleveland, Ohio 44110

Case Institute of Technology
Metallurgy Department
Attention Mr. S. V. Radcliffe
Cleveland, Ohio 44106

Chance Vought Corporation
Vought Aeronautics Division
P. O. Box 5907
Attention Mr. G. A. Starr
Dallas, Texas

Clevite Corporation
Attention Mr. Gail F. Davies
540 East 105th Street
Cleveland 8, Ohio

Crucible Steel Company of America
P. O. Box 88
Attention Dr. Walter Finley
Director of Research
Pittsburgh 30, Pennsylvania

Curtiss-Wright Corporation
Metals Processing Division
Attention Mr. F. C. Wagner
760 Northland Avenue
Buffalo 15, New York

Defense Metals Information Center
Battelle Memorial Institute
505 King Avenue
Columbus, Ohio 43201

DISTRIBUTION LIST
(Continued)

Douglas Aircraft Company, Inc.
Materials Research & Process
Attention Mr. L. J. Devlin
Santa Monica, California

Douglas Aircraft Company, Inc.
Attention Mr. C. B. Perry, C-345
Plant Engineering Supervisor
3855 Lakewood Boulevard
Long Beach, California 90808

Dow Chemical Company
Metallurgical Laboratory
Attention Dr. T. E. Leontis
Assistant to the Director
Midland, Michigan

E. I. du Pont de Nemours & Company, Incorporated
Engineering Research Laboratory
Attention Mr. Donald Warren
Wilmington 98, Delaware

Eaton Yale & Towne, Inc.
Research Center
Attention Library
26201 Northwestern Highway
Southfield, Michigan 48076

Fansteel Metallurgical Corporation
Attention Mr. A. B. Michael, Director
Metallurgical Research
2200 Sheridan Road
North Chicago, Illinois

GCA Viron Division
Instrumentation and Communication
Attention Mr. W. H. Schaumberg, Manager
7585 Viron Road, N.E.
Minneapolis, Minnesota 55432

General Astrometal Corporation
Attention Mr. L. Smiley
320 Yonkers Avenue
Yonkers, New York

General Cable Corporation
Research Laboratory
Attention Mr. J. Szilard
Director of Research
Bayonne, New Jersey

General Dynamics
Electro Dynamics Division
Attention Warren G. Mang, Product Manager
150 Avenel Street
Avenel, New Jersey

General Dynamics/Fort Worth
P. O. Box 748
Attention P. R. de Tonnaneour
Chief Librarian
Fort Worth, Texas 76101

General Electric Company
Attention Library, LMC Department
1331 Chardon Road
Cleveland 17, Ohio

General Electric Company
Aircraft Gas Turbine Division
Large Jet Engine Department
Building 501
Attention Engineering Manager
Metallurgical Engineering Operations
Cincinnati 15, Ohio

General Electric Company
Atomic Power Equipment Dept.
Attention Library
175 Curtner Avenue
San Jose, California 95125

General Electric Company
F.P.D. Technical Information Center
Building 100
Cincinnati 15, Ohio

General Electric Company
Metallurgy and Ceramics Laboratory
Metals Branch
P. O. Box 8
Attention D. W. Lillie, Manager
Schenectady, New York

DISTRIBUTION LIST
(Continued)

General Hefco Corporation
Attention Mr. Richard H. Wesley
3030 Bryan
Fort Worth, Texas 76110

General Motors Corporation
Manufacturing Development
GM Technical Center
Attention Mr. J. W. Kusiak, Dept. 30
Warren, Michigan 48090

Gulf States Tube Corporation
P. O. Box 952
Attention L. E. Branan, Metallurgist
Rosenburg, Texas 77471

H. M. Harper Company
Lehigh Avenue and Oakton Street
Attention Mr. K. G. Hookanson
General Manager, Metals
Division
Morton Grove, Illinois

Harvey Aluminum, Inc.
Attention Mr. G. A. Moudry
Technical Director
19200 South Western Avenue
Torrance, California

Harwood Engineering Company
Attention Mr. D. Newhall, President
South Street
Walpole, Massachusetts

Haynes Stellite Company
Division of Union Carbide Corporation
Attention Mr. G. A. Fritzlen,
Manager, Technology
Kokomo, Indiana

Hunter Douglas Research Company
Attention Mr. Neal Gammell
887 East Second Street
Pomona, California 92505

IIT Research Institute
Mechanics Research Division
Attention Asst. Director
10 West 35th Street
Chicago, Illinois 60616

IIT Research Institute
Metals Research Department
Attention Dr. W. Rostoker
10 West 35th Street
Chicago, Illinois 60616

Jeffrey Manufacturing Company
271 East First Street
Columbus, Ohio 43216

Jones & Laughlin Steel Corporation
Attention Mr. Robert S. Orr
Commercial Research
Librarian
3 Gateway Center
Pittsburgh 30, Pennsylvania

Kaiser Aluminum & Chem. Corp.
1625 "I" Street, N. W.
Washington, D. C.

The Ladish Company
Metallurgical Dept. Library
Attention Mr. Joseph Fischer
Cudahy, Wisconsin

Lehigh University
Attention Dr. Betzalel Avitzur, Assoc.
Prof. of Metallurgy and
Material Science
Bethlehem, Pennsylvania

Lockheed Aircraft Corporation
Manufacturing Methods Division
Attention Mr. Green
Burbank, California

Lockheed Missile and Space Co.
Advanced Materials D81-31
P. O. Box 504
Attention Mr. Ronald L. Greene
Sunnyvale, California

DISTRIBUTION LIST
(Continued)

Lombard Corporation
Attention Mr. Daniel A. Katko
Vice President
639 Wick Avenue
P. O. Box 177
Youngstown 1, Ohio

Marquardt Aircraft Corporation
16555 Saticoy Street
P. O. Box 2013 South Annex
Van Nuys, California

The Martin Company
Attention Mr. L. Laux, Chief
Manufacturing Research
& Development
Baltimore 3, Maryland

The Martin Company
Denver Division
Mail No. L-8, P. O. Box 179
Attention Mr. R. F. Breyer
Materials Engineering
Denver 1, Colorado

McDonnell Aircraft Corporation
Lambert-St. Louis Municipal Airport
P. O. Box 516
Attention Mr. H. Siegel
St. Louis 3, Missouri

National Academy of Sciences
National Research Council
Div. of Eng. & Industrial Resources
Attention Mr. E. V. Bennett
Washington 25, D. C.

Nuclear Metals, Inc.
Attention Paul Loewenstein
Concord, Massachusetts

North American Aviation, Inc.
International Airport
Attention Mr. Walter Rhineschild
Los Angeles, California 90045

Phelps Dodge
Aluminum Products Corporation
Rod Plant
P. O. Box D
Columbus, Tennessee 38401

Physmet Corporation
Attention Joseph S. Harvey
156 Sixth Street
Cambridge, Massachusetts 02142

Reading Tube Corporation
P. O. Box 126
Attention Mr. Griffith Williams, Jr.
Reading, Pennsylvania 19603

Republic Aviation Corporation
Attention Mr. A. Kastelowitz
Director of Manufacturing
Research
Farmingdale, Long Island, New York.

Reynolds Metals Company
Attention Mr. J. Harry Jackson
General Director, Metals
Research Division
Richmond, Virginia

Reynolds Metals Company
Attention Mr. Stuart Smith
503 World Center Building
Washington 6, D. C.

Rohr Aircraft Corporation
P. O. Box 878
Attention Mr. F. E. Zinnerman
Manager, Manufacturing
Research
Chula Vista, California

Ryan Aeronautical Company
Materials & Process Laboratory
Lindberg Field
Attention Mr. L. J. Hull, Chief
Metallurgist
San Diego 12, California

DISTRIBUTION LIST
(Continued)

Sandia Corporation
Livermore Laboratory
P. O. Box 969
Attention Mr. M. W. Mote, Jr.
Livermore, California

Sandia Corporation
Sandia Base
Attention Mr. D. R. Adolphson-Org 1131
Albuquerque, New Mexico 87115

Solar Aircraft Company
A Division of International Harvester Company
Attention Librarian
2200 Pacific Avenue
San Diego 12, California

Mr. W. B. Aufderhaar, Manager
Technical Service
Special Metals Corporation
New Hartford, New York 13413

Sunstrand Aviation-Rockford
Attention R. W. Diesner, 763 M
2421 11th Street
Rockford, Illinois 61101

Texas Instruments Corporation
Metals & Controls
Attention Mr. J. Buchinski
34 Forest Street
Attleboro, Massachusetts 02703

Titanium Metals Corporation of America
P. O. Box 2128
Attention Mr. W. M. Parris
Senior Research Engineer
Henderson, Nevada 89015

TRW Equipment Labs
23555 Euclid Avenue
Cleveland 17, Ohio

United Aircraft Corporation
Research Laboratories
Attention Mr. H. Peter Barie
East Hartford, Connecticut

United States Steel Corporation
Products Development Division
525 William Penn Place
Pittsburgh, Pennsylvania

Universal Cyclops Steel Corporation
Attention Mr. C. P. Mueller
Bridgeville, Pennsylvania

University of California
Los Alamos Scientific Laboratory
P. O. Box 1663
Los Alamos, New Mexico

Western Electric Company
Dept. 7224, Hawthorne Station
Attention Mr. Fred Radakovich
Senior Staff Engineer
Chicago, Illinois 60623

Western Electric Company
Engineering Research Center
Attention Mr. Frank J. Fuchs, Jr.
Princeton, New Jersey

Westinghouse Electric Corporation
P. O. Box 128
Attention Mr. F. L. Orrell, Section Manager, Development Contracts
Blairsville, Pennsylvania

Westinghouse Electric Corporation
Manager, Materials Department
P. O. Box 80864
Attention David C. Goldberg
Pittsburgh, Pennsylvania 15236

Westinghouse Electric Company
Bettis Field
Attention Mr. Kermeth Goldman
Pittsburgh, Pennsylvania

Wolverine Tube Division
Division of Calumet & Hecla, Inc.
Attention Mr. B. Moorman, Mgr.
Special Metals, Research & Development Div.
17200 Southfield Road
Allen Park, Michigan

Wyman-Gordon Company
Grafton Plant
Attention Mr. Arnold Rustay
Technical Director
Worcester Street
North Grafton, Massachusetts