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UNIDIRECTIONALLY SOLIDIFIED WROUGHT STEEL ARMOR

FINAL TECHNICAL REPORT

By

C. E. Bieniosek

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April 1, 1969

Prepared by

UNITED STATES STEEL CORPORATION

APPLIED RESEARCH LABORATORY

MONROEVILLE, PENNSYLVANIA 15146

Contract No. DAAG 46-67-C-0158(X)

ARMY MATERIALS AND MECHANICS RESEARCH CENTER

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Foreword

This report was prepared by the Applied Research Laboratory of United States Steel Corporation under U. S. Army Contract No. DAAG46-67-C-0158(X). The contract was administered by the U. S. Army Materials and Mechanics Research Center, Watertown, Massachusetts, with John M. Ingraham serving as technical supervisor. This is a final report and covers work conducted from July 1, 1967, through October 29, 1968.

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Illustrations

Unidirectionally Solidified
Wrought Steel Armor
23.011-100(1) G-10,000

April 1, 1969

By C. E. Bieniosek, K. F. Skidmore, and L. F. Porter

Approved by C. K. Russell, Division Coordinator, Steel Processing and Refractory Technology, and A. M. Rathbone, Division Chief, Ordnance Products

Abstract

Flemings and Ahearn demonstrated that cast steels with superior ductility can be produced by unidirectional solidification, which results in minimum macrosegregation and macroporosity and less microporosity than is found in conventional castings. To determine whether the advantages of unidirectional solidification could be utilized to produce a superior wrought steel armor, techniques were established for casting unidirectionally solidified slabs 10 by 16 by 5-1/2 inches weighing about 240 pounds. The slabs were homogenized by holding in evacuated stainless-steel boxes for 64 hours at 2400 F, and rolled to plates for ballistic testing.

Homogenization caused rounding of the inclusions and micropores and eliminated alloy segregation. Subsequent rolling to 1/2- and 3/4-inch-thick plate did not elongate the inclusions; therefore no stringers were formed. The plates were heat-treated by several different cycles. Plates from homogenized castings could be water-quenched without cracking, but oil quenching was used for most heat treatments since a severe quench was not necessary to obtain the desired hardness.

In ballistic tests, the best unidirectionally solidified and homogenized wrought steel armor plates did not crack or spall at a hardness of Bhn 555 and thus performed better ballistically than equivalent conventionally processed homogeneous steel plates and compared favorably with commercial dual-hardness armor plates.

Introduction

Background

Work by Flemings[1,2]* and Ahearn[3] has shown that cast steels with superior ductility can be produced by unidirectional solidification. Solidification is controlled by casting the metal in such a manner that heat is extracted primarily from one surface to produce a cast structure in which columnar grains extend from the chill surface completely through the casting. Steel thus solidified has been found to exhibit a minimum degree of macrosegregation and macroporosity, less microporosity, and higher ductility than conventionally cast steels.

These inherent advantages of unidirectionally solidified steel suggested the possibility of using this method to produce superior wrought steel armor. Accordingly, a research contract (U. S. Army Contract No. DAAG 46-67-C-0158(X) was awarded by the U. S. Army Materials and Mechanics Research Center to United States Steel Corporation to produce, test, and evaluate experimental armor plates hot-rolled from unidirectionally solidified slab castings. This report describes the results obtained under that contract.

Scope of Work

During the project, melting and pouring practices were established for the production of experimental unidirectionally solidified castings from two types of steel, 0.3C-5Ni-0.5Cr-0.5Mo-0.08V steel and 0.6C-1.0Ni-0.5Cr-0.5Mo steel. Twenty-eight 110-pound, six 140-pound, and six 240-pound unidirectionally solidified castings were produced by using three different types of chills representing a wide range of cooling rates (copper, cast iron, and refractory-brick chills). Selected castings were chemically analyzed for macrosegregation and metallographically examined for macrosegregation, microporosity, microsegregation, and dendrite arm spacing. Some of the castings were partly or completely homogenized by holding at temperatures ranging from 2300 to 2400 F for various lengths of time. Portions of the castings were hot-rolled to plates varying from 1/2 to 3/4 inch thick. The plates were quenched and tempered and then subjected to ballistic tests.

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* See References

Mechanical properties were obtained on castings and on plates. Homogenized castings as well as the plate product were chemically analyzed to determine changes occurring during the homogenization treatment and metallographically examined to ascertain the degree of homogenization. Special attention was focused on the behavior of nonmetallic inclusions in unidirectionally solidified castings during homogenization and hot rolling because it was expected that this would influence the ballistic properties. Also, the impact areas in ballistically tested plates were metallographically examined to help explain the formation of cracks.

Equipment and Experimental Procedures

Molds

Molds for unidirectional solidification, shown in Figure 1, were prepared by placing sand cores and exothermic pads made of Exomold "E" in a cast-iron mold. At the mold bottom, liquid steel was in contact with the cast iron, which acted as a chill. At the sides, the liquid steel was in contact with 1-inch-thick exothermic pads except for the bottom 1/2 inch, where the liquid steel was in contact with the sand cores. The top of the mold was covered with a 1-1/2-inch-thick exothermic slab. This arrangement assured heat extraction in the downward direction only. The mold cavity was 8 inches wide, 14 inches long, and 4 inches high. The solidified castings were approximately 3-1/2 inches high and weighed about 110 pounds.

To increase the solidification rate, a 2-inch-thick copper chill plate weighing about 200 pounds was inserted in the cast-iron mold. The sand cores and exothermic pads were then placed on top of the copper chill. Similarly, to decrease the solidification rate for comparison purposes, a 2-inch refractory brick was used instead of the copper chill. Thus, unidirectionally solidified castings were produced with three different chills—copper, cast iron, and refractory brick—each providing a different cooling rate. The exothermic pads and parts of the sand cores that were in contact with liquid steel were coated with a methyl alcohol base zircon wash. At first the chill surfaces were also coated with this wash. Later, however, this practice was abandoned in favor of bare chill surfaces.

The design of the sand cores and exothermic pads was modified during the program as follows: (1) the height of both the sand cores and exothermic pads was increased 1 inch so that the mold cavity measured 8 inches wide, 14 inches long, and 5 inches high and the solidified castings were approximately 4-1/2 inches high and weighed about 140 pounds; (2) the shape of the exothermic pads was changed from a slab-type to a wedge-type with the width increasing from 1 inch at the bottom to 1-1/2 inches at the top to provide more heat at the top of the casting where it is needed most; (3) an alumina insert was placed in the pouring basin to minimize heat losses when the steel was poured into the mold, Figure 2.

In a further modification, the width of sand cores was decreased by 1 inch to increase the dimensions of the mold cavity to 10 inches by 16 inches, and the height of the mold cavity was increased to 6 inches by placing 1-inch-thick strips of sand cores underneath the regular sand cores and exothermic pads. The mold was assembled on a 6-inch-thick copper block, which was wider than the original chill blocks and weighed about 1000 pounds. The cores were held in place by a form fabricated from 1/8-inch-thick steel strip, Figure 3. This arrangement was satisfactory, and no problems were experienced in containing the liquid steel in the mold. These final modifications permitted production of castings that were 10 inches wide, 16 inches long, and 5-1/2 inches high and weighed about 240 pounds, a scale-up of 2.2 from the initial 110-pound castings.

Steel Composition

Steels of two different aim compositions were produced, as shown in Table I. At the beginning of the work, Steel L, with an aim composition 0.28C-5.0Ni-0.5Cr-0.5Mo-0.08V was used. This composition was chosen because it was believed to be suitable for heavy homogeneous armor plate and because it could be used as the rear plate in dual-hardness armor systems.

Later, Steel H, with an aim composition 0.60C-1Ni-0.5Cr-0.5Mo was used. The alloy composition of this steel is close to that currently used for the front plate of dual-hardness armor, and the alloy composition is the same as that currently used for making high-hardness armor plate. The carbon content was deliberately increased above the level normally used for high-hardness plate to make it convenient to harden plates from the same heat to various hardnesses by changing only the tempering temperature. This was done in the expectation that armor plate rolled from unidirectionally solidified steel might perform better at higher hardnesses than conventional armor plate. Once the maximum hardness was established for unidirectionally solidified steel, the carbon content of the steel could be decreased to the minimum at which the desired hardness would still be consistently obtained.

Melting and Casting Procedure

Steel L was melted and alloy additions made in a 500-pound air-induction furnace. The molten steel was poured from the furnace into a preheated ladle from which it was lip-poured as fast as possible into the molds. After the molds were filled, loose exothermic powder was placed on top of the exothermic slab and covered with vermiculite insulation. The castings were allowed to cool in the molds overnight and then shaken out. Three unidirectionally solidified castings could be produced from one 500-pound heat of steel. When molds with different bottom chills were used, the copper-chill mold was filled first, the cast-iron-chill mold second, and the refractory-brick-chill mold last. Thus, the hottest steel was poured into the mold having the fastest cooling rate and the coldest steel into the mold having the slowest cooling rate. This procedure was followed so that liquid steel would be able to completely remelt any dendrites that might have formed and broken off during the filling of the mold cavity. Then nucleation would occur only at the chill and solidification would progress unidirectionally from the chill surface.

Steel H was vacuum-melted in a 300-pound vacuum-induction furnace and poured into the molds under 500 mm argon pressure. The exothermic top was covered by 1-inch-thick sand cores, but no additional exothermic material was placed on top. The castings were removed from the vacuum chamber about 10 to 20 minutes after the solidification was complete and then allowed to air-cool. Vacuum melting rather than air melting was used to lower the oxygen and sulfur contents and to minimize variations in the oxygen content. A list of heats from which unidirectionally solidified castings were produced is shown in Appendix I.

Solidification on a copper chill produced the smoothest bottom surface; solidification on a refractory brick produced the roughest surface. Sand particles were easily removed by shot blasting. The tops of the castings were smooth in areas where the exothermic material had not been in contact with the liquid steel. Where the exothermic material was in contact with the steel, dendrites were made clearly visible because of interdendritic shrinkage.

Homogenization of Unidirectionally Solidified Steel

Microsegregation in as-cast structures can be essentially eliminated by a homogenization heat treatment. This consists of holding the casting at very high temperatures (only slightly below the liquation point) for a prolonged period of time. The time required for complete homogenization depends on the elements being homogenized, the secondary dendrite arm spacing, and the homogenization temperature. Calculations following a method outlined by Kattamis and Flemings[4)] showed that holding for 64 hours at 2400 F would completely eliminate the microsegregation of the alloying elements manganese, nickel, molybdenum, and chromium in the top portion of the 5-1/2-inch-high copper-chilled castings where the secondary dendrite arm spacing was the greatest, about 270 microns, Appendix II.

The homogenization procedure consisted of the following steps:

1. The castings were machined on the sides and bottom surface to remove scale and adhering sand, and a 1/2-inch-thick layer was machined from the top surface of the casting to eliminate top porosity (shrinkage).

2. The machined casting was enclosed in an AISI Type 310 stainless-steel box by welding. A heavy-walled pipe nipple was provided for subsequent evacuation of the box.

3. The box was hot-evacuated at 1800 F for 12 hours and the nipple was forged shut.

4. The casting was homogenized in the evacuated box at 2400 F for times up to 64 hours.

Type 310 stainless steel was used for the homogenization box because of the high temperatures required for homogenization. A box made of 1/2-inch-thick low-carbon steel that was used for the first homogenization treatment was almost completely oxidized and could not be reused after holding for 64 hours at 2400 F.

Hot evacuation was employed for all but the first homogenization treatment. In the first homogenization the box was evacuated cold, but gas retained in the casting evolved during the subsequent homogenization treatment and caused bulging of the box. On the other hand, homogenization boxes that were hot-evacuated had a tendency to collapse during the homogenization treatment, indicating continuing low pressure within the box during the homogenization. The collapsed walls of the box tended to weld to the casting. This situation was corrected by placing high-alumina refractory spacers inside the box to separate the casting from the stainless-steel walls and to prevent the collapse of the homogenization box, Figure 4. The homogenization temperature of 2400 F was the maximum temperature at which the castings of the lower melting steel (Steel H) could be safely homogenized without the danger of incipient liquation and therefore was the temperature used for homogenization of both Steel L and Steel H. The liquation temperatures of the steels were determined with a hot stage microscope on small samples heated in argon.

Hot Rolling

Homogenized castings were hot-rolled on the laboratory rolling mill to thicknesses ranging from 1/2 to 3/4 inch. Castings of Steel L were heated to 2300 F and finished at 1750 F, without reheating between passes. Castings of Steel H were heated to 2150 F and finished at 1700 F. Cross rolling was accomplished by turning the casting section being rolled 90 degrees between each pass. For comparison, a few plates of Steel L were straightaway-rolled. Castings made of Steel H, containing 0.60 percent carbon, were heated to 2150 F and then cross-rolled. The final pass was made at a temperature of 1700 F.

Heat Treatment of Castings and Plates

A few sections of castings and all hot-rolled plates were quenched and tempered. Several different heat-treating cycles were employed to produce experimental armor plates; these are listed in Table II.

Essentially, the plates were double-austenitized and oil quenched, and then tempered to the desired hardness. This basic heat-treating cycle was modified several times. A higher initial austenitization temperature, 1750 or 1800 F, was used on some plates to assure complete solution of alloy carbides in austenite. Other plates were spheroidized at 1290 F to favor formation of stable alloy carbides that would not completely dissolve in the austenite before the final quenching and would thus facilitate complete transformation of austenite to martensite since the amount of retained austenite increases with the concentration of carbon dissolved in it.

A few plates were also water-quenched. Conventional armor plates have a tendency to crack when water-quenched. Plates produced from unidirectionally solidified steel did not crack when water-quenched from the austenitizing temperature of 1500 F or even from 1650 F. However, water quenching was not applied as a rule because a severe quench was not necessary to obtain the desired hardness. Instead, the less severe oil quench was applied to most plates.

To reduce the retained-austenite content, several plates, after oil quenching, were immediately refrigerated in a freon bath maintained at a temperature of -105 F. This step, however, failed to completely eliminate retained austenite.

Repeated tempering treatments were necessary to decrease the hardness of some plates to the desired level.

Ballistic Tests

The quenched and tempered plates were subjected to ballistic tests at the U. S. Steel ballistic range. For the tests, the plates were surface-ground. The hardness and thickness of each plate were measured, and ballistic tests were conducted with caliber 0.30 AP M2 and caliber 0.50 AP M2 projectiles at 0 degrees obliquity.

After the ballistic test, tension and Charpy V-notch impact-test specimens were machined from the better performing plates. In addition, impacted areas of the plates were examined metallographically.

Results and Discussion

Structure and Properties of Unidirectionally Solidified Castings

Macrostructure of Unidirectionally Solidified Castings

A 1/2-inch-thick longitudinal slice was cut from the center of each casting. The surface of the slice was machine-ground and etched to reveal macrostructure. The macrostructure of unidirectionally solidified castings was influenced mostly by the pouring temperature. When the pouring temperature was high, at least 150 F above the melting point, the structure was fully columnar. When the pouring temperature was lower, a mixed columnar and equiaxed structure was formed, as shown in Figure 5. Pouring rates up to 10 pounds per second had little effect on the structure of the castings, although faster pouring may to some extent compensate for slightly lower pouring temperatures. Gate location had only a minor effect on the structure of the castings when the pouring temperature was sufficiently high to produce a fully columnar structure.

The structures obtained with the various chills are shown in Figures 5, 6, 7, and 8. The columnar structure obtained in steel cast on the copper chill was considerably finer than the columnar structure of steel cast on cast iron, and that in turn was finer than the columnar structure of steel cast on the refractory brick.

Unexpectedly, steel poured on top of a refractory brick slab also solidified in a columnar pattern, in spite of the low heat-flow rates. The heavy exothermic layer on the top of the casting probably helped to promote the unidirectional solidification.

Dendrite Arm Spacing in Unidirectionally Solidified Castings

The secondary dendrite arm spacing is inversely proportional to the heat-flow rates. Secondary arm spacing was smallest in steel cast on the copper chill, larger in steel cast on cast iron, and greatest in steel cast on refractory brick, Figure 9. As expected, the secondary dendrite arm spacing, determined by metallographic examination, gradually increased with the distance from the chill. The measured spacings were about twice as large at equivalent distances from the copper chill as those reported by Polich, Nereo, and Flemings[1)] for

AISI 4340 steel cast on a water-cooled chill (50 to 180 microns versus 15 to 125 microns). This difference may have been caused partly by the more rapid cooling of the water-cooled chill in the work reported by Polich, Nereo, and Flemings and partly by the use of excess loose exothermic material on top of the castings in this work.

Macrosegregation in Unidirectionally Solidified Castings

To determine macrosegregation, through-thickness specimens were obtained from the center of the castings, sliced parallel to the chill surface into several segments representing various distances from the chill surface, and chemically analyzed. The analyses confirmed an almost complete lack of macrosegregation in unidirectionally solidified castings. Typical distribution of the alloying elements in several castings of Steel L unidirectionally solidified on copper chills is shown on Table III. Sulfur, which tends to segregate most severely in conventional castings, did not vary more than 50 percent from the bottom to the top of the unidirectional casting. Oxygen did not vary more than 44 percent. Whereas the sulfur tended to be higher at the top of the castings, the oxygen generally tended to be higher at the bottom. Carbon, nitrogen, aluminum and the major alloying elements did not vary significantly from the bottom to the top of the castings.

Effect of Homogenization Heat Treatment on Structure and Properties of Unidirectionally Solidified Castings

Mechanical Properties of As-Cast and Partly Homogenized Unidirectionally Solidified Steel

Sections of 3-1/4-inch-thick castings from Heat Y-9677 (Steel L) unidirectionally solidified by using (1) a copper chill, (2) a cast-iron chill, and (3) a refractory-brick chill were homogenized for 4, 8, or 16 hours at 2300 F. The unhomogenized sections of castings made with cast-iron and refractory-brick chills cracked on quenching and could not be evaluated. Table IV summarizes the mechanical properties obtained at various distances from the chill surface for the remaining castings.

In general, increased homogenization did not affect strength or toughness, but did result in increased reduction of area. For example, a 4-hour homogenization treatment increased the reduction of area of the copper-chill casting from 41.5 to 49.5 percent for samples taken 1/4 inch from the chill plate and from 17.7 to 38.3 percent for samples taken 2-3/4 inches from the chill plate. The reduction-of-area values for the castings made with the cast-iron chill were the highest, and the values for the castings made with the refractory-brick chill were the lowest. In general, the reduction of area of all types of castings decreased as the distances from the chill surface increased.

When the partly homogenized castings described above were hot-rolled to 1/2-inch-thick plate, the mechanical properties improved. Steel solidified on the refractory brick had higher impact values than steel solidified on copper or cast iron, as shown in Table V. The better impact values of the steel cast on the refractory brick can be explained at least in part by lower oxygen contents, which will be discussed later.

Structure of Fully Homogenized Unidirectionally Solidified Castings

The macrostructure of a fully homogenized casting is shown in Figure 10. As shown, the equiaxed grains present after homogenization are coarse near the chill surface and become progressively finer toward the top of the casting.

Table VI shows the maximum differences in content of selected elements between the dendrites and the interdendritic phase in unidirectionally solidified copper-chill castings before and after homogenization. Figures 11, 12, 13, and 14 show the microstructure of copper-chill castings before and after homogenization at increasing distances from the chill. The complete disappearance of dendritic structure is evident.

Changes in Chemical Composition During the Homogenization Heat Treatment

In addition to eliminating the microsegregation of such elements as nickel, manganese, chromium, molybdenum and vanadium, the homogenization heat treatment substantially reduced the hydrogen content of the steel. For example, one slab casting contained 2.82 ppm hydrogen before homogenization and 0.18 ppm after homogenization. The oxygen content was also slightly reduced. For example, one slab casting contained 25 ppm of oxygen before and 19 ppm after homogenization.

Some slab castings lost a small amount of carbon. For example, carbon content dropped from 0.68 percent before to 0.62 percent after homogenization. On the other hand, a piece of AISI Type 310 stainless-steel plate inserted into the homogenization box but separated from the slab casting by several 1/2-inch-thick alumina spacers showed an increase in carbon from 0.07 percent before homogenization to 0.14 percent after homogenization. Thus, some carbon appears to have migrated from the relatively high-carbon steel (0.6% C) across a rarefied gas atmosphere to the low-carbon stainless steel. However, castings that were homogenized in stainless-steel boxes that had been used several times did not show any loss of carbon.

Inclusion Studies

Shape and Distribution of Inclusions and Porosity in Unidirectionally Solidified Castings.

The distribution and shape of nonmetallic inclusions in unidirectionally solidified steel were studied in some detail. Figures 15 and 16 show the different shape of inclusions and microporosity observed in castings unidirectionally solidified on a copper chill as compared with those solidified on a refractory brick. Inclusions found in the casting solidified on the refractory brick had a more regular and round shape than the inclusions found in a casting solidified on the copper chill. With increased distance from the chill surface, inclusions tended to become larger and less numerous.

As expected, all the inclusions, as well as micropores in the as-cast material, were located in the interdendritic alloy-rich phase, Figure 16.

Samples obtained at various distances from the chill surface were examined by the Autoscan method. Autoscan is a fully automatic system for counting the number and measuring the size of constituents, such as inclusions, micropores, and intermetallic phases, which differ from one another in reflectance as seen in a polished section.[5] In this work, inclusions and micropores were counted by Autoscan at a constant speed over a constant area of 144 mm^2. As shown in Table VII and Figure 17, the copper-chill casting had about 2.5 times as many of the smallest, size 1, inclusions as the casting solidified on refractory brick. On the other hand, the copper-chill casting had only two size 5 inclusions and was free of size 6 inclusions, whereas the refractory-chill casting had eleven size 5 and two size 6 inclusions.

The number of small inclusions in the copper-chill casting decreased with increased distance from the chill surface, Table VIII. Distribution of inclusions in the refractory-chill casting in individual size groups was more uniform than in the copper-chill casting at the same distances from the chill surface. This was probably caused by the slow solidification rate and a low temperature gradient during solidification of the refractory-chill castings, Table VIII and Figure 17.

The distribution of inclusions was also analyzed by the ester-halogen method. Table IX shows the distribution of silica and alumina in castings and plates. Figure 18 shows the distribution of alumina inclusions at various distances from the copper chill or from the refractory chill. In both cases the amount of alumina decreased almost linearly as the distance from the chill surface increased. Again, the castings solidified on refractory brick contained significantly less alumina.

Figure 19 shows the shape and location of inclusions and pores close to the top of an unhomogenized casting. The same area is shown first unetched and then etched to emphasize the location of inclusions and pores with respect to the dendrite arms.

Figure 20 shows that the dendritic structure has been eliminated by homogenization and that the inclusions have become globular in shape and are not aligned with the grain boundaries of the equiaxed grains. Micropores also tend to assume a spherical shape. In Figure 20, the same area is shown first unetched and then etched. Even after prolonged homogenization time, areas surrounding some of the larger inclusions and micropores still appear to be richer in alloy content than areas free of inclusions and micropores. Apparently, inclusions and micropores tend to retard the diffusion of alloying elements during the homogenization treatment.

The effect of homogenization heat treatment is even more vividly illustrated in Figure 21, which shows the inclusions before and after homogenization in a 3/8-inch-thick specimen of AISI Type 310 stainless-steel plate that was inserted into the homogenization box and held at a temperature of 2400 F for 64 hours alongside a unidirectionally solidified casting. Apparently, elongated nonmetallic inclusions present in the stainless-steel plate were completely spheroidized during the homogenization heat treatment.

Shape and Distribution of Inclusions in Plates

A remarkably uniform distribution of inclusions was maintained in the hot-rolled plates from fully homogenized castings. Figure 22 shows the inclusions present on one such plate at a location that exhibited a very high concentration of nonmetallic inclusions. In addition to being uniformly distributed, the inclusions are much smaller in the plate than in the homogenized castings, Figure 22A. Moreover, hot cross-rolling the homogenized unidirectionally solidified castings did not flatten the inclusions or cause formation of stringers. At 500X magnification, Figure 22B, the inclusions appear to be duplexed and, although they are not completely spherical, they are not elongated. The uniform distribution and compact shape of the inclusions very probably contribute to the superior ballistic properties of the plates. Plates with fewer inclusions of the same shape and distribution as those shown in Figure 22 would be expected to exhibit still better ballistic properties.

As was shown for castings, plates hot-rolled from copper chill castings had the greatest number of the smallest, size 1 and 2, inclusions, and plates rolled from the refractory-chill castings had the greatest number of the large, size 4 and 5, inclusions, Figure 23 and Table X. In general, hot rolling substantially increased the number of small inclusions and decreased the number of large inclusions. This would indicate fracture of the inclusions and subsequent separation of the fragments by the matrix material, an observation reported by Singh and Flemings.[6)]

No banding was observed in plates hot-rolled from completely homogenized unidirectionally solidified castings. However, plates rolled from unhomogenized castings exhibited banding, as shown in Figure 24. After partial homogenization (holding for 32 hours at 2300 F), plates rolled from the top and middle third of a copper-chilled casting still showed banding, but there was no banding in plates rolled from the bottom third of the casting where the homogenization was complete, Figure 25.

Chemical Composition and Mechanical and Ballistic Properties of Experimental Armor Plate Produced From Unidirectionally Solidified Steel

Chemical Composition

The chemical composition of the heats of steel from which experimental armor plates were produced is shown in Table XI. Carbon was the only element that varied significantly and ranged in the plates from a low of 0.50 percent to a high of 0.66 percent. Sulfur ranged from 0.004 to 0.006 percent, oxygen from 11 to 19 ppm, nitrogen from 0.002 to 0.003 percent, phosphorus below 0.002 percent, and hydrogen from 0.18 to 0.35 ppm. Thus, the contents of most of the harmful nonmetallic elements were low, although still lower contents would be desirable.

Mechanical Properties

The mechanical properties of selected armor plates are listed in Table XII. It is interesting to note that the ultimate tensile strength of most plates was higher than expected on the basis of Bhn hardness. With the exception of Heat Z20140-1, the steels exhibited excellent ductility. The tensile specimens exhibited cup and cone fractures that were about equally divided between the two halves of the specimen in an irregular pattern, Figure 26. The CVN energy-absorption values were relatively low, ranging from 7 to 9 ft-lb at 78 F, except for the low-ductility Heat Z20140-1, but were good for low-alloy steels heat-treated to the range Bhn 550 to 600.

Qualitative Results of Ballistic Tests

A total of 20 plates were subjected to ballistic tests. The ballistic performance of the plates is described in Table XIII. The plates are rated relative to each other by velocity merit rating (actual velocities are not shown). The best ballistic performance was exhibited by plates Z20139-1, shown in Figures 27A and 27B, and Z20674-3. Both plates had the lowest carbon content, 0.50 percent, and a hardness of Bhn 555. Plates harder than Bhn 578 shattered upon ballistic impact.

Other plates, for example Z20142-2, did not crack but were easily penetrated by caliber 0.50 AP projectiles and had a lower velocity merit rating, Figures 28A and 28B. Plate Z20674-1, an 0.742-inch-thick plate, completely resisted penetration by three caliber 0.50 AP projectiles, one of which was propelled by the maximum safe powder charge. There were no cracks visible in the impact area when the plate was inspected after the tests. However, the following day a crack was observed running from one impact area to another. When this part of the plate was cut off, additional cracks appeared in the impacted area, Figure 29A. The remainder of the plate that did not show any surface cracks was ground thinner and again subjected to ballistic tests. This time the plate cracked after two shots and broke into four pieces after a third shot, Figures 29B and 29C. Two projectiles completely penetrated the plate and knocked out solid plugs. There was no back spalling.

Plate Z20675-1, a 3/4-inch-thick plate, also resisted penetration by caliber 0.50 AP projectiles and thus was ground thinner. When ballistically tested after grinding, the plate broke into three pieces after one shot and into seven pieces after two shots. No merit rating was obtained for this plate.

Plate Z20675-2, which was given the spheroidizing heat treatment prior to the final quench, did not break into pieces or crack even after eight shots, six of which completely penetrated the plate, Figures 30A and 30B. However, this plate was more easily penetrated than other plates of the same hardness and thus received a lower ballistic rating.

The better performances of plate Z20674-1, as compared with plate Z20675-1, both of which received the same heat treatment, may be attributed to the lower percentage of retained austenite in plate Z20674-1 (8%) than in plate Z20675-1 (11%), Table II. Eight percent retained austenite was the minimum amount found in plates that were subjected to ballistic testing in this program.

The absence of severe back spalling was encouraging. Projectiles with kinetic energies sufficiently high to completely penetrate the plates pushed out solid plugs of steel instead of causing back spalling. The homogeneous structure of the plate probably contributed greatly to this desirable effect.

In summary, unidirectionally solidified wrought steel plates performed ballistically better than equivalent conventially processed homogeneous high-hardness steel armor plates (i.e: velocity merit rating greater than 1.0), and compared favorably with commercial dual-hardness armor plate.

Structure Changes in Plates Caused by Ballistic Impact

Areas immediately below the ballistic craters in test armor plates were examined metallographically. Shear bands or white streaks that occur on projectile impact and are presumably produced by adiabatic heating in areas of high shear deformation were observed under the microscope on specimens etched in 5 percent nital, Figure 31. The nital etchant did not attack the shear band, and a specimen etched in picral showed very little detail, Figure 32. A sodium bisulfite etchant did attack it and developed what appeared to be the grain structure of the band. An electron micrograph of a plastic replica of the etched shear band surface is shown in Figure 33. The micrograph indicates that the average grain diameter in the shear band (white streak) region might be no more than 0.2 micron.

Thin foils containing sections of these shear bands were made and examined by R. C. Glenn and W. C. Leslie of the United States Steel Corporation Edgar C. Bain Laboratory for Fundamental Research. The foils were examined in a Philips EM300 microscope at 100 KV. The transition from tempered martensite in the bulk to the white streak structure was gradual. The electron-diffraction patterns showed a body-centered-cubic structure, and the rings in the pattern from the shear band indicate that the grain size in the shear band is ultrafine, Figure 34. The ring diffraction pattern of the shear band was present even with a 10-micron aperture, which selects an area approximately 1.3 microns in diameter. The electron micrographs and diffraction patterns in Figure 35 show the respective variations between the structures in the tempered martensite of the unaffected plate and the fine martensite of the shear band.

Shock waves are created in the armor plate by the conversion of the projectile impact energy to sonic shear stress waves within the plate. At certain discrete nodes these shock waves cause a hot plastic deformation of the tempered martensite.

The temperature and pressure in these regions are increased sufficiently to cause a transformation to austenite. The cold mass of the plate acts as a heat sink to provide a very rapid quench of the austenite to martensite. There is no time for grain growth in the austenite, and thus the resulting structure in the shear bands does not resemble conventional martensite. The elastic stress created by ballistic impact in the plate causes crack initiation within the shear band martensite. These cracks propagate into the tempered martensite and contribute to plate failure during ballistic impact. Similar shear bands have previously been studied by Abbott,[7] who reported that crater surface cracks propagate along shear bands that are formed in the plate at sonic speeds.

A microhardness survey within the shear-band microstructure showed an average hardness of R_C 67 (converted from Knoop hardness). The high hardness of shear bands has been described[8] as being due to the presence of a very fine cell structure (or to the fine-grain structure developed in this case) and to the segregation of solute carbon atoms to the cell walls where the dislocation density is highest.

Conclusions

The present investigation has shown that unidirectionally solidified slab castings can be produced by using copper, cast-iron, or refractory-brick chill blocks. As expected, the secondary dendrite arm spacing of the castings depended on the effectiveness of the chill and the distance from the chill surface. Complete homogenization of alloying elements was achieved in 5-1/2-inch-thick unidirectionally solidified (copper chill) slabs of 0.6C-1Ni-0.5Cr-0.5Mo armor steel by holding the slabs at 2400 F for 64 hours. The homogenization treatment caused consolidation of inclusions and micropores and perhaps changed the composition of inclusions so that they did not flatten or "stringer" during subsequent rolling to plate. Hot rolling significantly increased the number of small inclusions and decreased the number of large inclusions present.

Superior-quality homogeneous wrought steel armor plate was produced from unidirectionally solidified and homogenized slab castings up to 10 inches wide by 16 inches long by 5-1/2 inches high weighing up to 240 pounds. Several 3/4-inch-thick plates heat-treated to a hardness of Bhn 555 resisted complete penetration by caliber 0.50 AP projectiles. Somewhat thinner plates that were completely penetrated by 0.50 AP projectiles did not crack or back-spall. By comparison, the hardness of conventionally processed homogeneous steel armor must be kept below a hardness of Bhn 535 to prevent cracking or back-spalling.

As has been reported previously, shear bands (white streaks) were noted in the vicinity of the craters formed on ballistic impact in the unidirectionally cast and homogenized wrought steel armor plate, and fractures in the plate were found to be associated with the shear bands. Electron micrographs and electron-diffraction patterns of the shear bands revealed that they were composed of ultra-fine-grain martensite. The bands were of very high hardness. The high hardness is believed to be due to the very fine grain structure and the ability of this structure to hold carbon in solution.

Some of the microstructural and other factors that can adversely affect the ballistic properties of armor plate and ways suggested by the present investigation for the minimization of these factors are listed in Table XIV. Additional work based on the results of the present investigation may lead to the production of wrought steel homogeneous armor plate with hardnesses in the range Bhn 570 to 600 that would not crack or back-spall and to the improvement of dual-hardness armor plate. Additional studies are also recommended to further scale up the size of unidirectionally solidified castings and finally to develop procedures for producing production-size unidirectionally cast slabs and homogenized production-size plates of homogeneous and dual-hardness armor with superior ballistic properties.

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Appendix I

List of Heats From Which Unidirectionally Solidified Castings Were Produced

Steel L 0.3C-5.0Ni-0.5Cr-0.5Mo-0.08V, Air-Melted

ARL Heat Number	Charge, pounds	Chill Plate Type	Number of Castings	Purpose and Disposition
Y-9552	260	Cast Iron	1	Establish gating design and casting technique; macrosegregation studies.
Y-9553	520	Cast Iron	3	
Y-9622	520	Copper	3	Determine procedure for use of mold wash and exothermic material; macrosegregation studies.
Y-9623	520	Cast Iron	3	
Y-9677	500	Copper, Cast Iron, Refractory Brick	4	Study effect of solidification rates on size and distribution of inclusions. Determine mechanical properties of castings and of hot-rolled plates. Establish heat treatments.
Y-9678	550	Copper, Refractory Brick	3	Develop improved mold gating design.
Y-9813	550	Copper	4	Determine effect of various hot-rolling parameters on microstructure; homogenization and heat-treatment studies.
Y-9814	550	Copper, Refractory Brick	3	
Y-9850	550	Copper, Sand Mold	3	
Y-9851	550	Refractory Brick, Sand Mold	3	
Y-9864	550	Copper, Refractory Brick	3	Defective castings;*** scrapped

Appendix I (Continued)

Steel H 0.6C-1.0Ni-0.5Cr-0.5Mo, Vacuum-Melted

ARL Heat Number	Charge, pounds	Chill Plate Type	Number of Castings	Purpose and Disposition
Z20138	200	Copper	1	Defective casting ***
Z20139	200	Copper	1	* **
Z20140	200	Copper	1	* **
Z20141	200	Copper	1	**
Z20142	200	Copper	1	* **
Z20168	275	Copper	1	Defective casting ***
Z20169	275	Copper	1	
Z20674	250	Copper	1	* **
Z20675	250	Copper	1	**
Z20681	250	Copper	1	Not used, off analysis
Z20682	250	Copper	1	Not used, off analysis

* Mechanical properties determined.

** Ballistically tested.

*** Castings contained blow holes caused by entrapped particles of sand or exothermic mix.

Appendix II

Times Required for Homogenization of Low-Alloy Steel

Diffusion Coefficients:

For nickel

$$D_{Ni}^{Fe} = \left[0.344 + 0.012 \ (\%Ni)\right] \left[1 + 2.3 \ (\%C)\right] e^{-67,500/RT}$$

where R = gas constant = 1.987 cal/^{o}K mole

T = temperature, K

For steel containing 1% Ni and 0.5% C

$$D_{Ni}^{Fe} = 0.77 \ e^{-34,000/T}$$

where T = temperature, K

For manganese

$$D_{Mn}^{Fe} = 0.49 \left[1 + 2.53 \ (\%C)\right] e^{-66,000/RT}$$

For steel containing 0.5% C

$$D_{Mn}^{Fe} = 1.11 \ e^{-33,200/T}$$

For chromium

For steel containing 0.8% C

$$D_{Cr}^{Fe} = 10 \ e^{-75,000/RT}$$

$$\text{or} \quad D_{Cr}^{Fe} = 10 \; e^{-37,700/T}$$

For molybdenum

$$D_{Mo}^{Fe} = 6.8 \times 10^{-2} \; e^{-59,000/RT}$$

$$\text{or} \quad D_{Mo}^{Fe} = 6.8 \times 10^{-2} \; e^{-29,700/T}$$

Homogenization Times:

Homogenization of nickel is essentially complete when

$$\frac{D_{Ni}^{Fe} \theta}{L^2} = 0.4$$

D_{Ni}^{Fe} = Diffusion coefficient of nickel, cm^2/sec.

θ = time, seconds

L = distance between maximum and minimum concentration of nickel, cm.

Similarly for manganese

$$\frac{D_{Mn}^{Fe} \theta}{L^2} = 0.5$$

Likewise, assuming for chromium and molybdenum

$$\frac{D_{Cr}^{Fe} \theta}{L^2} = 0.5$$

$$\frac{D_{Mo}^{Fe} \theta}{L^2} = 0.5$$

Temperature, F	Diffusing Element	Homogenization Times, hours			
		L = 50μ	L = 100μ	L = 150μ	L = 200μ
2300	Ni	16	62	139	248
	Mn	8	32	72	128
	Cr	17	66	149	264
	Mo	13	52	116	208
2400	Ni	7	29	64	116
	Mn	4	15	33	60
	Cr	7	28	63	112
	Mo	7	27	60	108
2500	Ni	2	9	21	36
	Mn	2	7	16	28
	Cr	3	13	29	52
	Mo	4	14	31	64

Assuming L to be equal to one half the secondary dendrite arm spacing and a maximum secondary dendrite arm spacing of 300 microns, holding for 64 hours at 2400 F should be sufficient to homogenize the castings.

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Table I

Nominal Composition of Steels

Steel	C	Mn	P	S	Si	Ni	Cr	Mo	V	Al
	Chemical Composition, percent									
L	0.28	0.75	LAP*	LAP*	0.40	5.00	0.55	0.55	0.08	0.030
H	0.60	0.75	LAP*	LAP*	0.25	1.00	0.50	0.50	-	0.030

* Low as possible.

Note: L stands for low-carbon composition and H for high-carbon composition.

Table II

Heat-Treatment Schedule

Plate No.	Heat Treatment Type	Heat Treatment Procedure (Temp F)	Carbon Content, %	Brinell Hardness No.	Retained Austenite,* %
Z-20139-1	A	1 hr 1750, Oil; 1/2 hr 500 → 1500; 1 hr 1500, Oil; 2 hr 300, Oil; 2 hr 325, Oil; 2 hr 350, Air; 2 hr 425, Air	0.50	555	8
Z-20139-2	B	1 hr 1650, Air; 1 hr 1480, Air; 2 hr 1290, Air; 1 hr 1500, Oil; 2 hr 300, Air; 2 hr 325, Air	0.50	578	-
Z-20140-1	C	1 hr 1500, Oil; 1 hr 350, Air	0.66	600	14
Z-20140-2	C	1 hr 1500, Oil; 1 hr 450, Air	0.66	588	-
Z-20140-3	A-1	1 hr 1650, Oil; 1 hr 500 → 1500; 1 hr 1500, Oil; 2 hr 375, Oil	0.66	600	-
Z-20141	B-1	1 hr 1650, Air; 1 hr 1450, Air; 2 hr 1290, Air; 1 hr 1500, Oil; 2 hr 350, Air	0.62	555	-
Z-20142-1	A-2	1 hr 1650, Water; 1 hr 1500, Water; 1 hr 550, Air	0.50	557	-
Z-20142-2	A-3	1 hr 1650, Oil; 1 hr 1500, Oil; 1 hr 555, Air	0.50	555	-

(Continued)

Table II (Continued)

Heat-Treatment Schedule

Plate No.	Type	Heat Treatment Procedure (Temp F)	Carbon Content, %	Brinell Hardness No.	Retained Austenite, %*
Z-20168-A-1	A-4	1 hr 1650, Oil; 1 hr 1500, Oil; 1 hr 300, Air	0.64	555	-
Z-20168-B-1	B-1	1 hr 1650, Air; 1 hr 1450, Air; 2 hr 1290, Air; 1 hr 1500, Oil; 2 hr 350, Air	0.64	555	-
Z-20168-B-2	A-5	1 hr 1750, Oil; 1/2 hr 500 → 1500; 1 hr 1500, Oil; 2 hr 350, Air	0.64	578	-
Z-20168-B-3	A-6	1 hr 1750, Oil; 1/2 hr 500 → 1500; 1 hr 1500, Oil; 2 hr 375, Air	0.64	555	-
Z-20674-1	A-7	1 hr 1800, Oil; 1/2 hr 500 → 1450; 1 hr 1450, Oil; 1 hr Freon bath at minus 105 F; 1 hr 375, Air	0.50	555	8
-1-A	A-7		0.50	555	8
-2	A-7		0.50	555	8
-3	A-7		0.50	555	8
Z-20675-1	A-7		0.54	555	11
-1-A	A-7		0.54	555	11
Z-20675-2	B-2	1/2 hr 1650, Air; 1/2 hr 1450, Air; 2 hr 1290, Air; 1/2 hr Freon bath at minus 105 F; 2 hr 400, Air	0.54	555	11
-3	B-2		0.54	555	11

* Determined by X-ray analysis.

Table III

Unidirectional Solidification Experiments— Chemical Composition

Sample Location	Ladle or Check Analysis, %												
	C	Mn	P	S	Si	Ni	Cr	Mo	V	N	Sol. Al	Total Al	O, ppm
Heat Y-9552													
Ladle	0.29	0.66	0.004	0.007	0.25	4.96	0.54	0.52	0.085	0.006	NA	0.019	NA
1/4*	0.29	0.56	<0.002	0.004	0.22	4.91	0.53	0.51	0.082	0.006	0.004	0.007	124
1-1/4*	0.31	0.61	0.002	0.005	0.26	4.91	0.54	0.53	0.084	0.006	0.004	0.009	108
2-1/4*	0.31	0.61	0.002	0.005	0.26	4.91	0.54	0.52	0.085	0.006	0.004	0.008	107
1/4**	0.33	0.64	<0.002	0.008	0.30	4.93	0.54	0.54	0.088	0.008	0.003	0.004	85
Heat Y-9553 A													
Ladle	0.30	0.94	<0.001	0.011	0.42	4.96	0.56	0.52	0.080	0.005	NA	0.046	NA
1/4*	0.29	0.90	<0.002	0.007	0.39	4.88	0.54	0.52	0.086	0.006	0.012	0.018	NA
1-1/4*	0.29	0.91	<0.002	0.007	0.40	4.92	0.54	0.54	0.088	0.006	0.012	0.018	55
2-1/4*	0.29	0.90	<0.002	0.008	0.38	4.95	0.54	0.53	0.090	0.005	0.011	0.016	45
1/4**	0.29	0.92	<0.002	0.009	0.42	4.96	0.54	0.54	0.087	0.005	0.012	0.016	49
Heat Y-9553 B													
1/4*	0.30	0.90	<0.002	0.007	0.39	4.96	0.54	0.52	0.088	0.005	0.011	0.018	NA
1-1/4*	0.29	0.90	<0.002	0.007	0.38	4.92	0.52	0.52	0.086	0.005	0.011	0.014	50
2-1/4*	0.29	0.90	<0.002	0.008	0.38	4.95	0.53	0.53	0.086	0.006	0.012	0.016	49
1/4**	0.30	1.04	<0.002	0.012	0.51	5.00	0.56	0.56	0.091	0.006	0.011	0.016	Porous

(Continued)

Table III

Unidirectional Solidification Experiments—
Chemical Composition (Continued)

Sample Location	C	Mn	P	S	Si	Ni	Cr	Mo	V	N	Sol. Al	Total Al	O,ppm
	Ladle or Check Analysis, %												
Heat Y-9553 C													
1/4*	0.29	0.88	<0.002	0.007	0.38	4.94	0.54	0.52	0.086	0.006	0.012	0.020	NA
1-1/4*	0.29	0.89	<0.002	0.008	0.37	4.97	0.54	0.52	0.088	0.005	0.013	0.020	58
2-1/4*	0.29	0.90	<0.002	0.008	0.38	4.96	0.54	0.52	0.088	0.006	0.012	0.020	50
1/4**	0.27	0.86	<0.002	0.007	0.38	4.89	0.50	0.48	0.081	0.005	0.014	0.024	77
Heat Y-9622 A													
Ladle	0.32	0.89	0.002	0.008	0.30	4.94	0.52	0.52	0.081	0.007	NA	0.070	NA
1/4*	0.32	0.90	<0.002	0.009	0.28	4.91	0.53	0.54	0.080	0.007	0.017	0.028	67
1-1/4*	0.32	0.89	<0.002	0.010	0.27	4.91	0.54	0.54	0.081	0.007	0.022	0.028	60
2-1/4*	0.32	0.90	<0.002	0.011	0.30	4.91	0.54	0.54	0.081	0.008	0.019	0.026	57
1/4**	0.29	0.89	<0.002	0.010	0.30	4.85	0.54	0.51	0.079	0.008	0.015	0.023	57
Heat Y-9622 B													
1/4*	0.31	0.89	<0.002	0.008	0.28	4.84	0.55	0.52	0.082	0.008	0.019	0.026	57
1-1/4*	0.26	0.86	<0.002	0.006	0.25	4.86	0.53	0.49	0.074	0.008	0.019	0.024	47
2-1/4*	0.31	0.92	<0.002	0.008	0.30	4.95	0.55	0.54	0.081	0.009	0.020	0.025	37
1/4**	0.30	0.90	<0.002	0.008	0.28	4.86	0.55	0.52	0.078	0.009	0.019	0.024	42

(Continued)

Table III

Unidirectional Solidification Experiments— Chemical Composition (Continued)

Sample Location	Ladle or Check Analysis, % C	Mn	P	S	Si	Ni	Cr	Mo	V	N	Sol. Al	Total Al	O,ppm
Heat Y-9622 C													
1/4*	0.30	0.89	<0.002	0.008	0.28	4.89	0.56	0.53	0.082	0.008	0.016	0.022	43
1-1/4*	0.28	0.86	<0.002	0.007	0.26	4.89	0.52	0.50	0.075	0.008	0.020	0.025	44
2-1/4*	0.31	0.91	<0.002	0.009	0.29	4.96	0.55	0.54	0.080	0.008	0.018	0.022	47
1/4**	0.30	0.90	<0.002	0.008	0.30	4.92	0.54	0.53	0.078	0.008	0.018	0.023	47
Heat Y-9623 A													
Ladle	0.30	0.85	<0.002	0.009	0.44	4.83	0.53	0.52	0.077	0.008	NA	0.059	NA
1/4*	0.30	0.88	<0.002	0.011	0.46	+	0.54	0.53	0.073	0.008	0.028	0.031	63
1-1/4*	0.30	0.88	<0.002	0.011	0.47	+	0.54	0.54	0.076	0.009	0.028	0.030	51
2-1/4*	0.31	0.88	<0.002	0.011	0.47	+	0.53	0.53	0.071	0.009	0.027	0.032	53
1/4**	0.30	0.88	<0.002	0.012	0.47	+	0.53	0.52	0.08	0.008	0.025	0.028	52
Heat Y-9623 B													
1/4*	0.31	0.89	0.002	0.011	0.47	+	0.53	0.53	0.076	0.008	0.025	0.029	64
1-1/4*	0.30	0.88	0.002	0.011	0.47	+	0.52	0.54	0.078	0.008	0.027	0.030	43
2-1/4*	0.31	0.85	0.002	0.011	0.44	+	0.51	0.51	0.074	0.008	0.025	0.029	62
1/4**	0.31	0.89	0.002	0.012	0.48	+	0.54	0.54	0.078	0.008	0.028	0.031	52

(Continued)

Table III

Unidirectional Solidification Experiments—
Chemical Composition (Continued)

Sample Location	C	Mn	P	S	Si	Ni	Cr	Mo	V	N	Sol. Al	Total Al	O, ppm
	Ladle or Check Analysis, %												
						Heat Y-9623 C							
1/4*	0.31	0.86	<0.002	0.008	0.45	+	0.52	0.52	0.08	0.008	0.023	0.028	56
1-1/4*	0.31	0.85	<0.002	0.010	0.44	+	0.51	0.51	0.074	0.008	0.022	0.027	55
2-1/4*	0.31	0.85	<0.002	0.009	0.43	+	0.53	0.52	0.078	0.008	0.027	0.032	56
1/4**	0.31	0.86	<0.002	0.011	0.46	+	0.52	0.52	0.073	0.008	0.030	0.034	98

\+ Not determined.
* Inches from bottom of casting.
** Inches from top of casting.

Table IV

Mechanical Properties of Unidirectional Castings
Heat Y-9677

2300 F Homogenization, hours	Distance From Chill, inches	Yield Strength at 0.2% Offset, ksi	Tensile Strength, ksi	Elongation, %	Reduction of Area, %	CVN Energy Absorption at 80 F, ft-lb
			Copper Chill Plate			
0	2-3/4	168.2	188.1	8.3	17.7	22
	1-7/8	169.2	189.8	7.9	25.1	25
	1-1/4	171.2	190.6	9.5	22.8	26
	1/4	171.2	189.5	13.2	41.5	27
4	2-3/4	168.2	191.0	12.6	38.3	24
	1-7/8	167.2	189.4	13.3	41.8	23
	1-1/4	168.5	188.9	14.0	43.8	26
	1/4	167.5	187.4	14.9	49.5	25
			Cast-Iron Chill Plate			
4	2-3/4	167.8	188.8	14.0	44.5	27
	1-7/8	166.3	189.6	13.5	41.9	24
	1-1/4	168.1	189.2	14.1	42.0	26
	1/4	166.5	187.9	14.9	50.2	26
8	2-3/4	167.2	187.8	14.4	44.2	26
	1-7/8	166.8	189.3	13.5	42.3	26
	1-1/4	167.5	188.9	13.9	42.8	25
	1/4	168.0	188.3	14.6	50.4	25
16	2-3/4	168.8	188.8	14.0	44.8	27
	1-7/8	167.5	189.4	14.8	46.2	25
	1-1/4	166.8	188.2	14.7	47.5	27
	1/4	167.2	187.6	14.9	51.3	26

(Continued)

Table IV (continued)

Mechanical Properties of Unidirectional Castings
Heat Y-9677

2300 F Homogenization, hours	Distance From Chill, inches	Yield Strength at 0.2% Offset, ksi	Tensile Strength, ksi	Elongation, %	Reduction of Area, %	CVN Energy Absorption at 80 F, ft-lb
Refractory-Brick Chill Plate						
4	2-3/4	168.1	186.5	12.1	35.8	25
	1-7/8	169.2	188.5	11.4	32.6	22
	1-1/4	167.6	187.6	12.4	33.0	29
	1/4	167.8	187.4	13.3	39.1	24

Average Hardness R_c 41.

Note: Castings were heat-treated as follows:
Austenitized at 1650 F for 3 hours, water-quenched; austenitized at 1500 F for 3 hours, water-quenched; tempered at 1000 F for 1 hour.

Chemical Composition of Heat Y-9677

C	Mn	P	S	Si	Ni	Cr	Mo	V	Al	N
0.29	0.75	<0.002	0.003	0.36	5.00	0.56	0.54	0.084	0.043	0.007

Table V

Mechanical Properties of 1/2-Inch-Thick Plates
Heat Y-9677

Chill Plate Type	Hours at 2300 F	Yield Strength at 0.2% Offset, ksi	Tensile Strength, ksi	Elongation, %	Reduction of area, %	CVN Energy Absorption, ft-lb 80F	CVN Energy Absorption, ft-lb -40F
Longitudinal Specimens							
Copper	0	172.4	192.3	16.0	53.7	31	28
Copper	4	170.9	191.8	16.4	56.6	30	26
Cast Iron	0	172.4	192.5	16.4	57.4	34	30
Cast Iron	4	173.1	192.5	16.3	55.6	35	30
Cast Iron	16	172.9	191.8	16.5	56.3	35	31
Refractory Brick	0	170.9	191.5	16.7	55.5	37	32
Refractory Brick	8	172.8	191.2	16.4	55.0	36	32
Average		172.5	192.0	16.3	55.6	34	30

(Continued)

Table V

Mechanical Properties of 1/2-Inch-Thick Plates

Heat Y-9677 (Continued)

Chill Plate Type	Hours at 2300 F	Yield Strength at 0.2% Offset, ksi	Tensile Strength, ksi	Elongation, %	Reduction of area, %	CVN Energy Absorption, ft-lb 80F	CVN Energy Absorption, ft-lb -40F
Transverse Specimens							
Copper	0	172.8	192.6	17.0	55.1	32	28
Copper	4	173.4	193.0	16.6	55.7	30	29
Cast Iron	0	172.4	192.8	16.6	56.0	33	30
Cast Iron	4	172.8	192.3	16.5	57.0	35	31
Cast Iron	16	173.0	192.3	16.4	56.8	36	32
Refractory Brick	0	173.0	191.7	15.8	53.6	38	34
Refractory Brick	8	172.9	191.3	16.4	54.4	38	33
Average		172.9	192.3	16.5	55.7	34	31

Note: Plates were heat-treated as follows: Austenitized at 1650 F for 1 hour, water-quenched; austenitized at 1500 F for 1 hour, water-quenched; tempered at 1000 F for 1 hour.

Average hardness for all specimens: $R_c = 41.0$.

Table VI

Microprobe Analysis of a Unidirectionally Solidified Casting Before and After Homogenization

Sample	Area	Composition, percent Mn	Ni	Cr	Mo	V
Y-9677-a (as-cast)	Interdendritic matrix	0.9	5.6	0.7	1.7	0.2
	Dendrite	0.6	4.5	0.5	0.4	ND
Y-9677-b (homogenized 64 hours)	Maximum	0.8	5.2	0.6	0.7	0.09
	Minimum	0.8	5.1	0.5	0.6	0.09
Ladle Analysis		0.75	5.0	0.56	0.54	0.084

ND = None detected.

Table VII

Distribution of Inclusions and Micropores in the As-Cast Product*

Size Group	Size Range, microns	Average Number of Inclusions and Micropores per Chill Plate Type**		
		Copper	Cast Iron	Refractory Brick
1	1.6 to 3.2	207	158	81
2	3.2 to 6.4	182	150	71
3	6.4 to 12.8	76	85	51
4	12.8 to 25.6	19	21	50
5	25.6 to 51.2	2	3	11
6	51.2 to 102.4	0	0	2

* Unidirectionally solidified 5Ni-Cr-Mo-V (0.30C) steel: heat Y-9677.

** Data based on the average values of two Autoscan analyses per sample.

Table VIII

Size and Distribution of Inclusions and Micropores in Unidirectionally Cast 5Ni-Cr-Mo-V Steel (0.30C)*
Heat Y-9677

Size** Group	No. of Inclusions and Micropores Distance From Chill Plate, inches 1/4	1-1/4	1-7/8	2-3/4	Average No.
			Copper Chill		
1	293	201	140	196	207
2	219	181	132	195	182
3	50	86	82	88	76
4	5	22	27	21	19
5	1	2	5	3	3
6	0	1	0	0	0
			Cast-Iron Chill		
1	207	182	130	114	158
2	226	159	89	125	150
3	89	92	86	73	85
4	45	21	23	16	21
5	2	5	3	2	3
6	0	0	0	0	0
			Refractory-Brick Chill		
1	59	89	95	81	81
2	56	79	87	61	71
3	53	56	45	49	51
4	62	76	27	35	50
5	10	15	11	8	11
6	4	1	1	3	2

* Based on averages of two Autoscan analyses per sample.

** See Table VII.

Table IX

Results of Ester-Halogen Analysis of
Castings and Plates for SiO_2 and Al_2O_3
Heat Y-9677

Chill Type	Distance From Chill, inches	Oxides, ppm* SiO_2	Al_2O_3
Copper	1/4	28	175
	1-1/4	23	145
	1-7/8	32	150
	2-3/4	23	125
	Hot-Rolled Plate	18	135
Cast Iron	1/4	14	140
	1-1/4	15	125
	1-7/8	10	93
	2-3/4	13	115
	Hot-Rolled Plate	15	135
Refractory Brick	1/4	9	120
	1-1/4	13	105
	1-7/8	11	82
	2-3/4	12	69
	Hot-Rolled Plate	18	107

* Averages of two results.

Table X

Distribution of Inclusions and Micropores in Hot-Rolled Plate Product*

Size Group	Size Range, microns	Average Number per Chill Plate Type**		
		Copper ***	Cast Iron ***	Refractory Brick ***
1	1.6 to 3.2	248 (+41)	175 (+17)	100 (+21)
2	3.2 to 6.4	149 (-33)	129 (-21)	86 (+15)
3	6.4 to 12.8	64 (-12)	48 (-37)	54 (+ 3)
4	12.8 to 25.6	5 (-14)	7 (-14)	14 (-36)
5	25.6 to 51.2	1 (-1)	1 (-2)	3 (- 8)
6	51.2 to 102.4	0	0	0 (- 2)

* Unidirectionally solidified 5Ni-Cr-Mo-V (0.30C) steel; 80 percent reduction to 1/2-inch-thick plate: heat Y-9677.

** Data based on the average values of two Autoscan analyses per sample.

*** Numbers in parentheses show the change in the average number of inclusions and micropores as compared with the as-cast product, Table VIII.

Table XI

Chemical Composition of Steels From Which Experimental Armor Plates Were Produced

Heat Number	Condition of Steel	Composition, percent										ppm,	ppm,
		C	Mn	P	S	Si	Ni	Cr	Mo	Al	N	O	H
Z20139	As-Cast	*	*	*	*	*	*	*	*	*	*	*	*
	Homogenized	0.50	0.74	0.002	0.004	0.26	1.01	0.49	0.50	0.032	0.003	11	0.35
Z20140	As-Cast	*	*	*	*	*	*	*	*	*	*	*	*
	Homogenized	0.66	0.78	0.002	0.005	0.30	1.07	0.53	0.52	0.049	0.003	27	0.20
Z20141	As-Cast	0.68	0.74	0.002	0.004	0.24	1.05	0.48	0.50	0.054	0.003	*	*
	Homogenized	0.62	0.73	0.002	0.005	0.26	1.05	0.48	0.50	0.048	0.003	17	0.20
Z20142	As-Cast	*	*	*	*	*	*	*	*	*	*	*	*
	Homogenized	0.50	0.73	0.002	0.006	0.24	1.02	0.47	0.50	0.056	0.003	19	*
Z20168	As-Cast	0.64	0.77	0.001	0.004	0.25	1.08	0.50	0.52	0.035	0.002	25	2.82
	Homogenized	0.64	0.77	0.001	0.002	0.29	1.09	0.51	0.53	0.048	0.002	19	0.18
Z20674	As-Cast	0.55	0.72	0.001	0.002	0.25	0.99	0.49	0.49	0.067	0.003	36	*
	Homogenized	0.50	0.74	0.001	0.002	0.23	1.01	0.48	0.49	0.076	0.002	13	*
Z20675	As-Cast	0.54	0.70	0.001	0.007	0.27	1.01	0.48	0.50	0.079	0.002	36	2.28
	Homogenized	0.54	0.75	0.001	0.005	0.26	0.99	0.50	0.49	0.062	0.003	13	*

* Not determined.

Table XII

Mechanical Properties of Selected Wrought Steel Armor Plates

Plate No.	Hardness, Bhn	Yield Strength at 0.2% Offset, ksi	Tensile Strength, ksi	Elongation, %	Reduction of Area, %	CVN Energy Absorption, ft-lb 78F	CVN Energy Absorption, ft-lb -40F
Z-20139-1	555	197.2	340.4	4.75	27.4	7	3
Z-20140-1	600	174.8	351.0	2.0	2.4	3	2
Z-20140-2	588	245.2	337.0	9.0	29.0	7	2
Z-20142-2	555	262.0	307.0	8.7	34.2	8	7
Z-20674-1	555	272.2	334.1	8.0	30.1	9	7

Table XIII

Ballistic Performance of Unidirectionally Solidified Wrought Steel Armor Plates

Plate Number	Heat-Treatment Type*	Hardness, Bhn	Thickness, inch	Areal Density, lb/ft^2	Velocity Merit Rating
Z-20139-1	A	555	0.699/0.753**	28.5/30.7	1.39
-2	B	578	0.733/0.753**	29.9/30.7	1.36
Z-20140-1	C	600	0.503	20.5	1.29
-2	C	588	0.498	20.3	1.21
-3	A-1	600	0.506	20.6	1.28
Z-20141	B-1	555	0.543	22.2	>1.20
Z-20142-1	A-2	557	0.502	20.5	1.23
-2	A-3	555	0.505	20.6	1.28
Z-20168-A-1	A-4	555	0.538	21.9	1.26
Z-20168-B-1	B-1	555	0.533	21.7	1.34
-2	A-5	578	0.501	20.4	1.24
-3	A-6	555	0.529	21.6	1.24
Z-20674-1	A-7	555	0.742	30.3	1.34
-1A	A-7	555	0.700	28.6	1.33
-2	A-7	555	0.703	28.7	1.35
-3	A-7	555	0.702	28.6	1.39

(Continued)

Table XIII

Ballistic Performance of Unidirectionally Solidified Wrought Steel Armor Plates
(Continued)

Plate Number	Heat-Treatment Type*	Hardness, Bhn	Thickness, inch	Areal Density lb/ft^2	Velocity Merit Rating
Z-20675-1	A-7	555	0.758	30.9	>1.27
-1A	A-7	555	0.707	28.8	--
-2	B-2	555	0.704	28.7	1.28
-3	B-2	555	0.704	28.7	1.30

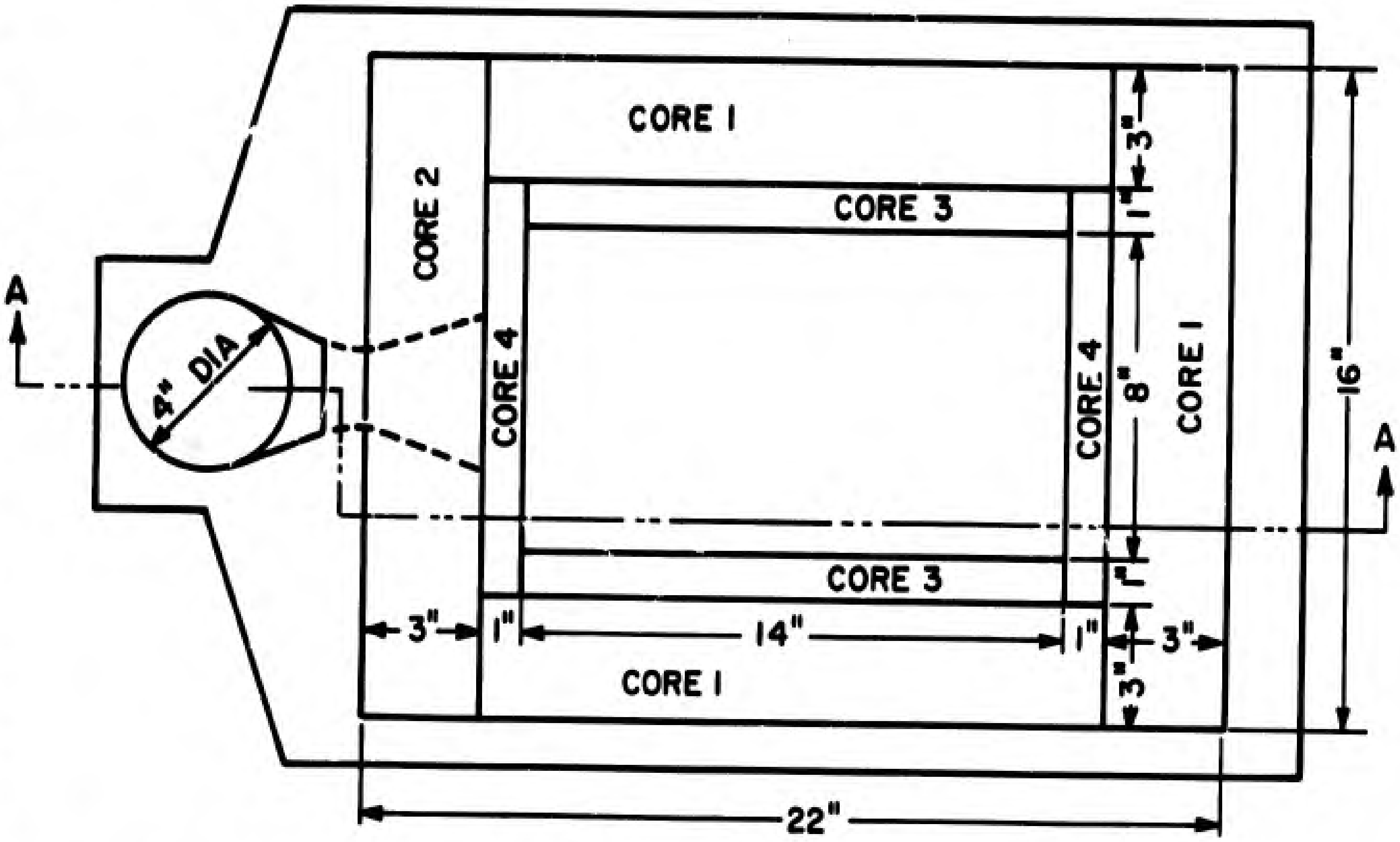
* See Table II

** Plates bowed during heat treatment and were subsequently ground; hence the variation in thickness.

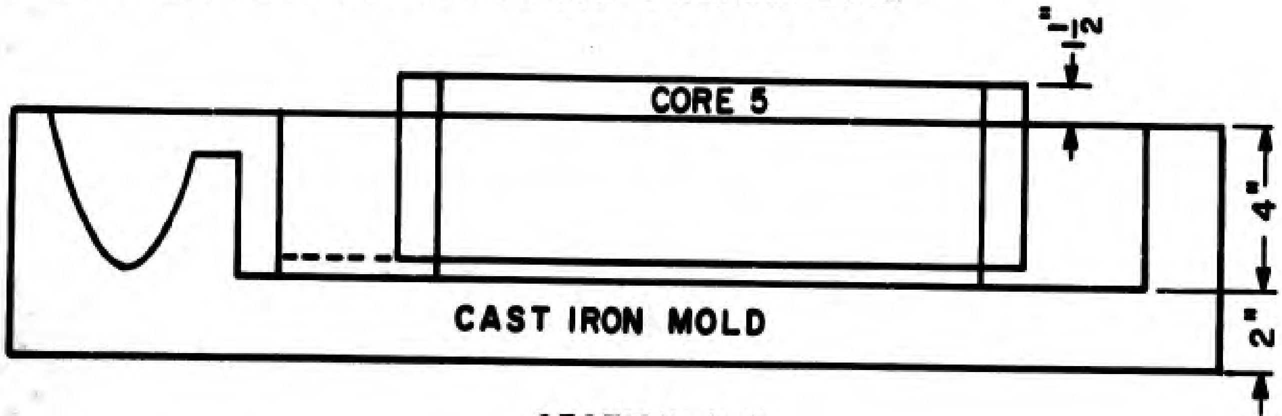
Table XIV

Factors Adversely Affecting Ballistic Performance and Suggested Solutions

Problems	Suggested Solutions
Macroporosity Macrosegregation	Unidirectional Solidification
Microporosity Microsegregation	Hot Working Homogenization Heat Treatment
Number and Size of Inclusions	Low Sulfur and Oxygen Content Fast Cooling Rates Hot Working
Inclusion Distribution	Unidirectional Solidification
Retained Austenite	Minimum Carbon Content for Desirable Hardness
Low Toughness	Optimum Alloy Content Rapid Heat Treatment
Back Spalling	Dual-Hardness Plate Homogenization Heat Treatment



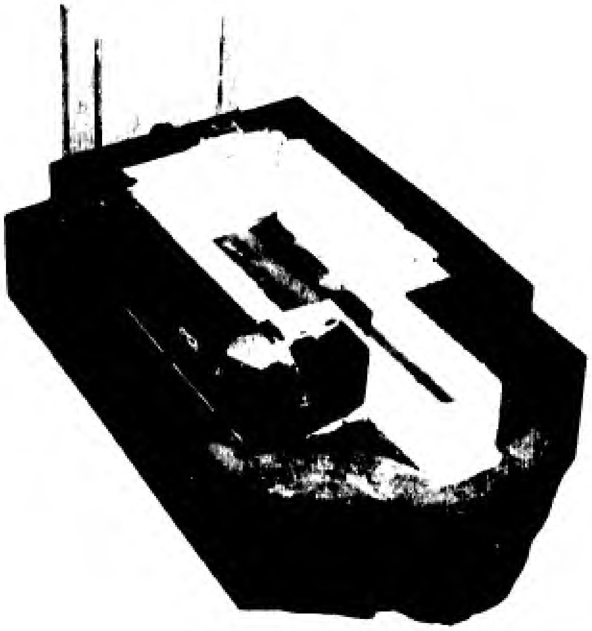
CORES I AND 2 AIR-SET SAND
CORES 3,4,AND 5 EXOTHERMIC CORES (EXOMOLD E)



SECTION A-A

MOLD FOR PRODUCTION OF 100-POUND UNIDIRECTIONALLY SOLIDIFIED STEEL INGOT

FIGURE I



A) Exothermic lid removed.

B) Ready for casting.

Figure 2. Unidirectional mold.

P-8439A-1
P-8439A-2

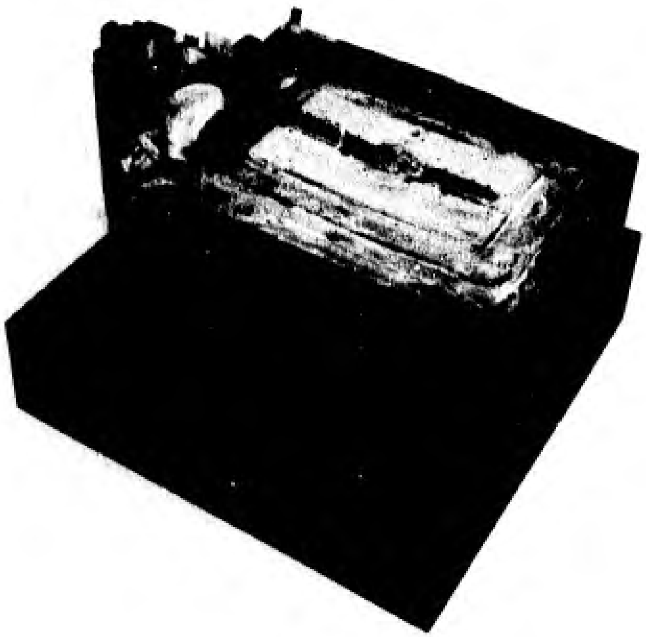


Figure 3. Simplified mold assembled on a 6-inch-thick copper block with a 240-pound steel slab casting.

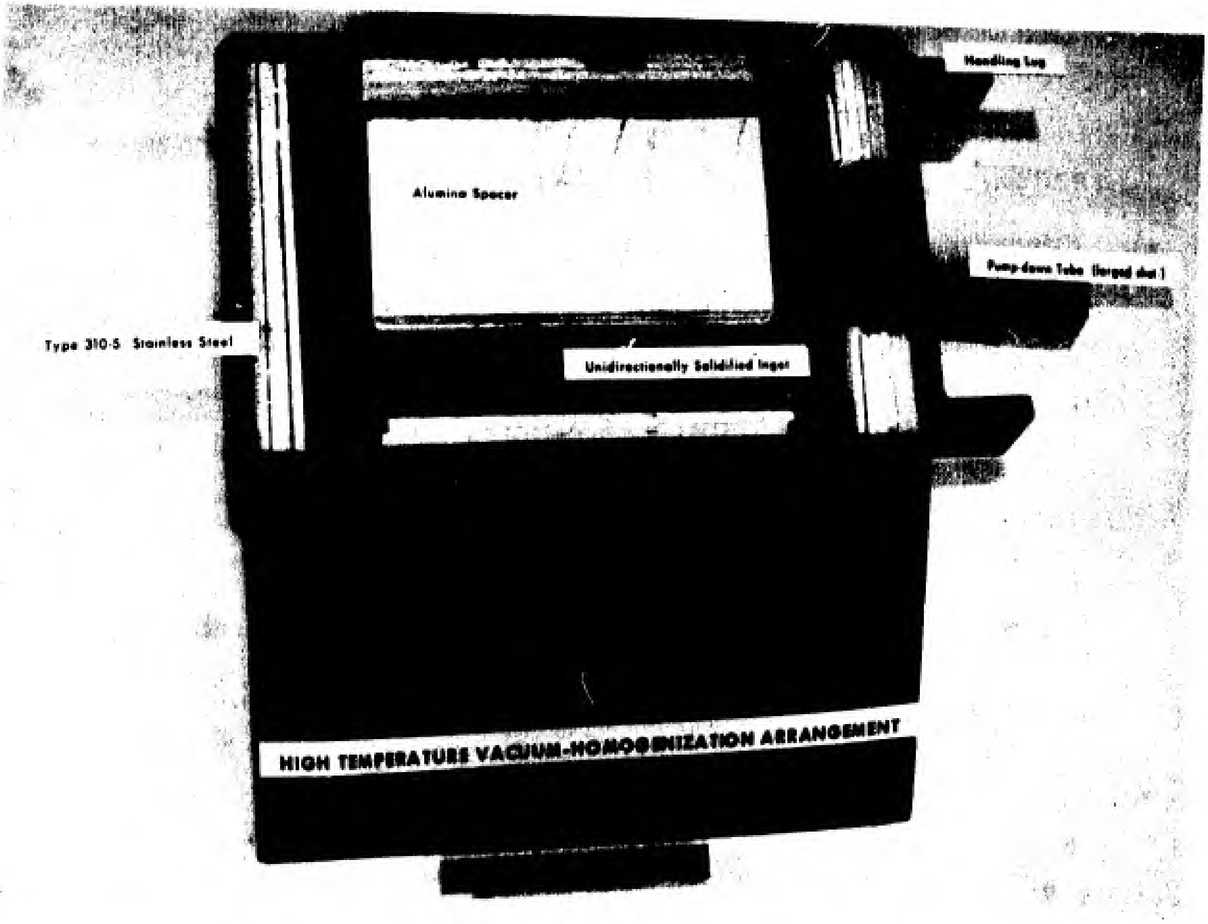
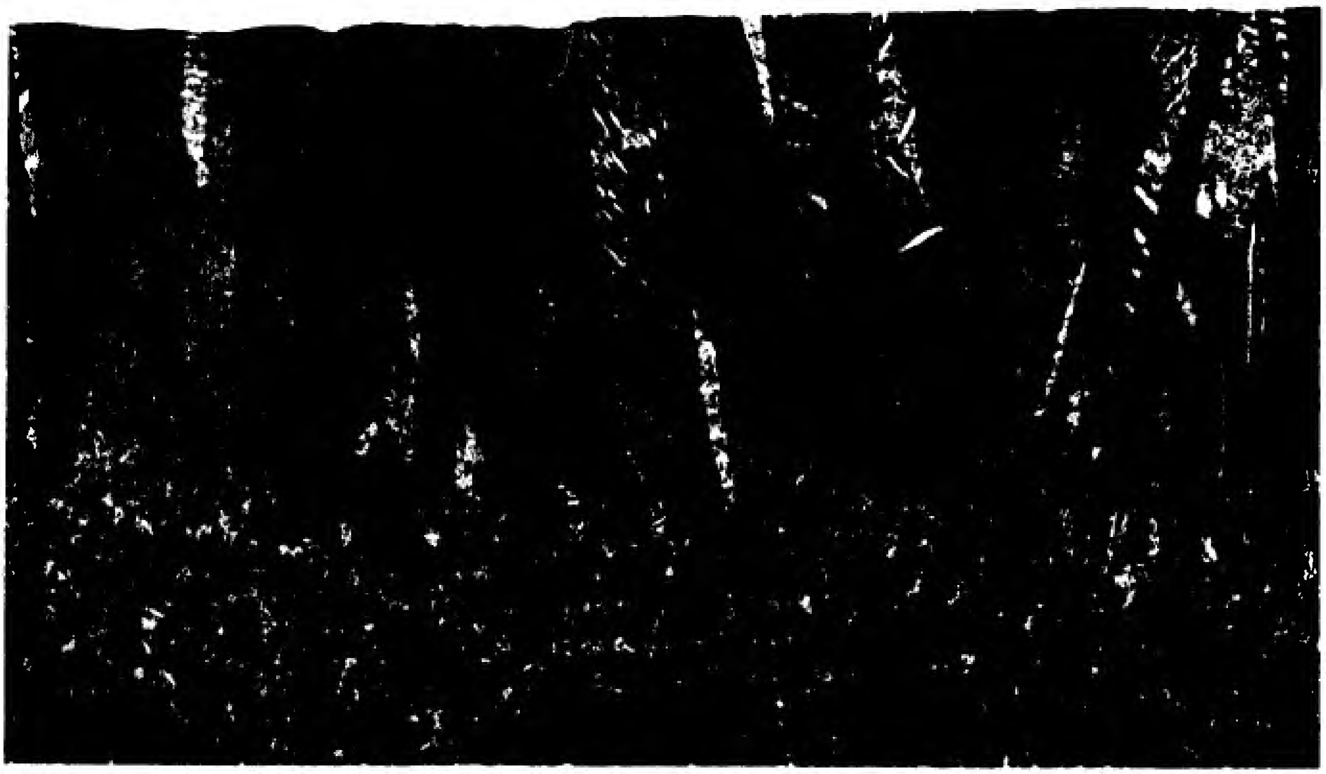


Figure 4. Homogenization box containing a unidirectionally solidified steel casting separated from the Type 310 stainless-steel walls by alumina spacers.

Top



Bottom

Figure 5. Section from longitudinal slice through center of casting showing mixed columnar and equiaxed grain structure. Pouring temperature 2760 F. Cast-iron chill. Heat Y-9553. X1.

Etchant: 1500 ml saturated aqueous solution of ferric chloride; 300 ml c.p. hydrochloric acid; 150 ml (30%) hydrogen peroxide.

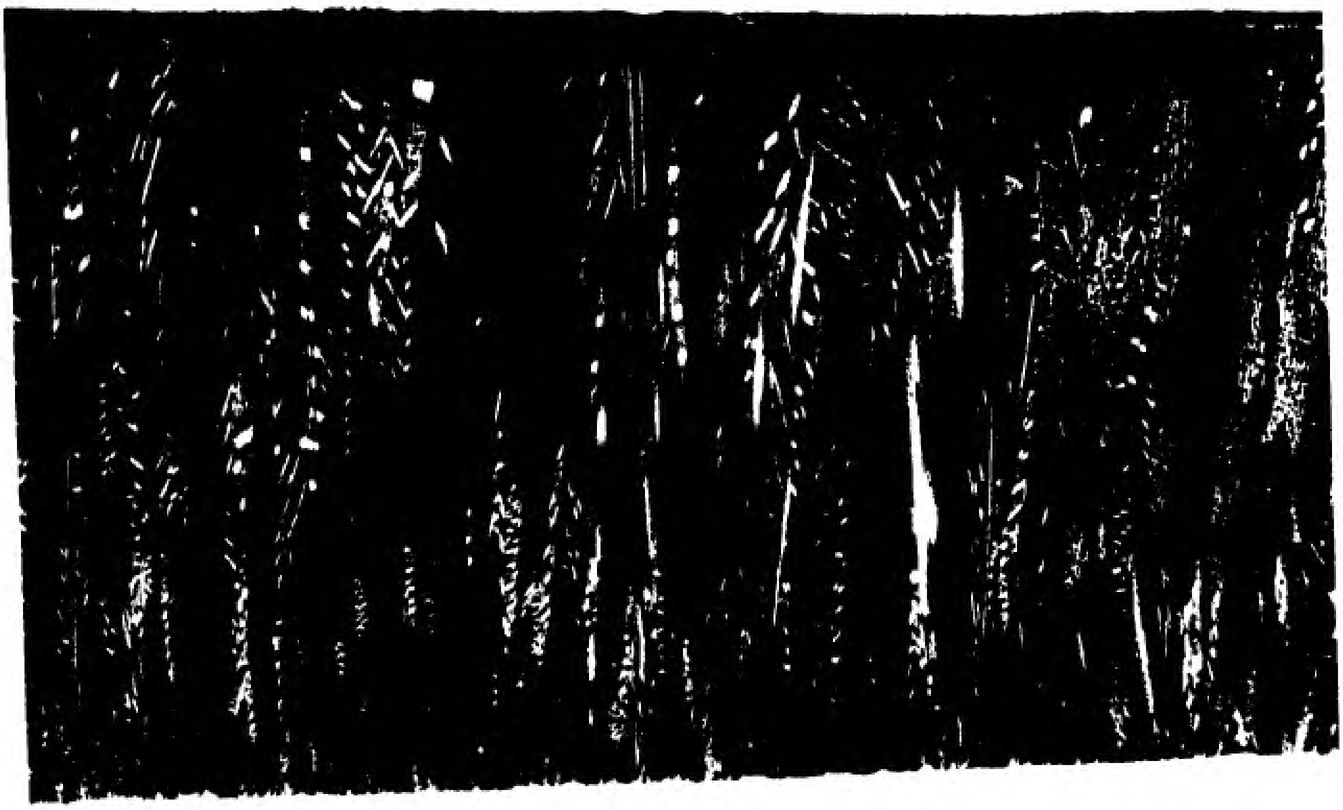
Top

Bottom

Figure 6. Typical columnar macrostructure of unidirectionally solidified steel cast on a copper chill plate. Longitudinal slice through center of ingot. Heat Y-9677-A. X1.

Etchant: See Figure 5.

Top

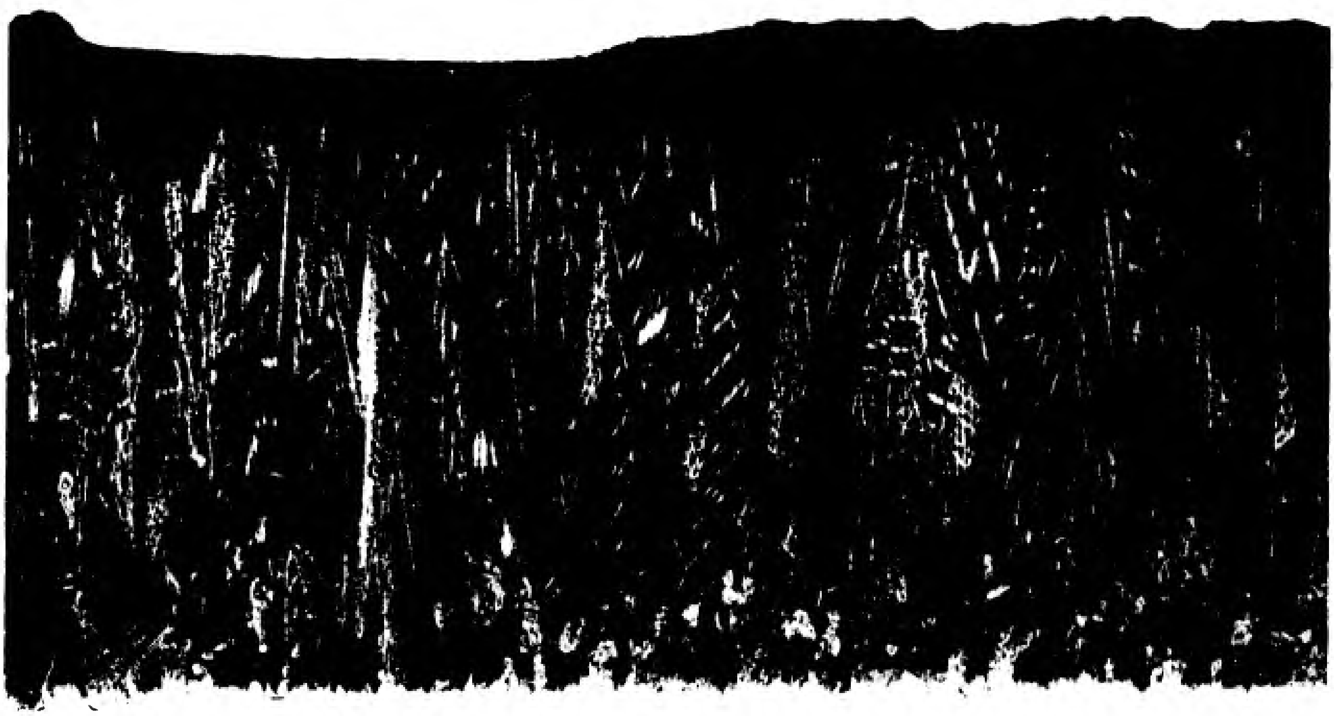


Bottom

Figure 7. Typical columnar macrostructure of unidirectionally solidified steel cast on a cast-iron chill plate. Longitudinal slice through center of ingot. Heat Y-9677-B. X1.

Etchant: See Figure 5.

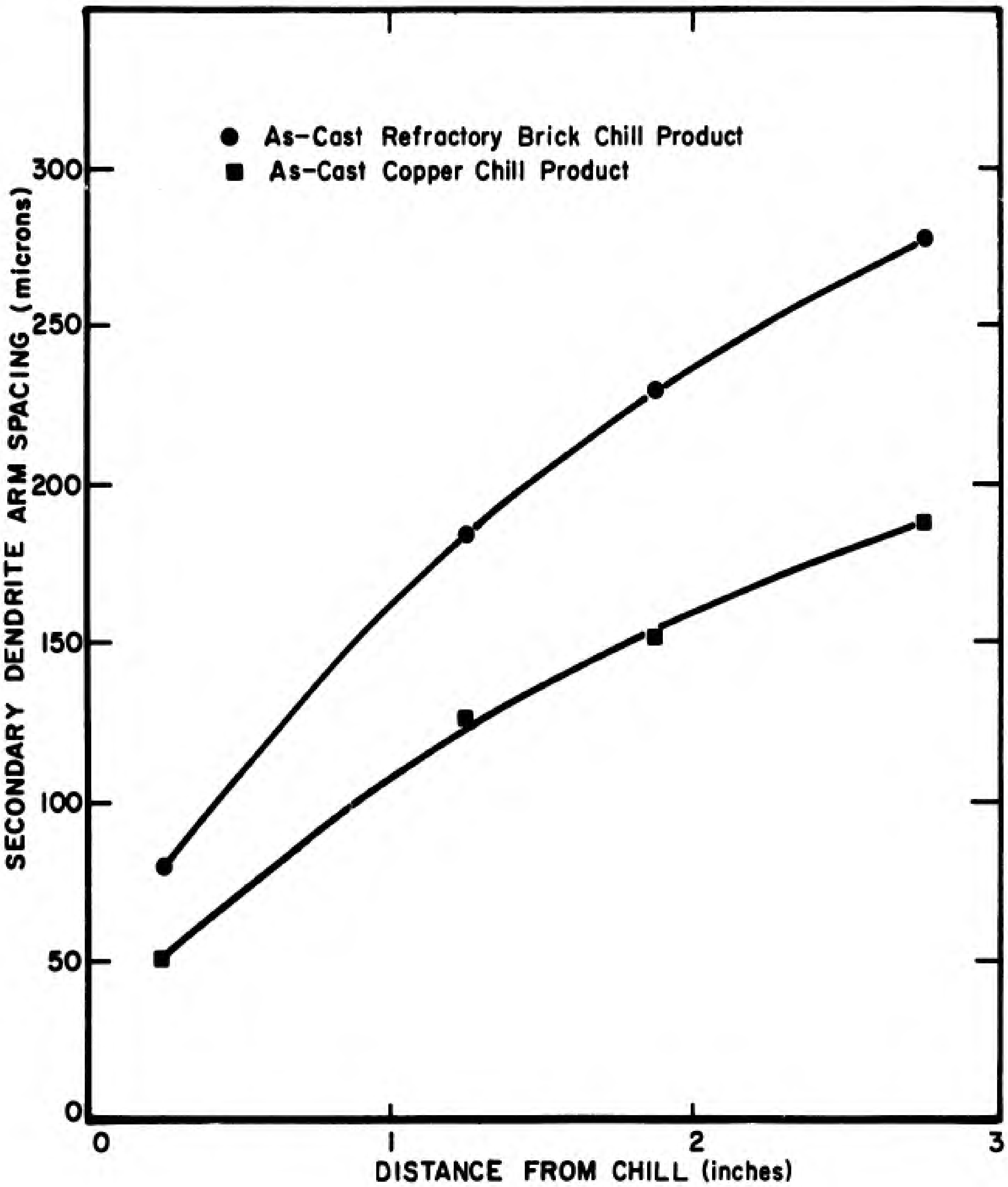
Top



Bottom

Figure 8. Typical columnar macrostructure of unidirectionally solidified steel cast on a refractory-brick chill plate. Longitudinal slice through center of ingot. Heat Y-9677-D. X1.

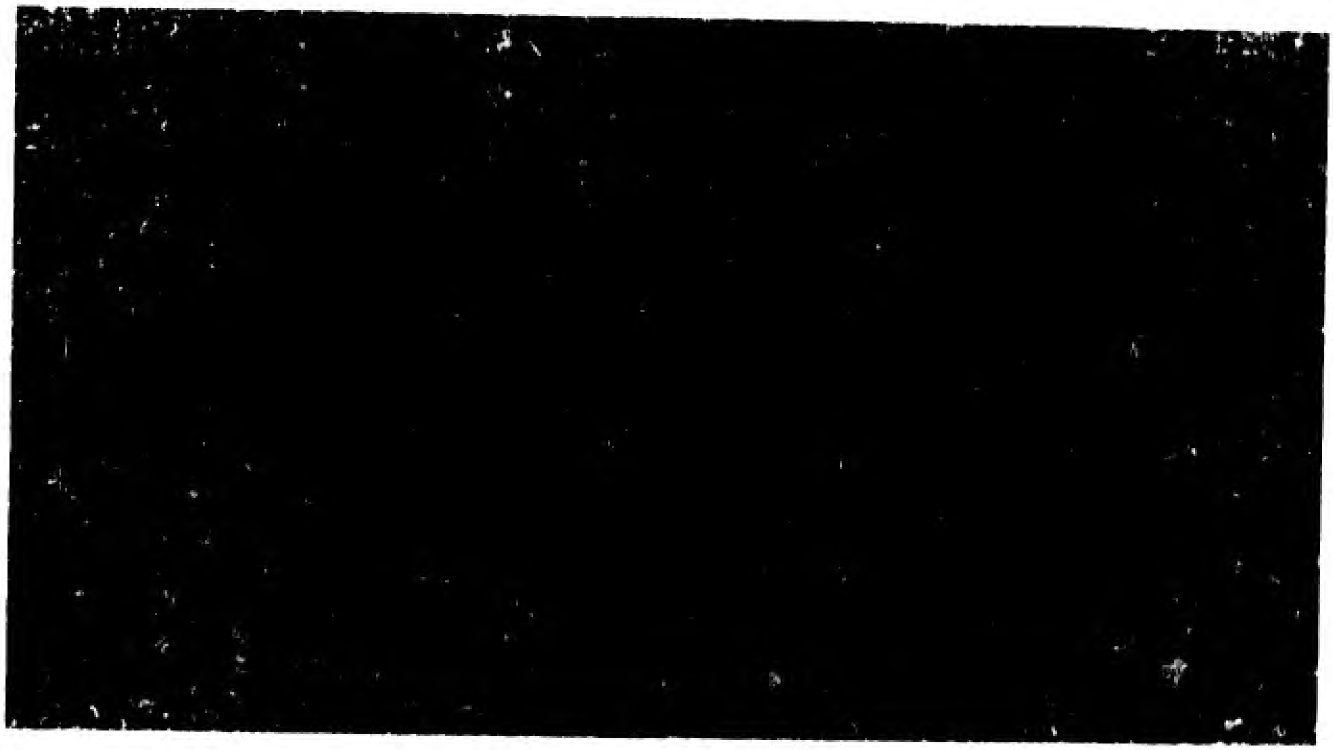
Etchant: See Figure 5.



EFFECT OF CHILL AND DISTANCE FROM CHILL ON SECONDARY DENDRITE ARM SPACING IN UNIDIRECTIONALLY SOLIDIFIED STEEL CASTINGS

FIGURE 9

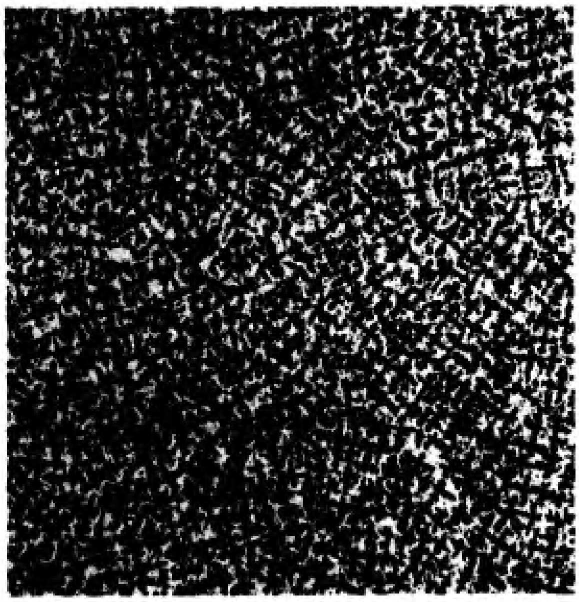
Top



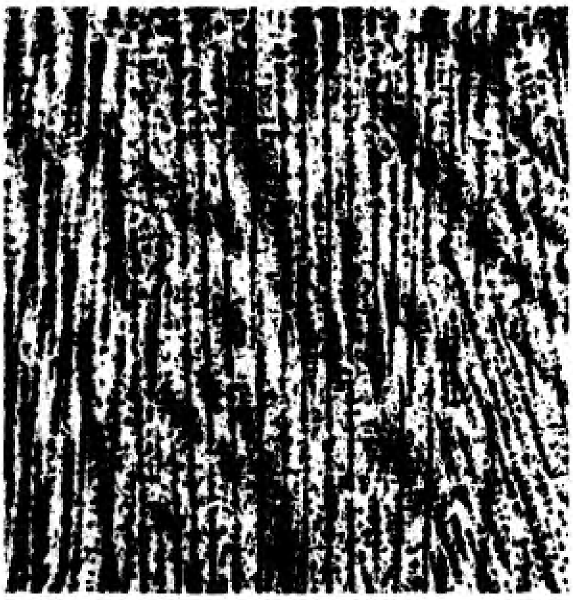
Bottom

Figure 10. Macrostructure of fully homogenized casting. Held for 64 hours at 2400 F. X1.

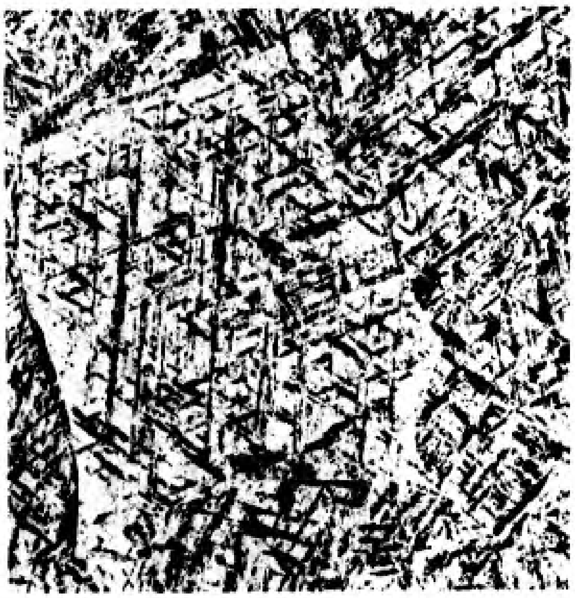
Etchant: See Figure 5.



A) Sectioned perpendicular to primary axes of dendrites. No homogenization. Primary arm spacing 102 μ.



B) Sectioned parallel to primary axes of dendrites. No homogenization. Secondary arm spacing 51 μ.

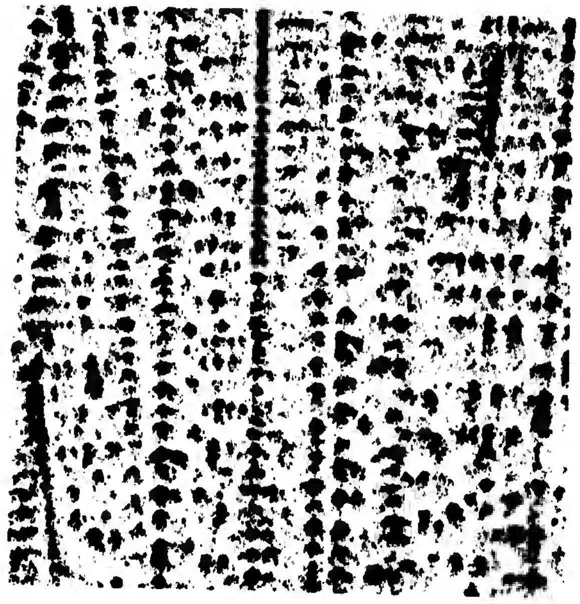


C) Microstructure after homogenizing for 64 hours at 2480 F.

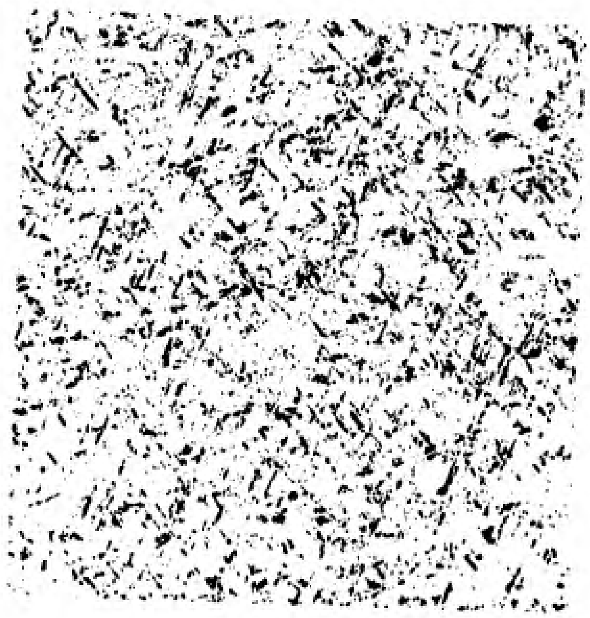
Figure 11. Sections taken 1/4 inch from copper chill plate. Oberhoffer's etchant. X25.

11-4263-B
11-4264-B
11-4265-B

A) Sectioned perpendicular to primary axes of dendrites. No homogenization. Primary arm spacing 254 μ.



B) Sectioned parallel to primary axes of dendrites. No homogenization. Secondary arm spacing 127 μ.



C) Microstructure after homogenizing for 64 hours at 2480 F.

Figure 12. Sections taken 1-1/4 inches from copper chill plate. Oberhoffer's etchant. X25.

11-4266-B
11-4267-B
11-4268-B

A) Sectioned perpendicular to primary axes of dendrites. No homogenization. Primary arm spacing 305 μ.

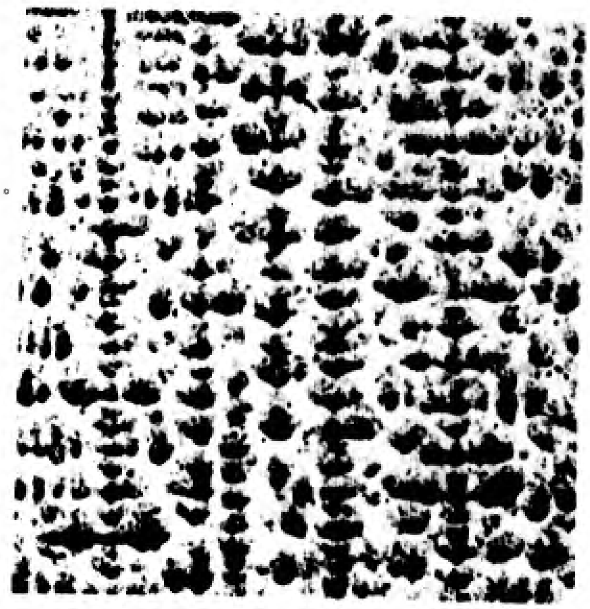
B) Sectioned parallel to primary axes of dendrites. No homogenization. Secondary arm spacing 152 μ.

C) Microstructure after homogenizing for 64 hours at 2480 F.

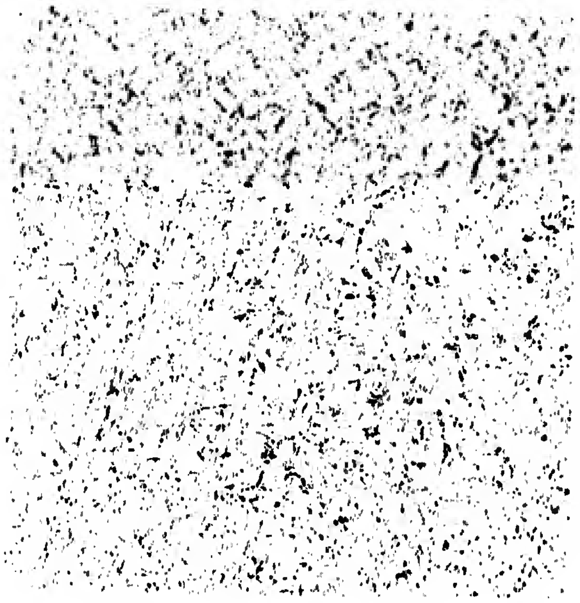
Figure 13. Sections taken 1-7/8 inches from copper chill plate. Oberhoffer's etchant. X25.

11-4269-B
11-4270-B
11-4271-B

A) Sectioned perpendicular to primary axes of dendrites. No homogenization. Primary arm spacing 380 μ.



B) Sectioned parallel to primary axes of dendrites. No homogenization. Secondary arm spacing 178 μ.



C) Microstructure after homogenizing for 64 hours at 2480 F.

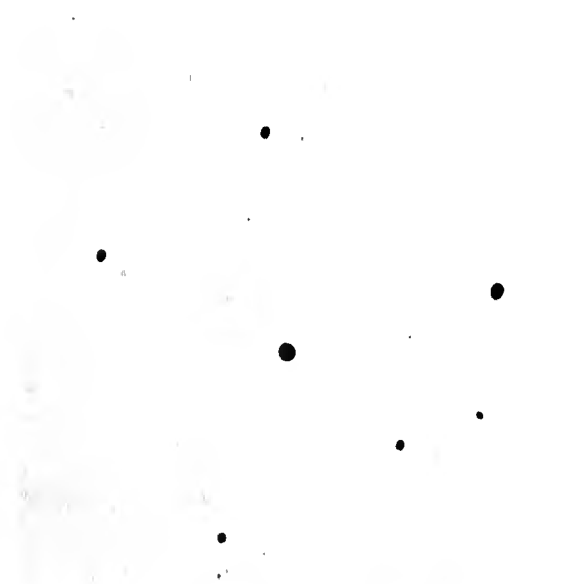
Figure 14. Sections taken 2-3/4 inches from copper chill plate. Oberhoffer's etchant. X25.

11-4272-B
11-4262-B
11-4273-B

A. 1/4 inch from copper chill plate.

B) 2-3/4 inches from copper chill plate.

C) 1/4 inch from refractory-brick chill plate.

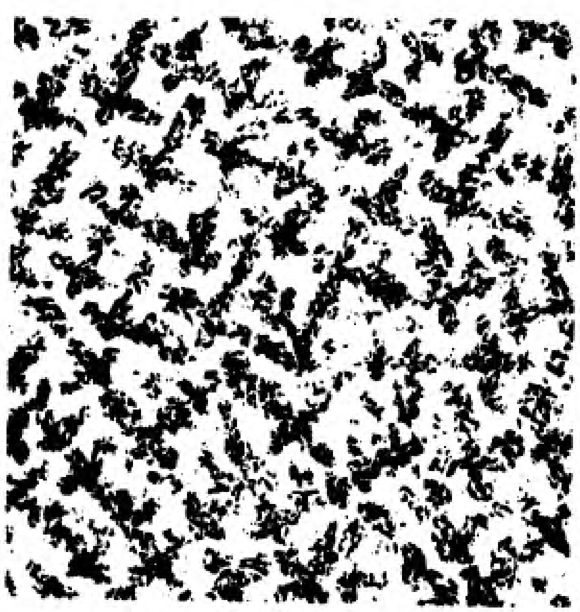


D. 2-3/4 inches from refractory-brick chill plate.

Figure 15. Inclusions and micropores in castings sectioned parallel to primary dendrite axes. Unetched. X100.

11-4274-B
11-4275-B
11-4276-B
11-4277-B

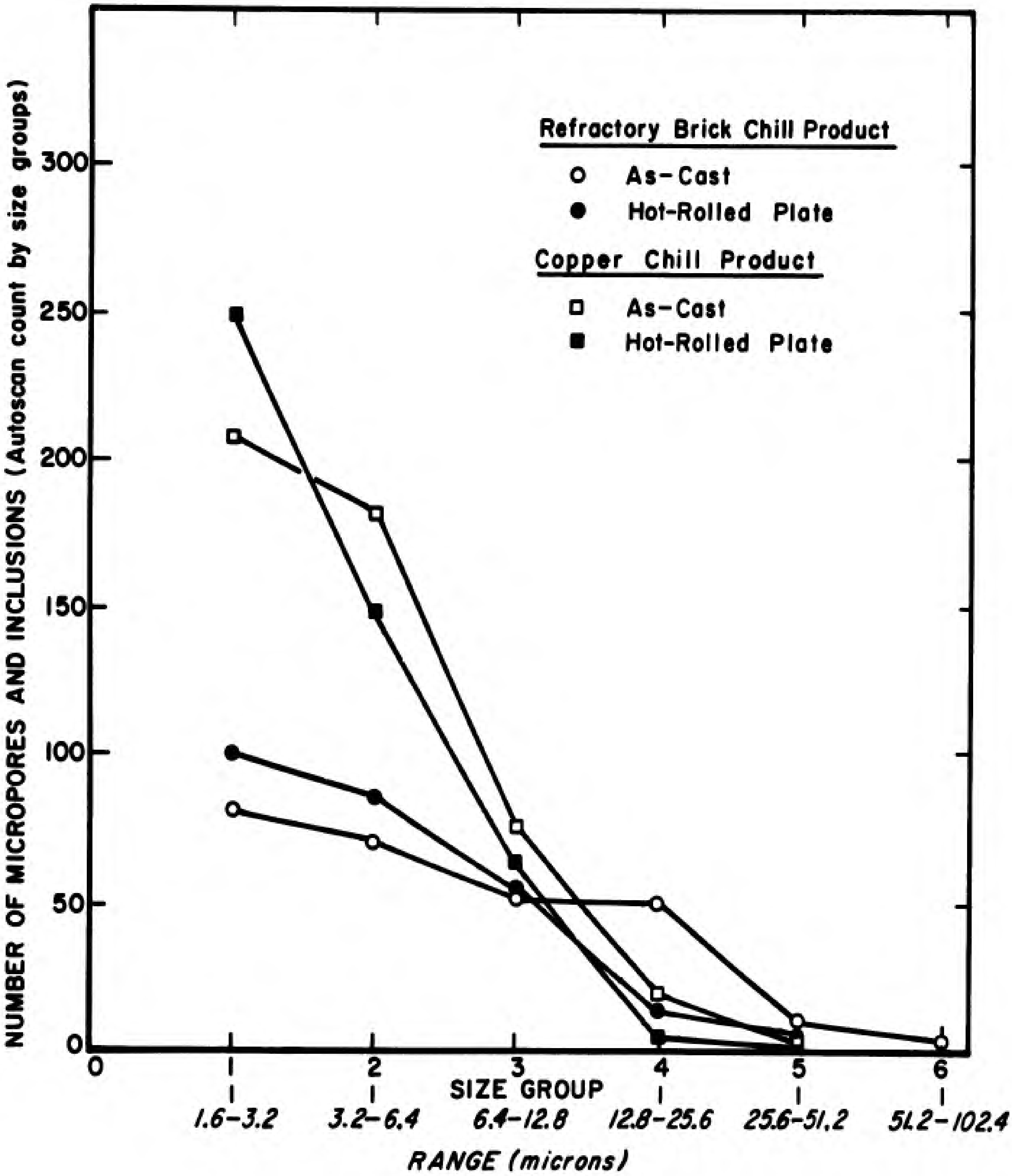
A) 3-3/4 Inches.



B) 1/4 Inch.

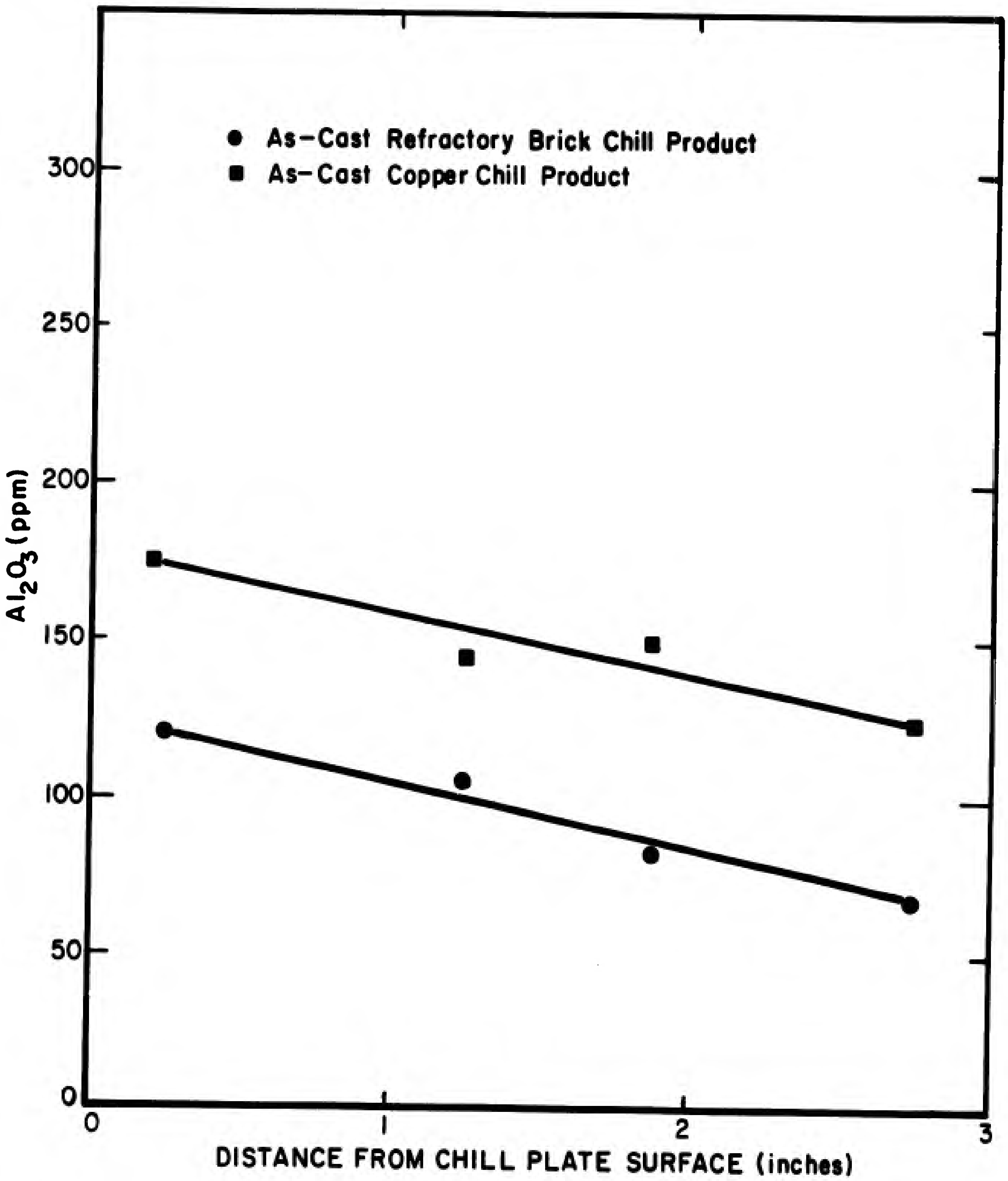
Figure 16. Locations of inclusions and micropores in castings sectioned perpendicular to primary dendrites at distances of 1/4 inch and 3-3/4 inches from copper chill. Oberhoffer's etchant. X100.

11-4279-B
11-4278-B



DISTRIBUTION OF MICROPORES AND INCLUSIONS IN AS-CAST AND HOT-ROLLED PLATE PRODUCT MADE BY USING REFRACTORY-BRICK AND COPPER CHILLS

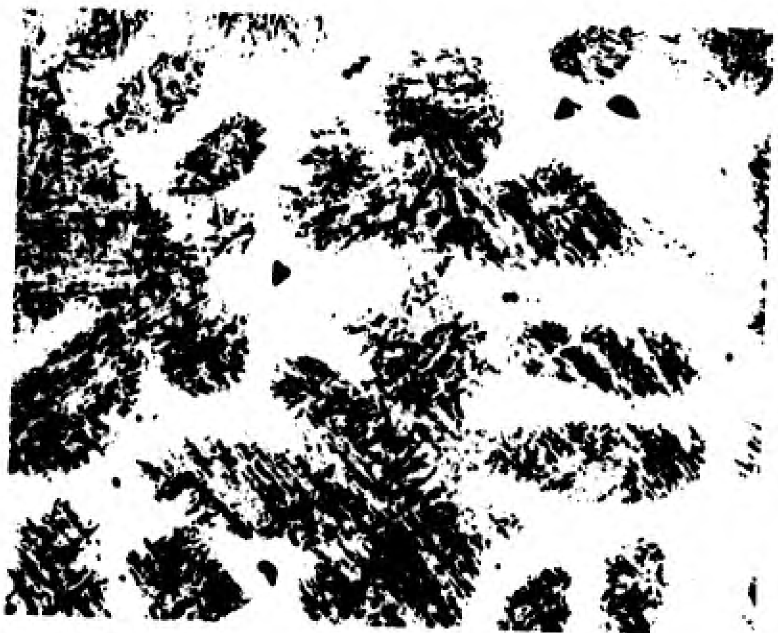
FIGURE 17



DISTRIBUTION OF ALUMINA INCLUSIONS IN
UNIDIRECTIONALLY SOLIDIFIED STEEL CASTINGS

FIGURE 18

A) Unetched.

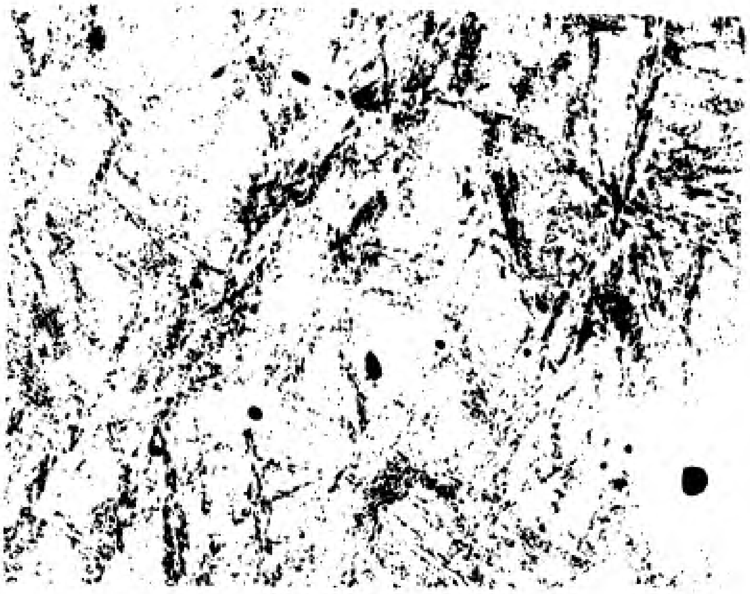


B) Etched in Oberhoffer's reagent.

Figure 19. Inclusions and microporosity in casting before homogenization. Sectioned parallel to chill plate, 3-3/4 inches from copper chill. X100.

11-4244-B
11-4245-B

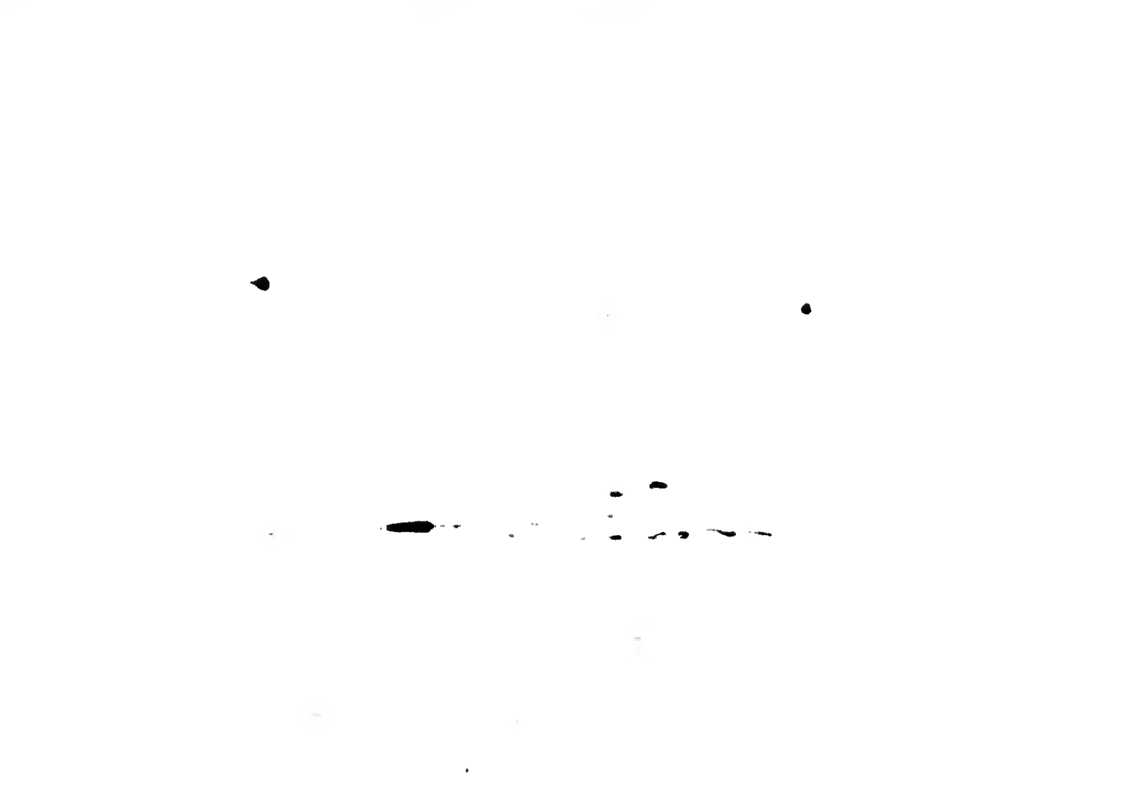
A) Unetched.



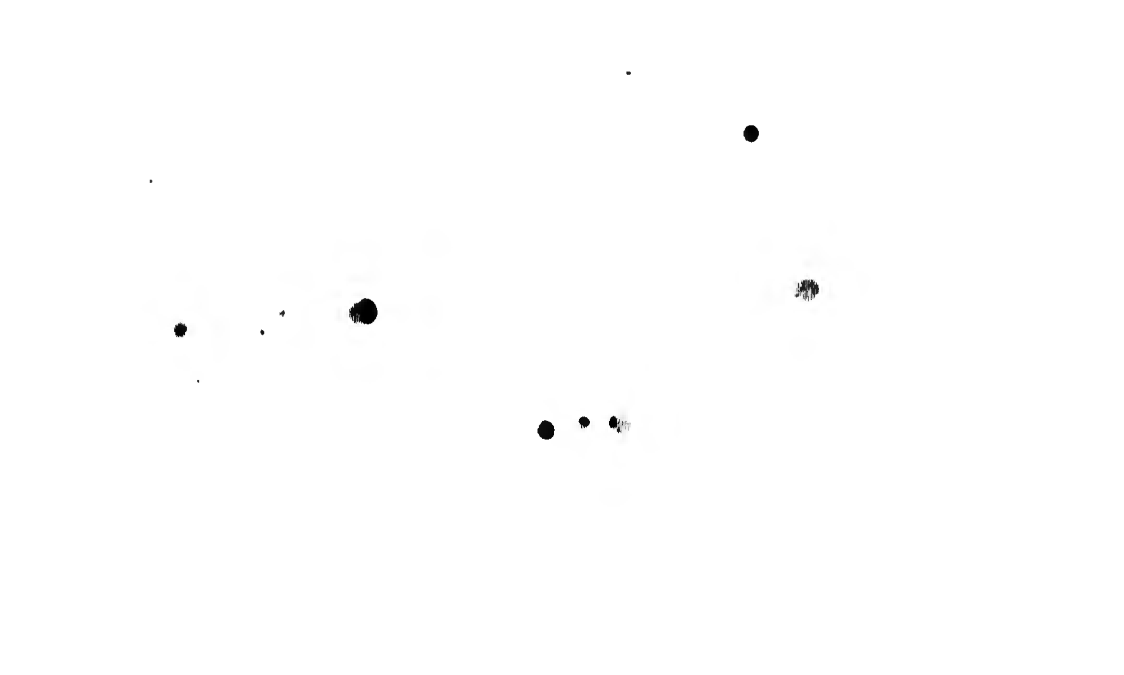
B) Etched in Oberhoffer's reagent.

Figure 20. Inclusions and microporosity in casting after homogenization. Sectioned parallel to chill plate, 3-3/4 inches from copper chill. X100.

11-4246-B
11-4247-B



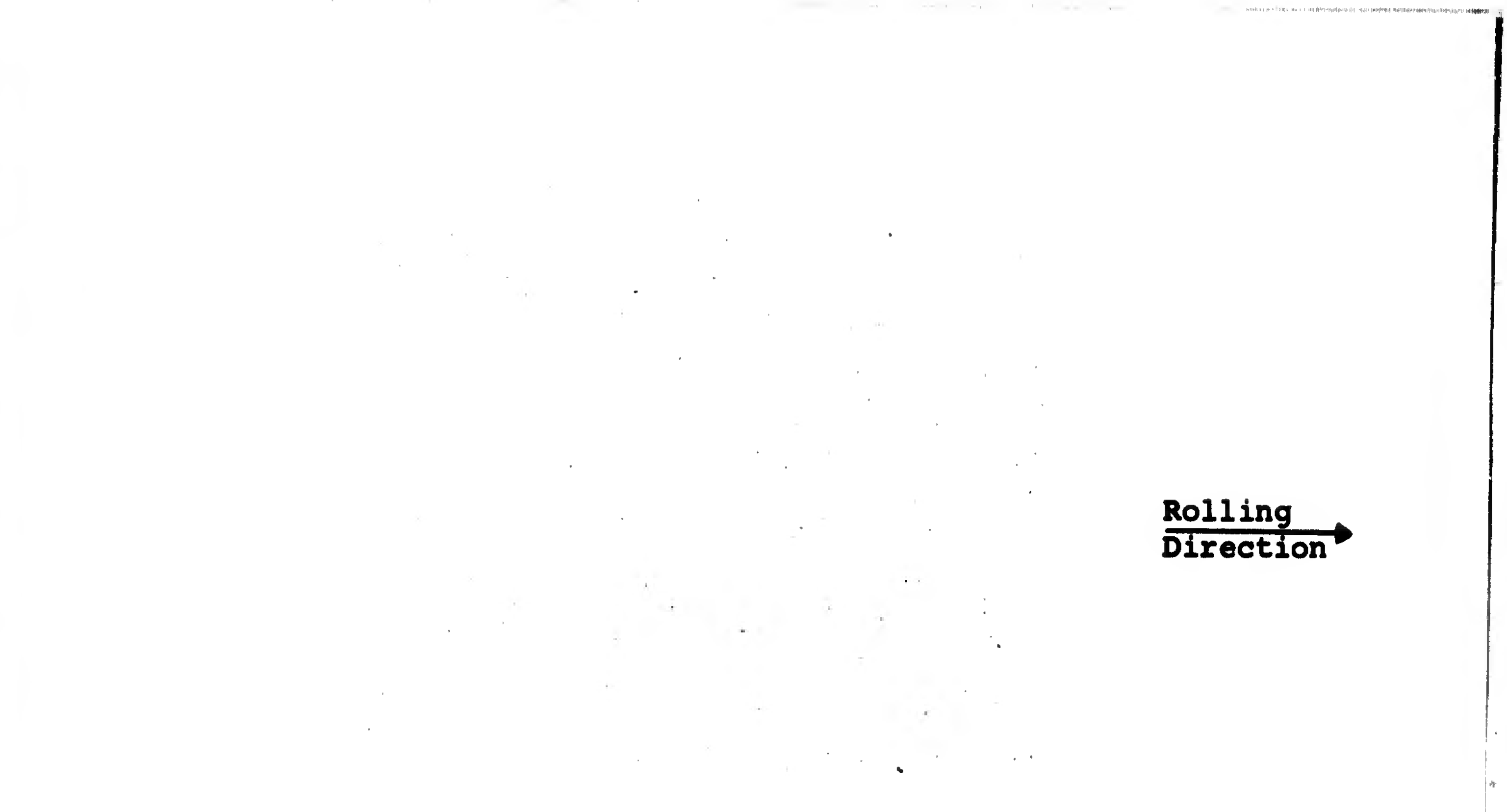
A) Before.



B) After.

Figure 21. Inclusions in Type 310 stainless-steel plate before and after holding at 2400 F for 64 hours. Unetched. X500.

11-4280-B
11-4281-B

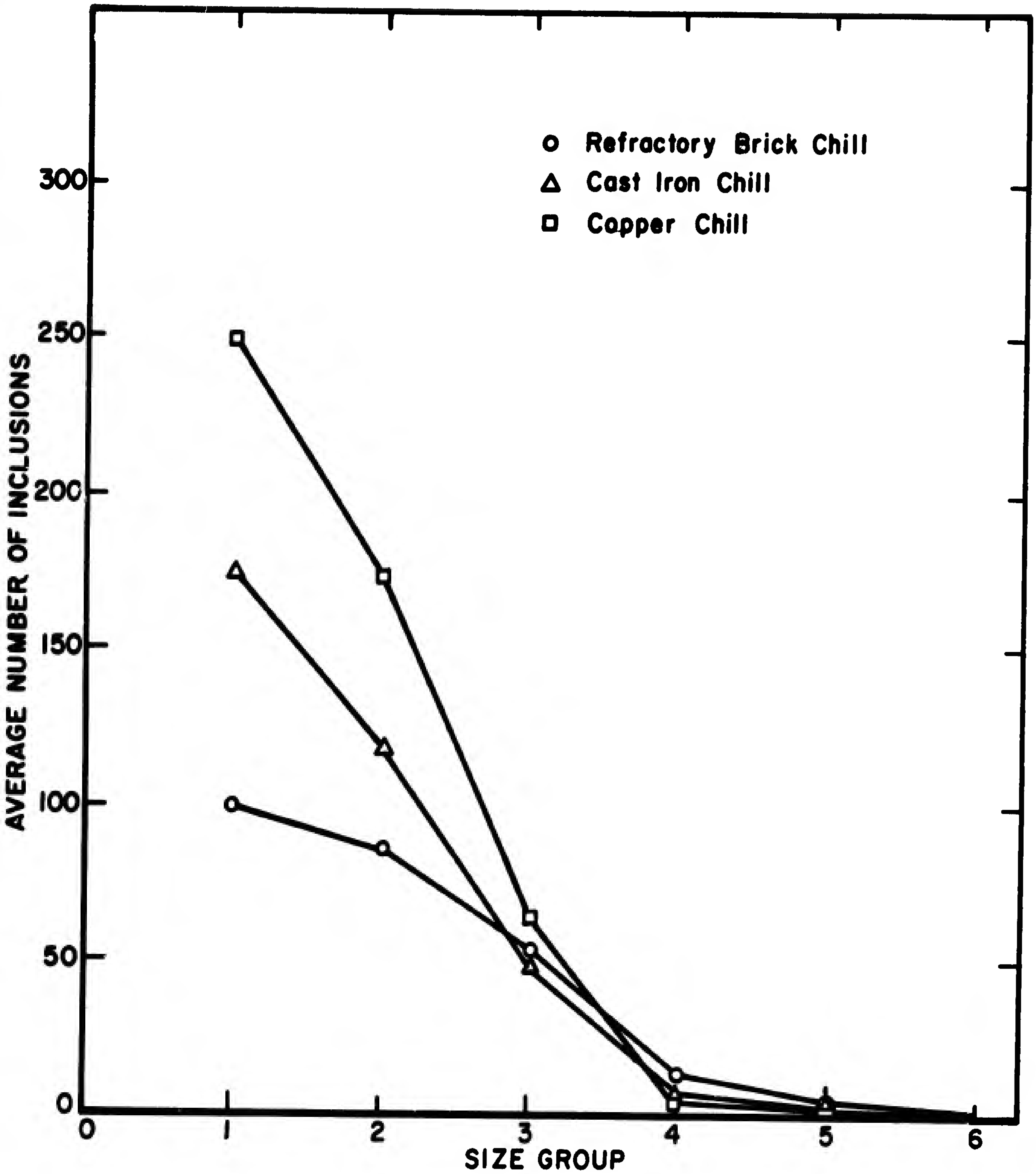


A) X100.

B) X500.

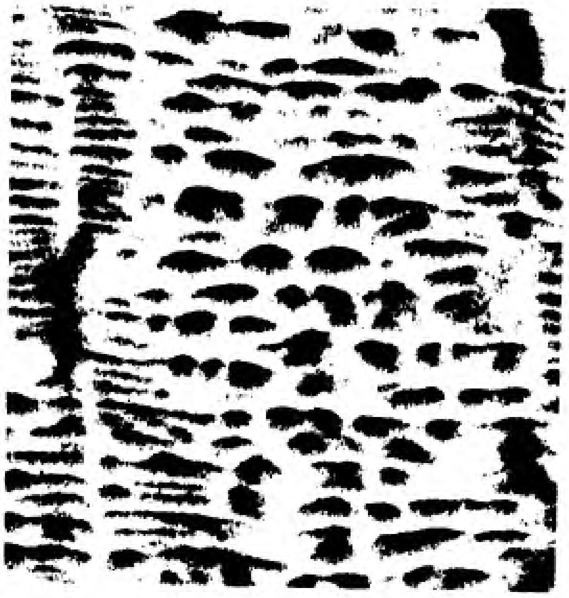
Figure 22. Inclusion distribution in 1/2-inch plate hot-rolled (87% reduction) from fully homogenized undirectionally solidified slab casting. Unetched.

11-4248-B
11-4249-B



DISTRIBUTION OF MICROPORES AND INCLUSIONS
IN THE HOT-ROLLED PLATE PRODUCTS

FIGURE 23



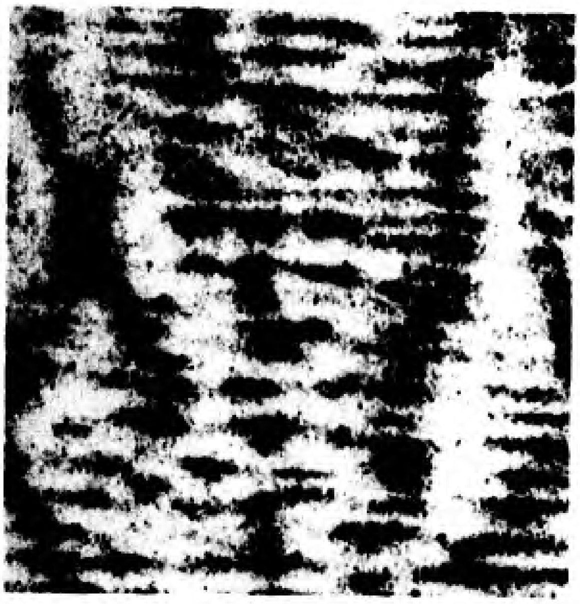
A) Hot-rolled from top third of the casting.

B) Hot-rolled from middle third of the casting.

C) Hot-rolled from bottom third of the casting.

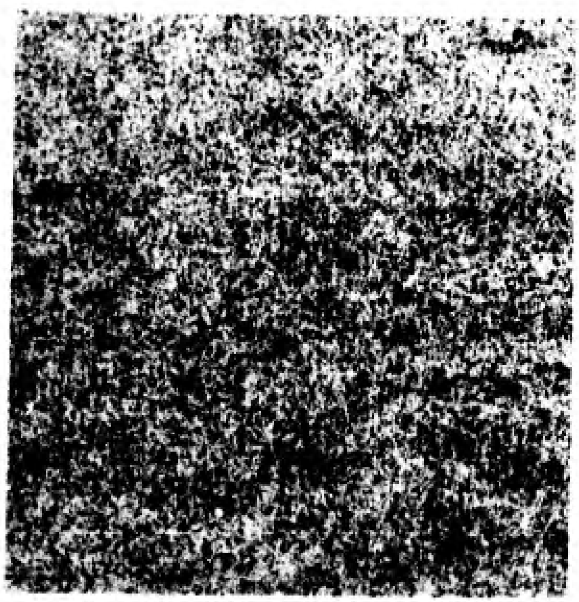
Figure 24. Segregation in 1/2-inch-thick plates hot-rolled from 1-inch-thick cast sections cut parallel to the copper chill plate and rolled normal to primary dendrites. No homogenization prior to rolling. Oberhoffer's etchant. X25.

11-4282-B
11-4283-B
11-4284-B



A) Hot-rolled from top third of casting.

B) Hot-rolled from middle third of casting.



C) Hot-rolled from bottom third of the casting.

Figure 25. Segregation in 1/2-inch-thick plates hot-rolled from 1-inch-thick cast sections cut parallel to the copper chill plate and rolled normal to primary dendrites. Castings homogenized 32 hours at 2300 F. Oberhoffer's etchant. X25.

11-4285-B
11-4286-B
11-4287-B

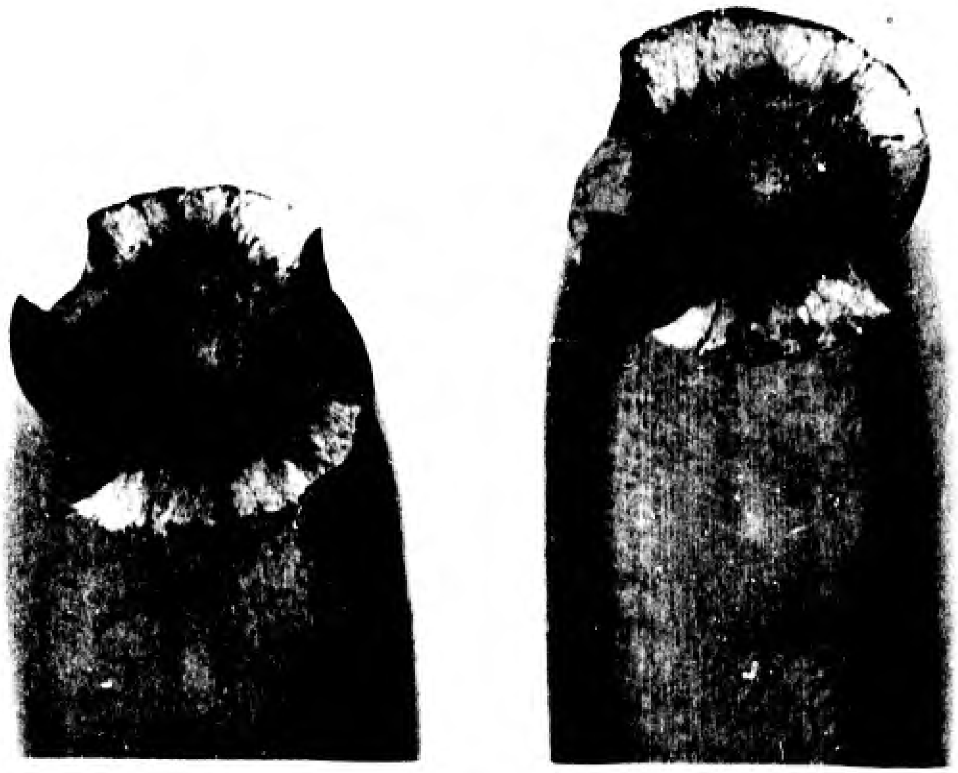


Figure 26. Typical cup and cone sections of a tension specimen from fully homogenized 0.60C-1.0Ni-0.50Cr-0.50Mo steel. X6.

Figure 27A. Plate Z20139-1, front. This plate exhibited the best ballistic performance of all the plates tested. Numbers 1 through 5 indicate the sequence of firing caliber 0.50 AP projectiles. Other numbers indicate the Bhn hardness and thickness of plate.

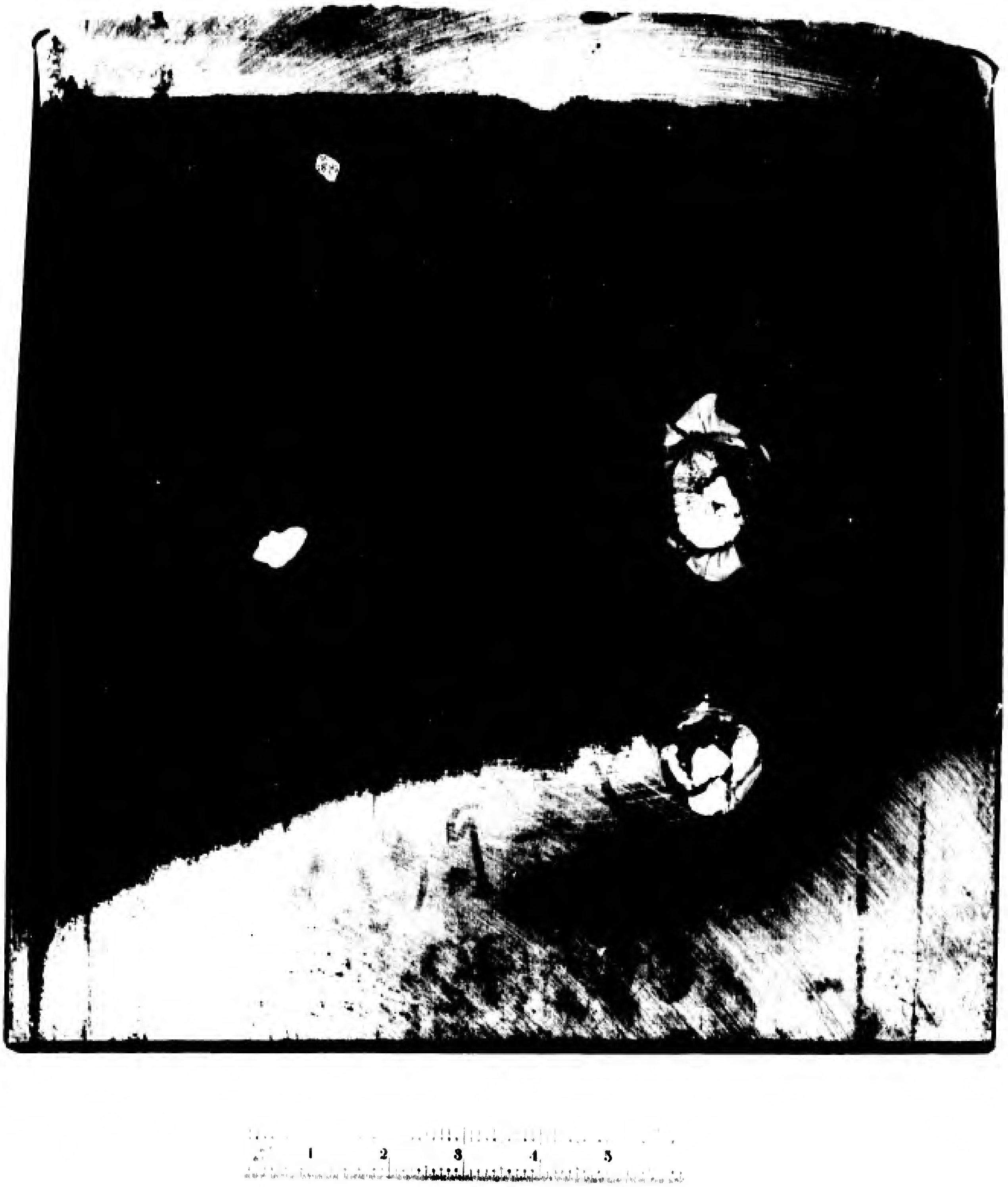


Figure 27B. Plate Z20139-1, back.

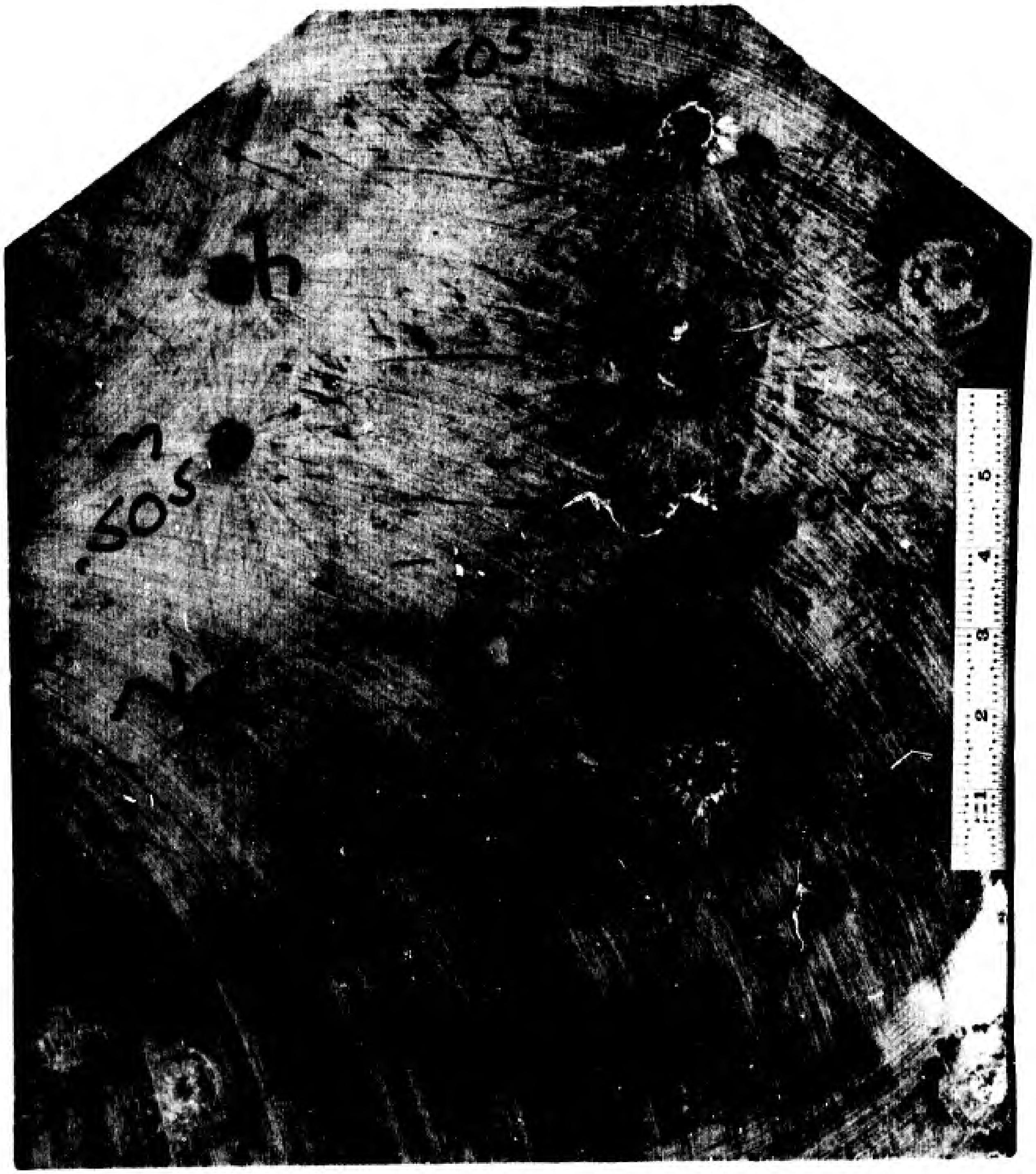


Figure 28A. Plate Z20142-2, front. This 1/2-inch-thick plate was easily penetrated by caliber 0.50 AP projectiles, right side of plate, and by a 20 mm fragment simulator, center, but not by caliber 30 AP projectiles, left side of plate.

Figure 28B. Plate Z20142-2, back. Notice clean plug-type holes formed by caliber 0.50 AP projectiles and by a 20 mm fragment simulator and bulges by caliber 0.30 AP projectiles.

Figure 29A. **Section of Plate Z20674-1, front. This 0.742-inch-thick plate completely resisted penetration by caliber 0.50 AP projectiles. Numbers indicate projectile firing order. X1.**

Figure 29B. Plate Z20674-1, front. This plate cracked after impact by two caliber 0.50 AP projectiles and broke into four pieces after the third shot. This plate was ground to 0.700-inch thickness from an initial 0.742-inch thickness. X1/2.

Figure 29C. Plate Z20674-1, back. Notice the solid plugs pushed out by caliber 0.50 AP projectiles. X1/2.

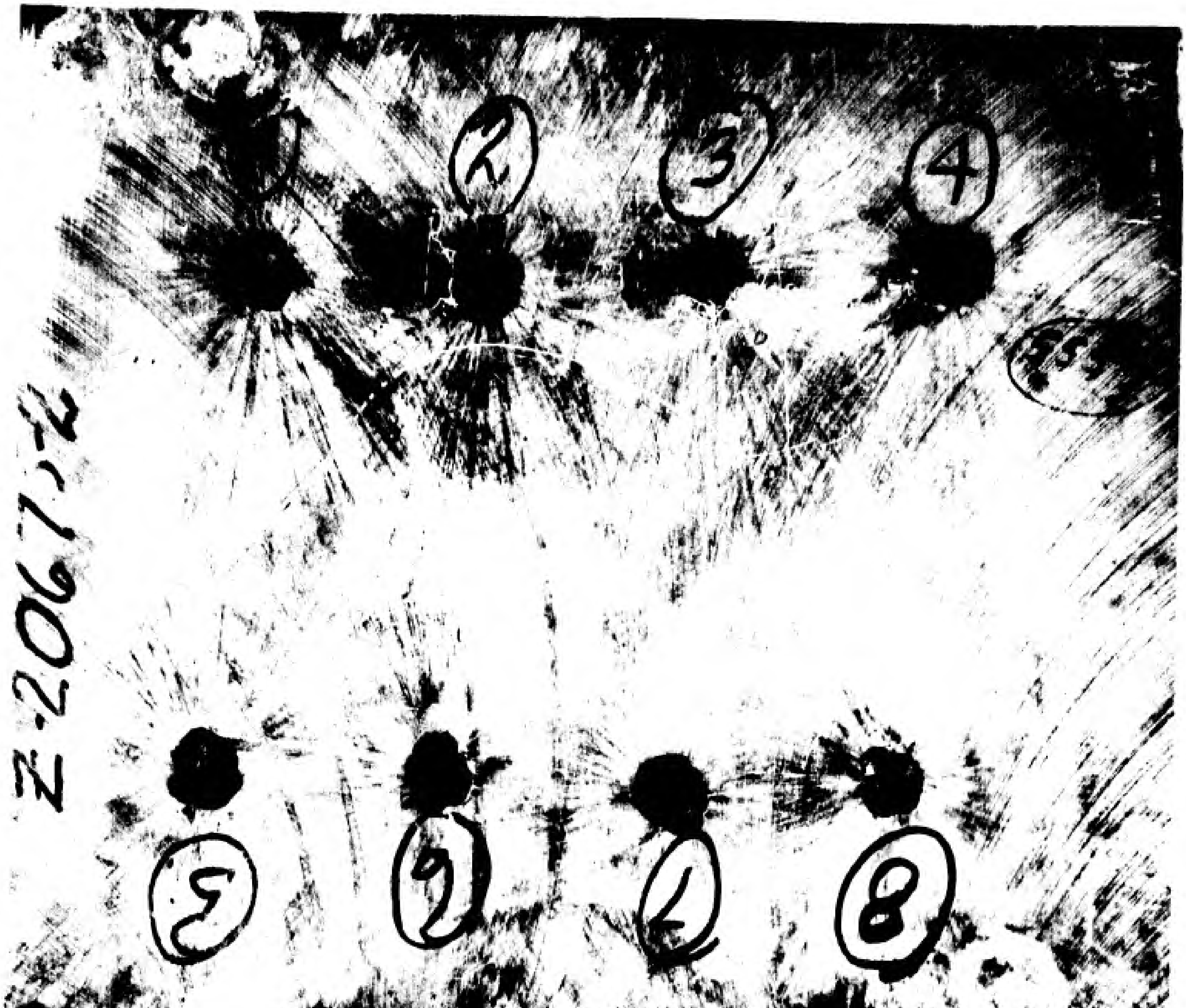


Figure 30A. Plate Z206? -2, front. This 0.704-inch-thick plate did not break into pieces or crack even after eight caliber 0.50 AP shots, six of which completely penetrated through the plate. X1/2.

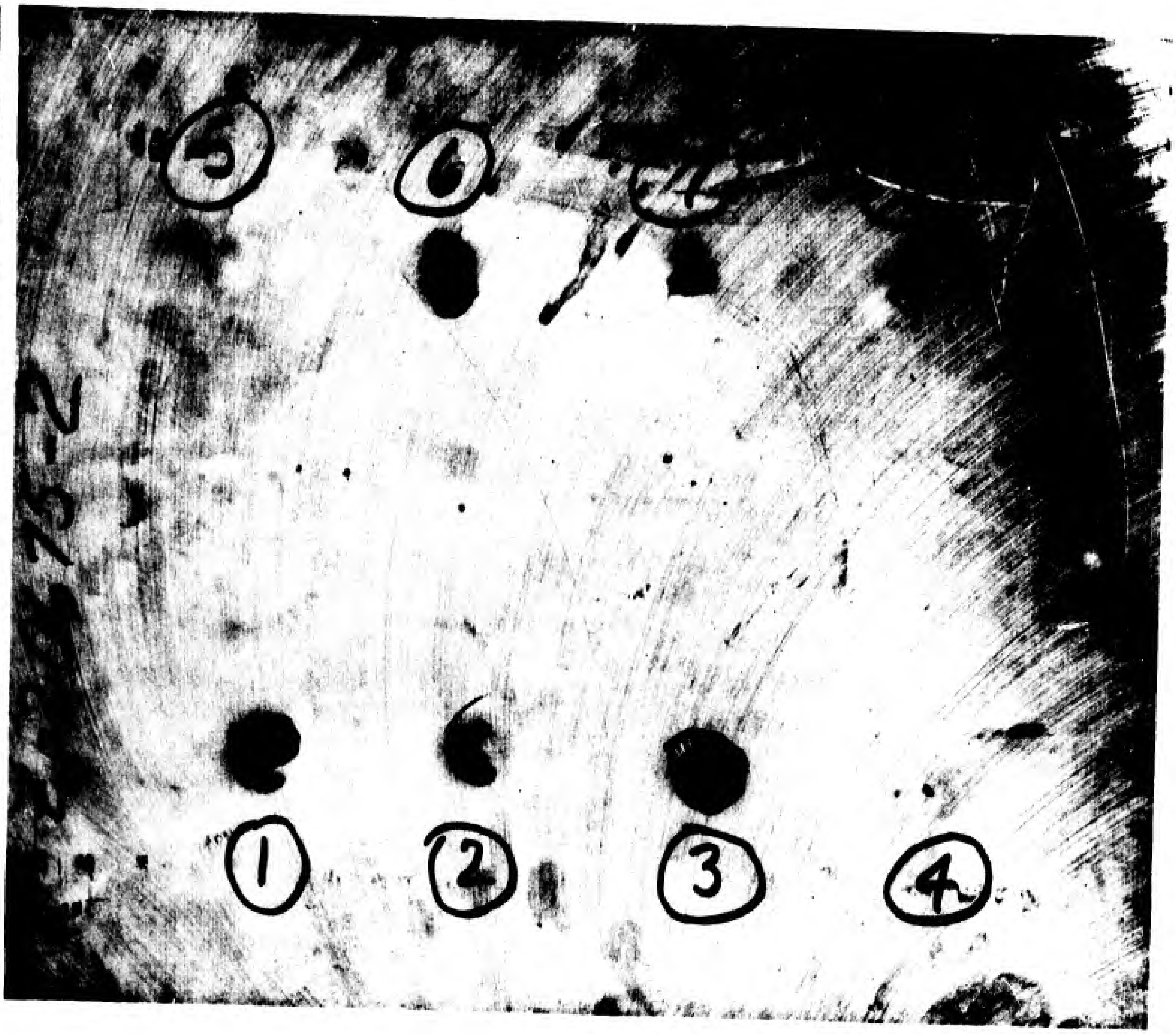


Figure 30B. Plate Z20675-2, back. Notice two caliber 0.50 AP projectiles retained in holes 2 and 3. X1/2.

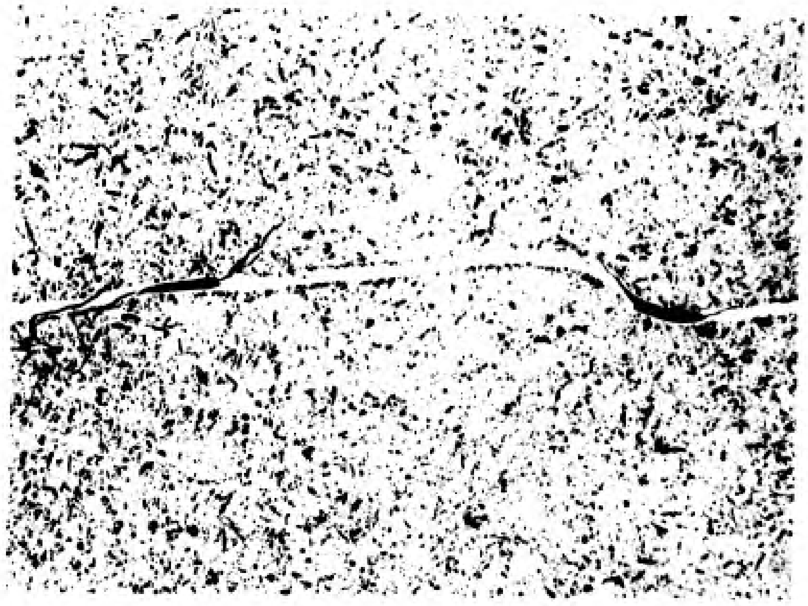


Figure 31. Shear band cracking in ballistically tested armor plate Z20168B-3. Band hardness (white streak) and hardness of partly tempered martensite (matrix zone) were determined by converting Knoop hardness measurements. The values were 67 R_C and 61 R_C, respectively. Etchant: 5% Nital, X200.

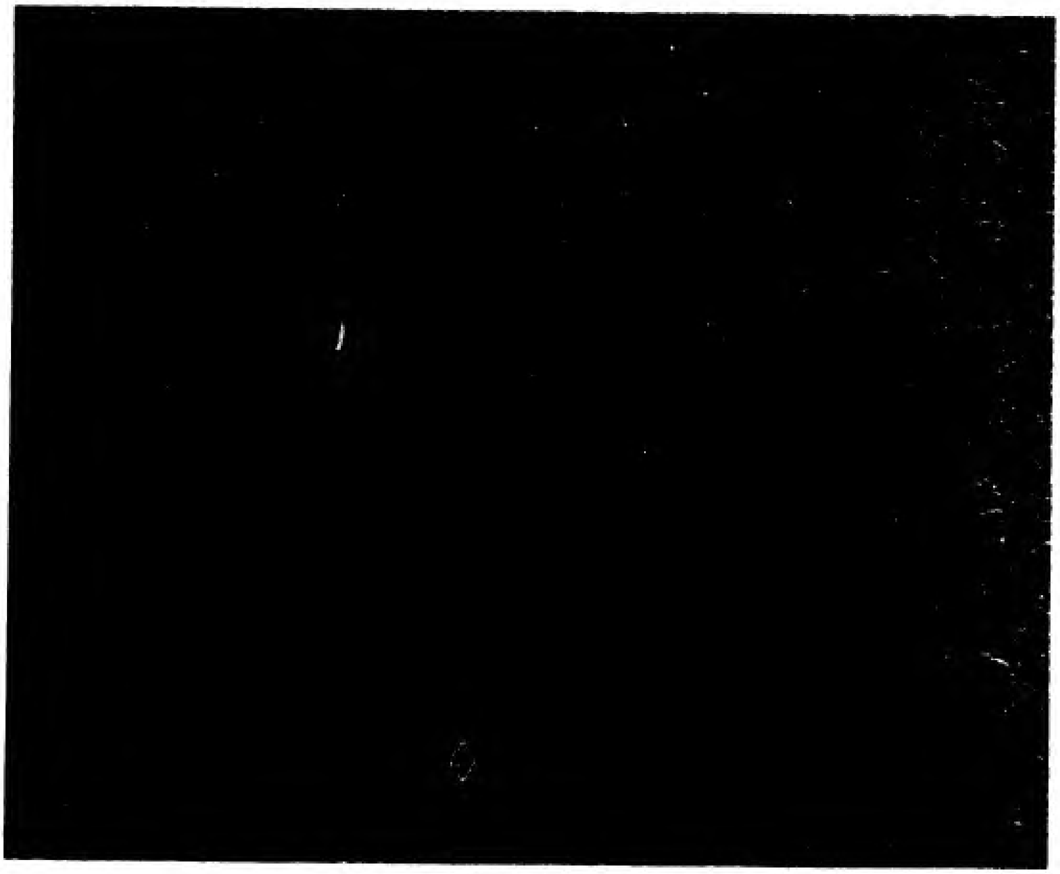


Figure 32. Section of shear band. Super picral etchant. X5000.

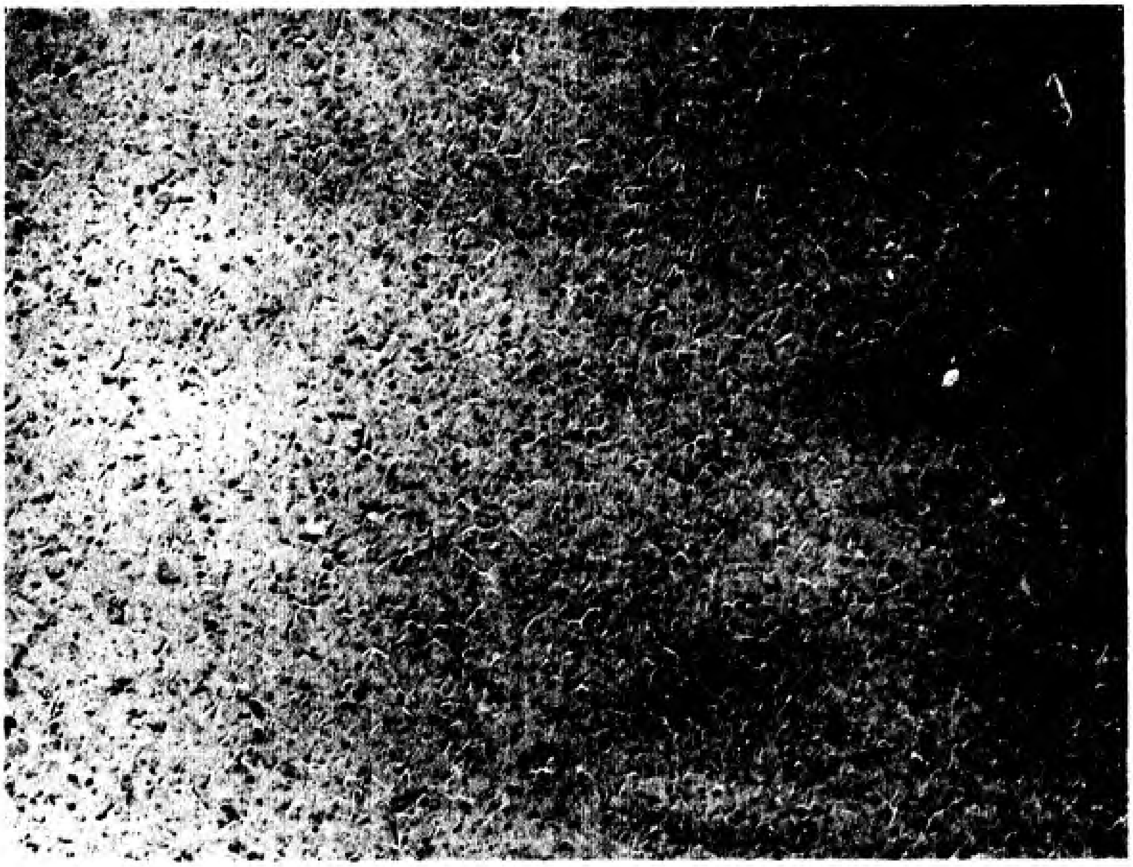


Figure 33. Ultrafine grains inside shear band. Grain size 0.2 μ. Sodium bisulfite etchant. X20,000.

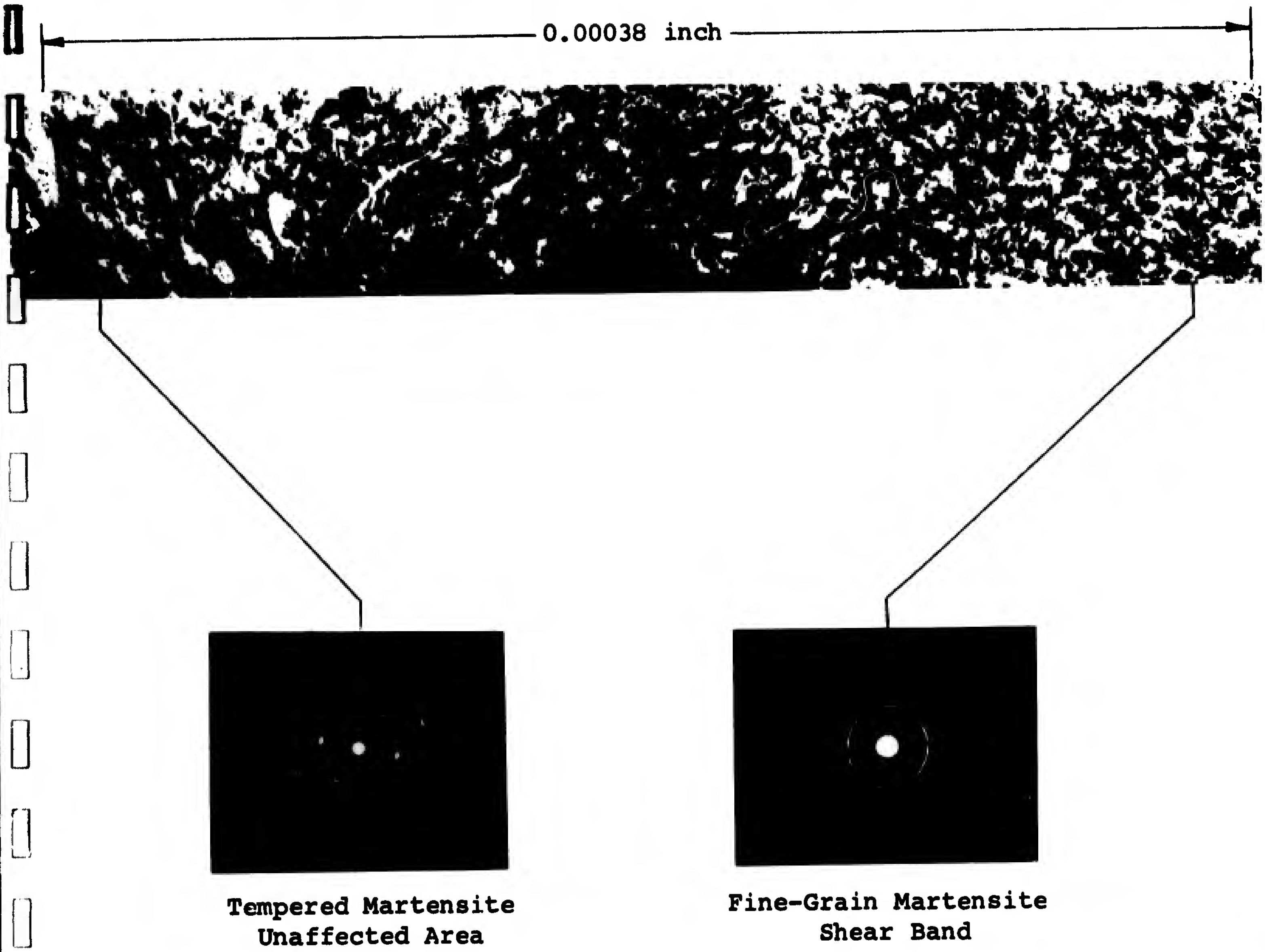


Figure 34. Composite electron transmission micrograph (42,000X-reduced one half) showing gradual structure change between unaffected area and the shear band, with respective electron-diffraction patterns, in ballistically impacted plate Z20674-3.

FRL-1787
1788
1789
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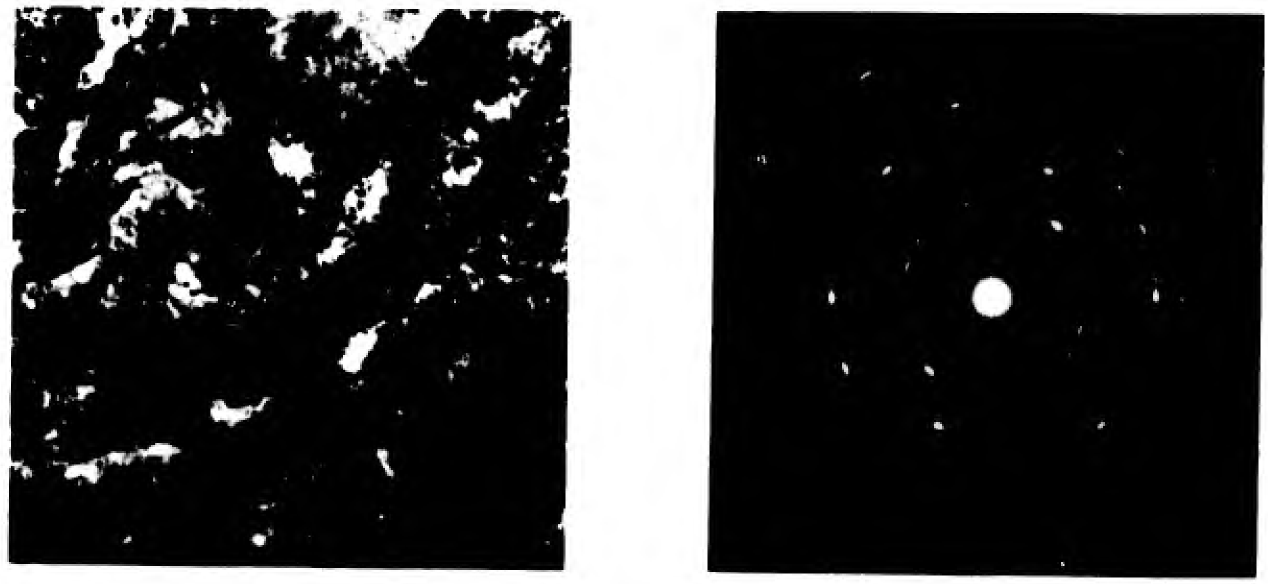
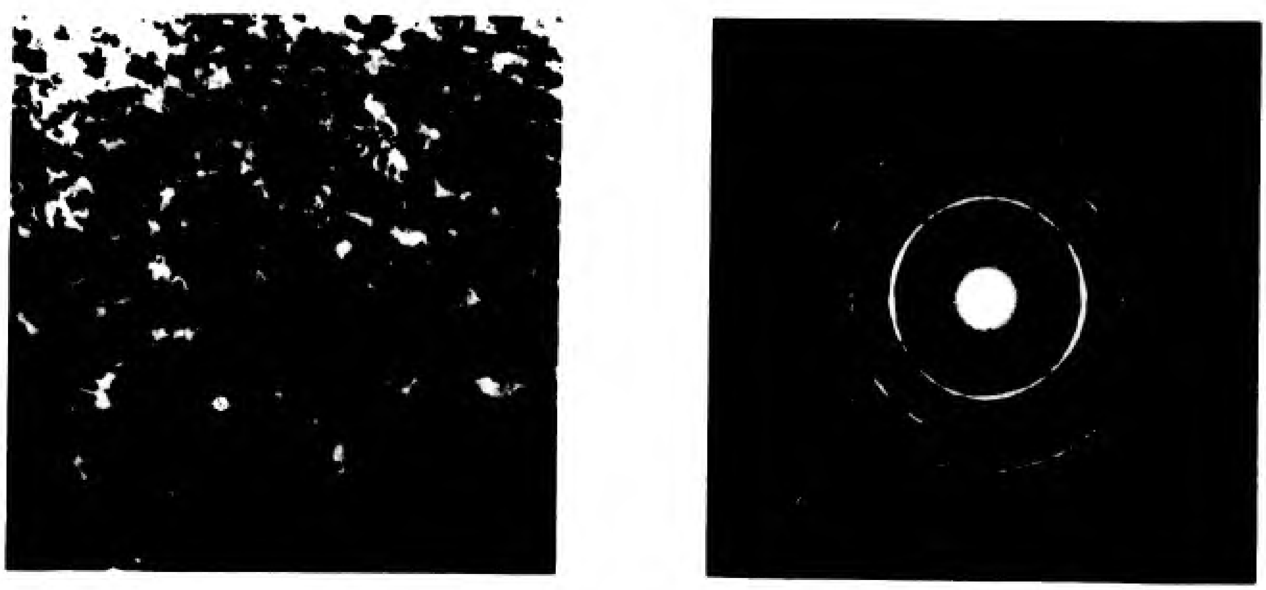
1793



A) Tempered Martensite - Unaffected Area



B) Fine-Grain Martensite - Shear Band

Figure 35. Electron transmission micrographs at X53,000 and electron-diffraction patterns in ballistically impacted plate Z20674-3.

FRL-1783
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1786

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5. AUTHOR(S) *(Last name, first name, initial)*

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13. ABSTRACT Flemings and Ahearn demonstrated that cast steels with superior ductility can be produced by unidirectional solidification, which results in minimum macrosegregation and macroporosity and less microporosity than is found in conventional castings. To determine whether the advantages of unidirectional solidification could be utilized to produce a superior wrought steel armor, techniques were established for casting unidirectionally solidified slabs 10 by 16 by 5-1/2 inches weighing about 240 pounds. The slabs were homogenized by holding in evacuated stainless-steel boxes for 64 hours at 2400 F, and rolled to plates for ballistic testing. Homogenization caused rounding of the inclusions and micropores and eliminated alloy segregation. Subsequent rolling to 1/2- and 3/4-inch-thick plate did not elongate the inclusions; therefore no stringers were formed. The plates were heat-treated by several different cycles. Plates from homogenized castings could be water-quenched without cracking, but oil quenching was necessary to obtain the desired hardness. In ballistic tests, the best unidirectionally solidified and homogenized wrought steel armor plates did not crack or spall at a hardness of Bhn 555 and thus performed better ballistically than equivalent conventionally processed homogeneous steel plates and compared favorably with commercial dual-hardness armor plates.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Solidification						
Homogenization						
Armor plate						
Ballistics						
Ingots, slab type						
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