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EXTRUSION OF THE
URANIUM-0.75 WEIGHT PERCENT
TITANIUM ALLOY

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U. S. ENERGY RESEARCH AND
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Research and Development
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Extrusion
Fabrication
Uranium-Base Alloys
Titanium Alloys

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EXTRUSION OF THE URANIUM-0.75 WEIGHT PERCENT TITANIUM ALLOY

Ross J. Jackson, Melvin R. Lundberg, and Joseph F. Boland

Abstract. Described are procedures for extruding the uranium-0.75 weight percent titanium alloy in the high alpha region (600 to 640 °C), and in the upper gamma region (900 to 1000 °C). The casting of sound extrusion billets has importance in the production of sound extrusions, and procedures are given for casting sound billets up to 1,100 kilograms. Also important in producing sound extrusions is the use of glass lubricants. Reduction ratios of greater than 50 to 1 were achieved on reasonably sized billets. Extrusion constants of 48,000 pounds per square inch (psi) [296 megapascals (MPa)] for alpha phase (630 °C) and 8,000 psi (56 MPa) for gamma phase (950 °C) were achieved. Gamma-phase extrusion has preference over alpha-phase extrusion in that larger billets can be used and temperature control is not as critical. However alpha-phase extrusion offers better surface finish, less die wear, and fewer oxidation problems. Billets up to 14 inches in diameter have been successfully gamma-extruded and plans exist for extruding billets up to 20 inches (508 millimetres) in diameter.

INTRODUCTION

Extrusion relates to the shaping process in which a forming blank or billet has been forced to plastically flow through a die orifice of the desired cross section under high pressure. In general, extrusion is used to produce cylindrical bars, hollow tubes, or tubes closed on one end. However shapes of irregular transverse and longitudinal cross sections may be produced from the more readily extrudable metals. The reaction of the extrusion billet with the container and die results in high compressive stresses which are effective in reducing the cracking of materials. The effect has importance relative to the increased utilization of extrusion in the working of metals that are difficult to form.

The two basic types of extrusion are *forward extrusion* (also called direct extrusion) and *back*

extrusion (also called indirect or inverted extrusion). In forward extrusion, the metal flows in the same direction as the ram travel; in back extrusion, the metal flows in the opposite direction of the ram travel. Figure 1(a) illustrates the process of forward extrusion. The heated metal billet is placed in a container and driven through the die by the ram. Figure 1(b) illustrates the back extrusion process. The piercing ram causes the metal to squirt back along the surface of the billet container to form a closed-end, hollow shape.

Tubes can be produced by forward extrusion by using a separate movable mandrel operating within the main ram (Figure 2). The clearance between the mandrel and the die wall determines the wall thickness of the tube. Tubes are produced either by starting with a hollow billet or by a two-step extrusion operation in which a solid billet is first pierced and then extruded.

The extrusion of unalloyed uranium is not new. When the first nuclear reactor was built in 1942 under the West stands of the Chicago University football stadium in Illinois, all of the uranium used had been fabricated by gamma extrusion. Today, gamma extrusion is a common procedure for breaking down ingots of unalloyed uranium. Most of the early information concerning the extrusion of unalloyed uranium, as summarized by Russell and Nelson,¹ has some application to the extrusion of the lean uranium-titanium alloys.

The uranium-0.75 weight percent titanium (U-0.75 wt % Ti) alloy (U-3.62 atomic percent Ti) is an economical, high density [18.5 grams per cubic centimetre (g/cm³)], precipitation hardening, engineering alloy possessing slightly improved corrosion resistance over that of unalloyed uranium. The main advantage of U-0.75 wt % Ti over unalloyed uranium is its heat treatability to

¹W. H. Russell and H. R. Nelson. *Extrusion of Uranium, in Metallurgy of Uranium and its Alloys*. J. C. Warner, Editor. U.S. Atomic Energy Commission, Washington, D.C. 1953. Page 42.

intermediate and extremely high strength levels. As an example, the tensile properties of unalloyed uranium typically range from 17,000 to 40,000 pounds per square inch (psi) [119 to 280 megapascals (MPa)] 0.2 percent offset yield strength with 5 to 18 percent elongation. Whereas, the U-0.75 wt % Ti alloy when heat-treated and

cold-worked can have yield strengths of 280,000 ps (1,960 MPa) with 8 percent elongations.

The U-0.75 wt % Ti alloy can be fabricated in the gamma region (800 to 1100 °C), or high alpha region (400 to 650 °C), and to a lesser extent in the low alpha region (below 300 °C). The purpose of

FIGURES 1(a) and (b). The two basic types of extrusion: forward extrusion (a) and back extrusion (b).

(a)

(b)

this study was to develop practical procedures for extrusion of large billets (up to 1,100 kilograms) of the U-0.75 wt % Ti alloy into tube and rod forms. [For SI (metric) use: 1 psi = 7 kilopascals; 1 kilogram = 2.2 pounds; and 1 inch = 25.4 millimetres.]

DISCUSSION

Preparing the Extrusion Billet:

Three procedures are used to mix constituents and cast extrusion billets of the U-0.75 wt % Ti alloy: (1) vacuum, consumable-electrode, arc-casting; (2) vacuum, consumable-electrode, arc-casting followed by vacuum-induction casting; and (3) vacuum-induction casting alone. All three methods work well with the exception that the first does not lend itself to hollow billets. The second method has been extensively evaluated and does provide a sound and homogenous extrusion billet, though at a premium cost. The third method, by far the most economical of the three, proved satisfactory and most current and future work will utilize the single vacuum-induction mixing and casting operation. Typical extrusion billets cast by these methods are shown in Figures 3(a), (b), and (c).

Feed Material

Depleted uranium (about 0.2 wt % U-235) in the form of virgin derby metal or recycle derby metal

(also called recycle D-38) is the starting uranium material. Derby uranium is a high-purity, bomb-reduced [uranium tetrafluoride (UF_4) with magnesium] ingot of uranium weighing about 300 kilograms (kg). The derby is provided by the Nuclear Division of Union Carbide Corporation at Paducah, Kentucky. A typical analysis would run 40 parts per million (ppm) carbon (C), 3 ppm hydrogen (H), 4 ppm oxygen (O), 10 ppm aluminum (Al), 20 ppm iron (Fe), 15 ppm magnesium (Mg), and 30 ppm silicon (Si).

Recycle derby is scrap derby D-38 reconsolidated by vacuum-induction melting and casting in stabilized zirconia-coated crucibles and molds. A typical chemical analysis of derby recycle metal would be that listed for virgin derby metal except with an increase in carbon to about 90 ppm. Since titanium *drosses* carbon from the melt, the recycle derby does not affect chemistry except for slight reductions in the titanium content.

The titanium was produced by the Kroll process, i.e., the magnesium reduction of titanium tetrachloride to produce titanium sponge. The sponge can be used directly or can be arc-melted into ingot form. A typical analysis of the magnesium-reduced titanium feed would be 20 ppm C, 100 ppm O, 250 ppm nitrogen (N), <50 ppm Al, <30 ppm copper (Cu), 1000 ppm Fe, 800 ppm magnesium (Mg), 400 ppm manganese (Mn), <100 ppm Si, and <300 ppm tin (Sn). Due to the small amount of titanium in the U-0.75 wt % Ti alloy, the purity of the constituent titanium has minor importance.

Recycle scrap U-0.75 wt % Ti alloy or other U-Ti compositions are good feed material. Various percentages of scrap alloy to virgin feed from 0 to 100 percent can be used successfully. However, extra care should be exercised in monitoring the chemistry of the final product when large amounts of scrap alloy are used.

Consumable-Electrode, Arc-Melting Method

A single arc melting of the constituent metals is often used to dissolve titanium [melting point (MP) 1668 °C] in the lower melting uranium (MP 1132 °C). The procedure is to construct an electrode of the

FIGURE 2. Schematic diagram of forward tube extrusion.

desired composition (as outlined below) and arc melt this under vacuum into a water-cooled copper crucible.

Preparation of Sandwich Electrodes for Arc Melting

1. A long hollow cylinder or box is fabricated from virgin derby or derby recycle uranium by alpha or gamma extrusion or alpha-sheet forming, respectively.
2. The uranium box and filler strips should be cleaned by pickling in nitric acid or electro-cleaning in a phosphoric acid water bath.

3. Place filler strips of titanium and uranium, sandwich-style into the hollow center to yield desired composition. Thin strips (about 0.1 inches thick) of titanium are desirable.

4. Bolt blocks and strips together at one end. A typical sandwich-box electrode could be 2 by 2 by 48 inches (50.8 by 50.8 by 1,219 millimetres).

Arc-Melting Procedure

Arc-melt several consumable sandwich electrodes into a slightly tapered, cylindrical, water-cooled

FIGURES 3(a), (b), and (c). Typical cast uranium alloy extrusion billets: (a) 1,000-kilogram induction cast hollow billet for forward extrusion into tube; (b) 1,100-kilogram induction cast solid billet for forward extrusion into rod; and (c) 360-kilogram arc-cast ingot which is sliced into blanks for back extrusion into a closed-end cylinder. (Dimensions in inches.)

copper mold using a DC normal polarity arc with the following parameters: leak rate, <50 micrometres (μm) per hour; vacuum during run, 2 to 8 micrometres; voltage, 26 volts; current for 6-inch ingot, 270 amperes. Eight 2 by 2 by 48-inch (50.8 by 50.8 by 1,219-millimetres) box electrodes will yield a 6-inch [152.4-millimetre (mm)] diameter cylindrical ingot about 44 inches (1,117 mm) long weighing approximately 300 kilograms. During the arc melting, unidirectional AC magnetic stirring is used. In arc-cast ingots used directly as extrusion billets, it is necessary to scalp about 0.25 inches (6.4 mm) off the diameters to have a completely solid ingot.

Vacuum-Induction Melting and Casting

Induction casting, as discussed earlier, may be used as a single-step operation, or may be a second operation following arc-melting. In the single-step operation, the uranium metal is manually intermingled with either titanium sponge, strips, or chunks in a melting crucible. In the case of arc melting first, the 6-inch (152.4 mm) arc-cast ingots are sawed into foot-long logs. Either power-hack sawing or abrasive silicon carbide cut-off wheels are satisfactory. The cut-off wheels are faster, but cost more and require venting. The sawed logs, along with any scrap U-0.75 wt % Ti alloy, are placed in a melting crucible having a bottom-pour mold arrangement.

A bottom-pour graphite crucible, stopper rod, and mold are used. A stabilized zirconia, water slurry (Zircoa Set 5) is first sprayed on the crucible, stopper rod, and mold, and then allowed to dry a day or longer. The thickness of the dried coating is about 10 mils (1 mil = 2.5×10^{-5} metres).

Melting occurs in a vacuum-induction furnace held at a pressure of about 100 micrometres before and during the melt. The crucible molds are arranged so that the top third or half of the mold lies within the 4-foot [1.2 metres (m)] long induction coil. This preheats the mold to about 600 °C at the bottom and 1000 °C at the top, thus allowing directional solidification and hot topping. The alloy in the crucible is heated to 1300 to 1350 °C and held for 15 to 30 minutes before pouring.

The solidus and liquidus temperatures for the U-0.75 wt % Ti alloy are about 1142 and 1163 °C, respectively. Thus, considerable superheat is put into the melt for drossing and fluidity. Generally for solid casting, the melt is held 15 minutes at 1300 °C; and for hollow cylinders, the melt is held 30 minutes at 1350 °C before pouring.

After soaking for the desired time and temperature, the stopper rod is lifted and the liquid-alloy gravity feeds the mold through a 1.5-inch (38 mm) diameter hole. The mold is filled in approximately one minute, and the power to the induction coils is kept on for 10 to 15 minutes after pouring to allow adequate hot topping. The power is then turned off and the furnace and casting allowed to cool overnight. If desired, the cooling can be speeded up by back filling with helium gas.

The main advantages of vacuum-induction casting are: (a) it is more economical than consumable-electrode vacuum arc casting; (b) there is a minimization of macrobanding and gross-ingot segregation because of the slower solidification rates; (c) drossing reduces interstitial levels, especially carbon, due to the greater volumes of liquid and the longer times in the liquid state; and, (d) it permits scrap to be fed directly into the stream without any impurity penalties.

Homogenization of the Billets

Three types of titanium segregation are expected in the U-0.75 wt % Ti alloy: dendritic coring, macrobanding (tree rings), and gross-ingot (inverse) segregation. The phase diagram predicts dendritic coring with composition variations of 2 to 8 at % Ti (0.4 to 1.7 wt % Ti) for the U-0.75 wt % Ti alloy. In large castings that are slow-cooled, these types of gradients are not seen. Macrobanding is a layered inhomogeneity with a small titanium gradient over a distance of about 0.063 inches (1.6 mm). This type of segregation is present in the large slow-cooled casting.

Macrobanding and remnants of dendritic coring can be removed by homogenizing the castings at 1050 °C for 6 hours in a vacuum-induction furnace. After soaking, the power is turned off and the

castings allowed to furnace cool overnight. Vacuum of 50 micrometres are maintained through the heating, soaking, and cooling cycles. Here again, back-filling with helium will speed up the cooling cycle if desired.

Scalping and Machining of Billets

The castings (extrusion blanks) are cleaned up and converted to final size by a machining operation. For solid blanks, about 0.13 inches (3.3 mm) is taken off the outside diameter (OD) and bottom, and 1 to 2 inches (25 to 50 mm) are sawed off the top. For blanks in the form of hollow cylinders, the hollow graphite core is machined out, followed by 0.13-inch (3.3 mm) alloy removal from the OD, inside diameter (ID), and bottom. One to 2 inches (25 to 50 mm) are sawed off the top. Chip samples for chemistry are taken during final machining: generally at 3 or 4 places on the OD, and if a hollow cylinder at 3 or 4 places on the ID also. Die-entry angles, etc., are also machined at this time, although the ingot is usually cast with the proper cone angle at one end. Machining is performed with single-point tooling and with a flow of coolant to prevent ignition of the pyrophoric alloy chips. Figure 4 shows two machined- and cleaned-hollow billets ready for extrusion into tubes.

FIGURE 4. Shown are the 14- and 10-inch (356- and 254-millimetre) outside diameter hollow billets in the machined and cleaned condition, prior to extrusion.

Lubricating the Extrusion Billet:

For extrusion of uranium and its alloys in the gamma phase, molten glass is being used as the lubricant and as a protective coating. The main advantages of glass as an extrusion lubricant derives from the low coefficient of friction, less than 0.01 at the gamma-extrusion temperatures. With conventional extrusion processes, a substantial portion of the required energy is consumed in overcoming the frictional drag against the container walls and die. With proper glass lubrication, the element of friction is greatly reduced so that the power required for extrusion can be more effectively used in deforming the metal. Furthermore, apart from the pressure peak at the beginning of extrusion (Figure 5), corresponding to the upsetting of the billet in the container and simultaneous early entry of metal into the die orifice, the extrusion pressure remains reasonably steady. This means that lubrication is constant for the duration of the extrusion stroke.

FIGURE 5. Typical curve of extrusion pressure versus ram travel for direct extrusion of the uranium-0.75 weight percent titanium alloy compared with several other uranium-titanium compositions.

For extrusion in the gamma phase, a mixture of two glass lubricants is used: Corning-9772, a borate-based glass [principally diboron trioxide (B_2O_3)]; and Graphite Products Corporation 1482, a glass ceramic in a liquid xylene carrier. The powder-like (100 mesh) Corning-9772, a solid, is added to the liquid Graphite-1482 until a thick slurry forms. The slurry is then painted on the cold extrusion billet with a paint brush. When preheating the extrusion blank, the furnace door is left open until the volatile carrier has been consumed (thick black smoke).

The Corning-9772 has a softening point of 340°C (644°F); and in the range of gamma-extrusion temperatures (800 to 1000°C , 1475 to 1825°F) has a viscosity of 100 to 300 poises (10 to 30 pascal-seconds) which is considered ideal for lubrication purposes. The glass lubricant protects the extrusion blank and extrusion from oxidation and also gives improved surface finishes. Corning-9772 has a thermal expansion coefficient of 14.5×10^{-6} per $^\circ\text{C}$, which is close to that of many uranium alloys. The matching of thermal expansion coefficients is important for oxidation protection during cool down as it minimizes glass spallation, and hence enhances protection. After cool down, the glass is water-soluble and may be removed by hot water or steam with minimum effort.

FIGURE 6. Shown is operator applying Fiskes 604-D lubricant to the preheated container and die, prior to insertion of the extrusion billet.

For both alpha- and gamma-phase extrusion, the dies and containers are lubricated with a powdered aluminum, a hydrocarbon oil carrier mixture (Fiskes 604-D). This lubricant consists mainly of aluminum with major amounts also of calcium, iron, magnesium, and silicon. The carrier oil (soluble in carbon tetrachloride) is a long-chained hydrocarbon oil with an additive package similar to 648 oil. Figure 6 shows Fiskes 604-D being applied to the 450°C preheated container and 260°C preheated die. For proper adhesion of the lubricant, a cleaning operation is necessary after machining the billet to final dimensions. For cleaning, the extrusion billet is suspended in a *chlorothene* VG® vapor. Steam coils are used to heat and vaporize the chlorothene VG.

In summary, the prescribed glass lubricant gives improved surface finish, less pressure is required for forming, less die and cone wear occurs, greater oxidation protection during preheat and cool down results, and undue heating of the tool material is reduced by the glass acting as a thermal insulator.

For extrusion in the alpha phase, two lubricants have been used. One procedure is to paint the billet with the Fiskes 604-D described earlier, and then preheat in an argon-atmosphere, electrical-resistance furnace. A more common procedure is to use Houghten's 980 salt as the lubricant. The billet is preheated in a salt bath of Houghten's 980 and the salt that adheres to the billet after removal serves as the lubricant. After extrusion, a vacuum-outgassing treatment is given the material heat treated in salt to reduce the hydrogen content. In future alpha extrusions, a glass lubricant similar to the one described earlier for gamma-phase extrusion will be evaluated.

Preheating the Extrusion Blank:

Gamma Extrusion

The extrusion blank is preheated 950 to 1000°C (1740 to 1830°F) as is a graphite crusher block (discussed later) in an argon-purged, resistance-heated furnace. The extrusion billet is first placed on a graphite saddle which serves several purposes:

(1) it allows easy furnace loading and transfer to the extrusion press; (2) it helps keep the billet hot during the transfer from the furnace to the press; and (3) it helps keep the furnace clean by collecting glass (the lubricant) runoff.

A fork-lift truck with 4-foot (1.2 metres) long forks loads the billet in the preheated furnace. The furnace door stays open until the lubricant carrier is consumed. If the graphite saddle is cold, the billet remains in the furnace about 2.5 hours; if the saddle is hot, the billet stays in the furnace about 1.5 hours. In either case, the billet remains at temperature for about a half hour. Solid billets are preheated to 950 °C and hollow billets to 1000 °C.

A fork-lift truck is used to transfer the hot billet and graphite saddle to the extrusion press. The transfer must be relatively fast (0.5 to 2 minutes) to keep any part of the ingot from cooling into the beta phase, prior to extrusion. The graphite saddle aids the transfer since it insulates the forks from the billet and also acts as a heat source to keep the billet hot.

Salt baths may also be used for preheating gamma-phase extrusions. Houghten-980 salt works, but at the high temperatures considerable vapor (probably toxic) generates. Another disadvantage of the salt compared to the glass relates to the higher fluidity of the salt at the higher temperatures, giving less lubrication and oxidation protection. Hydrogen contamination of the billet adds another disadvantage of the salt, and requires a subsequent vacuum anneal of the extruded product.

Alpha Extrusion

The extrusion billet is preheated 620 to 640 °C (1150 to 1185 °F) in a salt bath. The salt used is Houghten-980 which melts at 527 °C (980 °F) and contains a mixture of chlorides and carbonates. The salt does not noticeably attack the U-0.75 wt % Ti alloy and acts as an oxidation barrier while the billet is hot. The salt is relatively safe, i.e., no toxic vapors released, when heating in the high alpha range. Preheat times of 30 to 90

minutes are used, depending on the size of the extrusion billets. Good temperature control is important to insure that the billet does not enter the beta region during the extrusion operation. The transfer of the billet from the preheat bath to the extrusion press utilizes a chain and hoist system that also suspends the billet in the salt bath.

Extrusion Equipment:

Most extrusions are made with hydraulic presses. Hydraulic extrusion presses are classified into horizontal and vertical presses depending on the direction of travel of the ram. Vertical presses are well-suited for back extrusion. They have the advantages of easier alignment between the press ram and the die and the need for less floor space than horizontal presses, although more head room is required. Vertical presses will produce uniform cooling of the billet in the container, and thus symmetrical uniform deformation will result. In a horizontal extrusion press, the bottom of the billet which lies in contact with the container will often cool more rapidly than the top surface, and therefore the deformation will be nonuniform, sometimes resulting in warping and nonuniform wall thickness. Nonetheless, horizontal presses with their greater capacities (up to 14,000 tons) (13 gigagrams) and greater lengths of extrusion are popular for manufacturing of bars and tubes. The extrusions described in this report were on a 1750-ton (1.6 Mg) horizontal tube and rod press.

Lake Erie Extrusion Press

The Erie (a 1750-ton horizontal water accumulator operated rod and tube press) was initially designed to extrude uranium billets up to 20 inches outside diameter (OD) and up to 25 inches long (635 mm), plus follower and dummy blocks, totaling an additional length of 9 (228 mm) inches. The press is of horizontal four-column design with an internal piercing mandrel and a fixed-mandrel extrusion mechanism. A description of the press is given in Table I. Basically, the press consists of the resistance platen assembly and the main cylinder assembly, connected by four tie rods and supported on a welded steel frame. The central portion of

the press along with several U-Ti extrusions is shown in Figure 7. The mandrel cylinder assembly is housed within the main moving platen. Inserted in

TABLE I. Description of Erie 1750-ton horizontal water accumulator-operated rod and tube extrusion press.

<u>Press Capacity</u>		<u>*tons</u>
Maximum Extrusion Pressure (Floating Mandrel)		1,750
Main Ram (Pressure with Fixed Mandrel)		1,500
Mandrel Ram		150 or 250
Mandrel Return		101
Main Ram Return		244
Container Sealing		180
Container Stripping		100
<u>Strokes</u>		<u>*inches</u>
Stroke of Main Ram		80
Stroke of Mandrel Ram		36
Stroke of Container (Maximum)		12
Stroke of Die Slide		70
<u>Speeds</u>		
Maximum Extrusion Speed	500 inches per minute	
<u>Approximate Overall Dimensions</u>		<u>*feet</u>
Maximum Length of Press Exclusive of Runout Table		44
Maximum Width		12
Maximum Overall Height		14
Total Height of Low Pressure Prefill Tank		27
Total Height of High Pressure Accumulator Vessel		20
<u>Weight</u>		<u>*pounds</u>
Approximate Weight of Press		400,000
Approximate Weight of Pump and Accumulator System		235,000

*For SI (metric) use:

1 ton = 2000 pounds = 909 kilograms
(1 kilogram = 2.2 pounds).

1 inch = 25.4 millimetres.

1 foot = 0.305 metres.

the cylinder platen are the main and pull-back cylinders, each housing single-acting rams. These rams are connected to the moving crosshead which carries the extrusion stem, and which is equipped with a rotary stop, and is supported and guided on angular ways mounted on the frame. The hollow-bored forged steel main ram serves as the cylinder for the internal piercer assembly. Inserted in the resistance platen, which is supported on the welded steel bed, are two container shifting cylinders with a hollow ram and jack ram to shift the container for opening and stripping and to seal it against the die during extrusion, upsetting, and piercing.

The press features a three-positional, lateral die slide. The die backer and bolster are mounted in an opening at one end of the slide and transmit the extrusion pressure to the thrust bushing which is inserted in the resistance platen and serves to distribute the load while the die is locked in a horseshoe by means of pins. The other end of the slide has a horseshoe-shaped cavity in which the discard and dummy blocks are transferred out of the press. Mounted in the center position of the slide are the piercing die and back-up steel.

Hydraulic power for the press is supplied by a pistonless hydropneumatic accumulator station consisting of low pressure prefill vessel, high pressure water and air vessels, and a suitable number of high pressure water pumps, together with necessary controls and safety devices.

The press was purchased by the U.S. Atomic Energy Commission (AEC) in 1958 and installed at the Weldon Springs works run by Mallinkrodt Chemical Company near St. Louis, Missouri. The initial cost was about \$750,000. The Rocky Flats Division of Dow Chemical U.S.A., (an AEC prime contractor) obtained the press in 1969 off a surplus list and installed it at the plant in Golden, Colorado. The replacement cost of the press at current prices would be in excess of \$2 million.

Reduction Ratios:

The extrusion ratio is determined by dividing the original area undergoing deformation by the

final deformed area, i.e., reduction area ratio = A_0/A_f . Because volume remains constant during extrusion, the extrusion ratio may also be calculated by increase in length. An extrusion ratio of 4 to 1 indicates the length has increased by a factor of four.

For a given size of extrusion billet extruded under a particular set of conditions, an upper limit to the extrusion ratio can be obtained with a press of given capacity. When the change in dimensions produced by extrusion is expressed as percent reduction in area, slight increases in the percent reduction in the region of 90 percent result in large increases in the extrusion pressure. For example, the extrusion pressure is nearly doubled when the percent reduction is increased from 95 to 99 percent. This corresponds to a change in extrusion ratio from 20 to 100. The more easily extrudable uranium and U-0.75 wt % Ti alloy have been worked in the gamma phase at extrusion ratios of greater than 50 to 1, while the U-6 wt % niobium (Nb) alloy is sometimes worked at ratios as low as 2 to 1.

Extrusion Constants:

The extrusion constant, K , is a measure of the force required for extrusion, and is given by the expression:

$$F = A_0 K \ln \frac{A_0}{A_f}$$

Where, F = the extrusion force

A_0 = starting billet cross-sectioned area

A_f = finished extrusion cross-sectional area

The force, F , from which values of the extrusion constant are determined, is measured in two different ways. In one method, the force of extrusion is that peak force which the press exerts in starting the billet moving, called the breakdown force. The second method uses the so-called running force, that force which will keep the billet moving once started. The preference here is to use the breakdown force, for two reasons.

FIGURE 7. Shown is the center portion of the Erie press. Displayed also are several uranium-titanium extrusions.

The running pressures that are recorded are not constant throughout the extrusion due to varying frictional forces, thus some ambiguity would arise as to where the running force value must be taken. Secondly, the breakdown force is the force that determines, without applying a correction factor, whether or not the press will have the capacity to perform a particular extrusion by getting the billet started.

The values of K are dependent upon the temperature at the time of extrusion; the lubrication used in the extrusion process; the die material; design and finish; billet and die geometry; reduction ratio; and strain rate.

Gamma-phase extrusion constants for uranium and several of its alloys are given in Table II as are those for alpha phase extrusion. The gamma-phase extrusion constants are an order of magnitude lower than those for alpha-phase extrusion.

Die and Tooling Design:

The dies and tooling used in extrusion must withstand considerable abuse from high stresses, thermal shock, and oxidation. Highly alloyed tool steels are used to provide tough dies and tools with adequate elevated temperature strength. Figures 8 and 9 illustrate the tooling arrangement in extruding

the U-0.75 wt % Ti alloy into solid bar and hollow tube, respectively. Extensive use is made of H-13 tool steel, heat treated to a hardness of R_c 40-44. The die, die backing and holder, cone, container, and plunger are all H-13 tool steel. The H-13 alloy is classified as a chromium hot-work tool steel and contains 0.35 percent carbon (C), 5.0 percent chromium (Cr), 1.5 percent molybdenum (Mo), and 1.0 percent vanadium (V).

Other materials, such as the metal carbides, would probably have extended lives and provide better surface finishes when used as the die insert. However, these materials have not been evaluated and whether their extended life would justify the additional cost is not known. In the extrusion of the U-0.75 wt % Ti alloy, the only part of the tooling that wears significantly is the die insert itself. Thus, the die insert is the only part of the tooling that would justify a significantly higher cost material. With H-13 steel as the die insert, several extrusions can often be made before a new insert is required.

Several geometric angles are important in the extrusion of uranium alloys; namely, die angle, cone angle, and billet angle. The die angle is one-half the included angle. For a flat die [Figure 1(a)], the die angle is one-half of 180° , or 90° . For a conical die, this angle is less than 90° (Figure 8). In the case of uranium alloys, a

TABLE II. Experimentally determined extrusion constants for uranium and some of its alloys. (The extrusion constant is proportional to the extrusion pressure and inversely proportional to the reduction ratio.)

Material	Gamma Phase	Alpha Phase
	Temperature at 950°C (pounds per square inch)	Temperature at 630°C (pounds per square inch)
Uranium D-38	3,000 (21 MPa)	32,000 (224 MPa)
Uranium-0.75 Weight Percent (wt %) Titanium	8,000 (56 MPa)	48,000 (296 MPa)
Uranium- 2.2 wt % Niobium	20,000 (140 MPa)	90,000 (630 MPa)
Uranium- 4.2 wt % Niobium	24,000 (168 MPa)	—
Uranium- 6.3 wt % Niobium	28,000 (196 MPa)	—
Uranium-10 wt % Molybdenum	40,000 (280 MPa)	—

For SI (metric) use: 1 pound per square inch = 7 kilopascals (kPa), M = mega (10^6).

die angle of 45° is commonly used. The cone angle is one-half the included angle of the cone (Figure 10). For uranium alloys a cone angle of 30° works well. The billet angle is the cast or machined bevel on the nose of the billet and is measured from the center line of the billet. Billet angles slightly less than the cone angles are used so that some lubricant can be trapped between the billet and the cone.

The pressure required to produce extrusion is dependent on the way the metal flows in the container and extrusion die. Also certain defects which occur in extrusion are directly related to the way the alloy deforms during the process. Figure 8 illustrates streamline flow produced by the deformation of a square-grid network for direct extrusion through a conical die. This figure represents the extrusion of a well lubricated billet in which the billet slides along the container wall. Deformation in the billet is relatively uniform

until close to the die entrance. Here the center part of the billet moves more easily through the die than the metal along the container wall.

Elements at the center of the billet undergo essentially pure elongation in the extruded rod, which corresponds to the change in cross section from billet to extrusion. Elements near the sides of the billet undergo extensive shear deformation. The shear deformation which occurs over much of the cross section of the extruded rod requires an expenditure of energy which is not related to the change in dimensions from the billet to the extrusion. This *redundant work* is chiefly responsible for the increase in the actual extrusion pressure over that calculated on the basis of ideal deformation.

A specific die arrangement is shown in Figure 10 with the die alone shown in Figure 11. The design

FIGURE 8. Schematic die and tooling arrangement for gamma-phase extrusion of the uranium-0.75 weight percent titanium alloy into solid bar.

allows for extruding bars of U-0.75 wt % Ti from a 7.5-inch (190 mm) diameter billet to a 1.5-inch (38 mm) diameter extruded bar, corresponding to a reduction ratio of 17 to 1. The die illustrated is a conical die with a 45° half-die angle. This type of die is commonly used, but it may not represent the optimum condition for the U-0.75 wt % Ti alloy. The optimum die angle is a compromise which provides the lowest extrusion pressure with the longest die life. The determination of the optimum die angle for the U-0.75 wt % uranium alloy is still a matter for empirical investigation, but the 45° half-die angle is near the ideal.

The nonhomogeneous flow through an extrusion die can be modified by changing the die angle. Decreasing the die angle of a conical die so that it approaches the natural angle of flow through a flat die results in less shear deformation. However, even though more uniform flow results from smaller angle dies, the friction forces are higher.

Therefore, it does not necessarily follow that the extrusion pressure is lower when the deformation is more uniform.

The extrusion pressure decreases with decreasing die angle (assuming frictional increases do not offset the decreased pressure). More uniform deformation of the alloy results with small-angle dies. Additional control over the deformation can be obtained by changing the length of the bearing section in the die. An increased bearing length results in greater friction and hence greater pressure is required to maintain the flow. For uranium alloys, a 0.25 radius is used on the bearing surface with a relief angle of 15° .

Extrusion Temperatures:

Uranium and its alloys are extruded *hot* to take advantage of the decrease in flow stress or deformation

FIGURE 9. Schematic die and tooling arrangement for gamma-phase extrusion of the uranium-0.75 weight percent titanium alloy into tubing.

resistance with increasing temperature. Since hot working introduces the problem of oxidation of the billet and extrusion tools and softening of the die and tools as well as making it more difficult to provide adequate lubrication, it is advantageous to use the minimum temperature which will provide the metal with suitable plasticity. The upper hot-working temperature is the temperature at which hot shortness occurs, i.e., when some liquid forms. Because of the extensive deformation produced in extrusion, considerable internal heating of the billet also results. Therefore, the top working temperature should be safely below the hot-shortness range. For a given deformation,

lower working temperatures are generally possible with extrusion than can be used in forging or rolling because the high compressive stresses minimize cracking.

The temperature range of 900 to 1000 °C for gamma extrusion provides high plasticity and is significantly below the hot-shortness range (1142 to 1163 °C) and above the beta range (655 to 720 °C). It is important to not let part of the billet cool into the beta range prior to extrusion as this gives rise to severe extrusion defects. For alpha-phase extrusion where the alpha extrusion constant drops sharply with increasing temperature, the control of temperature is extremely important.

Temperature of the billet should be in the range of 620 to 640 °C. Lower temperatures raise the extrusion constant making deformation difficult,

FIGURE 10. Typical die-container arrangement for a 7.5-inch (190-millimetre) to 1.8-inch (45-millimetre) forward extrusion.

Legend

1. H-13 (R_C 40-44), 15.5-inch (394-millimetre) diameter by 6.5 inches (165 millimetres).
2. H-13 (R_C 40-44), 11.75-inch (298-millimetre) diameter by 2 inches (50 millimetres).
3. H-13 (R_C 40-44), 5-inch (127-millimetre) diameter by 3 inches (76 millimetres).
4. H-13 (R_C 40-44), 5-inch (127-millimetre) diameter by 2-inches (50-millimetres)
5. H13 (R_C 40-44), 7.75-inch (197-millimetre) diameter by 3.75-inches (95-millimetres).

FIGURE 11. Die configuration for the 7.5-inch (190-millimetre) to 1.8-inch (45-millimetre) forward extrusion shown in Figure 10. (Dimensions in inches.)

while higher temperatures along with deformation heating will cause spiking into the beta range (655 to 720 °C) and result in extrusion defects.

Extrusion Speed:

Ram speed is an important consideration in extrusion. Increasing the ram speed produces an increase in the extrusion pressure. A tenfold increase in the speed results in about a 50 percent increase in pressure. Greater cooling of the billet occurs at low extrusion speeds. When this becomes pronounced, the pressure required for direct extrusion will actually increase with increasing ram travel because of the increased flow stress as the billet cools. The higher the temperature of the billet, the greater the effect of low extrusion speed on the cooling of the billet. When the press is being used at near capacity, and the billet loses some plasticity due to cooling, the capacity of the press may be exceeded and the extrusion process stops. This results in a part-extruded billet and requires a major removal effort. Therefore, high extrusion speeds are required when the press is used at near capacity, especially with alloys that need high extrusion temperatures. The temperature rise due to deformation of the metal is greater at high extrusion speeds, and therefore, problems with hot shortness or beta-phase spiking may be accentuated.

The selection of the proper extrusion speed and temperature is best determined by trial and error for each alloy and billet size. For a given extrusion pressure, the extrusion ratio which can be obtained increases with increasing temperature within the alpha- and gamma-phase fields, respectively. For any given temperature, a larger extrusion ratio can be obtained with a higher pressure. The maximum billet temperature, on the assumption that no limitations arise from the strength of tools and die, is determined by the temperature at which incipient melting or beta-phase spiking occurs in the extrusion. The temperature rise of the extrusion will be determined by the speed of extrusion and the amount of deformation (extrusion ratio). For alpha phase extrusion of U-0.75 wt % Ti, ram speeds of 50 to 100 inches (1270 to 2540 mm) per minute are used. For gamma-phase extrusion

of the U-0.75 wt % Ti alloy, ram speeds of 50 to 200 inches (1270 to 5080 mm) per minute work well.

Crusher Block:

A graphite crusher or waster block is used for both alpha- and gamma-phase extrusions of the U-0.75 wt % Ti alloy. The crusher block is the same cross section as the ram platen and of sufficient thickness to extrude past the die orifice before the ram platen meets the cone. The crusher block serves two main purposes. One, it is preheated with the extrusion billet and serves to insulate the billet from the unheated ram platen, thus preventing undue chilling of the billet. Secondly, toward the end of the extrusion cycle, the graphite crusher block itself is extruded through the die orifice removing all metal from the container and die, thus eliminating the *nail head* effect. The metal extrusion is easily separated from the extruded crusher block, thus eliminating a sawing or shearing operation and the *nail head* scrap.

Extrusion Defects:

Because of the inhomogeneous deformation in the direct extrusion of a billet, the center of the billet moves faster than the periphery. As a result, a dead metal zone extends along the outer surface of the billet. Toward the end of the extrusion, the outer surface of the billet moves toward the center and extrudes through the die near the axis of the rod. Since the surface of the billet contains an oxidized skin, this type of flow results in internal oxide stringers. This defect can be considered to be an internal pipe, and is known as the extrusion defect. On a transverse section through the extrusion, this will appear as an annular ring of oxide. The tendency toward the formation of the extrusion defect increases as the container wall friction becomes greater or if beta phase forms in the outer periphery. If a heated billet is placed in a cooler extrusion container, the outer layers of the billet will be chilled and the flow resistance of this region will increase. Therefore, there will be a greater tendency for the

center part of the billet to extrude before the surface skin, and the tendency for formation of the extrusion defect is increased. For the U-0.75 wt % Ti alloy, the glass lubricant used serves to reduce friction and to insulate against beta-phase formation, thus causing the extrusion defect to form only at the tail end of the extrusion.

When extrusion is carried to the point at which the length of the billet remaining in the container is about one-quarter its diameter, the rapid radial flow into the die results in the creation of an axial hole, or funnel, in the back end of the extrusion. This hole may extend for some distance into the back end of the extrusion, and therefore this metal must be discarded. It has been reported for other metals that the length of this defect can be reduced considerably by inclining the face of the ram at an angle to the ram axis. A conical crusher block (female) and billet (male) are being readied to see if this defect type can be eliminated (illustrated in Figure 8).

A severe form of surface serrations observed on a few occasions, called the *fir-tree defect* or *cheveron defect*, probably results from the momentary sticking of the extrusion in the die land. The pressure builds up rapidly as the alloy tries to extrude internally to overcome the high friction at the die wall. This may also be due to the formation of beta phase near the die land and the correspondingly high extrusion constant of beta.

Because of the nonuniform deformation produced in extrusion, some variations will occur in structure and properties from the front to the back end of the extrusion in the longitudinal direction and across the diameter of the extrusion in the transverse direction. The first metal through the die receives less deformation than the remainder of the extrusion. The center portion of the extrusion will receive an intermediate amount of work, while the back end will receive the largest amount. Therefore, the front portion will have the lowest strength due to work hardening; the center an intermediate strength level, and the end portion the highest. Because of the severe shear deformation of the surface layers of the extrusion, this region is more highly deformed than the center.

The variation in deformation and work hardening along the length and cross section of the extrusion depends on the extrusion ratio. When the extrusion ratio is high, the deformation is more uniform along the length of the extrusion.

Characterization of gamma-phase extrusions of the U-0.75 wt % Ti alloys has not shown a large variation in strength properties along the usable length or cross section of the extrusion. The results relate to several reasons: (a) the glass lubricant is effective in minimizing friction and redundant work, (b) the U-0.75 wt % Ti alloy distributes deformation more readily than many alloys, and (c) the temperature of deformation removes most effects of work hardening. The uniformity of properties is also confirmed when extrusions are heated after they leave the press, the surface layers responding to aging and recrystallization in the same manner as do the centers.

Post Treatment of Extrusions:

The extrusions are ejected from the press onto a cold-roll table. The roll table is a heat sink extracting heat nonuniformly from the extrusion and will cause warpage especially in thin-wall tubing. To minimize warpage, it is necessary to roll the extrusion while the alloy cools to room temperature. This operation is done manually with tongs and hooks.

One problem with the U-0.75 wt % Ti alloy is that it will tend to burn up when left to cool in air after extrusion in the gamma region. The oxide forms an insulating barrier, allowing the part to completely disintegrate. This dilemma can be solved by spraying water on the extrusion while rolling it back and forth on the roll table (illustrated in Figure 12). On thick sections, warpage is not much of a problem while oxidation is. However, on thin-wall tubes warpage and oxidation can be a problem and a light water spray distributed uniformly must be used while rolling. Direct water quenching of thick sections of the U-0.75 wt % Ti alloy is to be avoided due to a cracking problem. No burn-up problem is evident with alpha-phase extrusion of the U-0.75 wt % Ti alloy.

FIGURE 12. Shown is an extrusion on the roll table being sprayed with water to speed up the cooling cycle, thus preventing excessive oxidation.

Some back extrusions can be cooled in the tooling thus eliminating the burn-up problem. Some extruded configurations can be immediately sprinkled with heat-treating salt or dipped in a molten-salt bath momentarily and allowed to cool in air under the protective salt film.

Often parts are to be aged after extrusion and prior to final machining, and it is desirable to start from a solution-quenched condition. However, quench cracking is a problem with the U-0.75 wt % Ti alloy. Solid bars over 0.5 inches in diameter can form centerline voids when water-quenched from the gamma region. However, no problem has been encountered on water quenching of 8-inch (203 mm) OD tubing with a 1-inch (25 mm) wall. Thus quenching from the gamma region does offer problems and each configuration should be evaluated individually.

Billets that are preheated in a salt bath are given a vacuum-anneal outgassing operation following extrusion to reduce their hydrogen levels. Heating at 800 to 850 °C for 4 hours in a 1×10^{-4} torr vacuum will reduce the hydrogen

to acceptable levels. [For SI (metric) use: 1 torr = 133 pascals.]

SUMMARY

The uranium-0.75 wt % titanium alloy is readily extrudable in the alpha phase (600 to 640 °C) and in the gamma phase (900 to 1000 °C). The casting of sound extrusion billets up to 1,100 kilograms in mass is common practice and has extreme importance in the production of sound extrusions. The use of glass lubricants has also been a major breakthrough in producing sound extrusions free of defects. Reduction ratios of greater than 50 to 1 have been achieved on reasonably sized billets. Extrusion constants of 48,000 psi (296 MPa) for alpha phase (630 °C) and 8,000 psi (56 MPa) for gamma phase (950 °C) have been achieved. Gamma-phase extrusion is preferred over alpha extrusion in that larger billets can be used and temperature control is not as critical. However, alpha-phase extrusion offers better surface finish, less die wear, and fewer oxidation problems. Billets up to 14 inches (356 mm) in diameter have been successfully gamma-extruded and plans exist for extruding billets up to 20 inches (508 mm) in diameter.