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# DEVELOPMENT OF THE MANUFACTURING CAPABILITIES OF THE HYDROSTATIC EXTRUSION PROCESS

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R. J. Fiorentino
J. C. Gerdeen
B. D. Richardson
A. M. Sabroff
F. W. Boulger

**BATTELLE MEMORIAL INSTITUTE**
**COLUMBUS LABORATORIES**

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MANUFACTURING TECHNOLOGY DIVISION
AIR FORCE MATERIALS LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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# FOREWORD

This final technical report in two volumes covers the work performed under Contract AF 33(615)-3190 from 1 December 1964 through 8 July 1967. Volume I covers the results of the experimental work in hydrostatic extrusion and Volume II contains the work relative to design and construction of high-pressure hydrostatic extrusion containers. The manuscript was released by the authors on 29 September 1967 for publication as an AFML technical report.

This contract with Battelle Memorial Institute of Columbus, Ohio, was initiated under Manufacturing Methods Project No. 8-198, "Development of the Manufacturing Capabilities of the Hydrostatic-Extrusion Process". It was administered under the technical direction of Mr. Charles S. Cook until September 1965 and then by 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 was conducted at Battelle with the prime responsibility assigned to the Metalworking Research Division and with Mr. R. J. Fiorentino, Associate Chief, as Project Engineer. Others contributing to the program were Mr. B. D. Richardson, Research Metallurgical Engineer, Mr. G. E. Meyer, Research Metallurgical Engineer, Mr. F. W. Fawn, Technician, Mr. A. M. Sabroff, Division Chief, and Mr. F. W. Boulger, Senior Technical Advisor. The late Mr. W. R. Hansen, Research Metallurgist, made a significant contribution to the program up to the time of his death in August, 1966. Mr. R. L. Jentgen, Associate Chief in the Structural Physics Division, assisted in the fluid and lubrication studies of the program. Dr. J. C. Gerdeen, Senior Research Mechanical Engineer in the Advanced Solid Mechanics Division, conducted the stress analysis for the high-pressure-container-design study. Mr. E. C. Rodabaugh, Mr. M. Vagins, Senior Mechanical Engineers, and Mr. T. J. Atterbury, Chief of the Applied Solid Mechanics Division, also assisted in this study. Mr. R. E. Mesloh, Research Mechanical Engineer of the Applied Solid Mechanics Division, designed an instrument for measuring fluid pressure at elevated temperatures. Data from which this report has been prepared are contained in Battelle Laboratory Record Books Nos. 21799, 21990, 23065, 23287, 23585, 23791, 23836, and 24446.

This project has been accomplished as a part of the Air Force Manufacturing Methods program, the primary object of which is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in economical production of USAF materials and components. The program encompasses the following technical areas:

Metallurgy – Rolling, Forging, Extruding, Casting, Fiber, Powder.
Chemical – Propellant, Coating, Ceramic, Graphite, Nonmetallics.
Fabrication – Forming, Material Removal, Joining, Components.
Electronics – Solid State, Materials and Special Techniques, Thermionics.

Suggestions concerning additional Manufacturing Methods development required on this or other subjects will be appreciated.

H. A. Johnson

H. A. JOHNSON, Chief
Metallurgical Processing Branch
Manufacturing Technology Division

# ABSTRACT

The purpose of the program was to develop the manufacturing capabilities of the hydrostatic-extrusion process. Specific applications studied were fabrication of wire, tubing, and shapes from relatively difficult-to-work materials such as refractory-metal alloys, high-strength steels, aluminum alloys, titanium alloys, beryllium, and other selected materials. Phase I was concerned with process optimization and Phase II with direct process application.

As part of Phase I, the effects of critical process variables on pressure requirements and product quality were studied for wrought and powder materials ranging from relatively high-strength easy to work materials such as aluminum alloys and steels to the relatively more difficult-to-work materials such as Ti-6Al-4V titanium alloy and superalloys. With these materials, fluids and lubricants tended to be the factor controlling pressure requirements and product quality. With almost every material extruded the limit in extrusion ratio was set by the design pressure capacity of the container except for the aluminum alloys where the limit was set more by the efficiency of the lubrication system.

In the hydrostatic extrusion of brittle materials, die design proved to be the most significant factor controlling the production of sound, good quality extrusions. New die-design concepts have opened up new fields for the application of hydrostatic extrusion to brittle materials.

Except for the aluminum alloys, the hydrostatic extrudability of the above range of materials was also investigated at 400 and 500 F. Again, fluids and lubricants were developed to enable the production of good quality extrusions. Of particular interest here was the wide range of lubricants that operated successfully at this temperature level.

As part of Phase II of the program, tubing, mill shapes and wire were produced from a variety of materials. For tubing, the floating-mandrel arrangement enabled higher extrusion-ratio capabilities than those for solid rounds. An analysis of the beneficial effects of the floating-mandrel arrangement is given.

T-sections were extruded from round billets and were re-extruded into smaller T-sections. Materials evaluated here were 7075-0 aluminum, AISI 4340 steel, Ti-6Al-4V alloy and Cb752 columbium alloy. The problem of sealing against leaks between the T-billet and die in the re-extrusion of shapes was overcome to some extent following the evaluation of several methods of sealing.

In the reduction of T-sections and wire, a technique of hydrostatic-extrusion drawing developed at Battelle was used. This method, called the HYDRAW technique, was used to reduce wire of Ti-6Al-4V alloy, beryllium, and TZM molybdenum alloy wire at single pass reductions of up to 60 percent. That reduction appeared to be by no means the limit of single-pass reduction achievable with these materials.

During the experimental program, a study of high-pressure container designs was made. Several design concepts that were analyzed are presented in detail in this report. The most promising concept for containing fluid pressures up to 450,000 psi in large-bore containers was that of using pressurized-fluid support as in the ring-fluid-ring design. This and other designs were analyzed on the basis of fatigue-strength criterion, which is believed to be a new and more sound basis for the design of high-pressure containers.

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VOLUME II

## TABLE OF CONTENTS

Page

SECTION 3

ANALYSIS OF SEVERAL HIGH-PRESSURE
CONTAINER DESIGN CONCEPTS

## TABLE OF CONTENTS
(Continued)

### SECTION 4

### HYDROSTATIC EXTRUSION CONTAINERS DESIGNED AND CONSTRUCTED IN THE PROGRAM

## LIST OF ILLUSTRATIONS

## LIST OF ILLUSTRATIONS
(Continued)

## LIST OF ILLUSTRATIONS
(Continued)

## LIST OF TABLES

## LIST OF TABLES
## (Continued)

## LIST OF SYMBOLS SECTION 3

$A_n$, $B_n$ = coefficients of materials in fatigue relations

$N$ = the total number of components in a container; N also denotes the outermost component

$n$ = a specific component when numbered from inside out; i.e., $n = 1, 2, \ldots, N$

$r_n$ = outside radius of component n, inches

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

$r_o$ = bore radius of container, inches (inside radius of liner)

$r_N$ = outer radius of container, inches

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

$K$ = over-all wall ratio of container, $K = r_N/r_o = k_1 k_2 \ldots k_N$

$K'$ = wall ratio of inner part of ring-fluid-segment container, $K' = r_3/r_o$

$E_n$ = modulus of elasticity of component n, psi

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

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

$p$ = bore pressure, psi, $p_o = p$ (internal pressure acting on the liner)

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

$q_r$ = residual interface pressure required at room temperature for a container designed for use at elevated temperature

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

$S$ = shear stress, psi

$S_r$ = semirange in shear stress for a cycle of bore pressure, psi

$S_m$ = mean shear stress for a cycle of bore pressure, psi

$S_{min}$ = minimum shear stress during a cycle of bore pressure, psi

$S_{max}$ = maximum shear stress during a cycle of bore pressure, psi

$\sigma$ = design tensile stress of ductile steel, psi ($\sigma \leqq$ ultimate tensile strength)

$\sigma_1$ = design tensile stress of high-strength steel, psi ($\sigma_1 \leqq$ ultimate tensile strength)

$(\sigma)_r$ = semirange in tensile stress for a cycle of bore pressure, psi

## LIST OF SYMBOLS SECTION 3
### (Continued)

$(\sigma)_m$ = mean tensile stress for a cycle of bore pressure, psi

$\sigma_y$ = yield tensile stress, psi

$\sigma_u$ = ultimate tensile stress, psi

$(\sigma)_{min}$ = minimum tensile stress during a cycle of bore pressure, psi

$(\sigma)_{max}$ = maximum tensile stress during a cycle of bore pressure, psi

$\sigma_r$ = radial stress, psi

$\sigma_\theta$ = circumferential stress, psi

$\sigma_z$ = axial (longitudinal) stress, psi

$\alpha_r$ = semirange stress parameter for high-strength steel, $\alpha_r = (\sigma)_r/\sigma_1$

$\alpha_m$ = mean stress parameter for a high-strength steel, $\alpha_m = (\sigma)_m/\sigma_1$

$M_1$ = bending moment on ring segment

$M_2$ = bending moment on pin segment

$u$ = radial displacement, inches

$v$ = circumferential displacement, inches

$\nu$ = Poisson's ratio

$r, \theta, z$ = cylindrical coordinates for radial, circumferential, and axial directions, respectively

$\Delta_n$ = interference required (as manufactured) between cylinder, n, and cylinder, n + 1, inches

$\Delta_{12}$ = interference required (as manufactured) between the liner, segments, and cylinder, 3, of the ring-segment and ring-fluid-segment containers, inches

$\alpha_1$, $\alpha_2$ = coefficient of thermal expansion of material comprising rings 1 and 2

# XXI

# INTRODUCTION

The purpose of this program was to develop the manufacturing capabilities of the hydrostatic-extrusion process. The program was divided into two phases with the following general objectives:

## Phase I. Process-Development Studies

Part 1. (a) To study the effect of critical process variables on pressure requirements and surface quality in hydrostatic extrusion of AISI 4340 steel, Ti-6Al-4V titanium alloy, and 7075 aluminum alloy.

(b) To correlate all available hydrostatic-extrusion-pressure data with material properties wherever possible in order to assist direction of the experimental effort and maximize the information developed on the present program.

Part 2. To explore the hydrostatic extrudability of TZM molybdenum alloy, beryllium, A286 iron-base superalloy, Alloy 718 nickel-base superalloy, powder compacts, and other selected materials.

Part 3. To conduct a design study for high-temperature, high-pressure hydrostatic-extrusion tooling based on (1) estimated pressure requirements for high-ratio extrusion of materials of interest to the Air Force, (2) latest high-pressure-vessel technology, and (3) latest tooling materials available.

Part 4. To conduct a process economic study on the construction, installation, and operation of equipment with the same operational and size requirements as the tooling developed in the previous program on Contract No. AF 33(600)-43328.

## Phase II. Process-Application Studies

Part 1. To evaluate the application of the hydrostatic-extrusion process for sizing and finishing conventionally hot-extruded (or rolled) structural shapes by various combinations of drawing and extruding. Primary emphasis was to be on AISI 4340 steel, although some effort was to be devoted to Ti-6Al-4V, 7075-0 aluminum, and selected refractory metals.

Part 2. To determine the feasibility of producing wire and filaments from beryllium, TZM molybdenum alloy, and Ti-6Al-4V titanium alloy by combinations of hydrostatic extrusion and drawing.

Part 3. To develop tooling and define process parameters necessary for the reduction of tube blanks to finish tubing from AISI 4340 steel, 7075-0 aluminum, and Ti-6Al-4V titanium.

The results of the experimental and analytical work connected with Phases I and II were covered in Interim Engineering Progress Reports I through IX.

This, the Final Technical Report in two volumes, contains the results of the program in their entirety. Volume I contains Section 1, "A Study of the Critical Process Variables in the Hydrostatic Extrusion of Several Materials" and Section 2, "Production Aspects of Hydrostatic Extrusion". Volume II contains Section 3, "Analysis of Several High-Pressure Container-Design Concepts" and Section 4, "Hydrostatic-Extrusion Containers Designed and Constructed in the Program". The experimental program started December 1, 1964, and was completed on July 8, 1967.

# XXII

## SUMMARY OF VOLUME II

The experimental work conducted in this program has taken the technology of the hydrostatic-extrusion process from the experimental stage to the threshold of its application in a production operation. Commercial exploitation of the process is possible without any further major experimentation and it is believed that this report gives the guidelines that will enable these steps to be taken immediately. What remains now is the complete design of production hydrostatic-extrusion equipment that will be competitive with conventional-extrusion equipment. At the time of this writing, a program is underway at Battelle-Columbus Laboratories in which such equipment is being designed. The program, "Design Study of Production Press for Ultrahigh-pressure Hydrostatic-Extrusion Equipment", is sponsored by the Metallurgical Processing Branch, Manufacturing Technology Division at Wright-Patterson Air Force Base, Ohio, on Contract No. AF 33(615)-67-C-1434.

One of the most important aspects of the aforementioned design study is the design of the high-pressure container. Section 3 of this report contains a thorough analysis of several concepts of high-pressure containers. This analysis will be drawn on heavily in the design study. Section 4 describes the development of three containers designed and constructed in this program.

Both Sections 3 and 4 are complete in themselves and each contains its own summary.