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EXTRUSION CLADDING OF URANIUM FUEL PLATES

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EXTRUSION CLADDING OF URANIUM FUEL PLATES

Robert J. Fiorentino, David C. Drennen, Charles J. Slunder,
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Two methods for extrusion cladding were investigated and evaluated. In the first, or coaxial method, the component parts of the extrusion assembly are concentric, and the fuel plate moves in the same direction as the hydraulic-press ram. In the second technique studied, the right-angle method, the fuel-plate motion is perpendicular to that of the ram.

Ribbed sheaths of aluminum were extruded satisfactorily on 3-in.-wide uranium plates in lengths up to about 10 ft. Lowest extrusion pressures were achieved with the most streamlined designs of mandrel tips, using flat-faced shear dies. Good results were obtained with billet and die temperatures of about 1050 F, at extrusion speeds up to 60 ipm. Extrusion pressures ranged from 25,000 to 60,000 psi.

End-cladding procedures were developed which involved attaching end plates machined from aluminum powder-metallurgy products (12 to 18 w/o Al_2O_3) to the core by means of T-shaped joints, and cladding the entire assembly with aluminum.

Excellent bonds were achieved, on uranium as well as on the end plugs. The median values obtained by stud weld tests were 26,000 psi for uranium, and 12,000 psi for the end plugs.

The importance of proper tool alignment and avoidance of imbalance of forces caused by pressure differentials within the extrusion container was demonstrated.

INTRODUCTION

During the past few years, the process of extrusion cladding has been receiving an increasing amount of attention as a potential, highly economical method of cladding fuel elements. It offers the possibility of mass producing accurately shaped claddings on a wide variety of fuel-element shapes. The necessity of subsequent machining and finishing operations may be held to a minimum. Moreover, the probability of achieving a strong metallurgical bond between the cladding and the core is good.

The adaptation of the extrusion process to the cladding of small uranium rods and bars was demonstrated by laboratory experiments conducted several years ago. The basic details that were established then to produce seamless aluminum sheaths, 0.030 in. thick, over 1/4-in. round and 3/16 by 3/8-in. rectangular uranium bars, were described in BMI-989, dated March 22, 1955. One of the original objectives of the program had been to produce a completely seamless envelope of aluminum around the core, with the ultimate goal of developing a process for the extrusion cladding of uranium flat-plate elements, approximately 0.180 in. thick by 3 in. wide [REDACTED]. The cladding was to be 0.030 in. thick with integral longitudinal ribs protruding from the 3-in.-wide faces. The equipment which was designed and constructed for this purpose is shown schematically in Figure 1. A vertical 700-ton HPM hydraulic press was used for this work. In order to produce a seamless cladding, it was necessary to avoid any separation and rewelding of metal streams which occur when bridge dies with

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Fig #1

FIGURE 1. SCHEMATIC DIAGRAM OF ASSEMBLY FOR EXTRUDING SEAMLESS CLADDINGS ON FLAT PLATES

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spider arms supporting a mandrel are used. In the equipment shown in Figure 1, the mandrel was threaded into a heavy support beam and supported over the container by tie rods. Also, this design required the use of a segmented ram passing through slots in the mandrel-support beam. While there were many problems involved in scaling up from the small-scale bars to the full-sized elements, a steel plate was successfully clad with a relatively thick sheath of aluminum in preliminary experiments with this equipment. When further studies of longitudinal seams in aluminum produced by pressure welding indicated that there would be no deleterious effects on the mechanical and corrosion protective properties of the cladding, it was decided to change the emphasis, and to concentrate on the development of an extrusion-cladding process having the same basic objectives, but with no limitation against the presence of longitudinal pressure welds. It was thought that this would result in simplified equipment design and operating features.

The progress of the work following this new avenue of attack is described in this report. Two variations in equipment design and method were investigated, identified in this report as the "coaxial" and the "right-angle" processes, respectively. In the coaxial process, the fuel core, mandrel, hollow aluminum billet, and extrusion ram are arranged concentrically. This is actually the same as the procedure developed for the seamless cladding, with the exception that a porthole mandrel is used, as discussed later. In the right-angle process, the extrusion ram moves at right angles to the direction of fuel core being clad. The design details of the equipment and the progress of the experimental work with these two techniques are described in the following sections.

COAXIAL EXTRUSION CLADDING

General Details of Equipment

Figure 2 is an assembly drawing showing the various parts of the equipment that was designed for cladding flat plates. Two cross sections are shown to illustrate the asymmetrical shape of the tools. The significant features to note are the porthole mandrel, and the concentric arrangement of the container, billet, ram, and hollow mandrel. The mandrel tip rests directly on the die, and the container rests on the ledge of the mandrel. Thus, in the vertical assembly, the downward pressure during extrusion keeps everything tight and in line. A sequence of operations for assembly, alignment, and dismantling was established. However, these are not described here, because they are considered to be specific for this equipment in the development stage. The procedures would not necessarily be the same in an improved design.

During the cladding operation, the core is fed through the hollow mandrel, and pressure is applied by the ram to the hollow, cylindrical billet, forcing the aluminum through the portholes located in the mandrel tip. The streams of aluminum issuing from the ports then surround and reweld around the fuel core, which is free to move through the mandrel and die. The configuration and dimensions of the cladding are

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FIGURE 2. ASSEMBLY WITH PORTHOLE MANDREL TIP
FOR EXTRUSION CLADDING FLAT PLATES

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determined by the die opening. A photograph illustrating the entry side of the portholes in the mandrel is shown in Figure 3. In Figure 4, the mandrel, showing the exit side of the six portholes and the slot through which the core passes, is pictured adjacent to an extrusion die.

Experimental Work

General

The initial tests with the assembly using a porthole mandrel demonstrated that the cladding of flat plates, 0.180 in. thick by approximately 2-3/4 in. wide, was feasible. A 0.030-in. aluminum cladding with six integral ribs, approximately 0.1 in. high by 0.1 in. wide was applied to several plates about 20 in. long. This was accomplished at a pressure of about 30,000 psi on the billet, and a billet temperature of approximately 1000 F. The extrusion ratio was calculated to be about 40 to 1.

The experimental work that followed was directed toward evaluating the effect of process variables, with particular attention paid to their influence on extrusion pressure. Knowledge of the conditions which would require the least amount of pressure is important in order to achieve the maximum extrusion speed and to extend extrusion-tool life. In a few experiments, the effect of variables on the nature and strength of the bond between the core and the cladding was also examined. In addition, considerable effort was directed toward developing techniques for cladding the ends of the fuel elements.

A number of process variables require attention and control to obtain uniformly clad plates meeting the specifications for fuel elements. Among these are (1) mandrel design, (2) die design, (3) mandrel tip-to-die distance, (4) temperature, and (5) extrusion speed.

In attempts to cover the effects of all of these factors in the minimum time, it was not possible to study each variable individually and systematically. Therefore, in many cases, only general comparisons could be made between tests. Experimental difficulties in achieving exact duplication of temperature due to the massive size of the tools and the slight, but gradual, change in the dimensions of some of the tools after a certain period of operation also made exact comparisons difficult.

Effect of Process Variables

Mandrel Design. It appears that the most critical factor in mandrel design is the shape or contour of the tip in the area surrounding the core slot. Several shapes varying from very blunt to quite streamlined have been tested. The shapes of the five mandrels employed in this investigation are shown in Figure 5.

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FIGURE 3. VERTICAL VIEW OF PORTHOLE MANDREL

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FIGURE 4. MANDREL AND DIE USED FOR CLADDING FLAT PLATES

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FIGURE 5. FIVE PORTHOLE MANDRELS OF VARIOUS DESIGNS USED IN THE COAXIAL EXTRUSION ASSEMBLY

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It was observed that the extrusion pressure was significantly influenced by mandrel shape. For example, under certain conditions, the extrusion pressure was about 28,000 psi when using the most streamlined mandrel. Under comparable conditions, the extrusion pressure was roughly 4000 to 6000 psi greater when using the more blunt ones. It is reasoned that this is because the aluminum flowing over the streamlined contour contacts the core at a smaller angle. In this case, the longitudinal component of force (parallel to the core) required to push the aluminum together with the core out of the die is achieved at the lower extrusion pressure.

The streamlined mandrels, however, tended to fail more easily than the blunt ones because of the thinner steel sections near the core slot. Compression or deflection of the long rectangular slot by the extrusion pressure often caused a permanent narrowing and sometimes produced cracking at the corners. An example of this type of failure is illustrated in Figure 6.

To prevent or minimize cracking, attempts were made to reduce slot deflection by designing new mandrels with thicker center webs supporting the center of the slot. In one design, the top surface of the center web was located flush with the edge of the slot to reduce the deflection that occurred by cantilever action. Another mandrel was designed with radiused corners in the slot to reduce the amount of stress concentration in those regions. These modifications appeared to reduce the tendency toward failure.

Another critical factor in mandrel design was the clearance between the core and slot. In the initial tests, the clearance on all sides of the core was about 0.006 in. while under no pressure. However, the inward deflection of the long slot by the extrusion pressure was sometimes sufficient to restrain the forward motion of the core during a cladding operation. It was found that this type of core restraint could be prevented by widening the center portion of the slot length to compensate for the deflection. For the most streamlined mandrel, a clearance on each side of 0.020 in. (0.040 in. total) in the center portion (about the middle third section) and 0.006 in. at the ends of the slot gave satisfactory results. In one test, a clearance of as much as 0.036 in. on each side was used and no back extrusion was noted. However, this large clearance was obtained by using a core that was 0.050 in. undersize in thickness, which resulted in a 0.055-in.-thick instead of a 0.030-in.-thick cladding. It is not known whether back extrusion would occur if, with the same clearance, only a 0.030-in.-thick cladding was applied.

It should be mentioned that, although relatively large clearances between the slot and core in the middle portion of the slot are required, this is not the case for the region near the slot corners. In this area, the clearance should be held to a minimum to reduce the extent of core shifting and rotation that might occur during the cladding operation. Such shifting or rotation would cause inconcentricity of the cladding and core, since the relative positions of the mandrel slot and die opening are fixed.

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FIGURE 6. MANDREL WITH SMALL CRACKS IN THE CORNERS OF THE RECTANGULAR CORE SLOT

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Die Design. The effects of several extrusion-die designs were also investigated. The contour of the lead-in surfaces of the shear, conical, radiused, and tapered dies used in the program are shown in Figure 7. The hexagonal-shaped recess concentric with the die opening is the chamber into which the metal streams flow and reweld. It was found that the shear dies produced the most uniform claddings with the best surface finish and at the lowest pressures. The radiused and conical dies were shown to direct the flow of aluminum so as to produce relatively sound solid-aluminum end sections behind the trailing end of the cores. This is a desirable feature when attempting to extrude end plugs integral with the cladding.

In addition to die-surface contour, the design of the die land or bearing was found to be quite important. To obtain a uniform cladding of the specified dimensions, it is necessary to design the shape and length of the die bearing to compensate for the unequal thicknesses of the ribs and the cladding layer. For instance, the bearing was made longer in the area that formed the heavy ribs than that which formed the 0.030-in.-thick cladding. If the die bearing were uniform in length, the rib regions would flow at a higher rate than the thinner areas and an uneven cladding layer would result. It is also important to keep the bearing surface area to a minimum in order to minimize the extrusion pressure.

One die was designed with a slightly tapered bearing which provided a slight wedging action on the extruding aluminum. It was found that this somewhat improved the soundness of the end plugs that were extruded integral with the cladding.

Mandrel Tip-to-Die Distance. It was found that the mandrel tip-to-die distance has an influence on the uniformity of the cladding and a minor effect on the extrusion pressure. For example, at the optimum mandrel tip-to-die distance, the core is carried freely through the die by the extruding aluminum. The core moves at a uniform speed determined by the extrusion ratio and the ram speed. Under these conditions, the cladding will be at the desired thickness. However, if the mandrel tip-to-die distance is too great, the free motion of the core is restricted because it must pass through more aluminum under pressure as it travels from the mandrel tip to the die face. This causes the core to move slower than the aluminum. The difference in speed results in an excessive buildup of aluminum around the core as it emerges from the die. Thus, the thickness of the cladding layer is greater than the die opening and the pressure required will be greater than that required for the proper mandrel-to-die distance. On the other hand, a mandrel-to-die distance that is too small restricts the flow of aluminum through the die, resulting in a cladding layer that is thinner than the die opening. In the coaxial work with the full-sized plate, the mandrel-to-die distance was varied in the range from 40 to 160 mils. In general, the range from 60 to 90 mils appears to be adequate to produce a cladding of satisfactory dimensions.

Temperature. Billet temperature is one of the most important factors affecting extrusion pressure. It seems reasonable to assume that, under a given set of conditions, the temperature of that portion of billet extruding out of the die at any given time determines the pressure required at that time. Therefore, die temperature was

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FIGURE 7. FOUR DIES OF VARIOUS DESIGNS USED IN THE COAXIAL EXTRUSION ASSEMBLY

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considered to be an important variable in the process. In order to keep extrusion pressure to a minimum, it was necessary to supply additional heat to the die to prevent chilling of the aluminum in this region.

In most cases, the liner and die temperatures were in the 1050 to 1075 F range. For some special tests, the die temperature was raised to the 1100 to 1125 F range for short periods of time. However, such high temperatures result in a rapid lowering of die hardness and therefore could not be used over a prolonged period.

Of similar influence to die temperature was the temperature of the core prior to cladding. In tests where the core was at room temperature before cladding, the core would heat up to some extent during the cladding operation. However, if the core did not reach the billet temperature at the time it was being clad, then it would chill the aluminum about to be extruded and a higher extrusion pressure would be required. By preheating the cores to the billet temperature before cladding, reductions of roughly 10 to 15 per cent in extrusion pressure were obtained. The following tabulation gives the effect of core preheating on the pressure at two different extrusion speeds.

<u>Extrusion Speed, ipm</u>	<u>Core Preheat Temperature, F</u>	<u>Extrusion Pressure, psi</u>
8	R. T.	35,000
8	1050	31,500
36	R. T.	56,000
36	1050	47,000

These preheating tests were made using steel cores. It is probable that uranium cores, because of their low elevated-temperature strength, could not be preheated to the billet temperature. Also, there is danger that the uranium might oxidize even though protected by a nickel plate. Perhaps a somewhat lower preheat temperature for uranium could be used and still effect a significant lowering of the extrusion pressure.

Extrusion Speed

Very high extrusion speeds may result in excessive pressures which in turn can cause deformation or rupture of the fuel element or perhaps even failure of the extrusion tools. Therefore, the maximum speed that can be achieved with this equipment ultimately depends upon the pressure of extrusion. As a precautionary measure against container failure, care was taken not to exceed an extrusion pressure of 60,000 psi on the billet.

The extrusion speed used in the experimental work was generally 6 to 8 ipm. A few tests at faster speeds were made to determine the effect on the other variables. In the following tabulation, the effect of speed on extrusion pressure is given at a die and liner temperature of 1050 F.

<u>Extrusion Speed, ipm</u>	<u>Core</u>	<u>Extrusion Pressure, psi</u>
6	Uranium	29,000
20	Uranium	40,500
32	Uranium	42,500
44	Steel	48,000

At a die and liner temperature of 1100 and 1075 F, respectively, it was possible to clad steel cores at 60 ipm and at pressures between 45,000 and 48,000 psi. Attempts were not made to extrude at any greater speeds. Neither the steel nor the uranium cores were preheated in these tests. Since core preheating was found to reduce extrusion pressure, it seems possible that faster extrusion speeds might be achieved at these pressures.

End Cladding

Two methods of cladding the leading and trailing ends of the fuel elements have been examined. One approach, called the integral method, consists of extruding aluminum on the ends as well as on the sides of the core. This is accomplished by first holding the core flush with the mandrel tip and extruding a solid section of aluminum ahead of the core. The core is then started at the desired time by forcing it into the aluminum until it is picked up and carried through the die. The trailing end of the core is clad by merely continuing to extrude aluminum after the core has passed through the die.

Attempts to clad both ends of fuel elements in this way were made with some success on 1/4-in. rounds and 3/16 by 3/8 in. rectangles in the small-scale work. In the work with flat plates, attempts were made to clad only the trailing ends. The results of these tests showed that small voids or pockets are formed behind the trailing end by the aluminum. It was found that these voids could be eliminated by tapering the end of the core. Also, it was found that conical and radiused dies and dies with slightly tapered bearings would minimize the formation of voids.

The second approach to end cladding consisted of mechanically attaching an end-plug of some suitable material to each end of the fuel core. With this arrangement, it remained only to clad over the sides of the fuel core and the attached end plugs. This was done by starting with the leading end plug within the die opening, and cladding the plug and core as in the standard procedure.

Two problems encountered in this phase involved the selection of suitable end-plug materials and determining a workable design for a mechanical joint between the plug and the core. It was found that the plug materials must have sufficient high-temperature strength to resist the high compressive forces exerted by the extruding aluminum. The material must also have a comparatively low thermal-neutron-absorption cross section and good corrosion resistance.

Standard 52S and 24S-T aluminum alloys were tried, but these either deformed severely or completely ruptured even at comparatively low extrusion pressures. Also, three experimental wrought aluminum alloys, identified as X5356-F, X2219-F, and M237-F, that were developed for high-temperature service were tested. These also were found to be too weak. However, several of the aluminum powder-metallurgy products were found to be quite satisfactory. The three experimental alloys tested were M257, M276, and M355, and contained roughly 8, 13, and 18 w/o Al_2O_3 , respectively. Of these, M276 and M355 exhibited considerably more strength than M257 and were found more satisfactory under high pressures. The results of the most severe tests conducted with these plug materials, both with and without preheating, are listed in Table 1. The better high-temperature strength of M355 over that of M276 is obvious when the amount of deformation of the two in the preheated condition is compared. But, where no preheating was used, both M355 and M276 were found to be equally suitable materials, M355 perhaps being slightly more brittle than M276.

TABLE 1. RESULTS WITH SINTERED $\text{Al-Al}_2\text{O}_3$ END PLUGS

Plug Material	Extrusion Pressure, psi	Liner Temperature, F	Extrusion Speed, ipm	Preheat Temperature, F	Condition of Plug After Cladding
M257	32,000	1025	6	R. T.	Slight deformation
M276	48,000	1075	60	R. T.	Slight deformation
M355	45,000	1075	60	R. T.	No deformation
M276	46,500	1075	36	1050	About 75 per cent elongation
M355	44,000	1075	36	1050	No deformation

The design of the mechanical joint between the end plug and the core was found to be somewhat critical. Of the various designs tested, the T-shaped joint appeared to be most suitable from the standpoint of ease of nickel plating and assembling. A photograph illustrating the latest T-joint design is shown in Figure 8. The various sections of the plug should be large enough to withstand the stresses exerted on them by the aluminum cladding. Also, the re-entrant corners should be radiused to minimize stress concentration.

Of the other designs tested, such as tongue-and-groove, lap, and dovetail joints, the tongue-and-groove configuration showed some promise under certain conditions. Failures of this joint were found to be minimized if the tongue was machined in the plug and the groove in the fuel element. In this way, the full cross section of the plug is available to withstand the pressure exerted by the aluminum.

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FIGURE 8. END-PLUG WITH DOUBLE T-JOINT ATTACHED TO ONE END OF A URANIUM CORE

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Properties of Clad Cores

An important property of the extrusion-clad fuel elements is the strength of the metallurgical bond between the cladding and the core. It is believed that good bond strengths would probably minimize the spread of corrosion if it should begin and also result in good heat transfer across the interface. The photograph in Figure 9 illustrates the aluminum-nickel and nickel-uranium diffusion layers in an extrusion-clad specimen developed during the cladding operation.

The bond strength was determined by welding 3/16-in. -diameter aluminum studs to the cladding and pulling the welded specimens in a tensile machine. The depth of penetration of the weld zone was believed to be too shallow to affect the properties of the diffusion layers.

In one experiment, the bond strengths were determined for three aluminum-clad nickel-plated uranium cores with unplated M276 plugs attached on each end. The specimens were clad at three different extrusion speeds in an attempt to determine any gross effect of speed on bond strength. Each clad specimen was composed of a 20-in. -long uranium core and two 3-1/2-in. -long end plugs. Neither the core nor the plugs were preheated before cladding.

The bond strengths were determined along the entire length of each specimen, 32 tests for the uranium core and 8 for the two end plugs. The results of the tests are given in Table 2 together with the conditions of extrusion. The median bond strength achieved between the aluminum and the uranium for all three specimens was excellent. In fact, it was of interest to find that 19 of the 128 studs used for the aluminum-uranium bond tests failed in tension themselves before the diffusion bond separated. This indicates bond strengths greater than the tensile strength of the studs (about 27,000 psi).

The median bond strength achieved between the aluminum and M276 end plugs was somewhat lower than that obtained with the uranium. Also, it appears that, on the basis of these three tests, the aluminum-M276 bond was somewhat adversely affected by extrusion speed in comparison with the aluminum-uranium bond. However, too few tests were made to warrant any definite conclusions. A photomicrograph of the interface between M276 and the extruded cladding layer is shown in Figure 10.

In another experiment, the bond strength was determined between the aluminum cladding layer and M276 and M355 end plugs that had been preheated in argon to 1050 F before cladding. For convenience, each plug was attached to the trailing end of a steel core. The results of the tests are tabulated below.

Plug	Bond-Strength	Extrusion Speed, ipm	Extrusion Pressure, psi	Temperature, F	
	Range, psi			Die	Liner
M276	22,000 to >27,000	36	46,500	1100	1075
M355	12,000 to >27,000	36	44,000	1100	1075

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FIGURE 9. ALUMINUM-NICKEL-URANIUM DIFFUSION LAYERS DEVELOPED DURING THE EXTRUSION-CLADDING OPERATION

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TABLE 2. RESULTS OF BOND TESTS ON ALUMINUM-CLAD URANIUM CORES
WITH M276 END PLUGS

Test	Median Bond Strength, psi		Extrusion Speed, ipm	Extrusion Pressure Range, psi	Temperature, F	
	Aluminum to Uranium	Aluminum to M276			Die	Liner
1	22,000	17,000	8	33,500 to 35,000	1100	1075
2	26,000	12,000	20	41,000 to 47,500	1100	1075
3	20,000	8,000	36	50,000 to 59,000	1100	1075

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FIGURE 10. INTERFACE BETWEEN AN M276 END PLUG AND AN EXTRUSION-CLAD LAYER OF ALUMINUM

The M276 is the bottom layer.

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In comparison with the results in Table 2, it appears that preheating the plugs may improve the bond strength. However, it should be noted that the M276 end plug was compressed from a thickness of 0.170 to about 0.115 in. and elongated about 75 per cent. It is possible that such deformation may have influenced the bond strength in some manner. The stronger M355 plug, on the other hand, did not exhibit any measurable deformation.

The cladding thickness was measured at several points along a specimen 28 in. in length. The specimen was selected randomly and may not be representative of the average. It was found that the thickness of the aluminum layer on each of the 2-3/4-in. -wide faces of the core did not vary appreciably (from 0.0006 to 0.0019 in.) along its length. The greatest variation in cladding thickness was attributed to the lack of concentricity between the core and cladding. The cladding thickness varied from 0.0265 in. on one side of the core to 0.0365 in. on the other. In this case, the maximum difference in thickness was 0.010 in. and the median difference was 0.006 in. No attempt had been made at the time to improve the concentricity. It seems quite possible that this can be improved by adjusting the alignment of the mandrel and die. Further improvement could be obtained by keeping the clearance between core and core slot to a minimum at the corners so as to reduce core rotation, as mentioned previously in the report.

RIGHT-ANGLE EXTRUSION CLADDING

Although the development of the coaxial process just described provided considerable background in extrusion cladding, it was felt that further progress could be made, and useful information obtained, if the extrusion equipment were redesigned to permit the cladding of longer lengths of uranium flat plates. Since this could not be done with the available equipment, a new right-angle design was devised which could be used to obtain additional information on the extrusion-cladding process. Equipment was designed to fit in the 700-ton vertical hydraulic press whereby the core moved horizontally at right angles to the motion of the ram. The advantages of this scheme were that the cladding could proceed on a continuous basis, rather than batchwise, merely by feeding cores in horizontally and stopping the press to insert new billets in vertically when necessary.

The basic principles of mandrel-tip design and flow of metal through portholes were retained. However, it was necessary to design the container to direct the flow of aluminum at right angles to the direction of ram travel.

General Details of Equipment

A schematic diagram of the assembly is shown in Figure 11. The main feature to note is the manner in which the mandrel and die are held in place by a large backup bolt threaded into the side of the container. The mandrel is tapered on its outside

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FIGURE 11. SCHEMATIC DIAGRAM OF RIGHT-ANGLE EXTRUSION-CLADDING ASSEMBLY

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surface so as to permit easy removal from the container after use. The die fits into a recess in the front of the mandrel, as shown in the photograph in Figure 12. The complete assembly is brought to the desired extrusion temperature by electric cartridge heating elements located in the container and bolt.

A cutaway view of the mandrel is illustrated in Figure 13. It can be seen that the mandrel contains two vertical chambers into which the billets are placed. Each chamber has two portholes which lead into the welding chamber. In a typical operation of this equipment, the billets are inserted in the chambers and the core to be clad is located so that the front end protrudes slightly through the die opening. Hydraulic pressure is then applied through two parallel rams to the billets, forcing them to flow through the portholes and into the welding chamber. As the welding chamber becomes filled, the aluminum contacts the core and carries it through the die opening. Figure 14 shows the extrusion assembly in place in the hydraulic press and a core partially inserted into the container. The photograph also shows the two parallel rams partially inserted in the billet chambers and the large backup bolt threaded into the front side of the container. Figure 15 shows a clad core as it appears coming out at the exit side of the container.

Experimental Work

General

Initial efforts were directed toward extruding a 0.030-in.-thick wall of aluminum on steel plates to test the new right-angle equipment. The calculated extrusion ratio of the billets and cladding cross-sectional areas was about 20 to 1. No difficulties were encountered in cladding 10-ft-long steel cores in these tests, which indicated that the design of the new tooling was basically correct. A photograph of two 10-ft-long clad steel samples is shown in Figure 16. Later, several nickel-plated uranium cores were also clad with a 0.030-in.-thick layer of aluminum. The following is a tabulation of the typical extrusion conditions used for these tests:

Container temperature	1050 F
Die temperature	1000 F
Extrusion speed	4 ipm
Extrusion pressure	30,000 to 35,000 psi
Mandrel-to-die distance	0.090 in.

The uranium plates used were 40 in. long and were connected together with a number of steel or M355 end plugs to make up various lengths, some up to 11 ft long. T-joints of the type illustrated in Figure 8 were used.

In cladding these uranium core assemblies, it was noticed on occasion that some of the M355 end plugs cracked or completely ruptured. In several instances, the uranium sections were ruptured also. These ruptures were usually preceded by a slowing down of the core movement (although the ram speed remained constant) and a gradual buildup of the cladding into a bulged, oversized layer. It was observed, too,

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FIGURE 12. MANDREL AND DIE USED IN THE RIGHT-ANGLE EXTRUSION-CLADDING ASSEMBLY

The die fits into the recess located in the mandrel.

FIGURE 13. CUTAWAY VIEW OF MANDREL SHOWING THE BILLET CHAMBERS, PORTHOLES, AND CORE SLOT

The aluminum partially extruded through the portholes is also shown.

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FIGURE 14. RIGHT-ANGLE EXTRUSION ASSEMBLY IN POSITION IN THE VERTICAL PRESS
A flat plate is inserted into the container.

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FIGURE 15. FLAT PLATE BEING CLAD WITH ALUMINUM

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FIGURE 16. TWO 10-FT-LONG FLAT PLATES CLAD WITH A 0.030-IN. THICK ALUMINUM LAYER CONTAINING FOUR INTEGRAL RIBS

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that the core tended to cock edgewise in a downward direction and the cladding appeared to be more bulged at the top than at the bottom of the core. It is believed these incidents are associated with unbalanced metal flow from the top and bottom portholes of the mandrel. This will be discussed in the next section in the report.

Efforts were also directed toward applying a 0.020-in. -thick cladding on flat plates of steel and uranium. In this case, the extrusion ratio was about 23 to 1. Several 10-ft lengths of steel plate were clad satisfactorily. However, only 1 to 2-ft lengths of uranium could be clad without rupturing. It was observed that the cladding was even more bulged and uneven than those produced when attempting to extrude a 0.030-in. -thick layer.

A noticeable improvement in the uniformity of the 0.020-in. cladding on steel cores was obtained when the downward cocking of the core was minimized by applying a small hand load to the core to counterbalance the cocking force. However, this technique was not effective with uranium because it lacks the necessary rigidity at elevated temperatures. Apparently, the forces encountered in attempting to apply a 0.020-in. -thick layer on uranium are sufficient to cause it to yield and ultimately rupture. An appreciable amount of camber in the uranium cores usually preceded the failures. Attempts were made to alleviate these difficulties by changing the mandrel design slightly.

Effect of Mandrel Design

In the original mandrel design, as shown in Figures 12 and 13, it had been anticipated that some difficulty might be encountered as a result of a pressure gradient or drop that would exist in the aluminum from the top to the bottom portholes. This gradient is due mainly to frictional resistance between the aluminum and the walls of the billet chambers. This difference in pressure would cause the core to be thrust downward and cock in the mandrel. The cocking action, in turn, would tend to restrain the forward motion of the core and contribute to its failure if extrusion were continued.

Attempts were made to improve the balance of metal flow in the mandrel by enlarging the bottom portholes. This improved the uniformity of the cladding from the top to the bottom appreciably. It is believed that further improvement would be obtained by so adjusting the top and bottom porthole areas that equal volumes of metal per unit time are extruded from each. This may also help to reduce the downward thrust which caused the core to cock. To minimize core cocking further, it would be necessary to reduce the pressure drop between the top and bottom portholes. It seems that this could be done by designing a mandrel with the top and bottom portholes closer together. If carried to the extreme case, perhaps the pressure drop could even be eliminated by merging the top and bottom portholes into one located on each side of the core slot. Each porthole would be positioned so that the aluminum stream extruding from it would contact the core on the center line of its width, thus avoiding the unbalanced force system which cocks the core. Of course, it would be necessary to design the shape of the porthole in a way so that the compression of the core slot would not be excessive.

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Billet-to-Billet Seams

The configuration and character of the seams formed in the cladding at the end surfaces of successive billets are of particular interest from a corrosion and strength standpoint. Such seams may have inferior properties because of the possibility of contamination from the aluminum oxide and impurities on the original billet surfaces. Of course, these seams are to be differentiated from "porthole" seams, i.e., those formed by the parting of the aluminum billet around the webs between portholes. In the latter case, clean, new aluminum surfaces are formed and quickly welded together again, thus reducing the possibility of contamination.

The general configuration of the billet-to-billet seams was first determined by the use of plasticine* billets. It has been observed that aluminum, when above its recrystallization temperature, and plasticine appear to have very similar flow characteristics. Therefore, by using plasticine billets of two different colors, it was possible to trace the progress of the seams formed in the cladding.

With the right-angle extrusion assembly, approximately 25 ft of standard-sized steel cores were clad by using successive red- and white-colored plasticine billets. Three pairs of 2-in. diameter by 9-in.-long billets were used at a calculated extrusion ratio of 20 to 1. It was interesting to find that the plasticine cladding had a sufficient amount of rigidity to pull the cores through the die without the aid of any external force. The seams were examined by carefully slicing and removing sections of the cladding at various points along the length of the cores.

The results of the plasticine experiment are illustrated schematically in Figure 17. The progress of the seams formed in the cladding is shown in Cross Sections (a) through (e) at points located about 85, 100, 140, 170, and 200 in. away from the leading end, respectively. It can be seen that the seam between the first and second pair of billets initially appeared toward the top of the cladding. Evidently, this is because the seam was extruded through the top portholes of the mandrel first. Later, another portion of the seam, which was extruded through the bottom portholes, appeared in the bottom half of the cladding as shown in Cross Section (c). On further extrusion, the plasticine from the second pair of billets contributed a gradually increasing proportion to the total cross section of the cladding. However, even after the appearance of the third pair of billets [Cross Section (e)], small portions of plasticine from the first pair remained in the lower center and bottom regions of the cladding. Some traces still remained in these regions after about 300 in. of core had been clad; whereas the portion of cladding at the top edge, supplied from the first pair, was substituted completely with portions from the second pair of billets [Cross Section (e)]. This is probably due to the fact that flow through the top portholes is much easier than through the bottom portholes.

It was interesting to find that the original 2-in.-diameter billet end surfaces were stretched out over lengths even greater than 25 ft. It would seem that such stretching would tend to spread out the impurities over larger areas, thus reducing their concentration and perhaps their effects on the properties of the cladding.

*Plasticine is a mixture of an inert mineral oil and a mineral filler, mainly calcite; organic dyes are added to impart color.

FIGURE 17. BILLET-TO-BILLET SEAMS IN THE CLADDING APPLIED TO A FLAT PLATE

Cross Sections (a) through (e) indicate the progress of seams from the leading to the trailing end of the plate, as shown by the extrusion of successive red and white plasticine billets.

The plasticine experiment was duplicated with aluminum billets in an attempt to correlate these results. The aluminum-clad steel cores were sectioned at locations corresponding to those taken from the plasticine cladding. These sections were examined metallographically and the seams observed were compared with those seen in the plasticine. A very definite similarity in the seam configurations was noted. Examples of the seam observed in one rib of the bottom pair of the aluminum cladding are shown in two cross sections, taken 1 ft apart, in Figures 18 and 19. The seam in Figure 18 appears to be quite similar to that shown in the top ribs of Cross Sections (a) and (e) of the plasticine cladding illustrated in Figure 17. The seam illustrated in Figure 19 resembles that shown in the bottom ribs in Cross Section (c) of Figure 17. In Figures 20 and 21 are shown the seams observed in the bottom edge of the aluminum cladding in two additional cross sections taken about 1 ft apart. These latter seams correspond very well with those shown in Cross Sections (d) and (e) of Figure 17. Such agreement supports the assumption that the flow characteristics of the two materials are quite similar.

Some portions of the seam in the aluminum cladding were somewhat thicker and more easily observed than others. Evidently, the thicker portions contained greater concentrations of impurities. However, certain portions of the seams present in a cross section of the plasticine cladding were often not observed in the aluminum. If the results of the plasticine experiment are assumed to be correlative, the absence of visible seams in the aluminum would indicate that the concentration of the normally visible impurities contained in these regions was relatively low. No doubt the stretching of the original surfaces affected the distribution of the impurities in the seams.

An attempt was made to determine roughly whether the presence of billet-to-billet seams in the cladding markedly affected its tensile properties. The aluminum cladding was removed as six 1-in. -wide strips cut transverse to the length of a steel core. Bonding between the rib portion of the cladding and the core caused some difficulty in their removal and may have damaged the strips somewhat. Variations in the cladding thickness also made it difficult to determine the minimum cross-sectional area. These factors should be considered in evaluating the results of the tensile tests.

The tensile strength of the claddings ranged from 7,400 to 10,400 psi, with an average of 8,500 psi. The average value taken from the literature of the tensile strength of annealed aluminum is 13,000 psi. It is not possible to attribute the lower strength of the cladding to any one or more specific factors. However, it is of interest to note that the cladding still exhibited substantial strength although billet-to-billet seams were present.

Properties of Clad Cores

A very limited number of bond-strength determinations were made on specimens clad by the right-angle method. Bond strengths ranging from 4,000 to over 27,000 psi were obtained in spot tests made on a nickel-plated uranium bar clad with a 0.030-in. layer of aluminum. It was observed that the weaker bonds were usually located in center portions of the cladding between the ribs. This may be associated with the possibility that the pressure exerted by the aluminum on the core is greater toward the

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15X

1/2 % HF

N51315

FIGURE 18. SEAM OBSERVED IN THE BOTTOM RIB IN A CROSS SECTION OF THE ALUMINUM CLADDING

15X

1/2 % HF

N51316

FIGURE 19. PROGRESS OF THE SEAM IN THE RIB SHOWN IN FIGURE 18, AS OBSERVED IN A PARALLEL CROSS SECTION 1 FT AWAY

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15X

1/2 % HF

N51317

FIGURE 20. SEAMS OBSERVED IN THE BOTTOM EDGE IN A CROSS SECTION OF THE ALUMINUM CLADDING

15X

1/2 % HF

N51318

FIGURE 21. PROGRESS OF THE SEAM IN THE BOTTOM EDGE SHOWN IN FIGURE 20, AS OBSERVED IN A PARALLEL CROSS SECTION 1 FT AWAY

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edges near the porthole opening than toward the center where the web is located. The higher pressure also may be associated with the larger bearing area toward the outer edges of the die opening.

It was interesting to find that bond strengths varying from 1,000 to 16,000 psi between a 0.030-in. cladding and an unplated steel core were obtained.

A few bond tests were made on uranium and steel cores clad with a 0.020-in. wall of aluminum. The bond strengths seemed to be slightly weaker than those obtained with the 0.030-in. claddings. However, this observation may not be significant since so few bond tests were made.

Concentricity measurements were also made on several specimens clad with 0.030- and 0.020-in. -thick layers of aluminum. The 0.030-in. -thick claddings on the 3-in. -wide faces of the core varied from 0.029 in. on one side to 0.034 in. on the other. The maximum difference, in this case, was 0.005 in. and the median difference was 0.0015 in. However, the cladding thickness on the top edge of the core was, on the average, about 0.022 in. thicker than on the bottom edge. The intended cladding thickness on the core edges was 0.140 in. The large difference in thickness is attributed to the fact that the core is thrust downward as a result of the pressure gradient in the aluminum. This forces the core to ride on the bottom surface of the core slot and, therefore, it is eccentric with the die opening. It seems that this could be corrected by either eliminating the pressure gradient in the aluminum or offsetting the core slot so that the core could rest on the bottom of the slot and still be concentric with the die opening.

The 0.020-in. -thick cladding varied from 0.018 in. on one side of the core to 0.022 in. on the other. The maximum and median difference was 0.004 and 0.002 in., respectively. However, the difference in cladding thickness on the core edges averaged about 0.074 in., much more than the difference obtained in the 0.030-in. claddings. Apparently, there was considerably more core restraint and bulging of the cladding in the 0.020-in. -cladding extrusions.

CONCLUSIONS

The feasibility of cladding uranium fuel elements with aluminum by the coaxial and right-angle extrusion techniques has been demonstrated.

With the coaxial method, a 0.030-in. -thick cladding with six integral ribs was extruded over uranium plates about 2-3/4 in. wide by 0.180 in. thick. Extrusion speeds up to about 60 ipm were achieved. Mandrel and die design, mandrel-to-die distance, and core temperature were found to have a significant influence on the extrusion pressure.

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A promising method of end cladding was achieved by attaching end plugs to the ends of the fuel element and cladding over the whole assembly. Sintered materials of aluminum and aluminum oxide powder were found to have sufficient strength for this application.

Limited efforts on the integral end-cladding method indicated that the shape of end surfaces of the fuel element and the die design have a significant influence on the production of sound integral end plugs.

Bond strengths with median values in the range from 20,000 to 26,000 psi were achieved between the aluminum and uranium. Median values from 8,000 to 17,000 psi and some higher were obtained between aluminum and sintered-aluminum-powder end plugs.

With the right-angle technique, a 0.030-in. -thick cladding with four integral ribs was applied satisfactorily over uranium plates about 3 in. wide by 0.180 in. thick. In addition, 0.020-in. -thick claddings were extruded on uranium plates with only limited success. However, it is believed that the possibility of achieving greater success with such thin layers is good.

Fairly good dimensional control and concentricity of the cladding were obtained with both extrusion-cladding methods. Still further improvement in concentricity seems quite possible.

The configuration of the billet-to-billet seams formed in the aluminum cladding extruded by the right-angle equipment was determined and correlated with similar tests using plasticine billets.

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