HYDROSTATIC EXTRUSION
Theory and Applications

Edited by

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and

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Preface

This book is intended to be a reference text on hydrostatic extrusion, a multidisciplinary technology involving the forming process of materials, tribology, high pressure engineering and so forth.

Until now only one book bearing the title of hydrostatic extrusion, by Prof. Alexander and Dr. Lengyel, has been published since 1971. Although there are chapters on hydrostatic extrusion in such books as THE MECHANICAL BEHAVIOUR OF MATERIALS UNDER PRESSURE edited by Dr. Pugh, METAL FORMING by Prof. Avitzur and HIGH PRESSURE TECHNOLOGY by Drs. Spain and Paauwe, it is regrettable that no up-to-date reference books on hydrostatic extrusion are available.

As is well known, hydrostatic extrusion is a nearly-ideal lubricated extrusion. Its advantages have been demonstrated by laboratory research in the past two decades, yet many manufacturers, however, still hesitate to adopt the technology in their plants. Their hesitation is certainly due to the lack of exact information on the process and its equipment and also to their unfamiliarity with the actual method of operation.

In order to provide a useful introduction to the subject for engineers who work in industries which plan to employ this technique and also to give exact and reliable information on the durability and performance of production facilities, as well as the capabilities of the process and the properties of extruded products, we decided to publish this book.

Starting with theories and computational methods, the processes of cold, warm and hot hydrostatic extrusion are described by experts in their respective fields. Then follows a chapter devoted to industrial hydrostatic extrusion plant equipment and the book concludes with an up-to-date account of hydrostatic extrusion of new materials, such as composites, special alloys, fine wires, or polymers.

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CHAPTER 1
INTRODUCTION

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The idea of employing hydrostatic pressure for metalworking was conceived as early as in the nineteenth century and a British patent was granted to Robertson in 1893 [1]. Experimental proofs of the pressure-induced ductility in metals and other materials, however, were not obtained until Bridgman made an extensive study of subject along with metalworking under pressure and published the result in the form of a monograph [2] in 1949. He invented a high-pressure seal, now called the 'Bridgman Seal', which was so effective that he found himself in a uniquely advantageous position to do high-pressure work. He spent the rest of his life studying the fascinating world of high pressure and left a mountain of research papers on the subject, which were later compiled in the form of a seven-volume monograph entitled COLLECTED EXPERIMENTAL PAPERS OF P. W. BRIDGMAN and published by Harvard University Press in 1964 [3]. An extremely versatile high-pressure unit bearing his name has long been manufactured by the Harwood Engineering Company of Newhall, with the assistance of Abbot, former Research Assistant of Bridgman, and has benefited countless researchers in the high-pressure field. A similar type of press was also produced by the Pressure Technology Corporation of America, headed by Bobrowsky.

In Great Britain, on the other hand, systematic work on the hydrostatic extrusion of metals and alloys was started by Pugh at the National Engineering Laboratory in Glasgow. He and his collaborators developed the technique of hydrostatic extrusion to such an extent that it is now established as a useful industrial process. In the Soviet Union high-pressure study was started by Vereshchagin at the High Pressure Laboratory of the Academy of Sciences and reports on hydrostatic extrusion began to appear in 1957 [4]. For a historical review of high-pressure work the reader is referred to an excellent paper by Vodar and Kieffer of the High Pressure Laboratory, C.N.R.S., Bellevue, France, included in the book, THE

MECHANICAL BEHAVIOUR OF MATERIALS UNDER PRESSURE, edited by Pugh [5]. Great progress in high-pressure engineering was made in the 1960's, as can be seen by the fact that the first conference exclusively on this subject was held at Imperial College in London and the first seminar on hydrostatic metalworking processes at Battelle Columbus Laboratories, both in 1967. During that decade the United Kingdom Atomic Energy Authority made an important contribution to the development of the technique of hydrostatic extrusion.

In Japan the early recognition of the importance of the study on the effects of hydrostatic pressure on the mechanical properties of materials by Nishihara, then at Doshisha University in Kyoto, led to a series of research at room temperature [6,7] and also at elevated temperatures [8,9,10]. The strength and ductility of carbon steel, magnesium, titanium, and zinc were determined at pressures up to 5 kilobars and temperatures up to 600°C. Later on he moved to Kobe Steel and was instrumental in organizing a powerful group of engineers for the production application of hydrostatic extrusion [11]. In industry, the Western Electric Company in the United States, ASEA in Sweden, Kobe Steel in Japan, and some other companies started to use the new technology on a commercial basis. The first international meeting devoted solely to this subject was held at University of Sterling in Scotland in June 1973 under the joint sponsorship of NEL and AIRAPT.

In the early period of development the main effort in the application of hydrostatic extrusion seems to have been expended on work with the difficult-to-form materials. It goes without saying that the deformation of materials is caused by tangential stresses while fracture is caused by normal ones. By applying hydrostatic pressure fracture will be suppressed without imparting a substantial change in the yield and flow characteristics of the materials. It is not without reason therefore that the brittle materials were the prime target for the application of the techniques of hydrostatic extrusion. In actuality, however, ductile metals were the first to be hydrostatically extruded commercially. Thus various sizes of copper tubing were produced using the ASEA manufactured Quintus hydrostatic extrusion plant by Lips BV, Holland. The extremely high reduction ratios obtainable in a single pass were an advantage but the process still had the limitation of being a batch one. The decade of the 1970's saw an increase in the commercial use of the batch-type production unit on one hand and of research and development of a continuous process on the other.

Quite a variety of ideas on the continuous process were conceived and some of them were subjected to experimentation. Beginning with 'Continuous Extrusion with Viscous Drag' by Fuchs [12], novel methods of 'Continuous Extrusion Forming' often called 'Conforming' by Green [13], 'Linear Continuous Extrusion' or 'Linex' by Black and Voorhes [14], 'Helical Extrusion' by Green [15], 'Extrolling' by Avitzur [16], and 'Hydrostatic Extrusion with Continuous Feed' by Kobe Steel [17] were proposed. Among them 'Conforming' seems to have been most developed at this time [18].

The theory of hydrostatic extrusion has also made great progress. A free-body approach, often called a slab method, was most frequently employed in the study of metalworking processes since the days of von Karman, and hydrostatic extrusion was not an exception. In hydrostatic extrusion, however, if certain conditions are fulfilled, a situation of hydrodynamic lubrication is realized between the billet and die, resulting in extremely low friction. By making use of the Reynolds equations the way to obtain this desirable state of lubrication has been clarified. The application of slip line field theory, extremum principles, especially the upper bound approach, and other energy methods, have been quite successful. Useful solutions were obtained and made it possible to predict the pressure required to effect the extrusion with a prescribed amount of reduction in area, to determine the optimum shape of the die, or to select process parameters, such as temperature or the rate of extrusion. Visioplasticity has been used to analyze displacement, velocity, strain, strain rate, stress, and temperature in the billet. More recently, the methods of finite elements, finite differences, or boundary elements have been applied to the mathematical analysis of stress and strain distributions in the billet. These mathematical tools, however, require the accurate constitutive equations of the billet material to be known as a basis of the calculation. It is a formidable job to spell out the constitutive relations for large strains with temperature, pressure, and strain rate as the process parameters. Furthermore, if the mechanical behavior of the billet material is dependent on time, as is the case with polymers or the metals at elevated temperatures, the work involved is almost insurmountable. Much work still remains to be done.

After two decades of research and development the techniques of hydrostatic extrusion have made progress to such a level that they are now established as an industrial process. The process has been successfully applied to copper tubings, copper-clad aluminum wire, fine wires of noble metals, tubings of aluminum alloys, Nb-Ti superconductors, honeycomb-shaped gamma-ray collimeters of scintillation cameras for medical use, aluminum-copper transition pieces of refrigerators and coolers, and so forth. With the application of high pressure alone metallic materials do not necessarily gain in ductility [19]. Under the combined action of pressure and temperature, however, any metals and alloys can be expected to behave in a ductile manner [20]. Hydrostatic extrusion at elevated temperatures has begun as early as in the mid 70's for aluminum and copper alloys [21] and steels [22] at Kobe Steel, where a new plant for hot hydrostatic extrusion is now in operation. Its application to a wider class of materials is yet to come.

When the recent development of the techniques of hydrostatic extrusion is reviewed, their application to polymeric materials cannot be overlooked. During the last decade a number of primarily crystalline polymers, especially high-density polyethylene, have been extruded with large reductions in area to the effect that their moduli as well as strengths may be raised to the level of steels. It is still at a research and development stage, but the outlook for obtaining novel materials of unprecedented modulus-to-density or strength-to-density ratios is bright. A new field for the commercial application of hydrostatic extrusion is being opened. Much work should be done, however, before these highly oriented polymers are produced commercially.

New studies on hydrostatic extrusion are going on at numerous research institutions throughout the world. Papers on the subject are published in the proceedings of the AIRAPT International High Pressure Conference, which is held approximately every other year, and many other technical journals. Although there are chapters on hydrostatic extrusion in books by Pugh [23], Avitzur [24], or Spain and Paauwe [25], monographs relevant to this subject have not been published in the last thirteen years since Alexander and Lengyel wrote the first and last book bearing the title of hydrostatic extrusion [26]. In the present volume, which is the second book ever published bearing the title of hydrostatic extrusion, theories and practices in this important field of plastic forming are presented in six chapters. The present chapter having provided a brief review of the development of hydrostatic extrusion, Chapter 2 contains mathematical theories presented by active researchers who have been and are still publishing interesting and important papers in this field. Available mathematical tools to analyze the process are reviewed and their application to lubrication and dynamics is described by college professors and factory managers. Chapters 3 and 4 are devoted to an explanation of the process by highly experienced researchers, managers, and technical consultants from Kobe Steel and Hitachi Cable who have joined forces to give a detailed description of cold, warm and hot hydrostatic extrusion processes. These chapters will be especially useful to factory managers who are contemplating introducing the techniques of hydrostatic extrusion into their production plants. Chapter 5 describes the plant equipment of hydrostatic extrusion and is based on the experience obtained by manufacturing the press and tooling at Kobe Steel and also by running the plant at Hitachi Cable. Chapter 6, the final chapter, describes the properties of the products along with the process characteristics which are affected by the properties of the billet materials. The considerable experience obtained by Hitachi Cable, in extruding composites on a production base, and by Battelle Columbus Laboratories, in working with a variety of metallic materials, is included. The selected studies conducted at Battelle include the thin-film hydrostatic extrusion process, products made by this process, hydrostatic extrusion of brittle materials with double-reduction dies, and hydrostatic extrusion of extra long billets with a stepped-bore container. Last but not least, the application of techniques of hydrostatic extrusion to fine wires of metallic materials is described along with the recent work on polymers.

The book is intended to be practical and of use to those employing high pressure to form materials at departments of planning, research, development, and in factories producing non-ferrous material, steel, and polymers. Engineers and scientists working in the aircraft, nuclear reactor, electrical, electronic, automobile, armament, and other heavy industries will find it useful to refresh their knowledge. Most of the materials covered are presented here in a book form for the first time. At the end of each chapter or section updated references are appended. These will be especially useful to graduate students and researchers at universities and research institutions.

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CHAPTER 2
THEORY OF HYDROSTATIC EXTRUSION

Section 1

FUNDAMENTALS OF HYDROSTATIC EXTRUSION

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1. Introduction

The most significant feature of the hydrostatic extrusion process is that there is no friction between the billet and the container wall and thus the length of the billet is not limited as it is in conventional extrusion. Also, the frictional forces between the die and the billet tend to be lower in hydrostatic extrusion because the lubricant is forced, by the high fluid pressure, to flow into the interface. A low frictional stress on the die surface permits a smaller die angle to be used which, in turn, results in more uniform deformation in the extruded product. On the other hand, the indirect driving of the billet through the compressible fluid sometimes makes it difficult to control the motion of the billet.

Since the working limit of hydrostatic extrusion is set mainly by the fatigue strength of the container it is essential to be able to predict the extrusion pressure for each application. The extrusion pressure is affected by geometrical factors such as extrusion ratio and die angle, as well as by the flow stress of the material and the friction forces between die and billet. The most effective way of reducing the extrusion pressure is by increasing the temperature of the billet.

At an early stage in the development of hydrostatic extrusion it was expected that the high fluid pressure would prevent fracture in materials having poor ductility. This is not the case since, under the same conditions of die angle, reduction and material properties, almost the same hydrostatic stress is generated in conventional extrusion as in hydrostatic extrusion. However, lower frictional forces in hydrostatic extrusion permit the use of lower die angles and higher extrusion ratios, both of which lead to higher hydrostatic stress and therefore to conditions which supress fracture. The uniform deformation near to the surface, caused by low friction, reduces the danger of surface cracking. Fracture can be suppressed by extruding into a high fluid pressure but then the hydrostatic extrusion pressure has to be raised accordingly [1].

It is found that the hardness of a product of hydrostatic extrusion is uniform over its cross-section. However, at large deformations hardness measurements are insensitive to variations in the amount of strain and residual stresses will still occur in the product.

In the next section the above fundamental aspects are explained further.

2. Flow Stress and Extrusion Pressure

(1) Equivalent Strain and Extrusion Pressure

To evaluate the strain in large plastic deformation the equivalent plastic strain $\bar{\varepsilon}$ is used. In simple compression or tension, the equivalent strain is equal to the absolute value of the logarithmic plastic strain,

$$\bar{\varepsilon} = \ln (l_1 / l_0) . \tag{1}$$

The equivalent strain rate $\dot{\bar{\varepsilon}}$ is the equivalent strain caused in unit time,

$$\dot{\bar{\varepsilon}} = d\bar{\varepsilon}/dt . \tag{2}$$

(2) Flow Stress

The resistance of material to further plastic flow is measured by the flow stress, $\bar{\sigma}$. The flow stress in uniform compression or tension is the absolute value of the true stress,

$$\bar{\sigma} = |P/A| , \tag{3}$$

where P is the applied force and A is the current cross-sectional area. The flow stress is equal to the equivalent stress defined by the von Mises yield criterion in complex stress systems.

(3) Flow Curve

The curve of equivalent plastic strain vs. flow stress illustrated in Fig.1 is called a flow curve. To simplify the analysis the flow stress is often assumed to remain constant with increasing plastic strain. The mate-