PRODUCTION OF ELECTROSLAG REMELTED HOLLOW INGOTS

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ABSTRACT

The development of a production process for the electroslag remelting of hollow shapes has been described. ESR hollows 21" O.D. x 10" I.D. and 16" O.D. x 10" I.D. have been produced. The hot workability of both sizes was found to be excellent, based on Gleeble hot ductility studies as well as actual forging and rolling experiments. For the 21" x 10" ESR hollow, hot working studies indicate that 35% work is sufficient to develop a fully wrought structure. Initial mechanical property data are all above specification limits for the forged hollows.

Introduction

The successful evolution of higher performance aircraft turbine engines has required the utilization of sophisticated alloys particularly for rotating components. The increased material costs associated with these compositions have been further increased by the poor yields experienced in their processing as well as the sensitivity of their properties to process variables. In addition, the use of more complex part configurations have decreased material utilization from ingot to finished part. The initial objective of the ESR hollows program was to reduce the cost of superalloy turbine engine components by establishing a new method for the production of ring shaped parts. It is anticipated that significant cost savings in both material utilization and processing costs would be realized with the use of ESR hollows. Of course the development of a cost effective manufacturing process for the production of ESR hollows will lead to their use as starting stock for a number of different applications such as large rotor shafts, weapons manufacture and oil field equipment. These additional applications will probably ultimately represent the largest market for ESR hollow preforms.

A number of investigations have been reported dealing with methods to produce electroslag remelted hollows. A brief review of the more pertinent methods which have been investigated for the production of ESR hollows will be given. The first work on ESR hollows was reported by Paton and Medovar.(1) One of the techniques used either a hollow electrode or multiple electrodes and the ingot was formed as a mandrel withdrew in a direction opposite to it. This they say minimizes tensile forces on the solidifying ingot skin and result in the elimination of I.D. cracking. By employing this technique tapered hollows for use in the production of tapered shapes can be produced. It is reported however that this technique is normally used for the production of large diameter short ($\sim$3') hollows usually with diameters greater than 10" O.D. A second technique for the production of hollows(2) involved using a solid electrode and a movable center mandrel as shown in Fig. 1. This method is also reported to be practiced in the USSR for the production of smaller diameter (<10" O.D.) ESR hollows. The main advantage of this technique is the ability to use a solid electrode which significantly decreases the electrode cost as compared to multiple or hollow electrodes.

In Japan, Ujiie(3) has developed a method, as shown in Fig. 2, for producing relatively small diameter thin walled hollows primarily for use as reformer tubes and other similar thin walled tubular products. This method employs a plurality of small wire or rectangular shaped electrodes in a continuous withdrawal system. However, there is a significant economic disadvantage in that the cost of the production of small multiple electrodes from hard-to-work superalloys would be significantly higher than a large single solid electrode. Other techniques for the production of ESR hollows have been discussed in the literature but will not be covered here. Early developmental work carried out at Stellite by Klein(4) investigated the possibility of making hollows using either a hollow electrode and stationary water cooled center mandrel technique, or the solid electrode and movable center mandrel technique, better known as the hot-piercing technique. The hollow electrode approach as shown in Fig. 3, while a viable process from a technical standpoint, is not cost effective because of the increaed

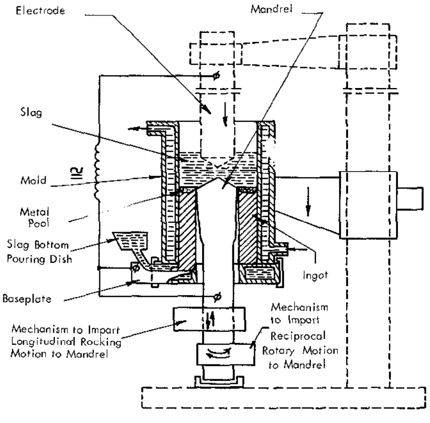


Fig. 1. USSR hot piercing hollow process.

cost of electrode production. In addition, the cost of the disposable water cooled center mandrel as well as its subsequent removal leads to an even greater expense.

In order for the ESR hollows to be acceptable as starting stock, they must exhibit acceptable mechanical properties after being processed to the desired shape. Again a number of property studies comparing ESR hollows, both as cast and wrought, with comparable solid ingots have been published. Paton et.al.(5) have reported that for thin wall tubes with a 3.1" wall thickness or less, that the as cast hollow properties correspond to the highest billet properties obtained from solid ingots. In addition, they also reported no change in mechanical property levels as a result of hot working hollows with up to a 4:1 reduction ratio. They concluded that hot working ESR hollows of this size is not necessary to obtain acceptable properties. Bhat(6) has reported that the tensile properties of the as remelted and heat treated D-6 ESR hollows were essentially equivalent to those obtained after an 80% reduction by ring rolling. The as cast hollows, however, did not possess sufficient elongation or reduction of area to meet the specification. However, for the material ring rolled to 80% reduction all the properties exceeded AMS 6431 specification. Klein(7) on a subscale basis has produced ESR hollows of HASTELLOY alloy X and HAYNES alloy No. 718 which were approximately 8" O.D. x 4 1/2" I.D. The macrostructure of these ingots as expected was exceptionally fine and consisted of vertically oriented columnar grains. A much finer dendrite arm spacing for the hollow as compared to that of a corresponding solid was reported. For HASTELLOY alloy X the segregation ratio using molybdenum was about one-half the magnitude measured in a corresponding solid ingot of the same diameter.

The subscale hollow ingots in the latter study were cut into mults and either ring rolled, cross-rolled or upset forged into disks or rings. The hot workability of the material was excellent and the as worked pieces exhibited good surfaces. For HASTELLOY alloy X it was found that a reduction of greater than 35% was needed to break up the as cast structure and yield a fully wrought product. For HAYNES alloy No. 718, ESR hollow sections which had been reduced 43% exhibited a uniform structure and acceptable mechanical properties. Material reduced only 33% did not pass the minimum mechanical properties and a significant amount of as cast dendritic structure remained.

Based on the encouraging results obtained in our previous studies conducted at Stellite, as well as the other studies briefly reviewed here, an ESR hollows program was initiated and funded by the Air Force Materials Laboratory, Manufacturing Technology Division, in June 1973.

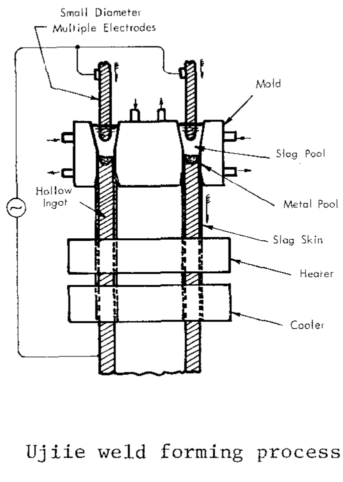


Fig. 2. Ujiie weld forming process.

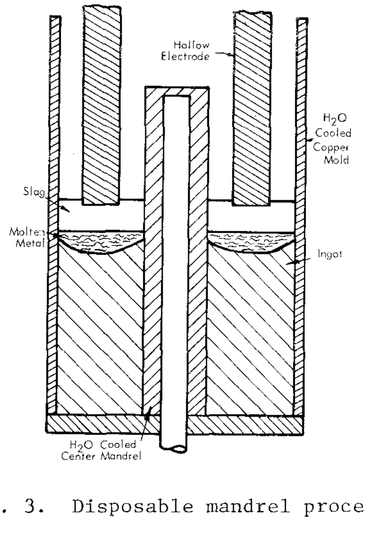


Fig. 3. Disposable mandrel process.

Experimental Work and Equipment Design

The basic program consisted of an initial subscale effort which looked at basically two processes; a tulip mold technique and the hot piercing technique. This first phase of the work was conducted using a furnace capable of producing 8" diameter hollows up to 20" in length. The investigation of the tulip mold process as shown in Fig. 4 was initiated primarily as a backup for the hot piercing process, however, it does have some unique features in that a mandrel which is suspended from the top is employed and electrodes which are significantly larger than in a standard straight sided mold are remelted to produce the ESR hollow. The use of the larger electrodes reduced somewhat the inherent increase in electrode cost using this technique. In addition, by using a top suspended mandrel the process is capable of producing hollows of any desired length and in fact it could be considered to be a continuous process if an ingot cutoff scheme and electrode change system were incorporated.

The hot piercing process as shown schematically in Fig. 5 was also investigated in the subscale portion of the work. During this phase of the program it was determined that indeed the hot piercing process was a viable technique and it was chosen as the process to be scaled up in a production size system. A number of interesting conclusions were reached, during the subscale portion of the program. During the early portion of the work it had been reported that fill ratios greater than one were not feasible from a heat transfer consideration in the ESR process; however, using both the tulip mold and hot piercing mold processes, fill ratios significantly over one were successfully employed. A second finding which had a significant bearing on the design of the equipment for the production unit was that precise level detection was needed in order to control surface quality as well as to eliminate the possibility of mandrel seizure by completely covering the hot piercing mandrel with molten metal. Although it was judged that either process if scaled up could have produced ESR hollows successfully, the hot piercing process was chosen due to its expected cost advantage over the tulip mold technique.

The scaled up ESR hot piercing technique was designed to be installed as part of the Center Station in an existing Consarc electroslag remelting unit.

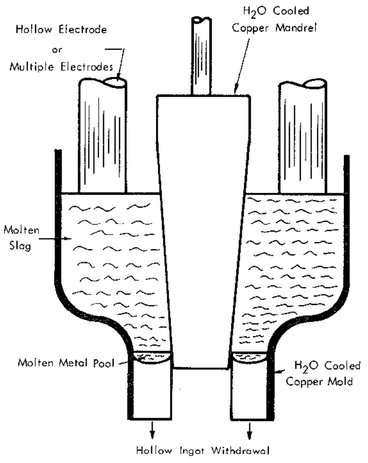


Fig. 4. Tulip mold technique for producing ESR hollows.

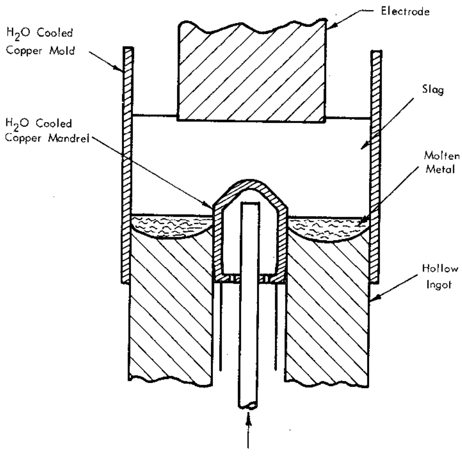


Fig. 5. Stellite ESR hollow process.

As designed, the system is capable of producing ESR hollow ingots up to 21 1/2" in diameter and 72" in length. The Center Station has the capability of employing both moving and static crucibles for hollows melting. The furnace is equipped with a continuous electrode weighing system and also a system for molten slag starting. For the program, basically two size hollows were to be investigated, a 21" O.D. x 10" I.D., and a 16" O.D. x 10" I.D. HAYNES alloy No. 718 was chosen as the scale up material.

A unique feature of Stellite's hollow unit is the level detection mechanisms. The primary level detection method is a nuclear system consisting of a Cesium 137 radioactive source and a Geiger tube as the detector. Basically, the system senses the level of the molten metal by detecting the intensity of the radiation as measured by the Geiger tube. The system is calibrated using conditions similar to standard operating conditions in order to be able to measure the molten metal level to within ±1/8". By means of appropriate control circuits the mandrel is driven upward at the desired speed to maintain the correct relative molten metal position on the mandrel. In addition to this, the system is equipped with pressure transducers which measure the actual pressure being applied to the mandrel, and thus by monitoring the change in pressure required, it can be determined whether the system is operating correctly. A sudden pressure decrease for instance indicates that a runout in the system is occurring. Conversely, if the pressure rises significantly, the ingot is shrinking and binding the mandrel, thus requiring more pressure in order to push the mandrel upward. If this excessive pressure becomes too severe one can override the system and push the mandrel faster than would normally be done based on the metal level reading as determined from the radiation source. In a number of cases this has been necessary due to slight changes in the actual intensity of the radiation observed as compared to the calibrated figure. That is, the measured intensity indicates that the metal level is at a position different from its actual position. It is felt that at this time both systems are necessary to operate the ESR hollow unit sucussfully.

Results and Discussion

A number of 16" and 21" diameter ESR hollow ingots of HAYNES alloy No. 718 have been produced utilizing the technology developed in this program. Two ESR hollows, a 21" O.D. x 10" I.D. x 45" long and a 16" O.D. x 10" I.D. x 67" long hollow that were remelted early in the program, are shown in Fig. 6. Both of these two early hollows have poor O.D. surfaces. It should be remembered however that during these initial runs no attempt was made to control the remelting parameters in order to optimize the surface quality since the prime objective was just to produce an ESR hollow. For comparison purposes, Fig. 7 shows a more recently remelted ESR hollow which exhibits a significantly better O.D. surface and is of the same quality as normally obtained for solid ESR ingots. Fig. 8 shows the typical I.D. surface of an ESR hollow. Work is continuing on improving the I.D. surface quality. An I.D. surface of the same quality as normal moving mold surfaces is anticipated when the program is completed.

After remelting, the hollows were sectioned for further evaluation. The transverse and longitudinal macrostructures of the 21" diameter hollow are exhibited in Figs. 9 and 10. The structure is relatively fine grained as expected due to the small cross section.

It is a much different structure than that obtained by centrifugal casting. Essentially no porosity exists and therefore no conditioning is necessary to remove unsound material prior to processing. Also the grain orientation in a centrifugal casting is radial while for an ESR hollow it is primarily vertically oriented. In addition the ESR process as has been documented yields an ingot which is of much better metallurgical quality than a centrifugal casting.

(21" φ x 45" x 3500 lbs.)(16" φ x 67" x 2170 lbs.)(16" φ x 56" x 1900 lbs.)

Fig. 6. Full scale ESR hollows produced early in the program.

Fig. 7. Recent 16" O.D. x 10" I.D. ESR hollow.

Fig. 8. I.D. surface of an ESR hollow.

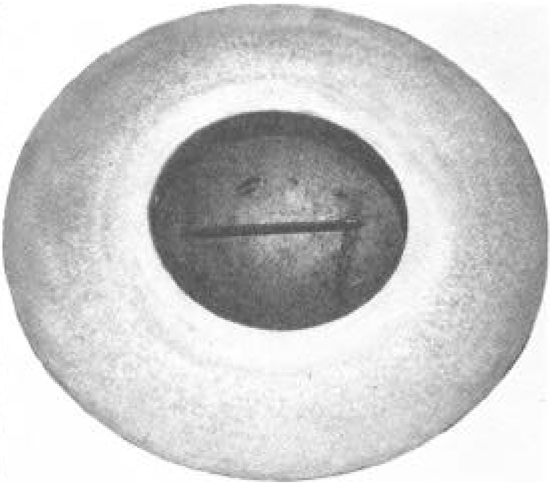


Fig. 9. Transverse macrostructure of 21" diameter ESR hollow ingot.

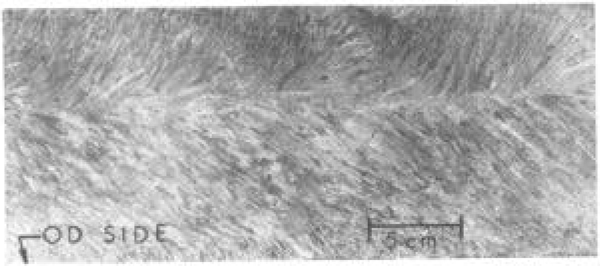


Fig. 10. Longitudinal macrostructure of 21" diameter ESR hollow ingot.

The electroslag remelting process normally produces an ingot with excellent hot workability[(8)] and it was expected that the ESR hollows would exhibit these same characteristics. In order to determine the hot workability of these hollows, Gleeble studies were conducted. The measured reduction in area obtained from the Gleeble specimens has been found to be a good measure of the hot workability of the material. The results of the Gleeble studies for HAYNES alloy No. 718 are given in Fig. 11 for both the 16" and 21" diameter hollow ingots. As can be seen, the material exhibits excellent hot workability as measured by these studies.

To simulate typical operations needed to produce ring shaped parts, test sections were cut from the 21" O.D. hollow and upset forged and rolled. The workability of these test sections during the total reduction of 75% was very good. After performing the appropriate heat treatments per AMS 5662C, mechanical property evaluations were conducted. The room temperature and 1200°F elevated temperature tensile test results are given in Table 1. All of the tests passed the specification minimum but the test section which was upset forged only, exhibited somewhat lower properties than those obtained for the upset and rolled material. Table 2 shows the results of the stress rupture tests. Again the results were above the specification and here, also, the

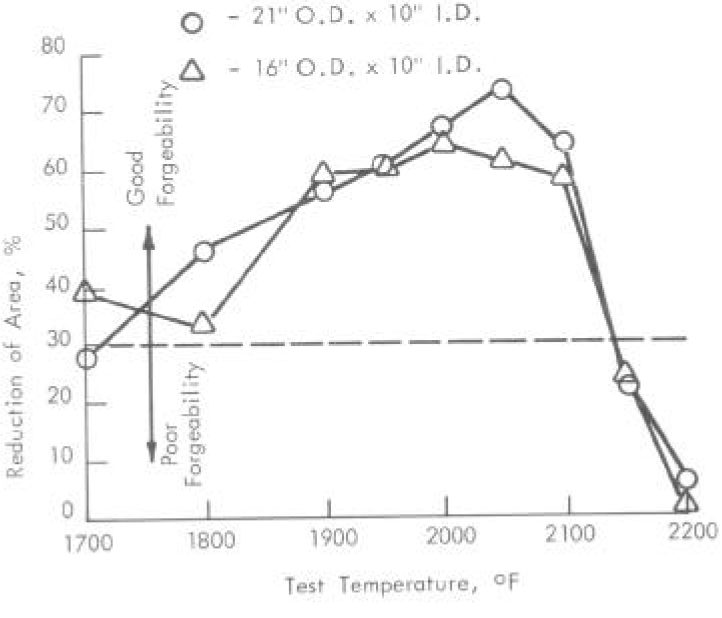


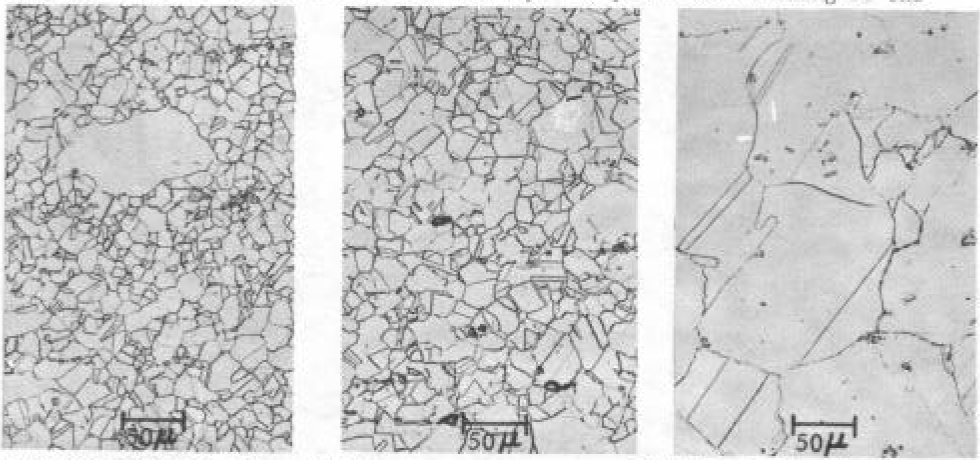
Fig. 11. Gleeble hot workability of HAYNES alloy No. 718 ESR hollows.

upset forged material had a somewhat lower stress rupture life and elongation than the material which was upset and cross rolled. The chemical analysis of the ESR hollow ingots from which the sections were taken is given in Table 3. All of the elements are well within AMS 5662C. Microstructural analysis of these samples revealed that all samples exhibited a fully wrought microstructure as shown in Fig. 12.

A sample from the ring section which was upset forged 50% and then cross rolled 50% exhibited a duplex microstructure. The large grained region had not yet undergone recrystallization while the rest of the material had just been recrystallized and exhibited a fine grain size. This structure is indicative of the finishing temperature being slightly too high. Most likely, a 25°F increase in the annealing temperature or a longer time at 1750°F would have resulted in a completely recrystallized microstructure. The section which was upset 35% and cross rolled 63% exhibited a uniform grain size, ASTM 7. This is consistent with the above result in that both samples were rolled from a 2050°F furnace and thus the latter section would finish colder since it was on the mill longer. The microstructure of the upset forging exhibited a dynamically recrystallized structure. This was a result of an intermediate reheat and thus a significantly higher final temperature. It had an exceptionially large ASTM grain size of 3 1/2. The difference in the observed property levels while all are acceptable are well explained by the microstructural observations.

Based on these initial studies ~4" thick mults of both the 16" O.D. x 10" I.D. and the 21" O.D. x 10" I.D. hollows were sectioned for full scale studies. In addition to assessing the hot workability of the full scale ESR hollows it was desired to obtain a preliminary indication of the amount of work which would have to be put into the material before obtaining a fully wrought structure. If as expected, due to the finer dendritic structure, and thus less micro segregation, the ESR hollow ingots can be employed with less total work than normally required to achieve wrought properties, a significant savings in processing would be possible. To determine the minimum amount of reduction necessary to achieve wrought properties the mults were worked to a total reduction of about 35 and 63%. The hot working was accomplished by either upsetting, upsetting and cross rolling, or cross rolling.

The good workability of the ESR hollows resulted, as shown in Fig. 13, in finished disks of excellent surface quality. No prior conditioning of the



ASTM Grain Size 8 1/2 - 4 1/2
Upset forged 50% and cross rolled 50%

ASTM Grain Size 7
Upset forged 35% and cross rolled 64%

ASTM Grain Size 3 1/2
Upset forged 75%

Fig. 12. Microstructure of HAYNES alloy No. 718 ESR hollow test forgings.

hollows either I.D. or O.D. was done before hot working. All material was processed from a 2050°F starting temperature per the standard industry practice. After rolling or upsetting samples were taken for microstructural and mechanical property determinations.

The microstructural examinations indicated that the material had a completely wrought microstructure even after only 35% reduction. However, the grain size of the material which was upset forged only was excessively large as shown in Fig. 14. This is especially true for the material reduced 35%. In the forging operation a material handling problem developed and the piece was reheated and only reduced about 10% the last time out thus causing the large grain size as described previously. The material which was cross rolled had a significantly finer and a very uniform grain size as shown in Fig. 15. Again the prime purpose of this preliminary hot working study was to assess the hot workability of the material and to determine how much reduction is necessary to obtain a wrought microstructure. Using the appropriate thermomechanical processing, it would be expected that the necessary grain size could be developed with only a 35% reduction. Studies are now in progress aimed at verifying this statement as well as determining the associated mechanical properties.

Table 1

Tensile Properties of 4 3/4" Test Forgings

Hot Working Operation	*Temp.°F*	*0.2%YS(ksi)*	*UTS(ksi)*	*% RA*
50% Upset Forged	RT	176 (OD)	201 (OD)	36.7 (OD)
+ 50% Cross Rolled	RT	169 (ID)	198 (ID)	37.9 (ID)
35% Upset Forged	RT	163 (OD)	195 (OD)	38.6 (OD)
+ 63% Cross Rolled	RT	154 (ID)	191 (ID)	38.8 (ID)
75% Upset Forged	RT	164 (OD)	183 (OD)	37.9 (OD)
		161 (ID)	183 (ID)	42.8 (ID)
AMS 5662C		150 (min)	180 (min)	8.0 (min)
50% Upset Forged	1200	145 (OD)	164 (OD)	42.2 (OD)
+ 50% Cross Rolled	1200	142 (ID)	161 (ID)	42.2 (ID)
35% Upset Forged	1200	135 (OD)	159 (OD)	41.7 (OD)
+ 63% Cross Rolled	1200	133 (ID)	158 (ID)	40.0 (ID)
75% Upset Forged	1200	135 (OD)	147 (OD)	40.3 (OD)
		132 (ID)	143 (ID)	42.2 (ID)
AMS 5662C		125 (min)	140 (min)	8.0 (min)

Table 2

Stress Rupture Properties of 4 3/4" Test Forgings
at 1200°F and 100 ksi

Hot Working Operation	Life (hrs)	Elongation (%)
50% Upset Forged	296.9 (OD)	12.7 (OD)
+ 50% Cross Rolled	263.9 (ID)	9.1 (ID)
35% Upset Forged	217.9 (OD)	11.6 (OD)
+ 63% Cross Rolled	243.0 (ID)	12.3 (ID)
75% Upset Forged	262.8 (OD)	7.6 (OD)
	139.5 (ID)	5.2 (ID)
AMS 5662C	23.0 (min)	4.0 (min)

Table 3
Chemical Analysis

	Electrode	ESR Ingot			AMS 5662C	
		Butt End	Center	Hot Top	Min.	Max.
Al	.55	50	.49	.47	.20	.80
B	.003	.003	.003	.003	-	.006
C	.06	.06	.06	.06	-	.08
Cb	5.06	5.02	5.06	5.04	-	-
Co	.28	.28	.28	.28	-	1.00
Cr	18.13	18.16	18.14	18.18	17.00	21.00
Cu	.04	.04	.04	.04	-	.30
Fe	19.00	19.15	19.00	18.96	remainder	
Mn	.20	.21	.20	.19	-	.35
Mo	3.03	3.03	3.03	3.02	2.80	3.30
Ni	52.79	52.51	52.77	52.75	50.00	55.00
P	<.005	<.005	<.005	<.005	-	.015
S	<.005	<.005	<.005	<.005	-	.015
Si	.18	.20	.17	.16	-	.35
Ta	.12	.10	.10	.10	-	-
Ti	1.00	.99	1.00	1.00	.65	1.15
Cn + Ta	5.18	5.12	5.16	5.14	4.75	5.50

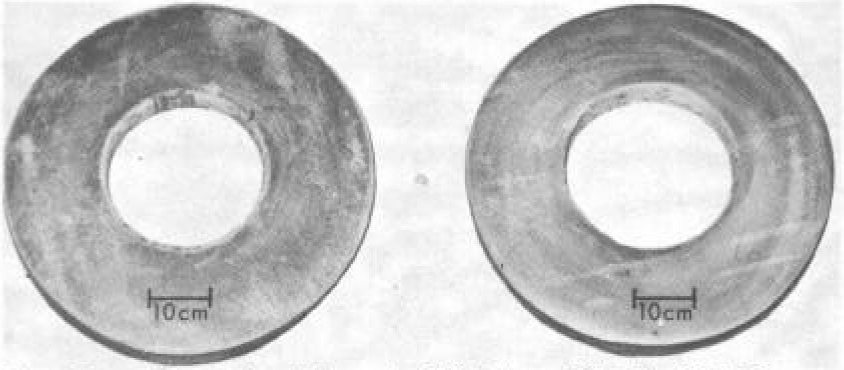


Fig. 13. Disks produced from the 21" O.D. x 10" I.D. ESR hollows.

ASTM Grain Size 1 1/2
Fig. 14. Upset forged photomicrograph.

ASTM Grain Size 5
Fig. 15. Cross rolled ESR hollow section.

Conclusions

A technique for the production of electroslag remelted hollows has been developed. The most critical portion of the process is the metal level detection system in that the metal level must be precisely known to prevent I.D. runouts as well as to obtain a good I.D. surface.

The hot workability of the production size 16" O.D. and 21" O.D. ESR hollows has been shown to be excellent as measured by the Gleeble studies and the actual disk forgings. No material was removed from the I.D. or O.D. prior to hot working. A significantly finer structure than for a solid ingot, as expected, was seen which should lead not only to better workability but to the possibility of obtaining a fully wrought microstructure with less total work in the ingot. Fully wrought microstructures were obtained with only 35% hot working although some of the samples exhibited an unusually large grain size which must be controlled by better thermomechanical processing.

The use of ESR hollows is expected to result in significant savings in both material and processing. Lower scrap losses should be seen as a result of the hollow billet and also because of the excellent workability of ESR material. Applications which require a high quality material such as large rotor shafts, gun tubes, critical down hole oil field applications, as well as aerospace components, all appear to be good candidates for ESR hollow materials.

Acknowledgments

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