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# DIRECT CAST TITANIUM ALUMINIDE STRIP

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NOTICE



This technical report has been reviewed and is approved for publication.

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The purpose of the Phase I research project is to demonstrate the feasibility of melting titanium alloys using Duriron's induction slag melting process and casting them into rapidly solidified strip by RIBTEC's melt overflow process. The strip might be used for SiC-Ti metal matrix composites for advanced airframe structures.


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## INTRODUCTION

A number of rapid solidification processes have been developed over the last three decades attempting to produce rapidly solidified titanium alloys. In 1983, RIBTEC developed a rapid solidification process called melt overflow (Figure 1). Molten metal overflows a reservoir onto the surface of a rotating chill block. The melt stream is not extruded through an orifice to contact the chill block like melt spinning techniques, rather, the melt pool overflows a reservoir to contact the moving chill surface.

The melt overflow process was originally developed to cast fine filaments and fibers by solidifying on the tips of grooves machined on the chill block surface. During the initial experiments with Melt Overflow, it was discovered that if the depth of molten metal against the chill block is significantly greater than root depth of the grooves, the melt will bridge between the grooves to cast strip rather than individual filaments. Strip may also be cast on a smooth or polished wheel surface.

The melt overflow process is ideally suited to direct casting of reactive metals and alloys using skull melting techniques. This was originally demonstrated during experiments performed at Battelle sponsored by RIBTEC. The Battelle experiments demonstrated that it is feasible to direct cast 1 inch wide Ti-6Al-4V alloy strip by melt overflow using induction melting. This project extends that work in attempting to cast wider titanium alloy strip using the induction slag melting process (formerly called Inductoslag Melting) operated by The Duriron Company, of Dayton, Ohio.

In 1980, The Duriron Company decided to investigate production of small and medium sized titanium and zirconium castings in-house using the induction-slag process developed by the U.S. Bureau of Mines (1). A schematic of the induction slag melting unit, installed at Duriron in late 1982, is shown in Figure 2. Currently, this is the world's only commercial induction melting furnace designed to both melt and pour reactive alloys.

A melt overflow chill block casting system was designed to fit into the lower chamber of the Duriron furnace. Titanium alloys are melted in the upper chamber then poured through a steel tube into a graphite funnel and tundish that delivers the liquid metal to the melt overflow casting unit.

The purpose of the Phase I research project is to demonstrate the feasibility of melting titanium alloys using Duriron's induction slag melting process and casting them into rapidly solidified strip by RIBTEC's melt overflow process. The strip might be used for SiC-Ti metal matrix composites for advanced airframe structures.

## PHASE I TECHNICAL OBJECTIVES

The objective of the Phase I research program was to demonstrate the feasibility of melting titanium alloys by the induction slag process and then casting rapidly solidified sheet and strip using Ribbon Technology Corporation's melt overflow process. RIBTEC originally proposed to cast rapidly solidified titanium alloy strip up to 15 cm (6 inches) wide using melt overflow but made attempts to cast 30 cm (12 in) wide strip.

Ti-6Al-4V alloy was originally proposed to be cast into strip because it is readily available and there is a substantial body of information on the microstructure and mechanical properties of rapidly solidified Ti-6Al-4V alloy. After the contract was awarded, the Air Force requested that the alpha-2 titanium aluminide be substituted for the Ti-6Al-4V alloy.

## PROCESS DESIGN

The induction slag melting furnace shown in Figure 2 was designed for casting investment molded titanium pump parts. The molds are normally loaded onto a platen in the lower chamber. The lower chamber is then sealed and evacuated. A flapper valve is opened between the two chambers an the mold is raised into the melting chamber where the parts are cast. After casting, the mold can be lowered into the lower chamber and the flapper valve closed to seal the melting chamber. The lower chamber can then be opened and the cast parts removed.

The first task was to design and build an experimental melt overflow casting unit to operate in the induction slag furnace without modifying the Duriron vessel. Therefore, the geometry of the furnace dictated the process design. All utilities were to be supplied through an ASA-8 flanged penetration in the top chamber of the furnace, otherwise, no modifications were allowed to the system.

Normally the melt overflow systems operated at Ribbon Technology use water cooled chill blocks to cast rapidly solidified sheet and strip. A solid chill block system was designed for the Phase I experiments because of the limited modifications allowed to the Duriron system. The chill block assembly included a two horsepower motor to drive the chill block. The framework was designed to support the chill block motor and tundish. A tachometer was mounted to one end of the chill block. An ASA-8 blank plate was modified to provide the electrical and instrumentation feedthroughs to supply the motor and tachometer.

All chill blocks for the melt overflow caster measure 10 inches diameter by 16 inches. Both copper and yellow brass were used to make chill blocks. These two materials were selected based on availability and our prior experience in casting titanium alloys.

Three different surfaces were machined on the chill block periphery. The one surface was polished smooth with jewelers rouge. Another surface was a 50 threads per inch (TPI) double lead helical groove that produces 100 threads per inch overall. The third surface was a 14 pitch (medium) 60 degree diamond knurl.

After the caster was mounted in the lower chamber of the Duriron vessel and raised on the plat to its highest point, it was still approximately 0.9 m (3 ft) away from the pour lip of the induction slag furnace. A steel tube, 25 cm (10 in) diameter, was used to pour the liquid titanium from the upper chamber to the lower chamber. Underneath the pour tube was a conical graphite tundish that delivered the liquid titanium to a graphite tundish that spread it onto the chill block.

A simple mass balance was performed on the melt overflow system to aid in the design of the tundish and funnel. First, consider the mass flow through the funnel:

$$\frac{dw}{dt} = A_N \cdot \rho_\ell \cdot C_D \cdot \sqrt{2gh} \quad (1)$$

where:

- $w$ = weight of liquid passing through nozzle
- $t$ = time
- $A_N$ = Area of the nozzle
- $\rho_\ell$ = density of the liquid
- $C_D$ = a friction factor (assume $C_D = 1$)
- $g$ = acceleration due to gravity
- $h$ = height of liquid in the funnel

The mass flow of strip cast on the chill block can be described as:

$$\frac{dw}{dt} = M \cdot W \cdot v \cdot \rho_s \quad (2)$$

where:

- $w$ = weight of strip
- $t$ = time
- $M$ = thickness of solidified strip
- $W$ = width of strip
- $v$ = casting speed
- $\rho_s$ = density of the strip

Combining equations (1) and (2) yields:

$$A_N \ \rho_\ell \ \sqrt{2gh} = M \ W \ v \ \rho_s$$

Solving for the strip thickness (M) gives:

$$M = \left(\frac{\rho_\ell}{\rho_s}\right) \frac{A_N \ \sqrt{2gh}}{W \cdot v} \qquad (3)$$

Equation (3) can be used to predict the maximum strip thickness (M) as a function of the size of the funnel opening ($A_N$), the level of liquid in the funnel (h), the width of the tundish (W) and the casting speed (v). Table I shows the results of calculations to predict strip thickness for different nozzle diameters and wheel speeds given a constant height of liquid in the funnel of 6 inches and a 12 inch wide tundish.

The melt overflow system used for these experiments does not achieve steady state conditions. In effect, the conditions are constantly changing: as the liquid titanium drains from the funnel to the tundish, the mass flow rate decreases continuously with time. Time is measured in seconds for performing each experiment before the titanium freezes in the funnel, tundish, and as cast strip.

Originally, we thought that it was best to deliver all of the liquid metal to the tundish. Experiments conducted by RIBTEC prior to this contract, used 1.25 inch diameter nozzles and 1.5 inch diameter nozzles. The original nozzles were machined from 1/4 inch thick steel strip which reacted with the liquid titanium.

The experiments performed during this contract were designed to restrict the flow of the titanium into the tundish. The nozzle diameter was either 3/4 inch or 7/8 inch for all experiments. Restricting the flow of titanium into the tundish was thought to reduce the splashing and turbulence of earlier experiments. Steel nozzles were replaced by titanium nozzles after the second experiment. Figure 3 shows a titanium nozzle insert after machining.

The tundish design evolved gradually after extensive water modeling using plexiglas tundishes and actual casting experiments. The tundish that evolved from these efforts was semicircular, 12 inches wide at the chill block and 1.5 inches deep. The tundish was machined from graphite and was capable of containing approximately six pounds of titanium.

Three positions of the tundish against the chill block were tested. The first position was on the horizontal centerline. The second position was elevated 3 degrees above center. The third position was 30 degrees above horizontal. In general, the higher the tundish position on the chill block, the thicker the product. Most experiments were performed with the tundish positioned near the horizontal centerline, in attempting to cast the thinnest, most rapidly solidified material.

Experiments were performed using a brass chill block to cast aluminum that was induction melted in air to physically model the casting system. All experiments were videotaped. Playback of the video recording showed that the original two piece conical funnel used by Duriron leaked around the nozzle. The funnel was replaced by a cylindrical one that was 6in ID by 7 in high.

Experiments were also performed under a NASA contract to design a system for conveying and collecting sheet and strip cast by melt overflow (2). The NASA study concluded that a series of rolls were the best way of conveying the strip around the chill block. A set of six rolls, two inches diameter by sixteen inches long, were designed and built for the melt overflow caster and tested at Duriron.

## PROCEDURES

Before each experiment, the chill block caster components were assembled. The components included a graphite funnel, a graphite tundish, a ten inch diameter chill block, a 2 hp motor and a tachometer. The assembled unit was installed in the lower chamber of the Duriron induction slag furnace. The base of the frame was clamped to the platen in the furnace. After the flapper valve was opened, the electrical and instrumentation connections were made to power the motor and tachometer.

Figure 4 shows the chill block assembly mounted in the lower chamber of the Duriron furnace. The motor was mounted under the chill block and the tachometer was mounted to the right of it. The assembly includes a set of six steel rolls to divert the strip into the bottom of the vessel.

The chill block assembly was raised on the platen approximately two feet. A steel tube was positioned between the pour lip of the induction slag furnace and the graphite funnel. The lower chamber door was closed and sealed.
The induction slag furnace was charged with approximately thirty pounds of melting stock for each experiment. Aluminum shot was bundled in aluminum foil and placed on a vibratory feeder for addition to the melt. No flux or slag was used during any of the experiments. After charging, the upper chamber door was closed and sealed.

The induction slag furnace was evacuated to approximately 10 microns. The vessel was then filled to roughly one half atmosphere of argon. The power was turned on and gradually increased in stages as the melting progressed. After the charge was fully melted, the bundles of aluminum shot were added on a vibratory feeder. The melt temperature was monitored using an IRCON pyrometer. As soon as the melt temperature stabilized, the chill block was brought to the proper rotational speed.

The Duriron induction slag furnace has an automatic, programmable pour rate. The furnace was shut off and poured automatically in about one second. The molten charge was poured into the steel tube. The tube drained into the graphite funnel were the metal was metered through a titanium nozzle into the graphite tundish and onto the chill block.

The entire casting process lasted for two or three seconds. Figure 5 shows the results of casting experiment just after the titanium alloy was poured from the furnace. The photograph is taken from the upper chamber of the Duriron furnace. It shows the pour tube that spans the transition between the upper vessel and the lower chamber just below the center of the photo. To the right of the pour tube is the titanium glowing in the tundish. Above the tundish is the chill block. The cast strip is glowing in the upper one third of the photo.

The titanium alloy strip was cast into the lower chamber of the induction slag furnace. The furnace was allowed to cool for one hour before it was evacuated, filled with air and opened. The titanium strip was removed. The chill block assembly was removed in the reverse steps of the installation procedure described above.

## RESULTS

Table II shows the experimental conditions used during each of the ten experiments performed during Phase I. Table III summarizes the weight of the titanium remaining in the pour tube, funnel and tundish. The weight of the cast strip is also given. Table IV shows the average width and thickness of the as-cast strip based on a sample size of ten measurements.

The first experiment attempted to cast Ti-6Al-4V alloy into strip. No secondary rolls were used. The 19 mm (3/4 in) diameter nozzle delivered only 2.7 kg (5.9 lbs) of metal to the tundish. The funnel was resting on the tundish. It increased the conduction heat transfer to the liquid titanium when the tundish filled resulting in rapid freezing in the tundish. It is likely that the tundish froze at the chill block interface to restrict the width of the strip to 51 mm (2 in).

Two modifications were made to the second experiment to increase the amount of titanium delivered to the tundish. First, the nozzle diameter was increased from 19mm (3/4 in) to 22 mm (7/8 in) and second, the funnel was raised above the tundish by 25 mm (1 in) to avoid contact with the liquid in the tundish.

The second experiment resulted in the widest strip cast to date; 178 mm (7 in). Nearly three times as much strip was cast (3 lbs) compared to the first experiment. The thickness of the strip averaged .38 mm (0.015 in).

The strip cast during the second experiment hit the flapper where it formed accordion-like layers. The Ti-6Al-4V alloy is tough and relatively ductile in the as-cast condition. It appears that the layers welded together, however.

The third experiment was our first attempt to cast alpha-2 aluminide. A polished brass chill block was used. The funnel was placed on top of the tundish by mistake, without a spacer. As a result, the liquid titanium froze in the tundish and cast only 10 g of strip. This was significantly less strip than was cast during the first experiment under the same conditions. The difference may be attributed to the polished wheel versus the threaded wheel surface. It appears that the threads increase the momentum transfer to the liquid metal resulting in more strip being cast when compared to a smooth, polished wheel.

The 22 mm (7/8 in) diameter nozzle delivered 7.6 kg (16.7 lbs) of titanium to the tundish. This is nearly three times the amount of titanium delivered through the 19 mm (3/4 in) diameter nozzle. The nozzle is shown in Figure 6. There appears to be little reaction between the nozzle and the liquid titanium. By contrast, at least 50% of each steel nozzle appeared to have melted during the first two experiments.

The fourth experiment attempted to duplicate the conditions of the second experiment but did not duplicate the results. The width of the strip was 38 mm (1.5 in). Two or three different strips were cast simultaneously rather than one wide strip. The liquid titanium appeared to wet the chill block unevenly and intermittently. Had the individual strips bridged together, a strip at least six inches wide would have been cast.

One possible reason that the strip didn't wet the chill block uniformly was that the tundish was on the horizontal center of the chill block. If the tundish were raised above center, then gravity forces the liquid metal against the chill block.

Therefore, the tundish was raised above horizontal during experiment five.

A 25 mm (1 in) high metal block was placed between the frame of the caster and the platen in Duriron's furnace. The metal block tilted the entire assembly approximately 3 degrees, thus raising the tundish above horizontal. In addition, a system of steel rolls was mounted against the chill block to direct the cast strip into the bottom of the vessel instead of allowing it to hit the flapper valve and form a layered accordion.

Figure 7 shows a photograph of the caster after experiment five. The tundish is shown at the bottom of the photo. It is completely filled with titanium. Below the titanium are the two support blocks for the funnel that was removed. Two strips were cast simultaneously. The thickness of the cast material found in the secondary rolls suggests that solid plus liquid may have been removed from the tundish at the end of the experiment. Strip that made it through the secondary rolls was 0.4 mm (0.016 in) thick and 19 mm (0.75 in) wide.

The rolls effectively direct strip away from the flapper valve, but the design must be modified to allow very thick strip and casting imperfections to pass through the rolls. Perhaps spring loading each roll along the chill block radius will solve the problem.

During experiment six the casting speed was increased from 3 m/s to 5 m/s. The secondary rolls were removed, but the other conditions were the same as during experiment five. It appears that the increased casting speed did result in a decrease in thickness from 0.58 mm (0.023 in) to 0.41 mm (0.016 in), all other factors being equal. Multiple narrow strips were cast simultaneously rather than one wide strip.

Obviously, freezing the tundish was a major problem. During experiments seven through ten, a NiChrome heating element measuring 15 cm (6 in) by 30 cm (12 in) wide was placed under the tundish. The heater used 110 volt AC current and was insulated by 6 cm (2.5 in) of Kaowool insulation from the caster frame.

The brass chill block surface had a 33 pitch diamond knurl on the periphery during experiment seven. The knurl pattern was used to increase the momentum transfer to the liquid and thereby increase the width of the strip. The thickness of the strip was 0.48 mm (0.019 in) compared with 0.041 mm (0.016 in) cast during the previous experiment on a 100 TPI grooved chill block. The width of the strip was 63 mm (2.5 in), however, which was the widest alpha-2 strip cast during any experiment.

Figures 8 and 9 show the as-cast surface appearance of strip cast on a knurled surface with strip cast on a 100 TPI grooved surface. Figure 8 shows the chill block cast surface of the knurled strip on the left and the grooved strip on the right. Gross porosity is evident in both cases. The smoothness is comparable, however. Figure 9 shows the free cast surface appearance with the knurled strip on the left again. Note that both samples of strip show a dimpled surface. The dimples may be an indication that the strip was cast from solid plus liquid from the tundish.

The weight of strip cast during experiment seven was greater than any of the previous experiments. It appears that the tundish heater increased the weight of strip cast during each experiment that it was used. As much as 4.8 kg (10.6 lb) of strip was cast using the tundish heating element. The average weight of the cast strip per experiment was 3.6 kg compared to 0.8 kg per experiment without the heater.

The strip cast during experiment seven contained less aluminum than the other alpha-2 alloy heats because 1 kg of aluminum pellets had not been added to the melt by mistake.

Experiment eight used a copper chill block with 100 TPI grooves at the periphery. The thickness of the strip was 0.51 mm (0.020 in) compared to 0.41 mm (0.016 in) for strip cast on a yellow brass chill block with 100 TPI grooves. It appears that copper casts thicker strip than yellow brass, all other factors being equal.

The tundish position was increased to 30 degrees above the horizontal center of the chill block for experiments nine and ten. During experiment nine, a copper chill block with 100 TPI grooves was used. The strip thickness increased from 0.51 mm (0.020 in) to 0.56 mm (0.022 in) by raising the tundish.

The brass chill block with 100 TPI grooves showed a greater increase in thickness when the tundish was raised to 30 degrees above horizontal during experiment ten. The thickness of the strip cast at horizontal was 0.41 mm (0.016 in) during experiment six compared to the 0.53 mm (0.021 in) thick cast during experiment ten. This result is exaggerated however, because the depth of the slot in the front of the tundish was 25 mm (1 in) during experiment ten but it was 12.5 mm (0.5 in) during experiment six. The increased depth of liquid metal against the chill block also contributed to the thicker strip.

## CONCLUSIONS

1) The feasibility of direct casting titanium alloy strip up to 178 mm (7 in) wide has been successfully demonstrated. Additional experiments are needed to increase the width of the as-cast strip.

2) Increasing casting speed decreased the strip thickness, all other factors being equal. A 67% increase in surface speed resulted in a 30 % decrease in as-cast strip thickness during experiments with a yellow brass chill block with 100 TPI grooves machined on the periphery.

3) The copper chill block produced thicker strip than the yellow brass chill block, all other factors being equal. This appears to hold true regardless of the tundish position against the chill block. However, the alpha-2 alloy does not wet as well to either copper or brass chill blocks as the Ti-6Al-4V alloy.

4) A knurled casting surface produced wider and slightly thicker alpha-2 alloy strip than a surface with 100 TPI grooves. The knurled surface may improve the bonding characteristics of the metal matrix composite.

5) Heating the tundish had a significant affect on the amount of strip cast. The weight of the strip averaged 3.2 kg/experiment with a heater versus 0.8 kg/experiment without the heater.

6) Increasing the angle of the tundish above the horizontal center of the chill block increased the thickness of the strip. The strip thickness increased 10 % on a copper chill block by raising the tundish from 3 degrees to 30 degrees above horizontal.

7) Increasing the angle of the tundish above the horizontal center of the chill block increased the amount of strip. The average weight of as-cast strip doubled by raising the tundish from 3 degrees to 30 degrees above horizontal when using a tundish heater.

8) Titanium nozzles react less than steel nozzles in the funnel. Titanium nozzles should be used exclusively during future experiments.

9) Secondary rolls can be used to direct the as-cast strip vertically downward, away from the chill block. The system developed for this program requires modifications to accommodate thicker strip or casting imperfections.

10) There is a limited amount of superheat that can be transferred to the liquid titanium in the induction slag furnace. Modifications to the melt overflow casting system

are needed to reduce the heat loss in the pour tube, funnel and tundish and thereby retain as much superheat as possible during casting.

11) The as-cast alpha-2 alloy strip is more brittle than the Ti-6Al-4V alloy strip. The ductility of the alpha-2 alloy may increase with decreasing strip thickness. Additional experiments are needed to attempt to cast thinner strip.

## RECOMMENDATIONS

RIBTEC has demonstrated the feasibility of direct casting titanium alloy strip up to 178 mm (7 in) wide by the melt overflow process. Additional research is needed in the following areas to improve the direct cast strip:

1) It is important to determine why the alpha-2 alloy strip is relatively brittle. A microstructural analysis and chemical analysis to measure the abundance of interstitial elements in the alpha-2 alloy may lead to the answers.

2) Redesign the melt overflow caster to allow it to be raised as close to the induction slag furnace as is practical. Decreasing the pour height from the furnace to the tundish will decrease the heat losses to the system. It may be possible to eliminate the pour tube entirely.

3) Heat as many of the metal delivery components as possible. The tundish heater greatly increased the amount of titanium alloy strip that was cast. The pour tube and funnel might also be heated.

4) Redesign the secondary rolls to accommodate thick strip or casting defects on the strip. The design should include a system for coiling the strip as it is cast.

5) Investigate the effects of the knurled surface on casting wider strip. It appears that the strip cast on the knurled wheel may be wider than that cast on a grooved wheel.

6) Physically model the titanium experiments by casting aluminum or copper strip by melt overflow to gain insight on the effects of process variables on the strip dimensions.

7) Investigate molybdenum and other refractory metal coatings on the chill block to increase wetting and decrease thermal fatigue.

8) Design experiments to determine the optimum conditions to cast wider, thinner strip. The effects of casting speed, position of the tundish, superheat, and contact between the melt and chill block will be investigated. Alternative tundish designs should also be considered.

## REFERENCES

1. Clites, P.G.,USBM Bulletin 673, (1982).

2. NASA Contract Number NAS1-18288

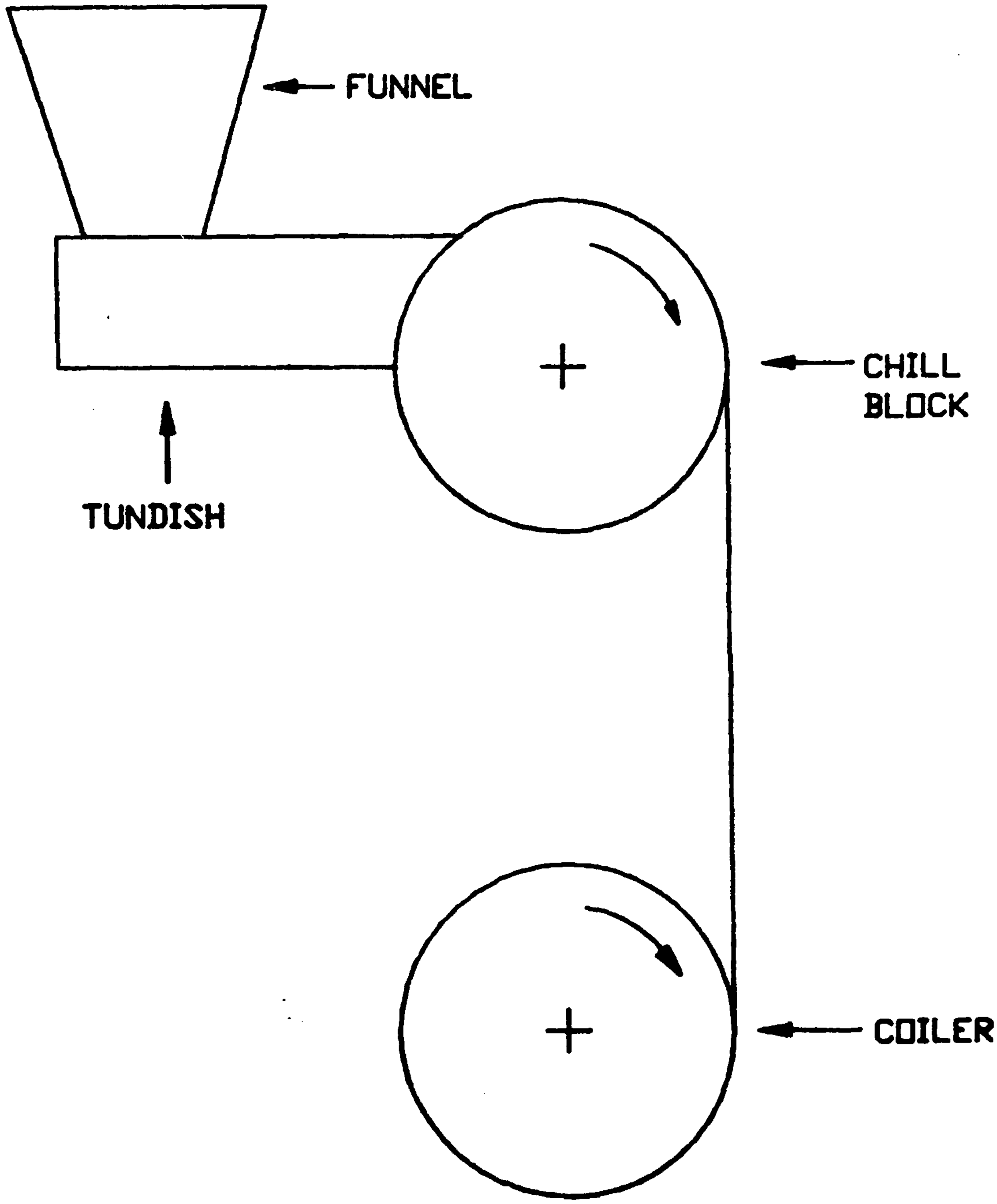


FIGURE 1. SCHEMATIC DIAGRAM OF PROPOSED MELT OVERFLOW CASTING SYSTEM

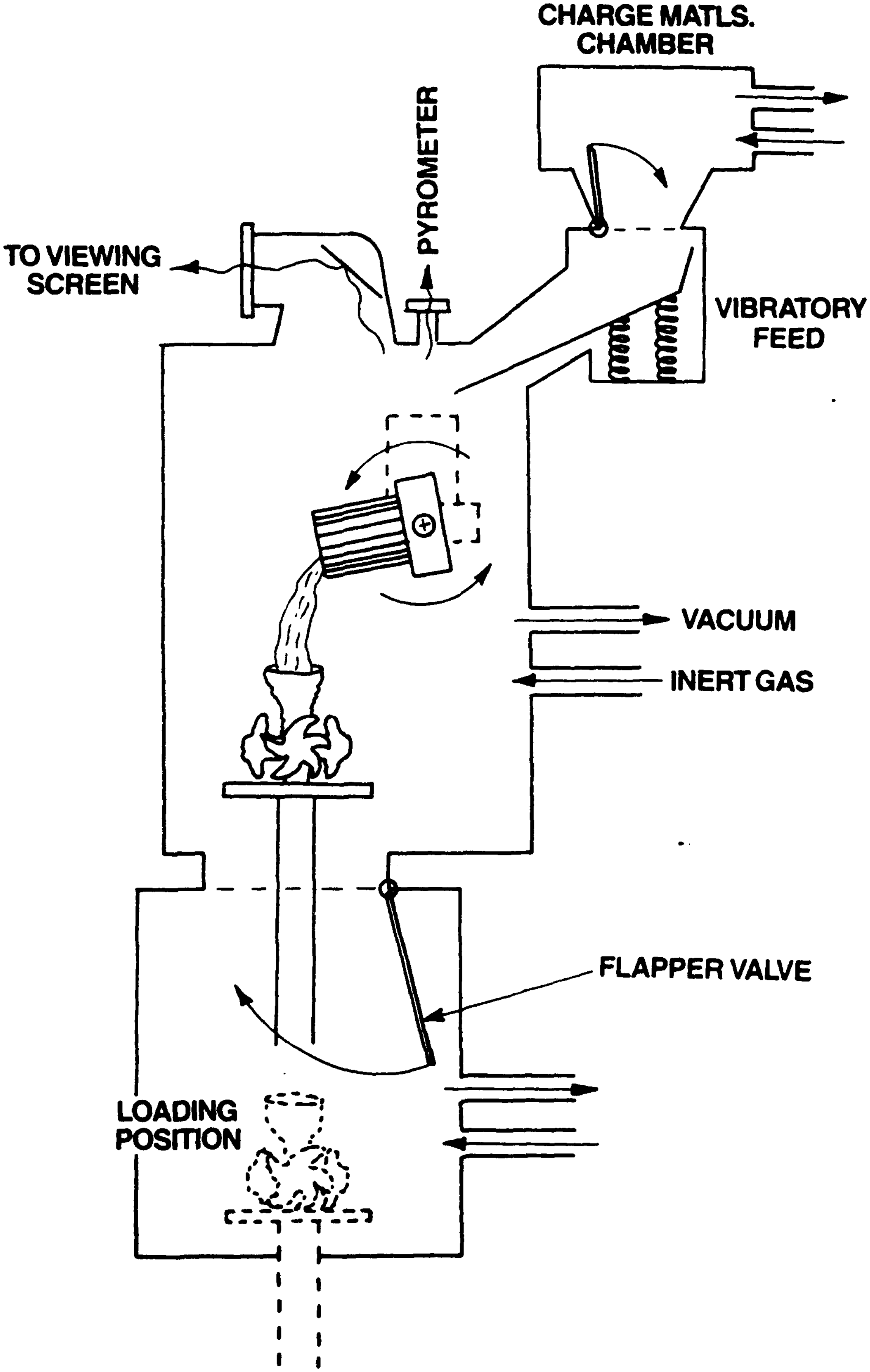


**FIGURE 2—REACTIVE ALLOY INDUCTION MELTING UNIT**

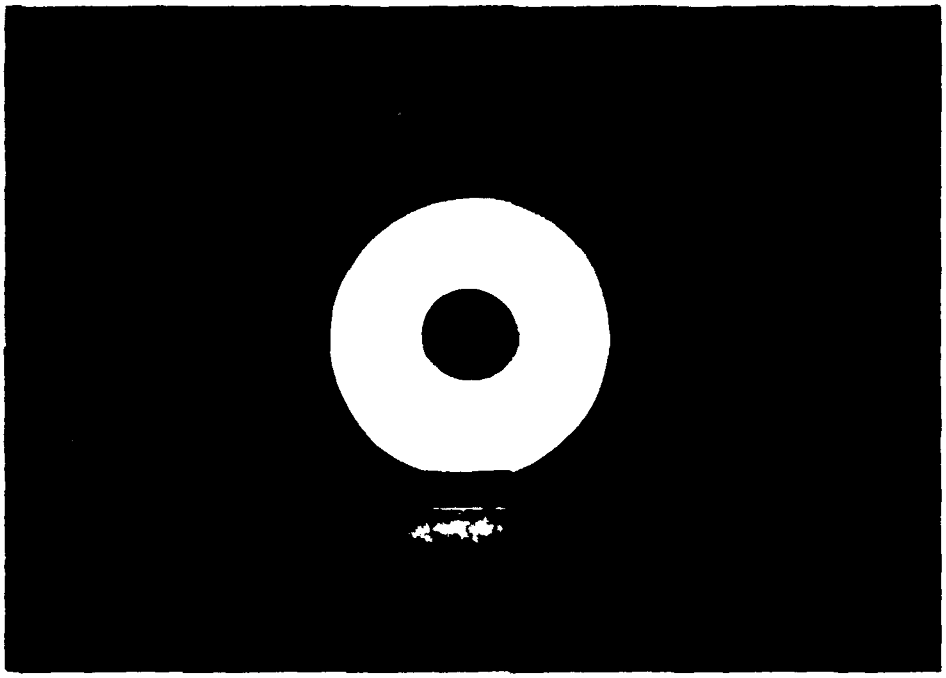

FIGURE 3. TITANIUM NOZZLE USED FOR MELT OVERFLOW

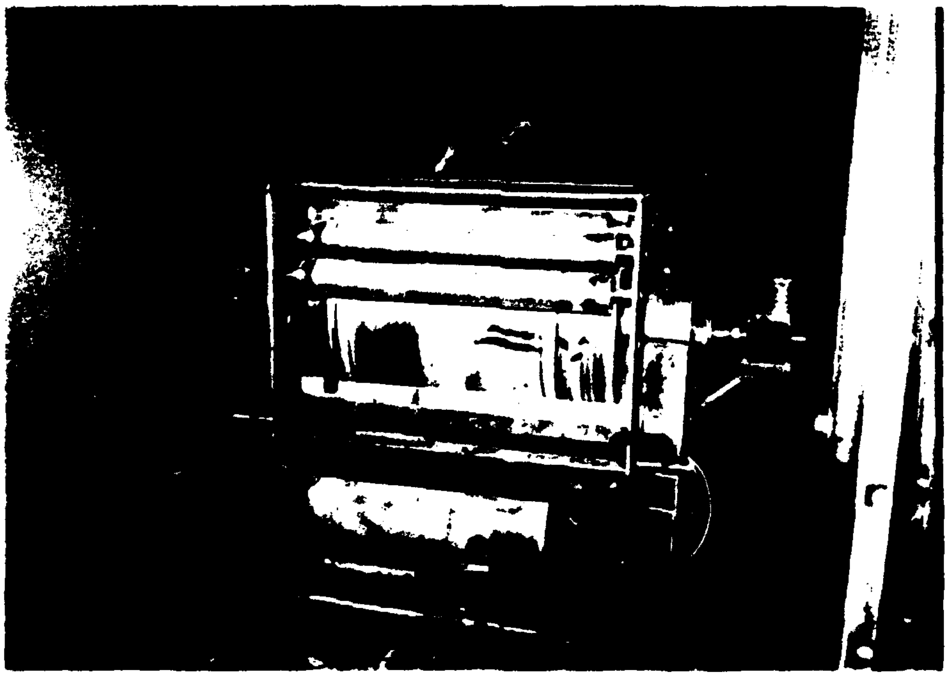

FIGURE 4. MELT OVERFLOW CASTER INSTALLED IN DURIRON FURNACE


FIGURE 5. PHOTO OF MELT OVERFLOW CASTING EXPERIMENT

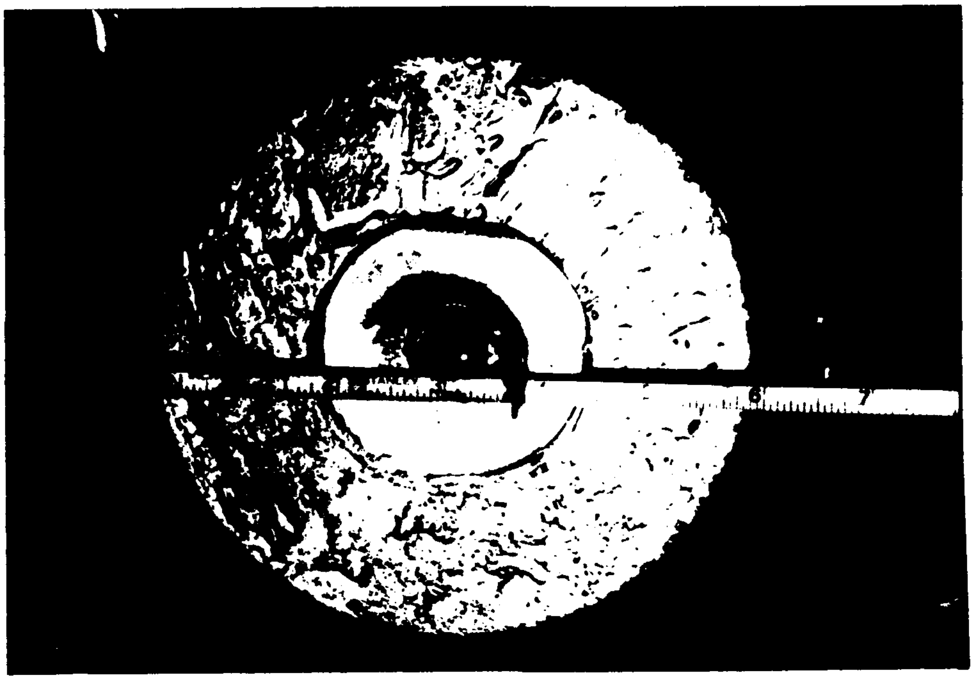

FIGURE 6. TITANIUM NOZZLE AFTER POURING

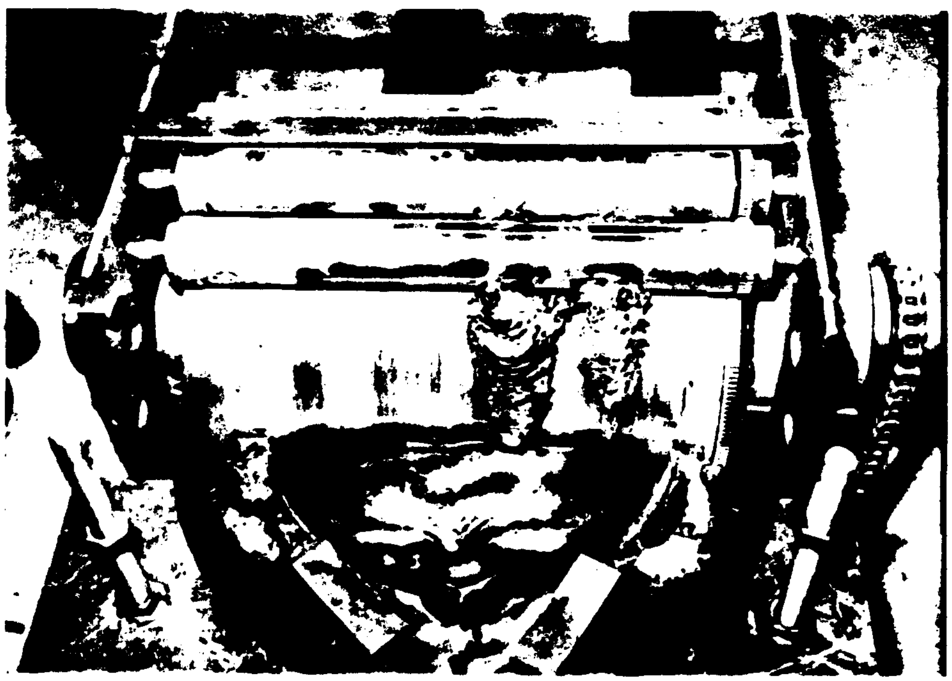

FIGURE 7. MELT OVERFLOW CASTER AFTER EXPERIMENT FIVE

FIGURE 8. CONTACT SURFACE FOR KNURLED (LEFT) AND GROOVED (RIGHT)

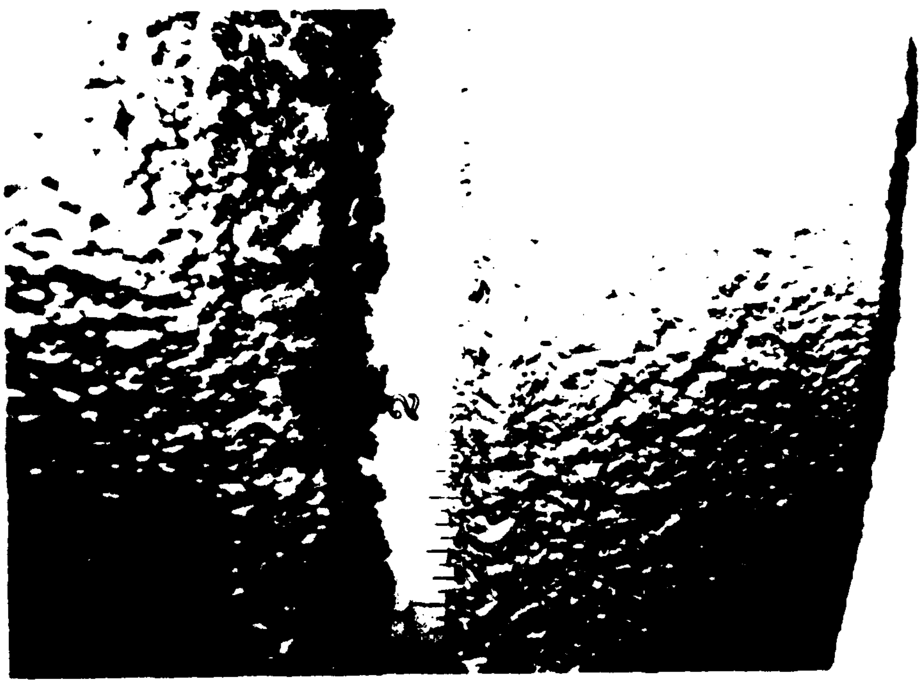

FIGURE 9. FREE SURFACES FOR KNURLED (LEFT) AND GROOVED (RIGHT)

TABLE I. CASTING 12 IN WIDE STRIP WITH 6 IN OF HEAD PRESSURE

| speed ft/s | dia=1/2 | dia=5/8 | dia=3/4 | dia=7/8 | dia=1 | dia=1 1/4 |
|---|---|---|---|---|---|---|
| | | THEORETICAL MAXIMUM STRIP THICKNESS (INCHES) | | | | |
| 0.5 | 0.166 | 0.259 | 0.373 | 0.508 | 0.664 | 1.038 |
| 1 | 0.083 | 0.130 | 0.187 | 0.254 | 0.332 | 0.519 |
| 2 | 0.041 | 0.065 | 0.093 | 0.127 | 0.166 | 0.259 |
| 3 | 0.028 | 0.043 | 0.062 | 0.085 | 0.111 | 0.173 |
| 4 | 0.021 | 0.032 | 0.047 | 0.064 | 0.083 | 0.130 |
| 5 | 0.017 | 0.026 | 0.037 | 0.051 | 0.066 | 0.104 |
| 10 | 0.008 | 0.013 | 0.019 | 0.025 | 0.033 | 0.052 |
| 15 | 0.006 | 0.009 | 0.012 | 0.017 | 0.022 | 0.035 |
| 20 | 0.004 | 0.006 | 0.009 | 0.013 | 0.017 | 0.026 |
| 25 | 0.003 | 0.005 | 0.007 | 0.010 | 0.013 | 0.021 |
| 30 | 0.003 | 0.004 | 0.006 | 0.008 | 0.011 | 0.017 |
| 35 | 0.002 | 0.004 | 0.005 | 0.007 | 0.009 | 0.015 |

TABLE II. EXPERIMENTAL CONDITIONS DURING TITANIUM CASTING EXPERIMENTS

| HEAT NUMBER | ALLOY COMPOSITION (nominal) | CASTING SPEED (m/s) | NOZZLE DIAMETER (mm) | SUBSTRATE | SURFACE FINISH | POSITION ON WHEEL |
|---|---|---|---|---|---|---|
| 1 | Ti-6Al-4V | 3 | 19 | BRASS | 100 TPI | CENTER |
| 2 | Ti-6Al-4V | 3 | 22 | BRASS | 100 TPI | CENTER |
| 3 | Ti-14Al-21Nb | 3 | 22 | BRASS | POLISHED | CENTER |
| 4 | Ti-14Al-21Nb | 3 | 22 | BRASS | 100 TPI | CENTER |
| 5 | Ti-14Al-21Nb | 3 | 22 | BRASS | 100 TPI | 3 DEG TILT |
| 6 | Ti-14Al-21Nb | 5 | 22 | BRASS | 100 TPI | 3 DEG TILT |
| 7 | Ti-7Al-23Nb | 5 | 22 | BRASS | KNURL | 3 DEG TILT |
| 8 | Ti-14Al-21Nb | 5 | 22 | COPPER | 100 TPI | 3 DEG TILT |
| 9 | Ti-14Al-21Nb | 5 | 22 | COPPER | 100 TPI | 30 DEGREES |
| 10 | Ti-14Al-21Nb | 5 | 22 | BRASS | 100 TPI | 30 DEGREES |

TABLE III. WEIGHTS OF CHARGE, SKULLS AND CAST STRIP (LBS)

| HEAT NUMBER | CHARGE | TUBE | FUNNEL | TUNDISH | STRIP | MISC |
|---|---|---|---|---|---|---|
| 1 | 36.5 | 4.5 | 12.3 | 4.8 | 1.1 | NA |
| 2 | 26.4 | 3.5 | 13.2 | NA | 3.0 | NA |
| 3 | 30.0 | 6.9 | 13.0 | 13.5 | .0 | 3.2 |
| 4 | 30.0 | 6.9 | 15.4 | 10.4 | 1.9 | NA |
| 5 | 30.0 | 6.9 | 15.4 | 10.4 | 1.9 | NA |
| 6 | 30.0 | 5.8 | 11.0 | 9.3 | 3.5 | NA |
| 7 | 27.5 | 7.2 | 8.5 | 6.7 | 4.9 | NA |
| 8 | 30.0 | 6.1 | 12.2 | 8.7 | 3.8 | NA |
| 9 | 30.0 | 5.7 | 9.8 | 3.4 | 10.6 | NA |
| 10 | 30.0 | 6.5 | 9.0 | 7.0 | 8.8 | NA |

TABLE IV. DIMENSIONS OF CAST STRIP

| HEAT NUMBER | CASTING SPEED (m/s) | STRIP WEIGHT (kg) | AVERAGE STRIP WIDTH (mm) | (in) | AVERAGE STRIP THICKNESS (mm) | (in) |
|---|---|---|---|---|---|---|
| 1 | 3 | 0.50 | 50.8 | 2.00 | 0.356 | 0.014 |
| 2 | 3 | 1.36 | 177.8 | 7.00 | 0.381 | 0.015 |
| 3 | 3 | 0.01 | NA | NA | NA | NA |
| 4 | 3 | 0.86 | 38.1 | 1.50 | 0.533 | 0.021 |
| 5 | 3 | 0.86 | 25.4 | 1.00 | 0.584 | 0.023 |
| 6 | 5 | 1.59 | 19.1 | 0.75 | 0.406 | 0.016 |
| 7 | 5 | 2.22 | 63.5 | 2.50 | 0.483 | 0.019 |
| 8 | 5 | 1.72 | 31.8 | 1.25 | 0.508 | 0.020 |
| 9 | 5 | 4.81 | 44.5 | 1.75 | 0.559 | 0.022 |
| 10 | 5 | 3.97 | 38.1 | 1.50 | 0.533 | 0.021 |