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EVALUATION OF CONTINUOUS-CAST STEEL FOR PROJECTILE BODIES

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APRIL 1982



US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
LARGE CALIBER
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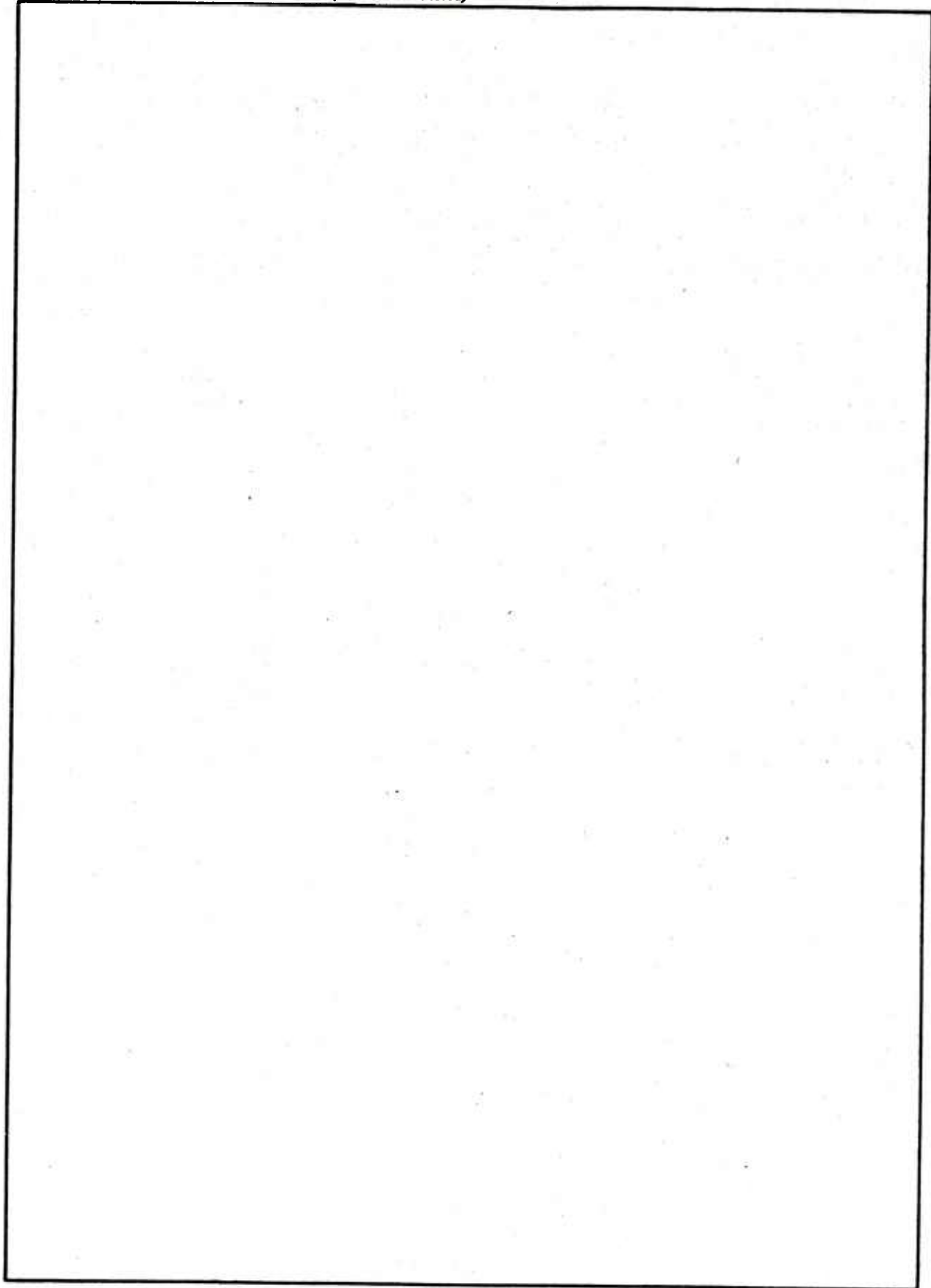
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A quantity of 105-mm M1 projectile bodies was made from continuous-cast steel to determine the suitability of this steel for manufacture of 105-mm projectile bodies. The hot cup-cold draw forming process was used to evaluate both hot and cold forming characteristics. A metallurgical evaluation of this steel was also performed. Continuous-cast steel with a reduction in area of at least 4:1 was determined to be suitable for manufacture of projectile bodies.		

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INTRODUCTION

One of the few recent innovations in the steel industry has been the continuous casting of steel. Other metals such as aluminum and copper alloys are routinely continuously cast. However, steel (with its higher melting point, longer solidification ranges, and lower heat transfer rates) has presented problems which have been only recently overcome.

The advantages of the continuous-casting process are that it eliminates casting into ingots, reheating of ingots, and primary rolling of ingots into blooms. Thus, continuous-casting allows the direct casting of an intermediate product from molten steel, resulting in substantial savings in energy and in facility and manufacturing costs.

The first successful application of continuous-casting of steel was the casting of slabs for rolling into sheet and plate products. The slabs presented a large surface area for cooling, and the high reduction in area when the plates were rolled into sheet or plate compensated for lower density centers.

Once the technology had been established for slabs, it was subsequently applied to billets. However, the first billet casters made a lower quality product which was comparable to merchant-quality steel or structural steel. This technology has advanced to the point where a forging quality product and, in some instances, a higher quality product can be made on a billet caster.

The purpose of this project was to determine whether or not there are any unique characteristics of a continuous-cast product which would make it unsuitable for ammunition manufacture. National Presto Industries, Inc., was selected to fabricate 105-mm M1 projectiles from continuous-cast steel for two primary reasons: The size of the raw material used in their process was within the range available from continuous casters and allowed for subsequent hot rolling after casting. Also, the hot cup-cold draw process used by National Presto allowed evaluation of both hot forging and cold working operations.

As early as 1968 National Presto was approached by a small continuous-cast-steel producer to fabricate some 105-mm M1 projectiles from the small producer's product. National Presto made a small quantity of projectiles and shipped them to Frankford Arsenal for examination. Although National Presto reported no problems in forming the projectile bodies, the quality of the continuous-cast billets used was not as good as forging-quality billet. Therefore, National Presto was informed that a more extensive program would be required to arrive at a specification which would assure a consistently high quality product.

In 1972, at the request of representatives of Republic Steel Corp., National Presto made some projectiles on a trial basis. At this time an MMT project request had been submitted concerning an investigation of continuous-cast steel. The original scope of this project was to process projectiles made from steel produced by three different steel suppliers. Funding for the project was received in Fiscal Year 1974. At that time the steel industry was being taxed to capacity, and, although National Presto contacted approximately 14 continuous-cast steel suppliers in this country and Canada, no positive response was received. Later Roblin Steel Company supplied some unworked continuous-cast steel

and, in August 1975, Republic Steel finally agreed to supply AISI 1018 steel. The steel from these two sources was examined, and sufficient data were provided to enable the use of hot rolled continuous-cast steel under certain manufacturing conditions.

This report summarizes the contractor's final report (ref 1) but is primarily concerned with a metallurgical examination of the raw material, process pieces, and finished projectile bodies from the two sources of continuous-cast steel.

ENGINEERING STUDY

Republic Steel Continuous-Casting Process

Republic Steel uses a straight mold, vertically cooled casting machine which casts four strands at a time, each strand measuring 254 x 222 mm (10 x 8.75 in.). A 136 Mg (150 ton) ladle containing a heat of steel is brought up from the melt shop to the 61 m (200 ft) level of the casting tower. The melt temperature is lowered to the proper casting temperature [approximately 22° C (40° F) above the liquidus temperature of the alloy] and the melt is stirred with an argon lance to minimize segregation and temperature stratification.

The ladle is then moved into position over the tundish which distributes the hot metal to the four molds positioned underneath the tundish. The hot metal is introduced into the molds through ceramic shrouds to prevent oxidation of the metal stream. The mold is open ended, 0.6 m (2 ft) in length, and water cooled.

To start the cast, a dummy strand is positioned to close off the bottom of the mold. Hot metal is introduced into the mold, and the solidification process begins. After the shell has solidified around the periphery of the mold, the dummy strand, together with the first portion of the continuous-cast strand, is withdrawn from the mold at a rate of 0.016 to 0.019 m/s (40 to 45 in./min).

From this point on, casting and solidification proceed on a continuous basis. The mold oscillates in a vertical mode to prevent sticking. As the cast billet leaves the mold, the center is still molten. To accelerate solidification, water is sprayed on the outside of the billets.

When the strands have cooled to approximately 927°C (1700°F), torch cutters are used to cut billets in lengths of approximately 6 m (20 ft). Each cut billet is moved by automatic transfer mechanisms from the vertical position to the horizontal position at ground level. The billet is automatically end-stamped to indicate heat number, strand number, and consecutive number (a number assigned to each billet as it is cut off a strand during casting of the heat). The billets are allowed to cool, are surface conditioned, and are reheated to rolling.

To provide steel for this project, Republic Steel rolled the unworked billet down to 89 mm (3.5 in.) round-cornered, square bar steel, thus achieving approximately an 85% reduction in cross-sectional area.

Processing Republic Steel Product into Projectile Bodies

A contract was placed with National Presto to process approximately 1000 105-mm M1 projectiles from AISI 1018 continuous-cast steel supplied by Republic Steel. The projectile bodies were manufactured by the same process as is used for the conventional material made from ingots (ref 1). To provide background information in support of the metallurgical study, behavior of the continuous-cast steel at each operation in the production process is presented briefly:

Receive Steel

For their normal production, National Presto orders AISI 1018 steel fully killed, nonaging, and made to fine-grain practice, (an aluminum-killed product). It further specifies a 0.10% maximum on silicon to facilitate cold working of the material. National Presto orders 89 mm (3.5 in.) round cornered, square bar steel with a 12.7 mm (0.5 in.) corner radius and a diagonal measurement of 115.2 mm (4.536 in.).

The continuous-cast steel supplied by Republic Steel had a ladle analysis of 0.15% silicon, which was over the maximum allowed. The explanation by Republic Steel for the high silicon content was that they cannot fully aluminum-kill the steel on the continuous caster due to the formation of aluminum oxides during casting. Sufficient aluminum is added to the mold to refine the grain, but most of the deoxidation is achieved with silicon.

The bars also were generally oversize by 1.59 mm (0.06 in.) and varied in cross-sectional dimensions. To correct this condition, the mults had to be cut shorter.

Saw Mults

Saw blade usage was equivalent to that for ingot-cast steel, as was sawing time.

Heating for Forging

Because of the larger cross-section of the continuous-cast steel, the operating temperature of the induction heaters had to be increased 55.5°C (100°F) to bring the continuous-cast steel up to the normal forging temperature of 1065°C (1950°F).

Forge

Forging tonnage was measured at the cabbage operation and was determined to be 22.5% higher, or 306 Mg (337 tons) for continuous-cast steel versus 249 Mg (275 tons) for ingot-cast steel. National Presto personnel reason that this increase in tonnage was due to the shorter mult. Another contributing factor could be the coarse dendritic structure of the continuous-cast steel as compared to steel rolled from ingot. Tool life might be somewhat better for the continuous-cast steel because of a cleaner reaction with the workpiece.

Rough-Turn

Maintaining weight at the rough-turn operation was a problem because of cross-sectional variations in the bars. Tool life was not as good with the continuous-cast steel as with ingot-cast steel.

Cold Draw

Cold draw tonnage for continuous-cast steel was equivalent to that for ingot-cast steel. A higher incidence of breakage at the open end of the drawn piece occurred with the continuous-cast steel. This operation is a very severe forming operation since the back end of the punch is tapered to form the thread flat. The higher silicon content and the coarse dendritic structure of the steel are the probable causes of this higher incidence of breakage.

Trim-to-Length

Tool life was shorter at this operation due to tool breakage because of the broken edges resulting from the cold-draw operation. Many pieces which were broken during cold draw were cleaned up during the trim-to-length operation.

Coin

Coining was satisfactory. However, the tool had to be set ahead by 0.51 mm (0.02 in.) because the continuous-cast steel had greater springback than did the ingot-cast steel.

Form Nose

A greater number of projectile bodies developed folds during the nosing operation. In many instances this problem was due to the fact that the piece did not clean up during the trim-to-length operation. As with the coining operation, tooling had to be advanced by 0.51 mm (0.02 in.).

Stress-Relieve

Stress-relief experiments with the continuous-cast steel projectile bodies indicated a higher stress relief temperature was required than with National Presto's normal steel. Their steel is stress-relieved at 426.6°C (800°F), whereas temperature of 524°C (975°F) was required to develop suitable mechanical properties in the projectile bodies made from continuous-cast steel.

This higher temperature exceeded National Presto's furnace capabilities, and the contract was amended to allow the projectile bodies to be heat-treated by a commercial heat-treater. A wide spread in hardness resulted, indicating inadequate control by the heat-treater. Hardness ranged from 4.0 to 5.3 mm Brinell diameter, with 4.1 to 4.3 mm being an acceptable range. A total of 93% of the stress-relieved projectile bodies fell within the acceptable range. Subsequent heat-treating experiments on projectile bodies of 4.0 mm hardness indicated that after a 524°C (975°F) stress relief at Frankford Arsenal, acceptable mechanical properties were achieved.

Finish-Machine

All finish-machine operations were identical to those for ingot-cast steel.

Magnetic-Particle Inspect

Normal production of 105-mm M1 projectile bodies does not include magnetic-particle inspection. This inspection was made a requirement in this project to insure that no defects peculiar to the processing of continuous-cast steel developed. No magnetic particle standards existed, so any magnetic particle indication was considered a reject. Approximately 10% of those projectile bodies inspected had magnetic-particle indications. Representative indications were metallurgically examined and results are discussed later in this report.

Metallurgical Study of Republic Steel Product

Raw Material

Macroetched sections removed from random bars of the Republic-supplied steel are shown in figure 1. These macrographs are generally equal to or better than the macroetch standards for special-quality bar steel from ingot-cast steel. Some dendritic structure is evident in the center of the macroetched sections; however, this structure is often also evident in ingot-cast steel. Aside from this dendritic structure, little segregation is evident; center soundness also appears excellent. No evidence exists of corner cracking, a defect which is common to continuous-cast steel and which occurs during solidification. However, view 1A, figure 1, shows evidence of surface conditioning. Generally, the surface finish of continuous-cast steel is superior to that of steel rolled from ingot.

The macrospecimen shown in view 1A, figure 1, was subsequently cut up for metallurgical examination. Metallographic specimens were prepared from the edge, midsection, and center of the macrospecimen. Unetched microstructures are shown in figures 2 through 4. Considerable microporosity is evident in the center of the bar. This microporosity diminishes somewhat at the midpoint between the center and edge, as shown in figure 3, and essentially disappears at the edge. This microporosity does not have any oxides or sulfides associated with it and will close up during subsequent forging operations.

Etched samples of the specimens depicted in figures 2 through 4 are shown in figures 5 through 7, respectively. The microstructure is shown to be very uniform from center to edge, with no evidence of microsegregation as would be apparent in an unworked continuous-cast structure. This structure is very similar to that expected in bars rolled from ingot-cast steel.

To determine if any alloy segregation exists in a continuous-cast bar, a chemical analysis was made of specimens taken at the edge and at the center of the macrospecimen shown in view 1A, figure 1. Table 1 shows the results of these analyses to be very close, with slightly lower carbon at the center. These results compare favorably with Republic Steel's ladle analysis, also shown in table 1, except that the silicon is lower than that shown in the ladle analysis and is at the maximum silicon content as specified by National Presto.

Normally, ingot-cast steel would exhibit a greater amount of alloy segregation because of the slower solidification rates associated with the large cross-section of the ingot. In ingot-cast steel, carbon and silicon would be lower at the edge and would increase toward the center. Heating to rolling temperature and rolling to finished size helps redistribute these alloys somewhat, but a segregated condition is still usually evident in the end product. Continuous-cast steel has the advantage of rapid solidification, which reduces alloy segregation.

Forging

Aside from the increased tonnage required in the hot forging operation, little difference was distinguished between the two steels. A portion of the cavity surface, which is excellent, is shown in figure 8. Also evident is a slight amount of earing at the open end of the forging which is normal for ingot-cast steel. No unusual defects resulted from the forging operation, and the extent of rework such as removing seams and tool marks was the same as with ingot-cast steel.

Cold Draw Operation

Representative examples of chipping or breaking of the rim in the cold draw piece are shown in figures 9 and 10. A cross section of a cold drawn piece is shown in figure 9; also shown is the degree of taper formed between the punch and die at the open end. A tendency for pinching of the metal at the open end results in occasional breakage. Many of these defects were machined off during trim-to-length; however, the irregular surfaces shown in figures 9 and 10 produced the excessive tool breakage during the trimming operation. The process piece shown in figure 9 probably could not be salvaged; however, the process piece shown in figure 10 could be salvaged. Some projectile bodies which did not cleanup during trim were nosed, which usually led to the condition discussed below.

Nosing

The nosing operation performed at National Presto is done at room temperature without benefit of any stress-relief after cold draw. The taper put on the open end of the cold-drawn piece severely cold works the steel in this area. The nosing operation is different from most forming operations in that the steel is gathered or thickened. For this thickening to occur, uniform metal flow is required. A nick or chip on the open end of the process piece will interrupt the metal flow and will result in a fold during the nosing operation.

Two views each of two separate projectile bodies with nosing defects are shown in figures 11 through 14. The projectile body shown in figures 11 and 12 has sheared through the wall during nosing, displacing steel to the inside and producing cracks farther down the nose. These cracks are more evident in figure 12.

The projectile body shown in figures 13 and 14 folded inward during nosing, also displacing steel to the inside, which is more evident in figure 13. This defect does occur in regular production with ingot-cast steel and is not believed to be in any way associated with the material properties of continuous-cast steel. Projectile bodies with defects like those depicted in figures 11 through 14 cannot be salvaged. However, some projectile bodies with less severe defects were salvaged.

Macroetched specimens of base sections of two projectile bodies are shown in figures 15 and 16. Little evidence exists of remnants of dendritic structure, and the specimen appears comparable to ingot-cast steel. Segregation (depicted by black spots) also is comparable to or better than that occurring in ingot-cast steel.

Magnetic-Particle Indications

The principle disadvantage of magnetic-particle inspection is the difficulty in determining depth or severity from a surface indication. These projectile bodies had already passed through inspection station CD-1 at National Presto, which requires a 100% visual inspection, and had been accepted. Representative projectile bodies with magnetic-particle indications were selected and returned to Frankford Arsenal for metallurgical evaluation. Of all the projectile bodies examined, only one appeared to have a crack, which occurred in the nose of the projectile body (figure 17). This crack is the remnant of a fold caused during nosing which did not clean up during the nose boring operation. Since the flow lines are perpendicular to the surface on the right of the crack, the indication is that a folding action has occurred.

Typical remaining projectile bodies having magnetic-particle indications are shown in figures 18 through 20. The defect shown in figure 18 occurred just above the band seat and extends 0.25 mm (0.010 in.) below the surface. This defect appears to be a lap which would occur during the cold draw operation. The defect shown in figure 19 is another lap of lesser magnitude.

The defect in view A, figure 20, is the remnant of a seam in the bar stock, which was not completely removed during machining of the hot forged cup. Some iron oxide scale, associated with the defect, is evidenced in the higher magnification photograph in view B, figure 20. All of the defects indicated by magnetic-particle inspection, with the exception of the nose crack, would not interfere with the safe functioning of the projectile because of their orientation and shallow depth. The nose crack, however, is severe enough to warrant rejection of the projectile.

Mechanical Properties of Republic Steel Projectile Body

Mechanical properties were measured on projectile bodies selected on the basis of hardness. Two projectile bodies with hardness outside the acceptable range (one above and one below) and one projectile body with acceptable hardness were selected. An additional projectile body with hardness that exceeded the acceptable range was subjected to a second stress-relief heat treatment at 524°C (975°F) for 30 minutes and was then tested for mechanical properties. Results of these measurements are shown in table 2. The mechanical property results of the low hardness projectile body are below the minimum yield strength requirement for the M1 [448.2 MPa (65,000 psi)]. However, the percent elongation far exceeds the 15% minimum requirement for the M1. Conversely, the

high-hardness projectile body does not meet the minimum elongation requirement in the nose and is at the minimum in the band seat. (The base results are provided for information only since the M1 is not normally tested in the base and transverse ductility is not a requirement.) The projectile body within the acceptable-hardness range meets all of the requirements, as does the high-hardness projectile body which was re-stress relieved. This points out the fact that the projectiles were subjected to a nonuniform heat-treatment by the commercial heat-treater.

Roblin Steel Unworked Continuous-Casting Process

Roblin Steel supplied only enough steel to make five forgings and five projectile bodies. Roblin Steel produces approximately 108 Gg (120,000 tons) of carbon and alloy steel per year in the form of bar and rod sections up to 38.1 mm (1.5 in.) in diameter. Their steel is rolled from 101.6 mm (4 in.) square continuous-cast billets. Hot metal is produced in two 27.2 Mg (30 ton) direct-arc furnaces which use a 100% scrap charge. Two strands are cast simultaneously, are allowed to solidify in the vertical position, are then bent to the horizontal position, and are parted by flame cutting. The only other forging application of unworked continuous-cast steel known by Roblin Steel is for the production of high-performance forged crankshafts produced by General Motors.

Only a small amount of steel was processed because National Presto could not accommodate the 101.6 mm (4 in.) square cross-section. Forge tooling and billet heaters are sized for 88.9 mm (3.5 in.) round cornered square bar steel with quite precise diagonal dimensions. For the process pieces that were run, the billets were machined to 88.9 mm (3.5 in.) square steel.

Metallurgical Study of Roblin Steel Product

Raw Material

A macrograph of an unworked continuous-cast steel billet typical of the quality Roblin Steel produces is shown in figure 21. A coarse dendritic structure is evident; however, the soundness appears to be good. Areas 1 and 2 of figure 21 were selected for microscopic examination. Stains evident on the macrograph in area 1 indicated a small amount of porosity as shown in the unetched micrograph in figure 22. Area 2 represents the very center of the unworked continuous-cast steel billet and, from the macrograph, could have been interpreted as showing porosity. However, the micrograph of area 2 in figure 23 shows no porosity. The structure shows wiedmanstatten ferrite (white phase) and very fine pearlite (dark phase) which is indicative of an unworked continuous-cast steel structure. What appeared to have been porosity was an area of segregation which was attacked by the macroetch.

Another similar section typical of the quality Roblin Steel produces is shown in figure 24, with areas of specific interest indicated. Area 1

of figure 24 shows a stain which indicates a separation adjacent to a dendrite. This separation occurs when the volume of liquid metal between dendrites is not sufficient to fill the space upon solidification. Another cause is deformation of the unworked continuous-cast steel billet while liquid metal is remaining between dendrites. This deformation is caused by twisting of the billet while it is being extracted from the mold and by bending of the billet from a vertical position to a horizontal position. This condition is shown in figure 25 and is distinguished from a crack by its being a series of connected and disconnected voids. This type of defect will heal itself with subsequent hot working, because normally no oxides are associated with the voids. The center of the billet (fig. 26) also shows interdendritic porosity. The difference in microstructure on either side of the porous area is due to alloy segregation, with the alloy probably being manganese.

Process Pieces

The unworked continuous-cast steel appeared to have less ductility in hot forging than the conventional AISI 1018 material. A forging made from the unworked continuous-cast steel, with a large crack starting at the open end, is shown in figure 27. Such defects occur occasionally with ingot steel, but the defects in those instances are due to seams in the surface of the bar. Unworked continuous-cast steel has excellent surface finish and, since this steel has not been rolled, the presence of seams is unlikely.

Several mm of the open end of two other forgings were removed and macroetched (figures 28 and 29). Small cracks are evident on the face of the open end of the forging, and a coarse dendritic structure is also evident. Another view of the crack in figure 29 (fig. 30) shows small defects 180° apart. The defects occur at locations where the flow lines diverge; thus, the coarse dendritic structure results in greater directionality of properties, which would be a problem under production conditions. Microscopic examination of these small cracks did not shed any more light on their cause and did not show any massive inclusions which could have caused initiation of these cracks.

Another condition evident in forgings made from unworked continuous-cast steel is the formation of blisters on the cavity surface as shown in figure 31. Cross-sections of a blister at higher magnifications are shown in figure 32. Again, no evidence in the microstructure indicates what would cause the defect. A probable cause is that gas is trapped in voids near the center of the unworked continuous-cast steel billet. During forging, the voids are distributed next to the punch on the cavity surface. Expansion of the entrapped gas at the forging temperature causes the blisters once the support of the hot forge punch is removed.

The macroetched structure of a forging is shown in figure 33. The dendritic structure is still evident in the base area and along the cavity surface. The dark spots are areas of alloy segregation rather than voids.

A defect occurring in projectile bodies made from unworked continuous-cast steel occurring during the nosing operation and similar to those defects experienced with the Republic Steel products is shown in figure 34. Cracks similar to those shown in figures 28 and 29 could also cause this defect if not completely removed prior to cold draw and nosing.

The macroetched base section of a projectile body is shown in figure 35 and the dendritic structure is still evident. Some segregation is also evident. The manner in which alloy segregation affects the microstructure is shown in figure 36. The darker area in the center of the photograph has a higher percentage of pearlite, which is due to a higher concentration of manganese. Unworked continuous-cast steels are more prone to exhibit segregation because they have not been worked and reheated as has the Republic Steel continuous-cast product.

Some scattered porosity was also evident in the base of the projectile body, as indicated in figure 37. This defect appears to be dendritic porosity which did not close during forging since the base does not undergo as much deformation as the sidewalls. A comparison of the microstructure in figure 37 with the microstructure in figures 22, 23, 25 and 26 shows the degree of refinement obtained by reheating for forging.

Mechanical Properties of Roblin Steel Projectile Body

One of the nosed projectile bodies was stress-relieved at 482°C (900°F) for 1 hour and was subjected to mechanical property testing. Two tensile specimens were removed from the rotating band area 180° apart, and one specimen was removed from the base, 25.4 mm (1 in.) from the center line. All of the specimens comply with the minimum requirements for the M1 projectile of 448.1 MPa (65,000 psi) yield strength and 15% elongation. These properties compare favorably with the properties of 105-mm M1 projectiles made from ingot-cast steel, as is shown in table 3.

Ballistic Testing

A quantity of 100 projectiles made from the Republic Steel hot rolled continuous-cast product were ballistically tested at Jefferson Proving Ground.

A total of 50 projectiles were fired for a first-article-sample test as specified in MIL-P-60547C (the item specification for the 105-mm M1 projectile). This test requires the firing of 30 rounds at ambient temperature and at excess pressure and 20 rounds at ambient temperature and at service pressure. These projectiles were recovered and measured after firing. Deformation greater than 0.025 mm (0.010 in.) on either the body diameter or bourrelet diameter was cause for failing the test. Loss or breakup of metal parts was also cause for failing.

The remaining 50 projectiles were fired at -53.9°C (-65°F) and at excess pressure. These projectiles were also recovered and subjected to the same acceptance criteria as the first-article sample. The purpose of this test was to determine if the hot rolled continuous-cast steel had any unusual sensitivity to firing stresses at low temperature. Test results of all rounds were acceptable (ref 2).

Fracture Toughness Test

The plane strain fracture toughness of the Republic Steel hot rolled continuous-cast product was determined and was compared with ingot-cast 1018 steel. The plane strain fracture toughness characterizes the resistance of a material to fracture in a neutral environment in the presence of a sharp crack. This value may be used to estimate the relation between failure stress and defect size for a steel in service.

Test Procedure

Since the wall thickness of a 105-mm M1 projectile does not permit a fracture toughness to be machined from it, billet stock had to be used for this test. Billet ends were normalized at 871°C (1600°F) and were cold-rolled to a 37.5% reduction in area. This steel was then stress-relieved at 398.9°C (750°F) for 1 hour. Standard tensile specimens were removed from the long transverse direction and were tested at -53.9°C (-65°F) and 22.2°C (72°F) at varying strain rates. Compact fracture toughness specimens conforming to ASTM Standard E399 were machined from the cold-rolled billets in an orientation where the width of the specimen was in the long transverse direction and the notch was parallel to the longitudinal axis. The specimens were then tested in accordance with ASTM Standard E399.

Test Results

Mechanical properties of the tensile specimens tested at various strain rates and various testing temperatures are shown in table 4. A consistent trend does not exist with respect to the effect of strain rate on mechanical properties. However, the properties tend to be lower at room temperature than at -53.9°C (-65°F). The yield strength is comparable to results obtained from projectiles (table 2), with the exception that percent elongation for the tensile specimens is lower due to specimen orientation.

Results of plane strain fracture toughness testing at various strain rates and temperatures for this hot rolled continuous-cast steel are shown in table 5. A consistent relationship between strain rate and fracture toughness values does not exist. However, a relationship does exist between testing temperature and fracture toughness [which is higher at room temperature than at

-53.9°C (-65°F)]. Fracture toughness at room temperature is higher for the hot rolled continuous-cast steel than for the ingot-cast steel (table 6). This increased room temperature toughness may be due to a lower fracture toughness transition temperature in the hot rolled continuous-cast steel. The fracture toughness of hot rolled continuous-cast steel in general compares favorably with that of the ingot-cast steel.

Specification Requirements

Based on experience with the Republic Steel hot rolled continuous-cast product, the macroetched standards should be the same as those implied for special quality bar and semi-finished forging quality billet, depending on product size required. Unworked continuous-cast steel will not meet these requirements.

Chemistry requirements of continuous-cast steel should remain the same as ingot-cast steel with the realization that if a fully aluminum-killed steel is required, the source of supply may be limited.

Since current material specifications (ASTM or Military) do not specifically limit the use of continuous-cast steel, no supplement to these specifications is required.

To allow the use of a continuous-cast steel for manufacture of projectile bodies an additional requirement should be added to the drawing as follows: "Continuous-cast steel shall be permitted provided that, subsequent to casting, the steel shall be hot rolled to a minimum of 75% (4:1) reduction in cross-sectional area.

CONCLUSIONS

Hot Rolled Continuous-Cast Steel

1. To produce a continuous-cast steel with quality equivalent to an ingot-cast steel, a reduction in cross-sectional area of at least 4:1 after casting is required.
2. Hot rolled continuous-cast steel is suitable for manufacture of projectile bodies by either the hot cup-cold draw process or by the hot-forge-and-machine process.
3. Base soundness (lack of porosity) of projectile bodies made from hot rolled continuous-cast steel is acceptable and is comparable to that of bodies made from ingot-cast steel.

4. Plane strain fracture toughness of hot rolled continuous-cast steel is equivalent to that of ingot-cast steel.

5. To attain mechanical properties comparable to those of ingot-cast steel, the hot rolled continuous cast steel requires higher stress-relief temperature than does ingot-cast steel.

6. Hot rolled continuous-cast steel is less ductile in cold drawing and nosing operations than is the ingot-cast steel.

7. In the manufacture of projectile bodies, a higher reject rate occurred with bodies made from hot rolled continuous-cast steel than occurred with bodies made from ingot-cast steel. However, this reject rate could be reduced if tooling and processing were optimized (such as has been done for the ingot-cast steel).

Unworked Continuous-Cast Steel

1. Unworked continuous-cast steel is not suitable for manufacture of projectile bodies by either the hot cup-cold draw process or by the hot-forge-and-machine process because of its low ductility, its poor dimensional control, and the presence of blisters on the cavity surface.

2. Unworked continuous-cast steel is not comparable in quality to ingot-cast steel.

3. Unworked continuous-cast steel is less ductile in cold drawing and nosing operations than is hot rolled continuous-cast steel.

4. Some evidence of base unsoundness (presence of porosity) appeared in projectile bodies made from unworked continuous-cast steel.

RECOMMENDATIONS

1. Unworked continuous-cast steel should not be adopted as an acceptable steel for manufacture of projectile bodies.

2. Hot rolled continuous-cast steel should be adopted as an acceptable steel for manufacture of projectile bodies. However, this adoption should be subject to the incorporation in the TDP of the following requirement:

"Reduction by Rolling: Subsequent to casting, the continuous-cast steel shall be reduced in cross-sectional area by hot rolling until the area is 25% of its original size (that is, a 4:1 reduction)."

3. The TDP for manufacture of projectile bodies should be changed to show the acceptability of hot rolled continuous-cast steel for manufacture of projectile bodies, subject to the conditions in recommendation 2 above.

REFERENCES

1. National Presto Industries, Inc., Final Report, Contract No. DAAA25-75-C-0614 (undated).
2. "Engineering Design Test of Projectile, 105-mm, M1 Type, Continuous Cast Steel," U. S. Army Jefferson Proving Ground, Test Report 76-703, Jefferson Proving Ground, Madison, IN, July 1976.

Table 1. Chemical analysis of Republic Steel continuous-cast product

Element	Wt. (%)		Ladle analysis
	Check analysis		
	Edge	Center	
Carbon	0.20; 0.19	0.18; 0.18	0.185
Manganese	0.66	0.66	0.68
Phosphorus	0.002	0.002	0.007
Sulfur	0.018	0.018	0.023
Silicon	0.10	0.10	0.15
Nickel	0.02	0.06	0.07
Copper	0.05 to 0.15	0.05 to 0.15	0.14
Chromium	0.06	0.06	0.08

Table 2. Mechanical properties of Republic Steel projectile bodies

<u>Specimen</u>	<u>Yield strength</u>		<u>Tensile strength</u>		<u>Elongation (%)</u>
Low-hardness projectile body					
<u>Ogive area</u>	<u>MPa</u>	<u>psi</u>	<u>MPa</u>	<u>psi</u>	
1	302.6	43,900	415.0	60,200	37
2	315.7	45,800	417.1	60,500	37
Band seat area					
1	336.4	48,800	441.9	64,100	33
2	290.9	42,200	437.1	63,400	32
Base area	466.1	67,600	557.8	80,900	17
High-hardness projectile body					
1	692.9	100,500	768.8	111,500	13
2	683.9	99,200	763.3	110,700	14
Band seat area					
1	628.8	91,200	710.9	103,100	15
2	626.7	90,900	708.8	102,800	15
Base area	601.9	87,300	677.1	98,200	8

Table 2 (cont)

Acceptable-hardness
projectile body

<u>Ogive area</u>	<u>Yield strength</u>		<u>Tensile strength</u>		<u>Elongation (%)</u>
	<u>MPa</u>	<u>psi</u>	<u>MPa</u>	<u>psi</u>	
1	631.6	91,600	693.6	100,600	17
2	597.8	86,700	670.2	97,200	18

Band seat area

1	555.0	80,500	631.6	91,600	17
2	524.7	76,100	614.3	89,100	16

High-hardness projectile body
subjected to second stress-relief heat treatment*

Ogive area

1	654.9	95,000	717.1	104,000	16
2	666.1	96,600	722.6	104,800	16

Band seat area

1	581.2	84,300	664.0	96,300	17
2	615.7	89,300	688.1	99,800	17
Base area	534.3	77,500	622.6	90,300	14

* At 524°C (975°F) for 30 minutes.

Table 3. Comparison of mechanical properties of projectiles of Roblin Steel projectile bodies with ingot-cast projectile bodies.

<u>Specimen</u>	<u>Yield strength</u>		<u>Tensile strength</u>		<u>Elonga- tion(%)</u>	<u>Reduction in area (%)</u>
Unworked continuous cast steel*						
	<u>MPa</u>	<u>psi</u>	<u>MPa</u>	<u>psi</u>		
0° bourrelet	584.6	84,800	657.7	95,400	18	54
180° bourrelet	558.4	81,000	538.4	92,600	20	56
Base	523.9	76,000	628.7	91,200	17	53
Ingot-cast steel						
0° bourrelet	634.9	92,100	708.7	102,800	15	51
180° bourrelet	630.1	91,400	721.1	104,600	15	48
Base	550.1	79,800	641.1	91,800	11	19

*Stress relieved at 482°C.

Table 4. Mechanical properties of Republic Steel hot rolled continuous-cast steel cold-rolled 37.5% RA

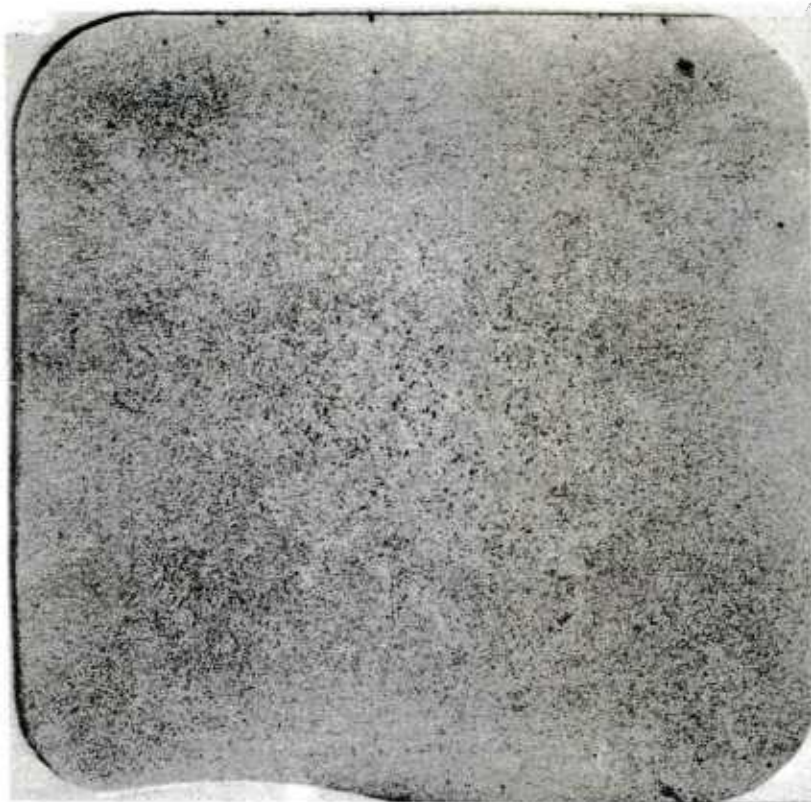
Testing temp		Strain rate (mm/mm/sec)	Yield strength		Tensile strength		Elongation (%)	Reduction in area (%)
°C	°F		Ksi	MPa	Ksi	MPa		
-53.9	-65	Quasi-static	621.8	90.2	697.7	101.2	5.2	21.0
-53.9	-65	1.9	663.2	96.2	697.7	101.2	10.8	29.3
-53.9	-65	1.9	594.3	86.2	614.9	89.2	8.4	25.9
-53.9	-65	44.0	739	107.2	752.8	109.2	6.6	13.0
-53.9	-65	60.0	580.5	84.2	594.3	86.2	10.2	32.5
22.2	72	Quasi-static	586	85.0	624.6	90.6	5.2	14.6
22.2	72	1.9	566.7	82.2	594.3	86.2	7.4	21.6
22.2	72	1.3	551.5	80.0	594.3	86.2	4.8	16.8
22.2	72	39.0	621.8	90.2	649.4	94.2	7.8	23.8
22.2	72	50.0	621.8	90.2	649.4	94.2	9.0	31.2

Table 5. Plane strain fracture toughness of Republic Steel hot rolled continuous-cast steel cold-rolled 37.5% RA

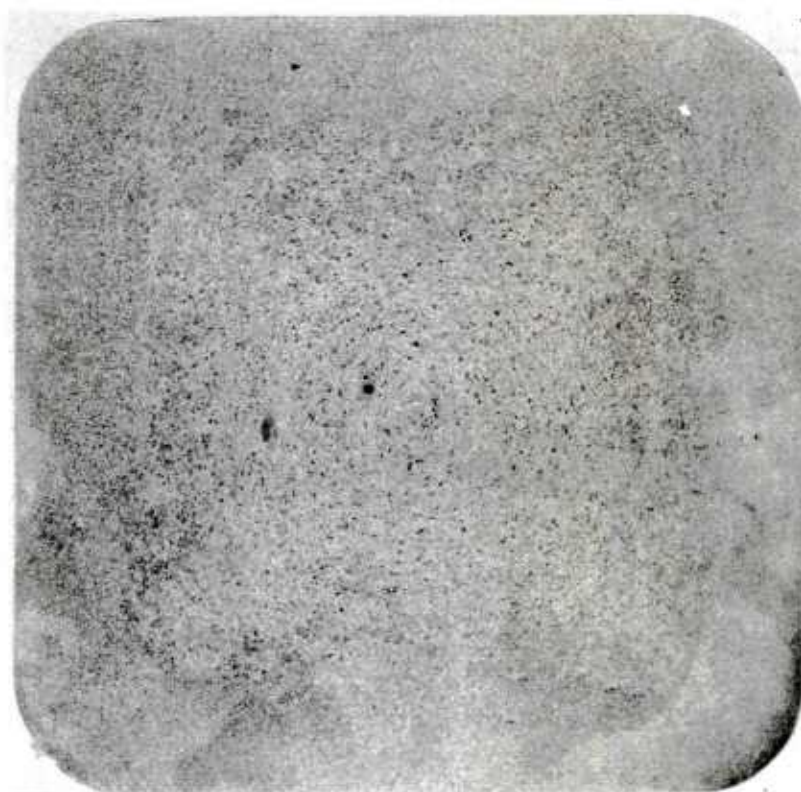
Testing temperature		Strain rate (mm/mm/sec)	Yield strength		Plane strain fracture toughness	
<u>°F</u>	<u>°C</u>		<u>MPa</u>	<u>Ksi</u>	<u>MPa/m</u>	<u>Ksi/in.</u>
-53.9	-65	Quasi-static	621.8	90.2	1612	37.2
-53.9	-65	0.74	659.8	95.7	1560	36.0
-53.9	-65	0.92	659.8	95.7	1326	30.6
-53.9	-65	11.70	628.7	91.2	1639	37.8
22.2	72	Quasi-static	586	85.0	2623	60.5
22.2	72	0.40	559.8	81.2	2545	58.7
22.2	72	1.10	559.8	81.2	2250	51.9
22.2	72	8.00	621.8	90.2	2679	61.8
22.2	72	8.00	621.8	90.2	2601	60.0

Table 6. Plane strain fracture toughness of ingot-cast steel cold-rolled 37.5% RA

Testing temperature		Strain rate (mm/mm/sec)	Yield strength		Plane strain fracture toughness	
°C	°F		MPa	Ksi	MPa/m	Ksi/in.
-53.9	-65	Quasi-static	620.5	90.0	1535	35.4
-53.9	-65	Quasi-static	620.5	90.0	1583	36.5
-53.9	-65	1.4	734.9	106.6	1353	31.2
-53.9	-65	1.6	734.9	106.6	1375	31.7
-53.9	-65	8.8	650.1	94.3	1314	30.3
-53.9	-65	11.2	650.1	94.3	1435	33.1
22.2	72	Quasi-static	537.7	78.0	1821	42.0
22.2	72	Quasi-static	537.7	78.0	1789	41.2



1A

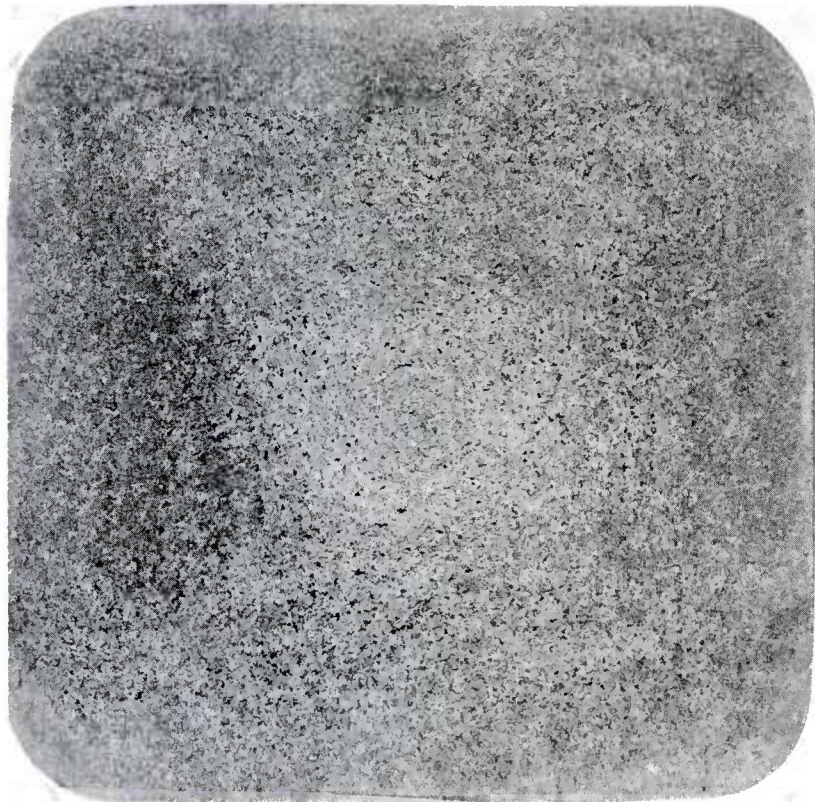


1B

Figure 1. Macroetched bar sections - Republic Steel (1X)



1C



1D

Figure 1. (cont) Macroetched bar sections - Republic Steel (1X)



Figure 2. Microporosity at center of bar section 1A - Republic Steel (100X)



Figure 3. Microporosity midway between center and edge of bar section 1A - Republic Steel (100X)

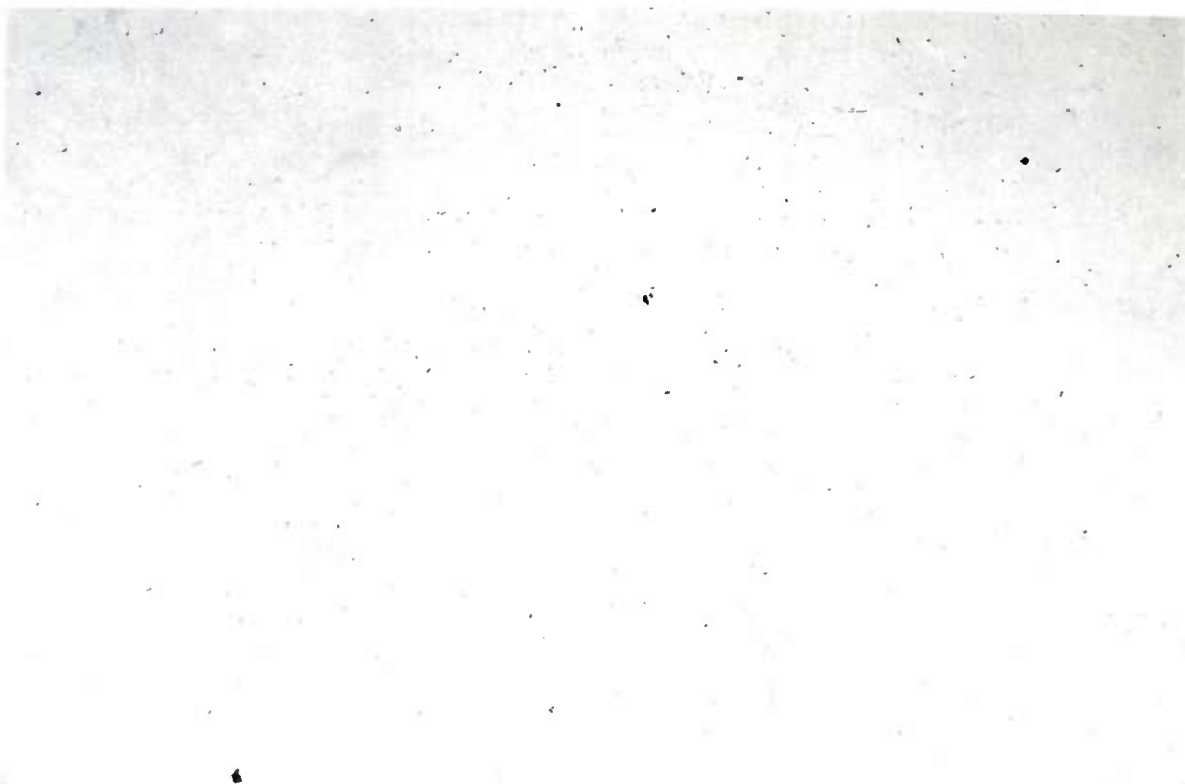


Figure 4. Microporosity at edge of bar section 1A - Republic Steel (100X)

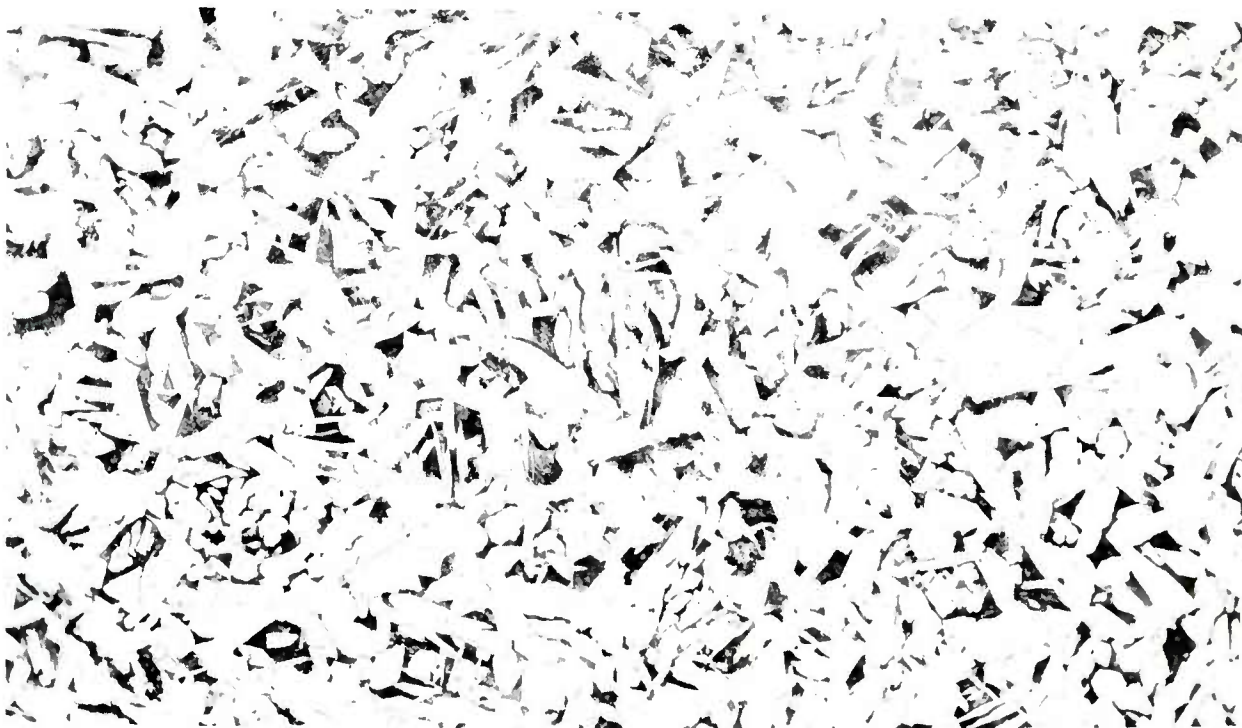


Figure 5. Microstructure at center of bar section 1A, picral etch - Republic Steel (100X)

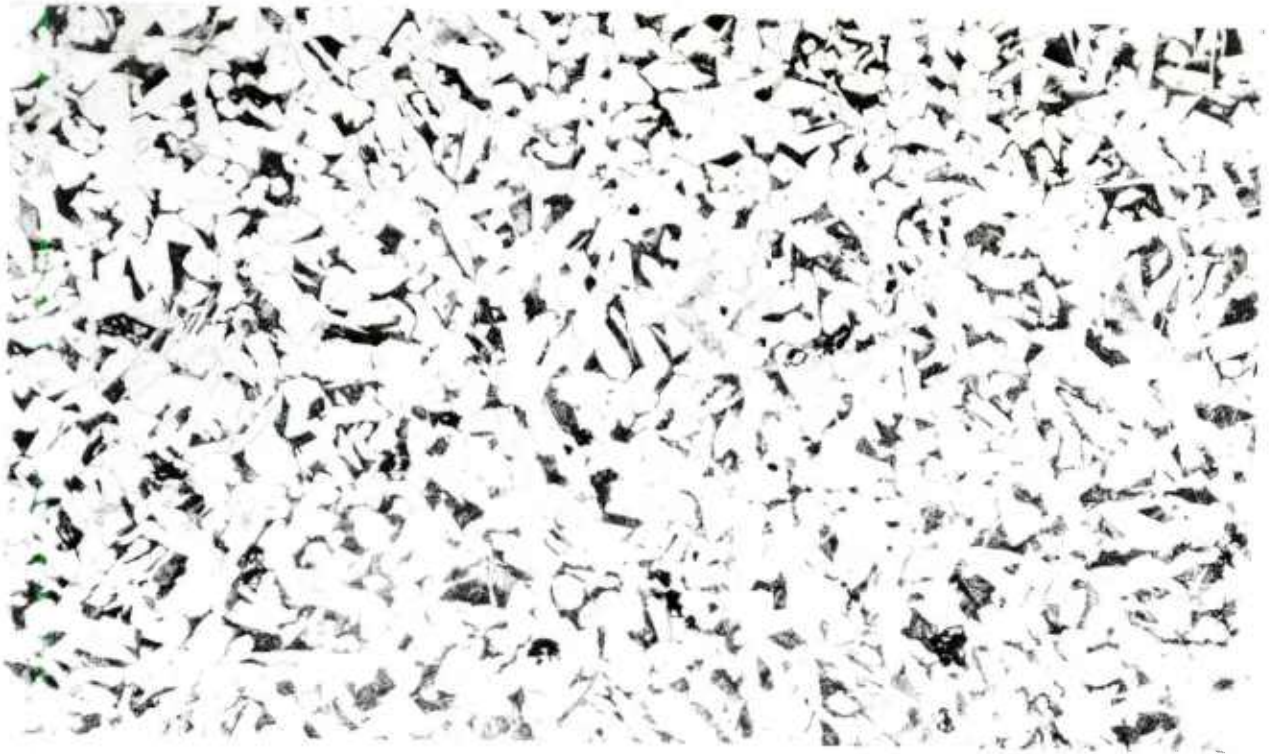


Figure 6. Microstructure midway between center and edge of bar section 1A, picral etch - Republic Steel (100X)

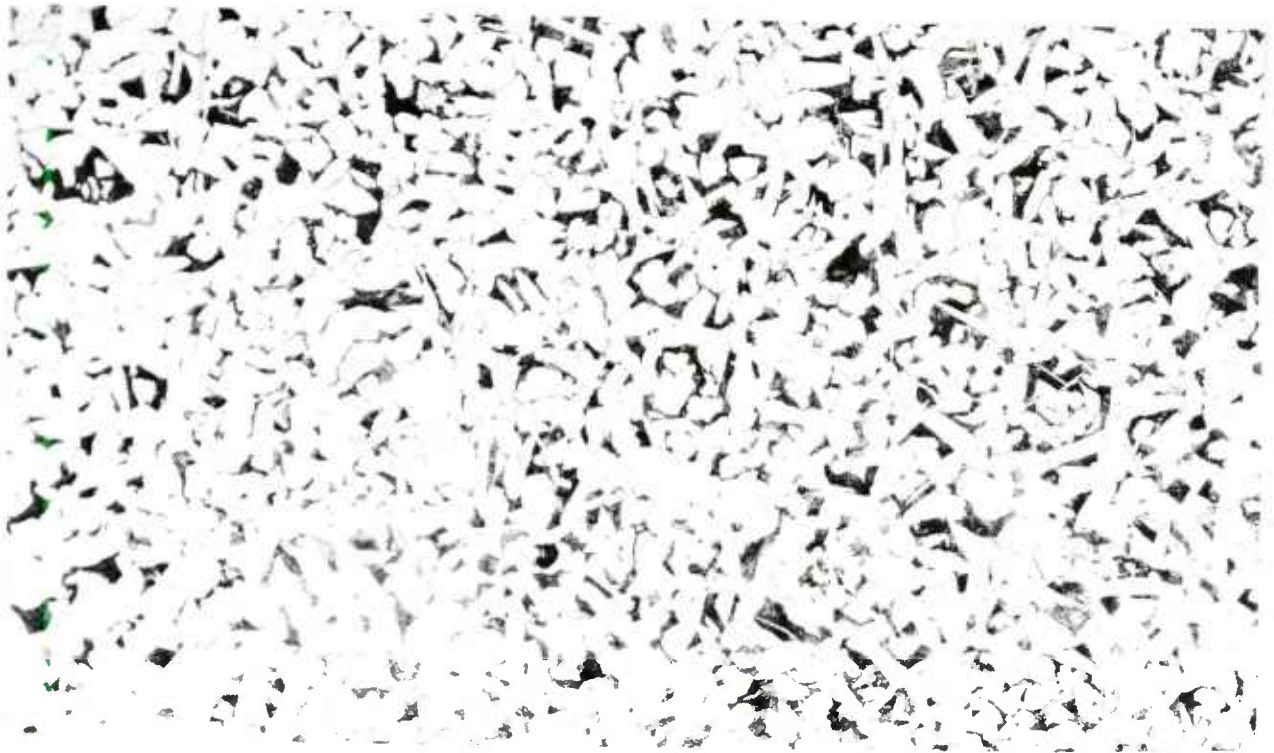


Figure 7. Microstructure at edge of bar section 1A, picral etch - Republic Steel (100X)

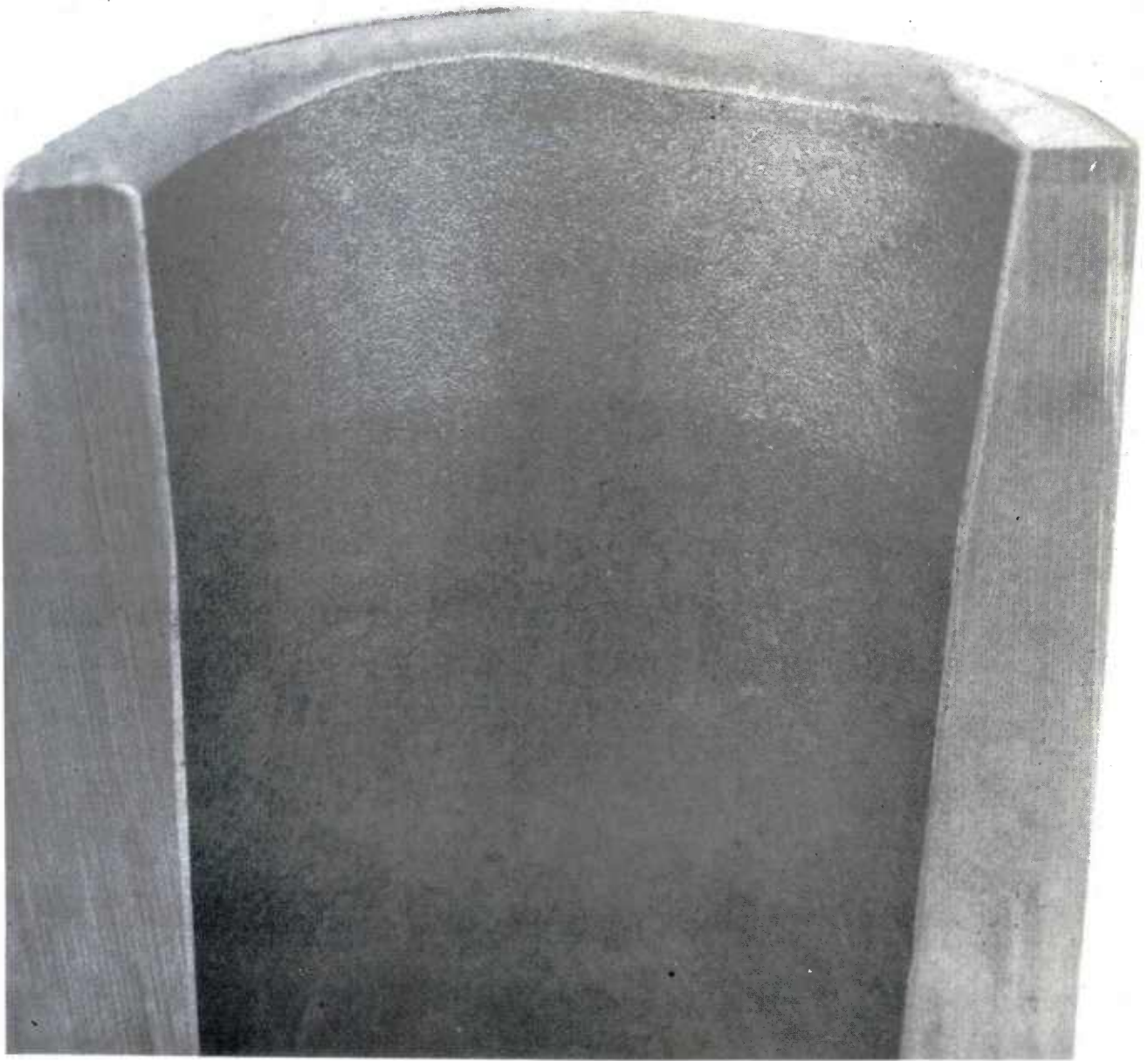


Figure 8. As-forged cavity, after shotblasting, of projectile made from Republic Steel product

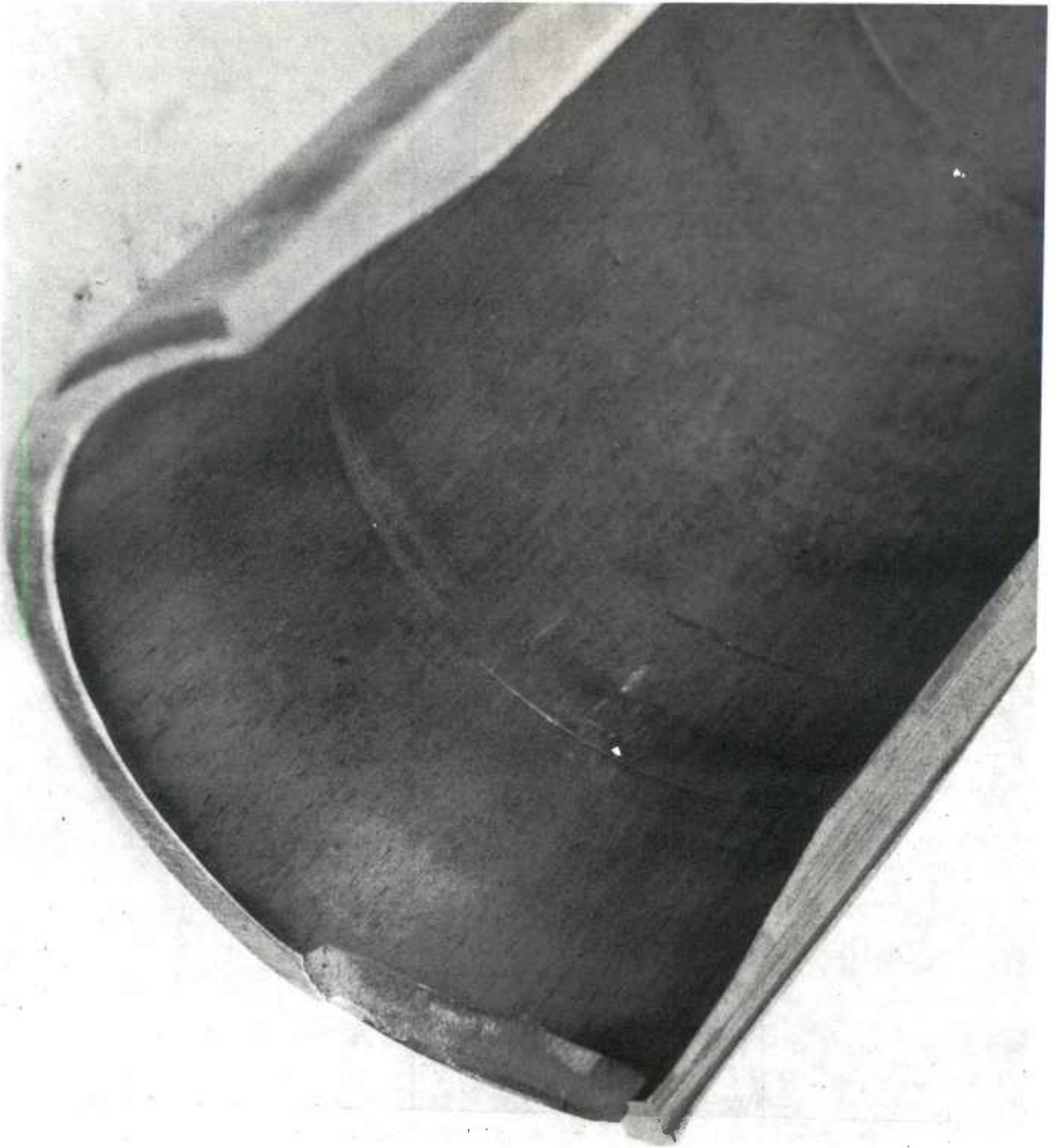


Figure 9. Example 1 of cold-drawn process piece showing breakout at open end - Republic Steel



Figure 10. Example 2 of cold drawn process piece showing breakout at open end - Republic Steel

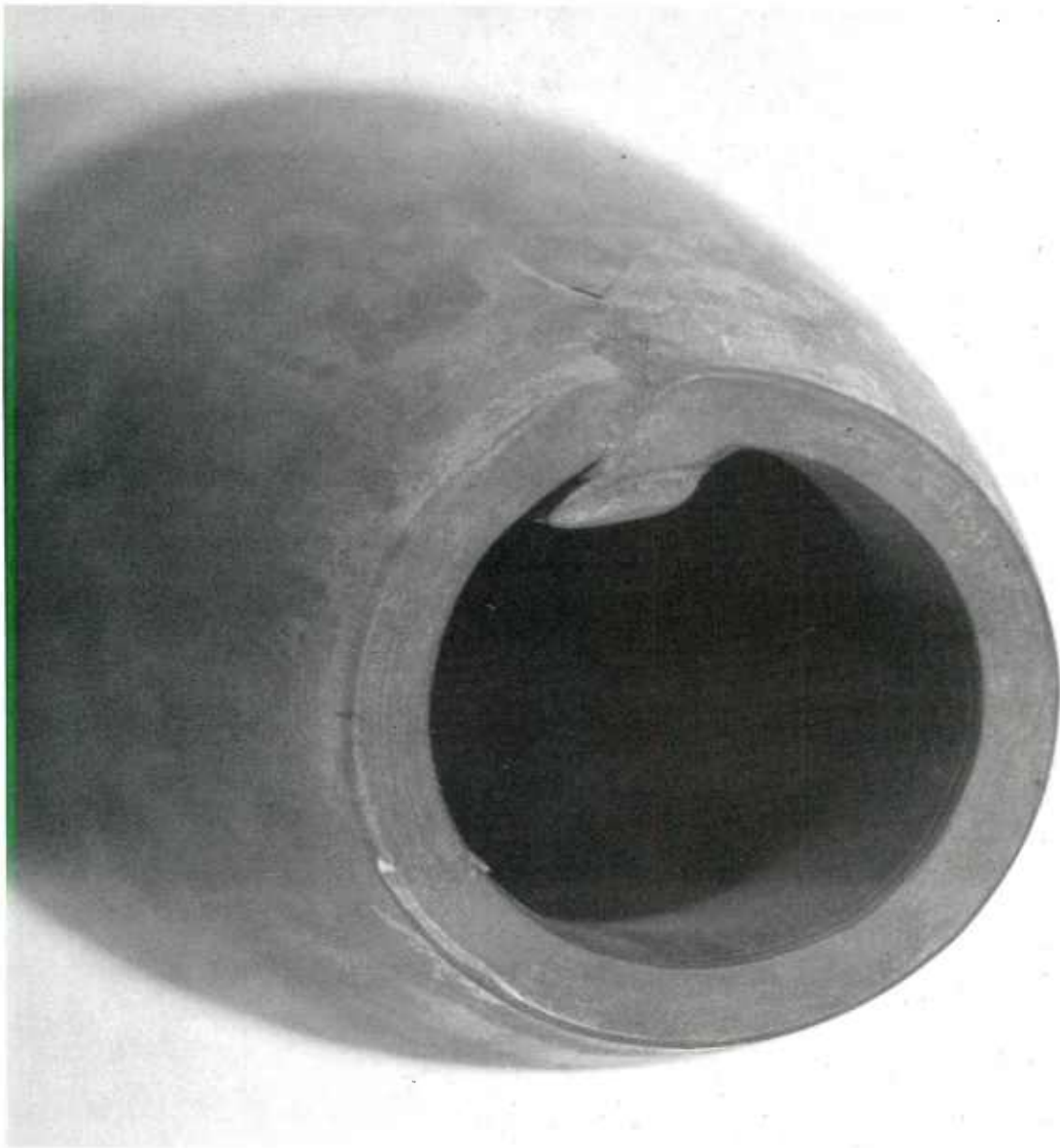


Figure 11. Example 1 of nosing defect (fold), internal view - Republic Steel



Figure 12. Example 1 of nosing defect (fold), external view - Republic Steel

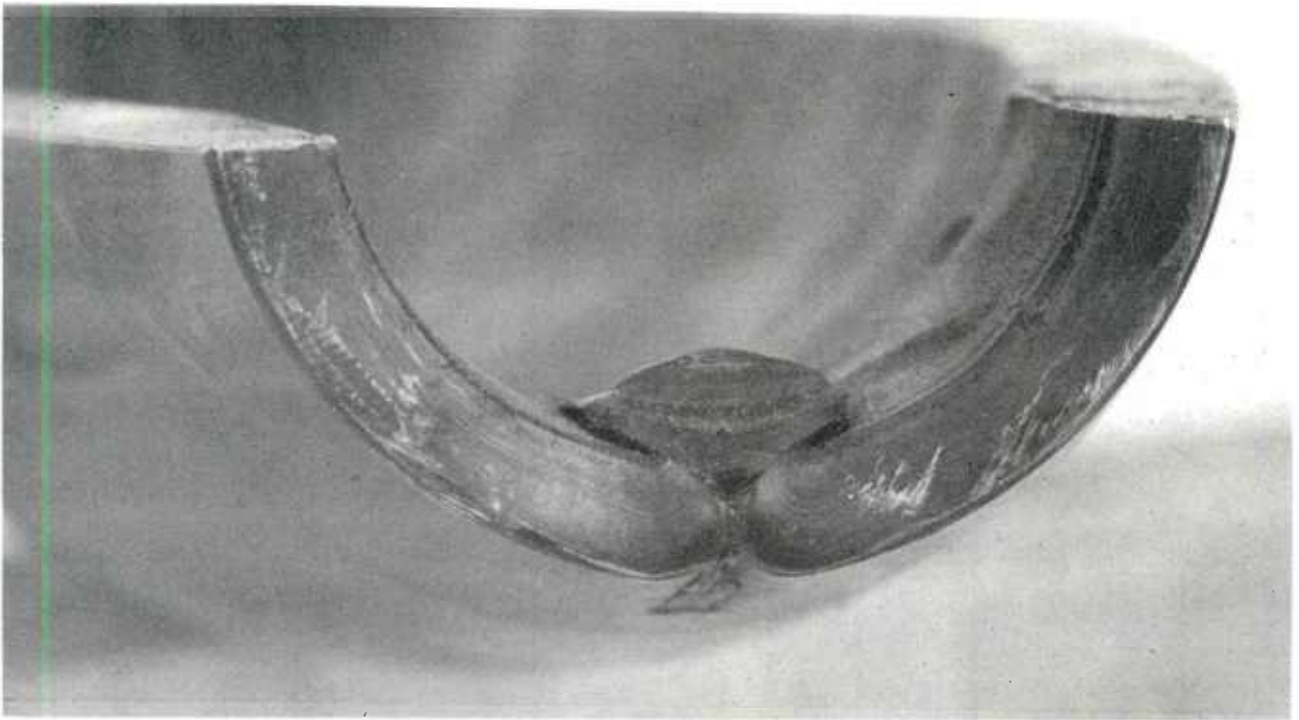


Figure 13. Example 2 of nosing defect (fold), internal view - Republic Steel



Figure 14. Example 2 of nosing defect (fold), external view - Republic Steel

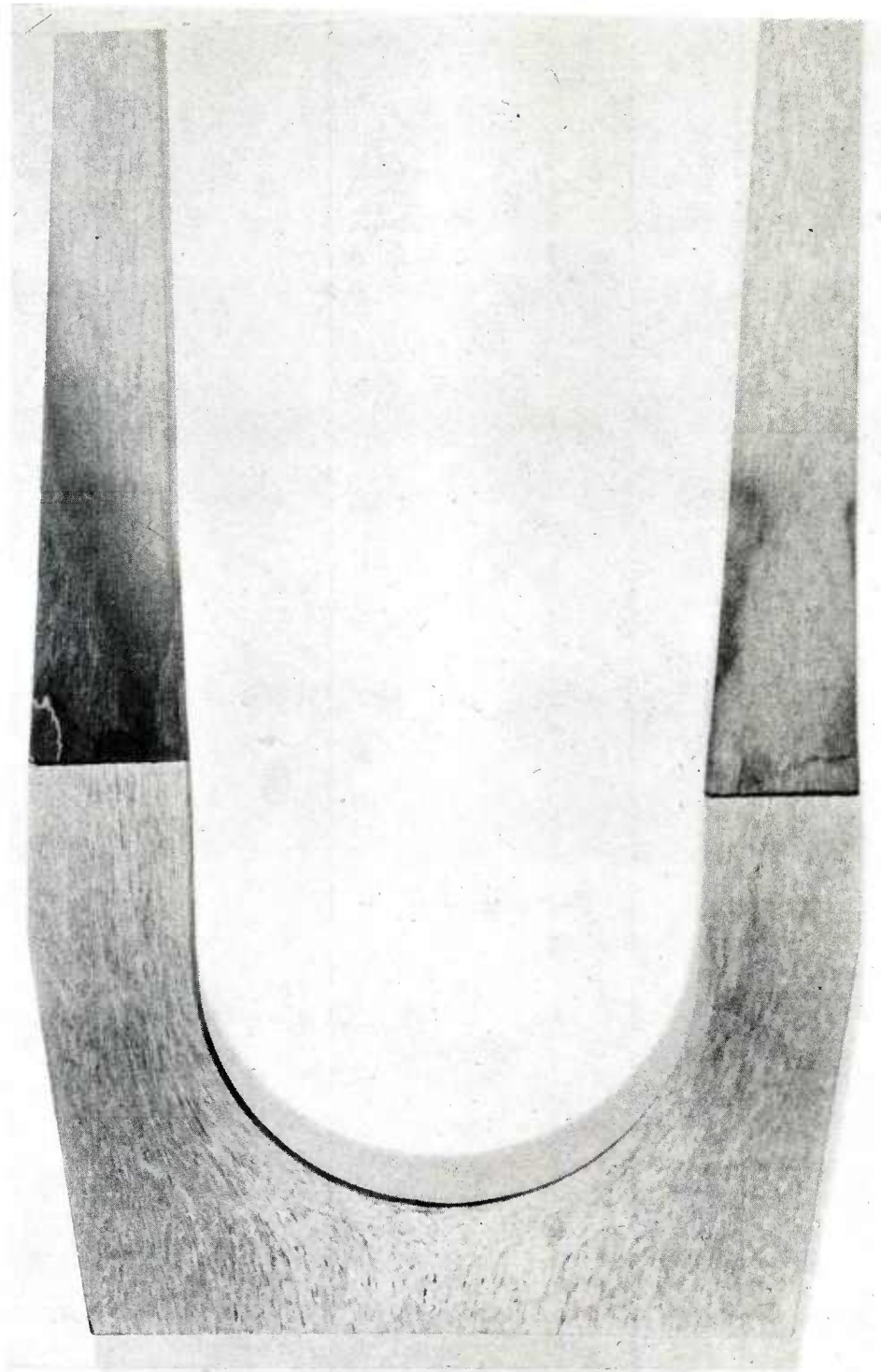


Figure 15. Example 1 of macroetched base section of projectile made from Republic Steel product

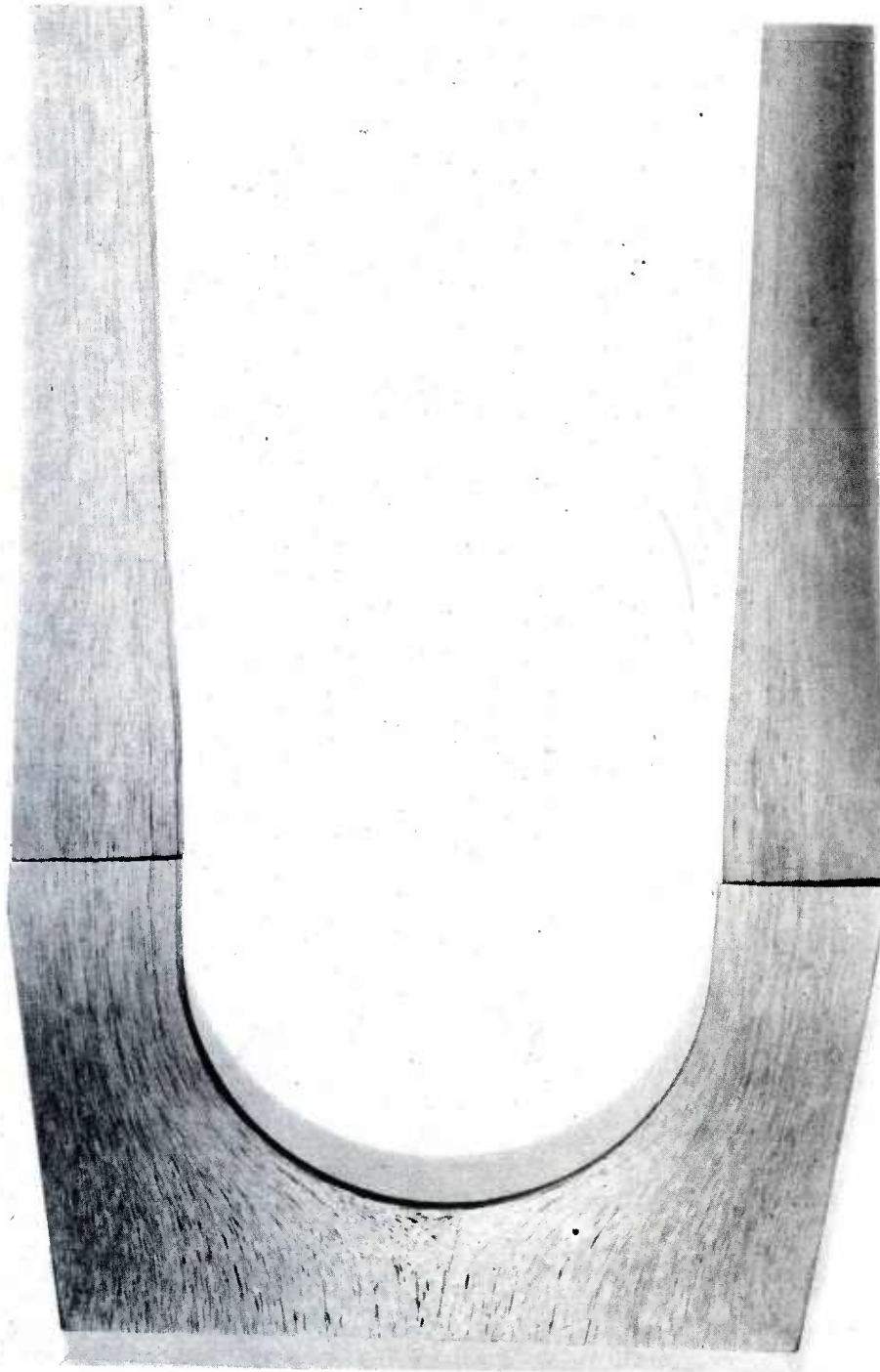


Figure 16. Example 2 of macroetched base section of projectile made from Republic Steel product



Figure 17. Microstructure of magnetic particle indication of nosing defect, picral etch - Republic Steel (100X)

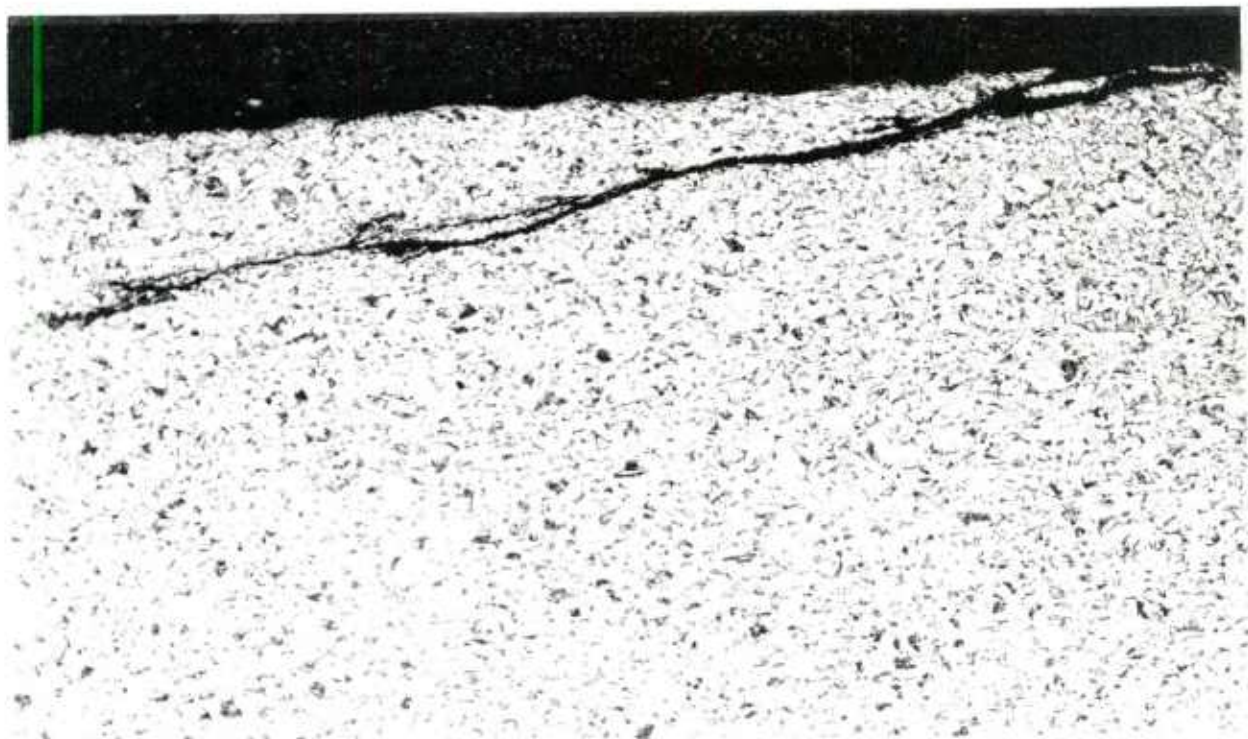


Figure 18. Microstructure of magnetic particle indication of band seat area, picral etch - Republic Steel (100X)

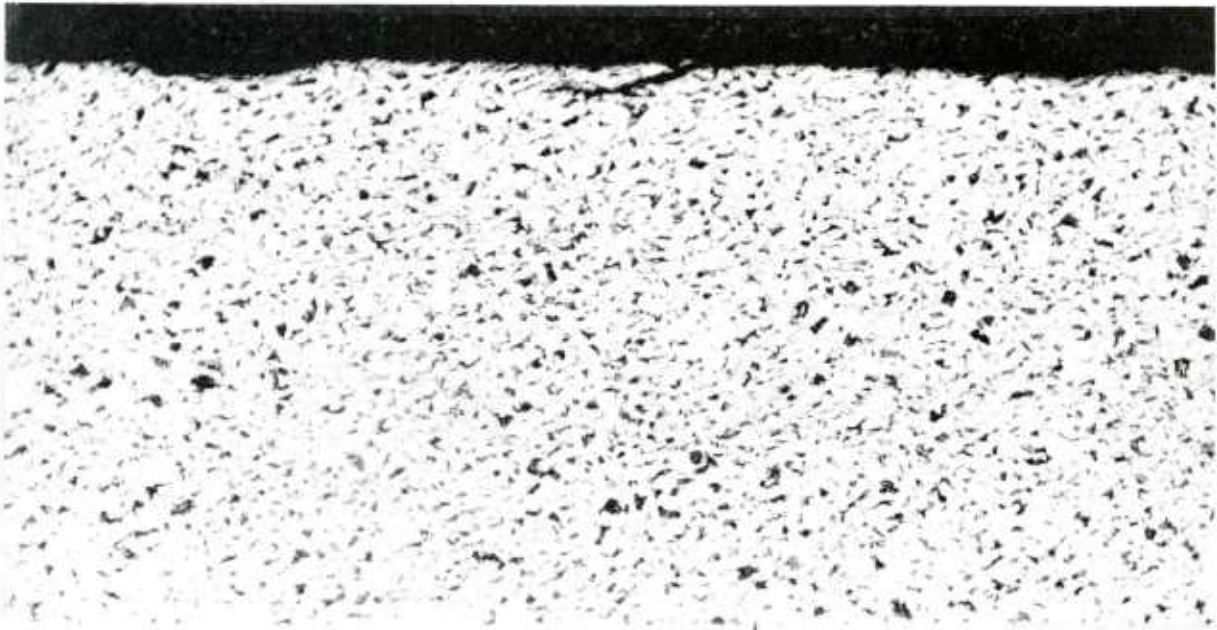
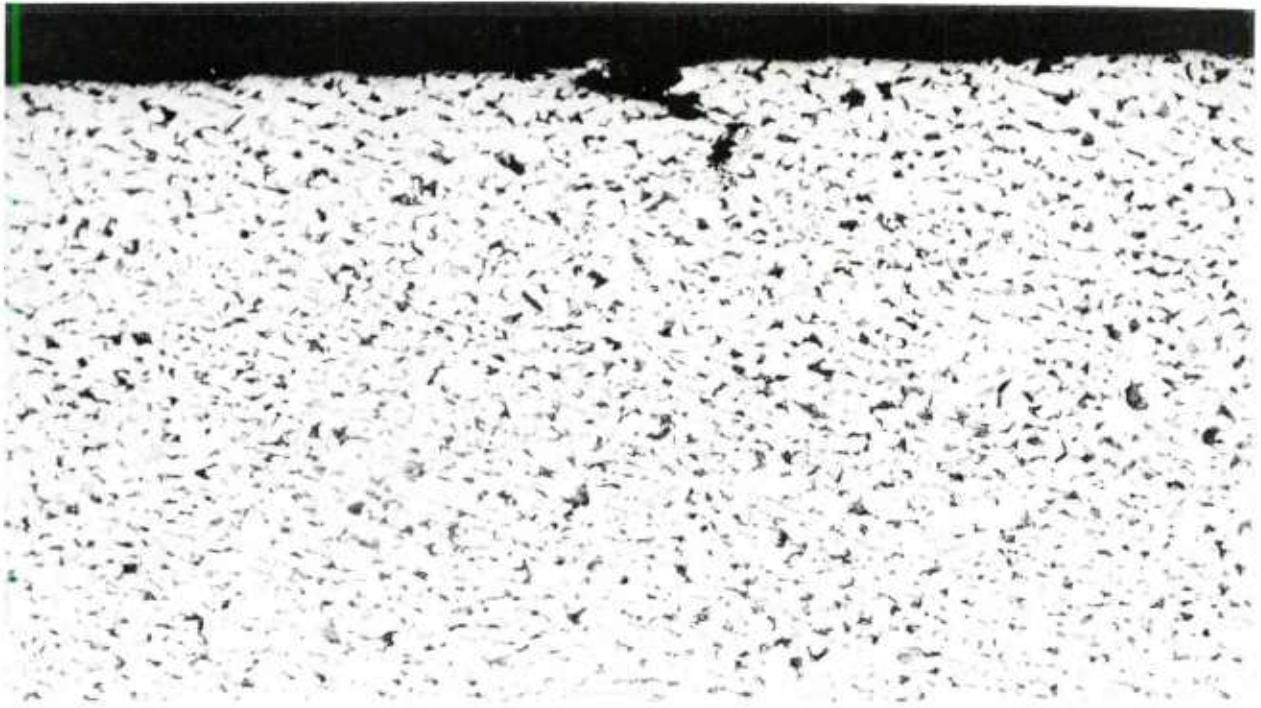
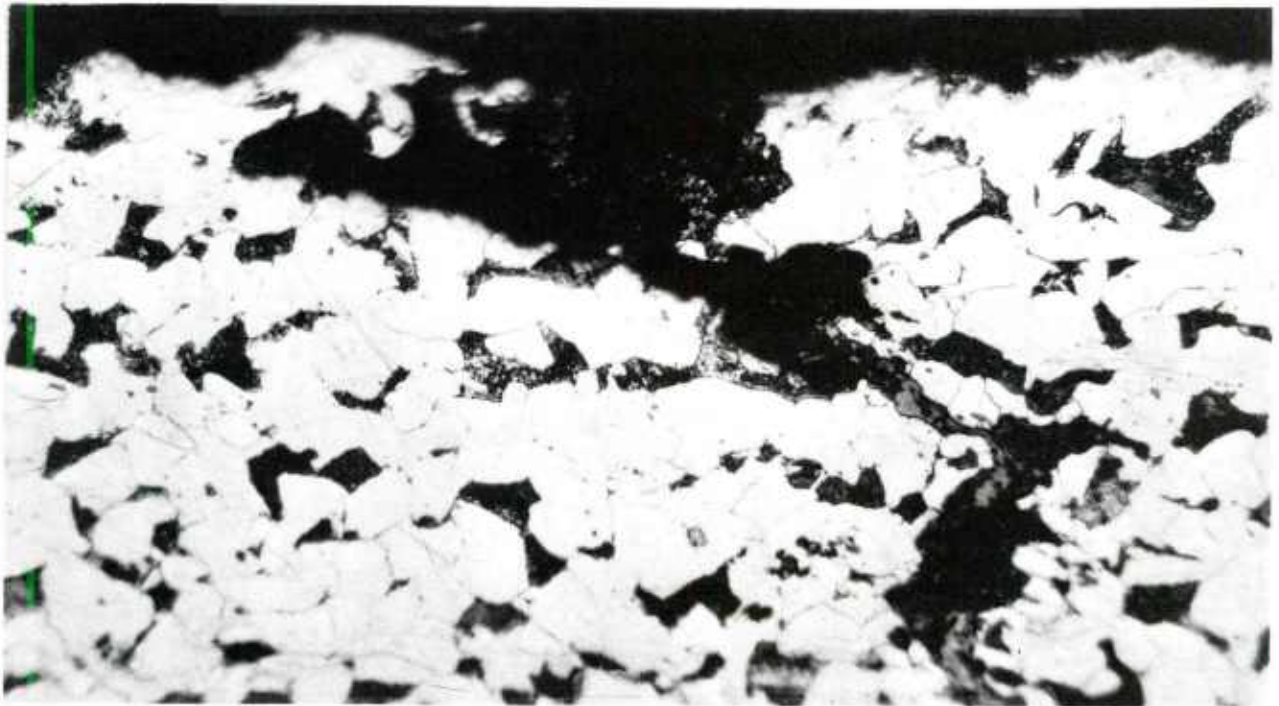


Figure 19. Lap-type defect revealed by magnetic particle testing, picral etch - Republic Steel (100X)



A (100X)



B (500X)

Figure 20. Remnant of seam revealed by magnetic particle testing, picral etch - Republic Steel (100X and 500X)

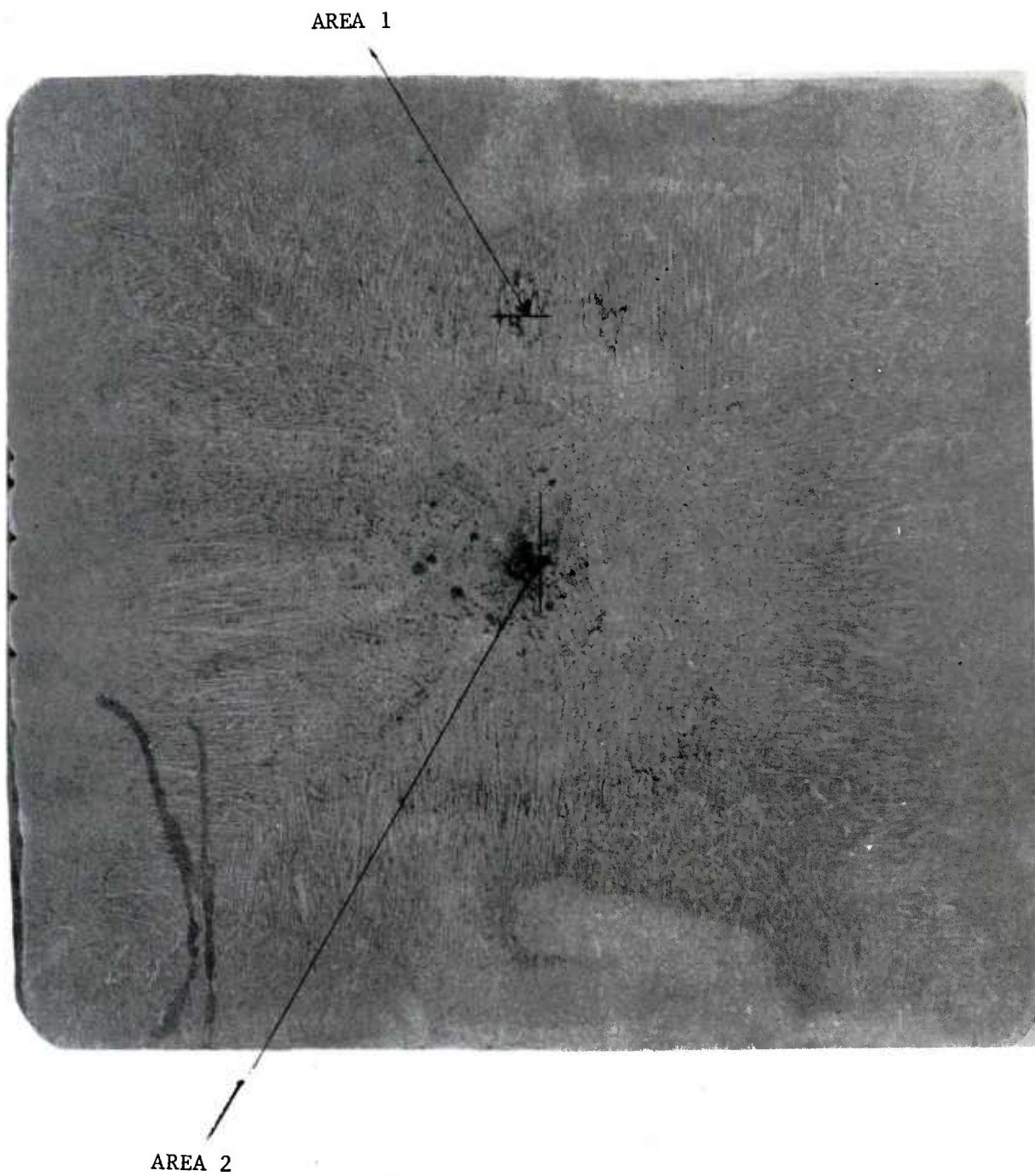


Figure 21. Macroetched bar section 1 - Roblin Steel (1.5X)

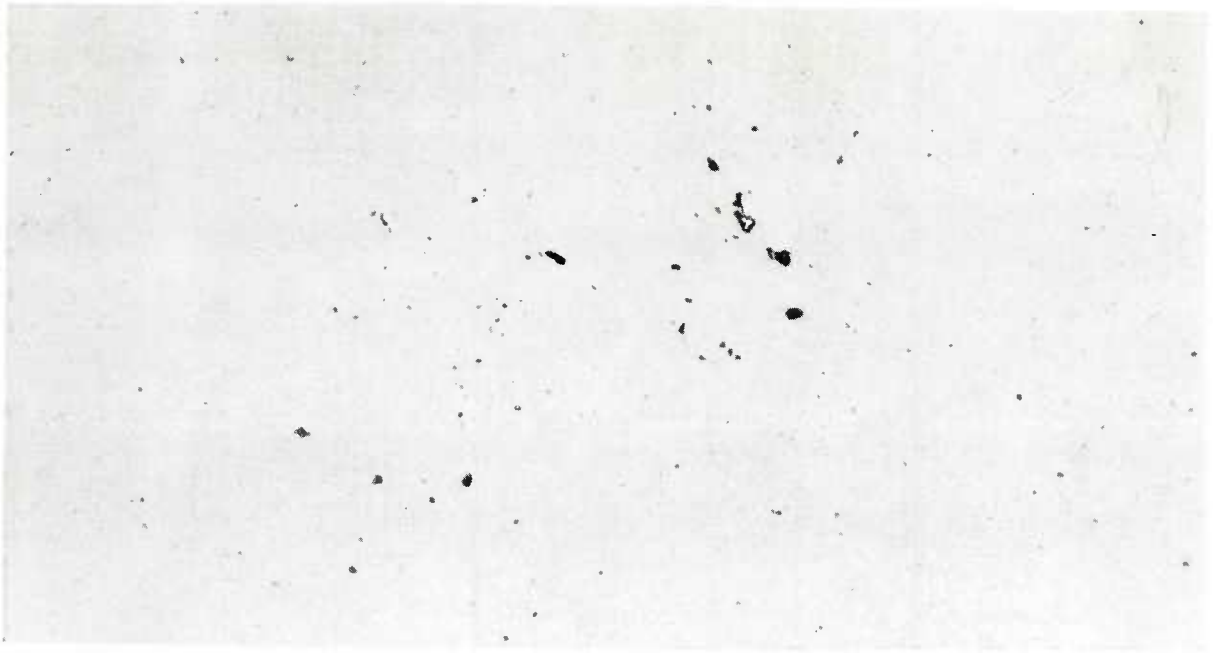


Figure 22. Porosity evident in area 1 of macroetched bar section 1 - Roblin Steel (100X)

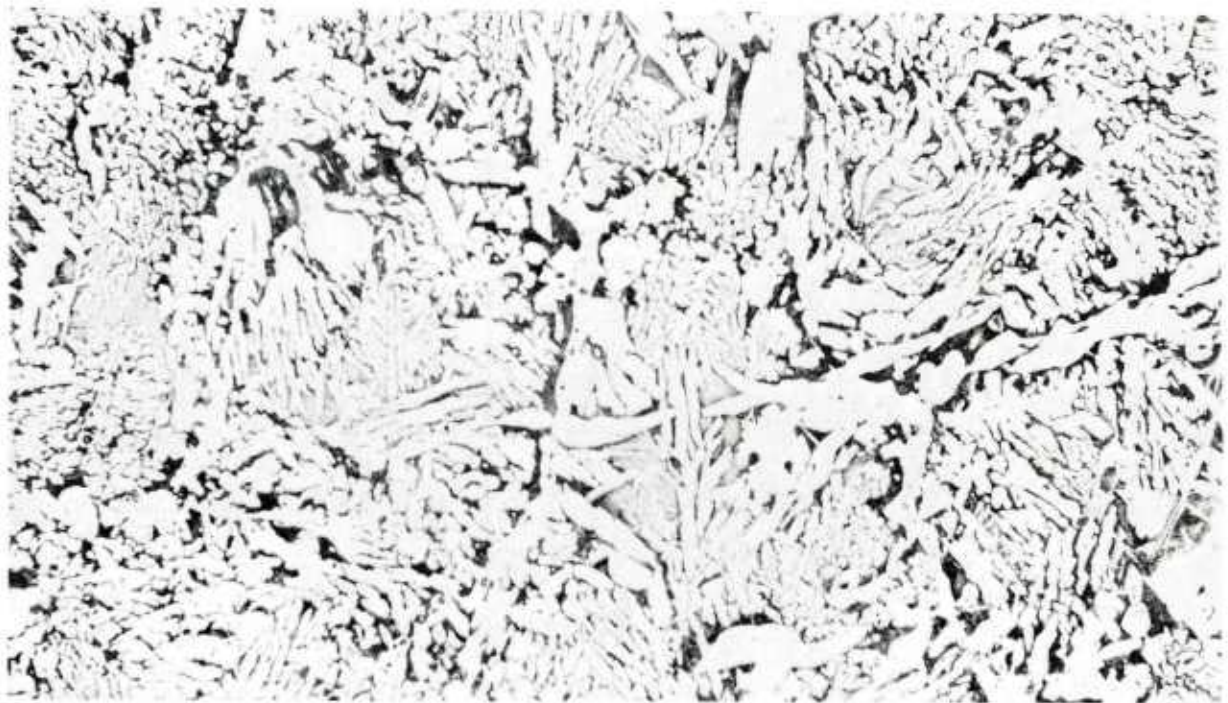


Figure 23. Microstructure in area 2 (center) of macroetched bar section 1, picral etch - Roblin Steel (100X)

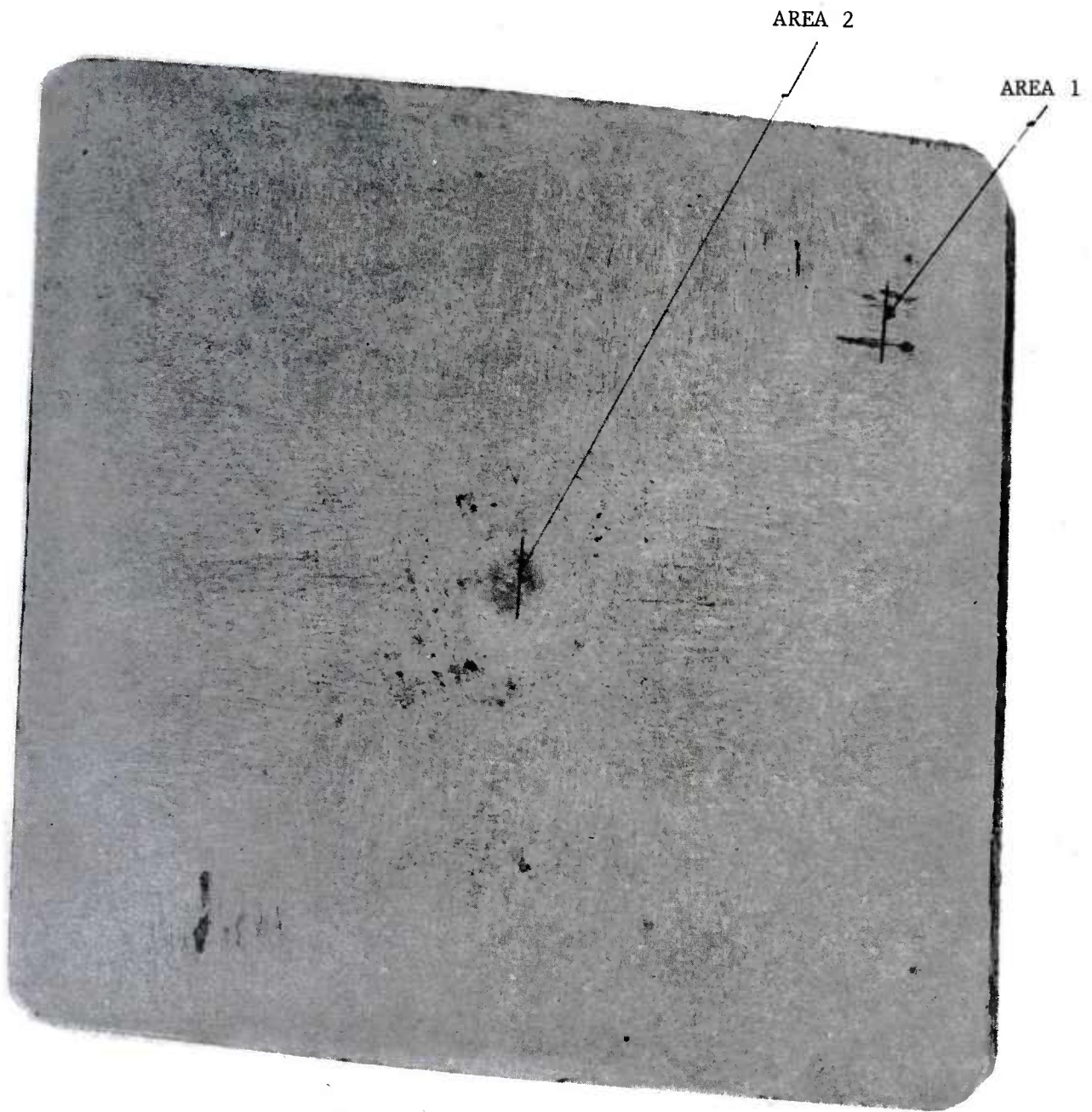


Figure 24. Macroetched bar section 2 - Roblin Steel (1.5X)

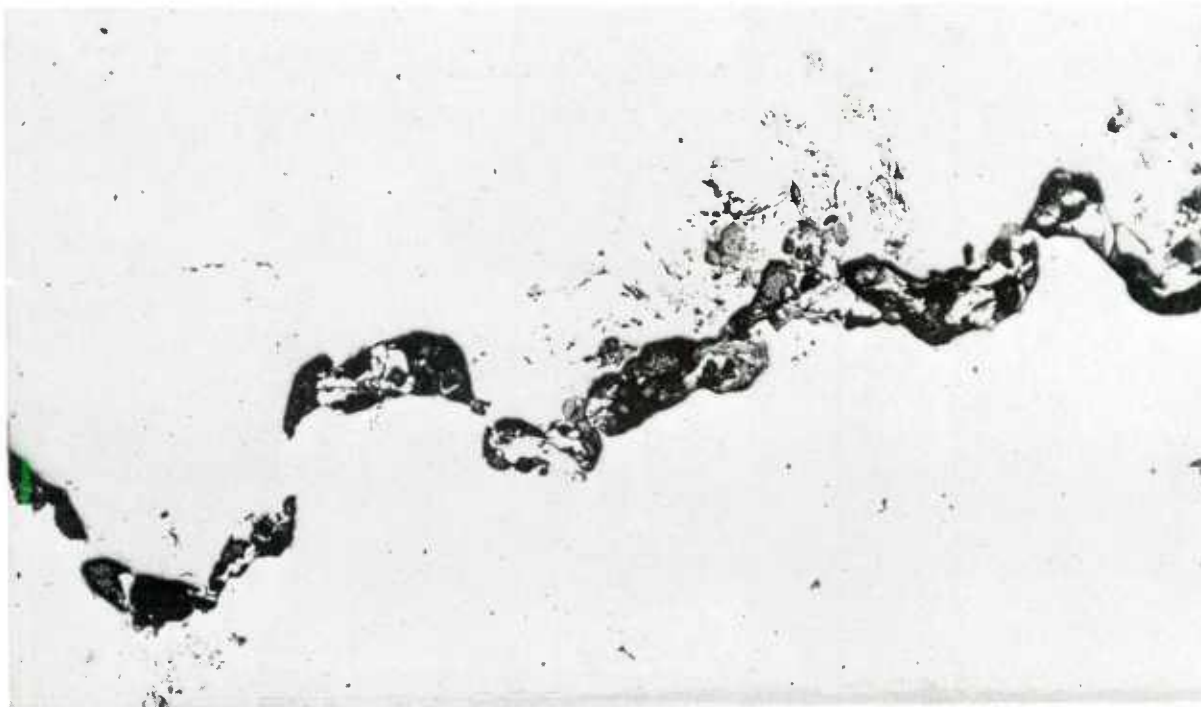


Figure 25. Discontinuities in area 1 of macroetched bar section 2 - Roblin Steel (100X)

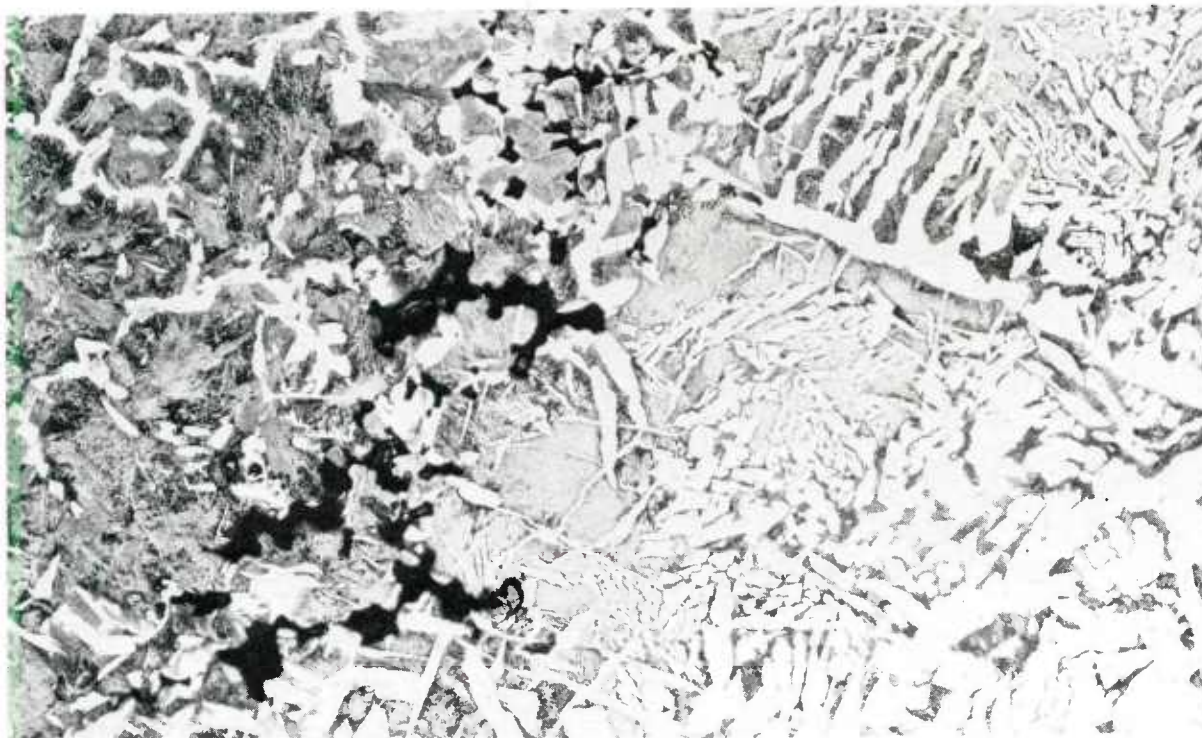


Figure 26. Porosity in area 2 (center) of macroetched bar section 2, picral etch - Roblin Steel (100X)



Figure 27. Defective forging made from Roblin Steel product



Figure 28. Cracks evident on open end of forging made from Roblin Steel product



Figure 29. Cracks and divergent dendritic flow lines on forging made from Roblin Steel product

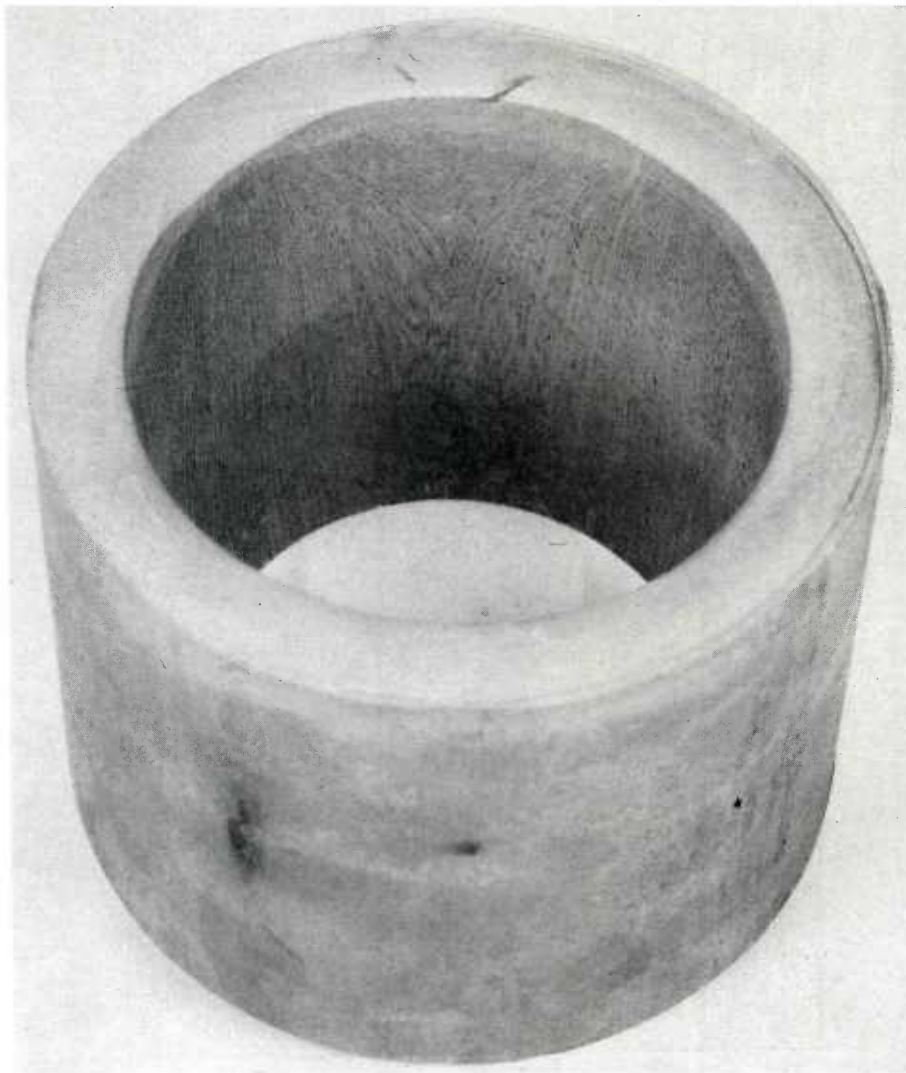
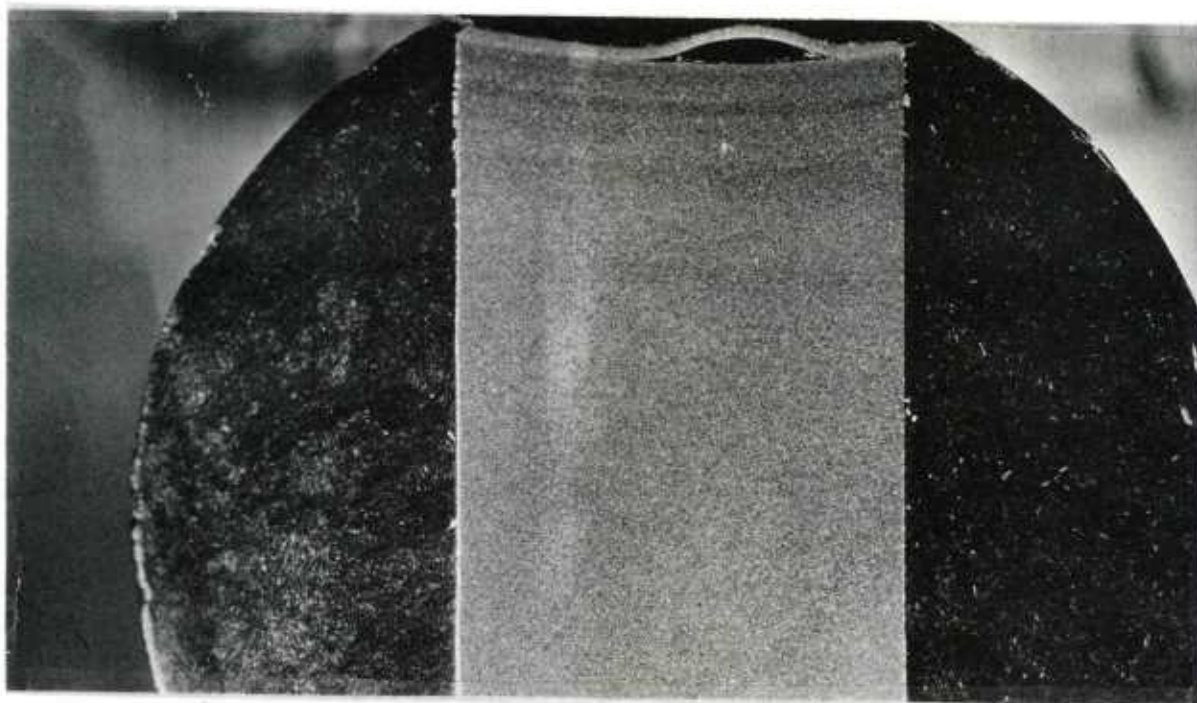


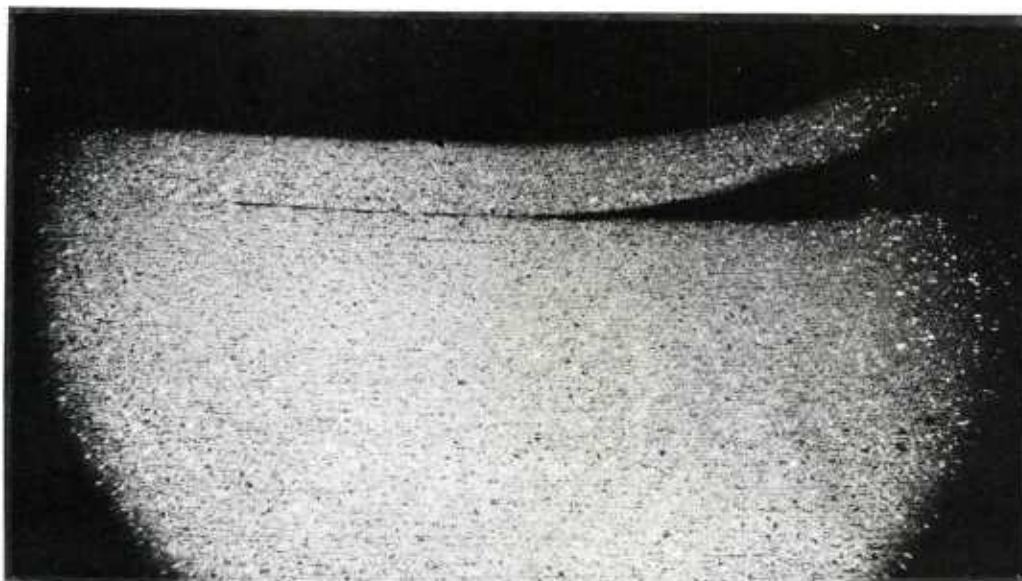
Figure 30. Opposite side view on forging shown in figure 29 - Roblin Steel



Figure 31. Blisters on cavity surface of forging made from Roblin Steel product (0.5X)



A (3X)



B (30X)

Figure 32. Cross-section of blister on cavity of forging made from Roblin Steel product (3X and 30X)

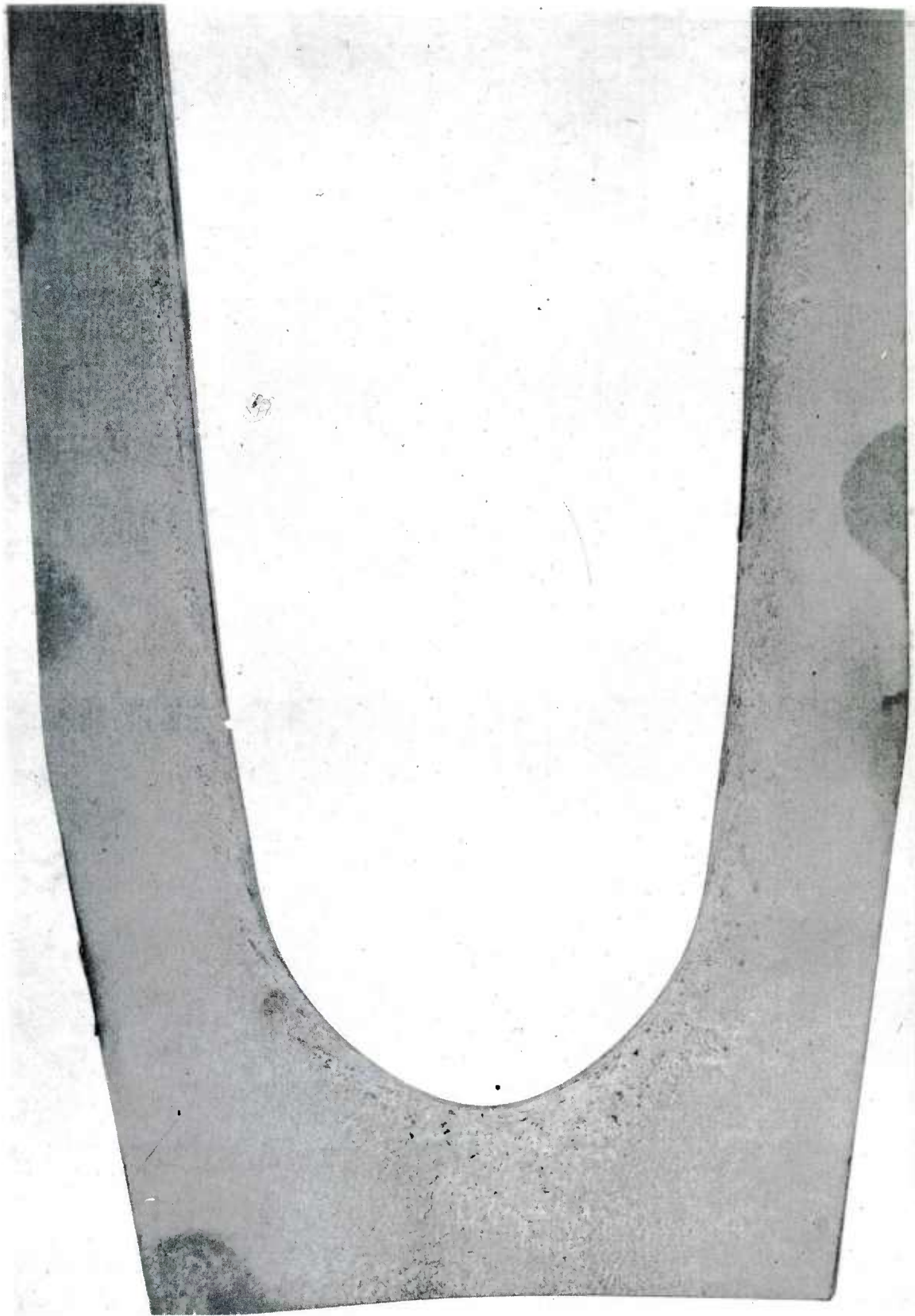


Figure 33. Macroetched section of forging made from Roblin Steel product

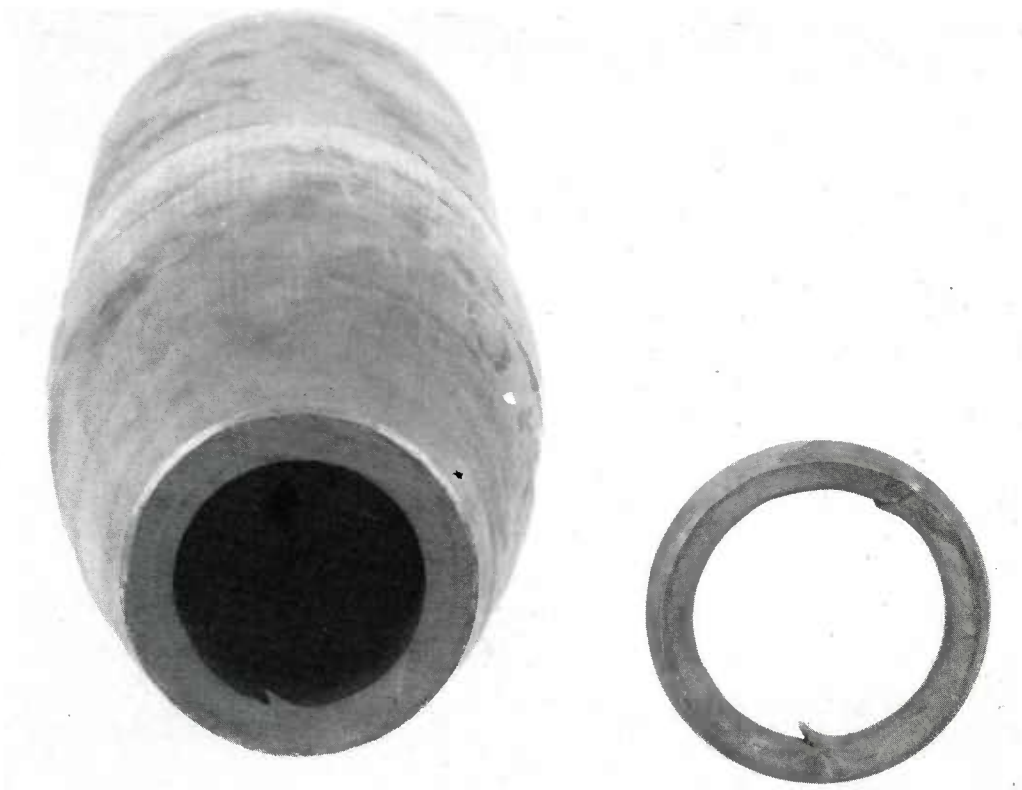


Figure 34. Nosing defect in projectile made from Roblin Steel product



Figure 35. Macroetched base of projectile made from Roblin Steel product

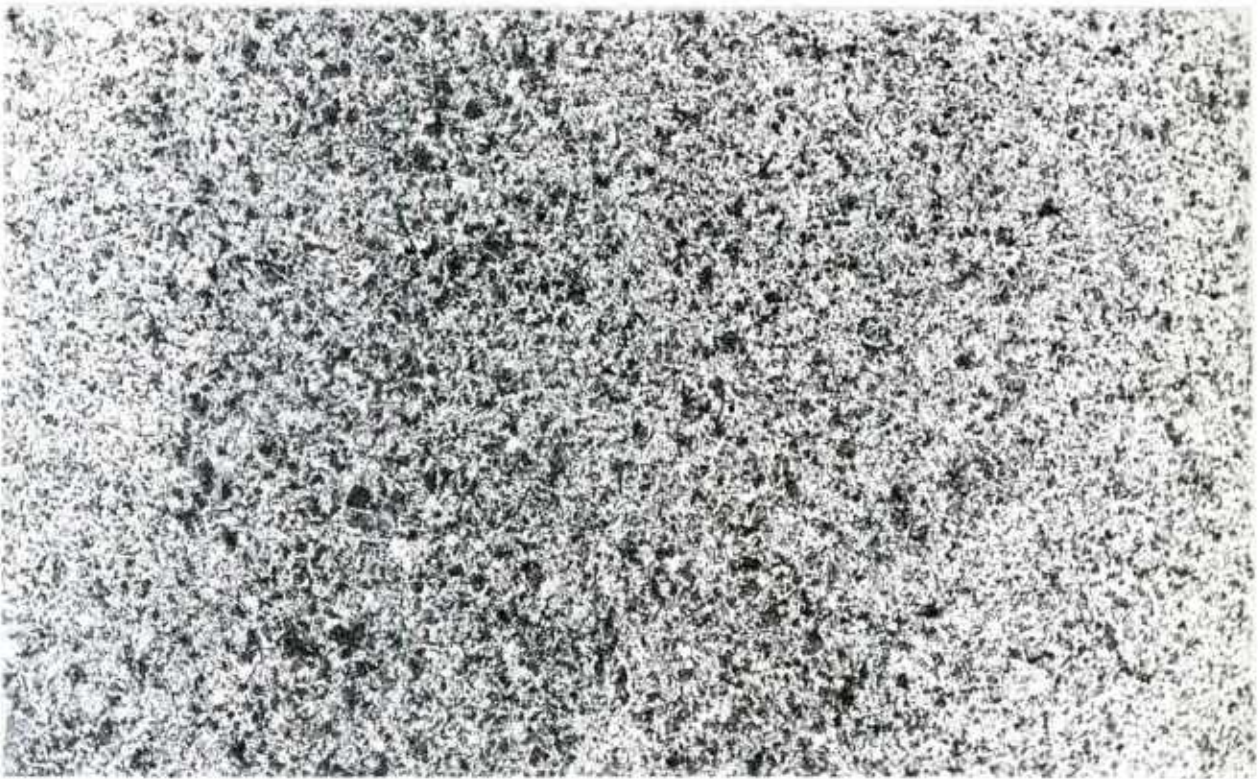


Figure 36. Microsegregation in Roblin Steel product, picral etch (100X)

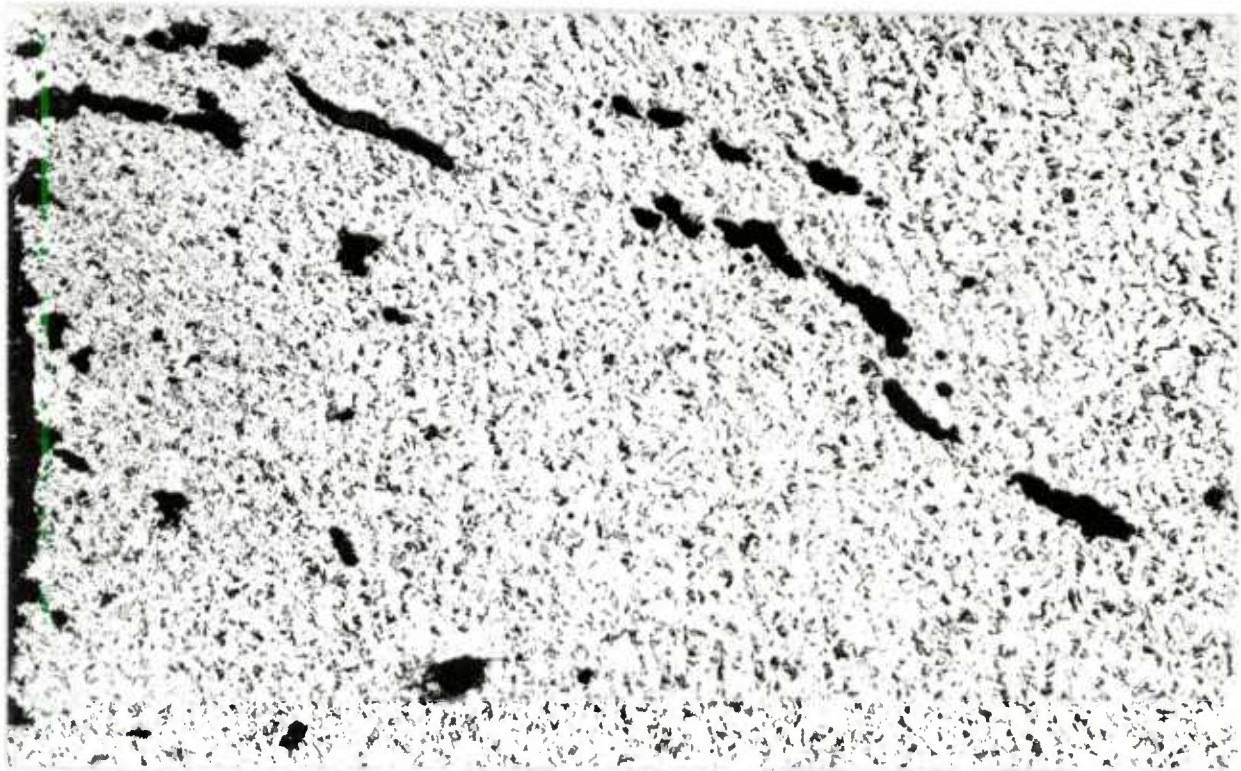


Figure 37. Dendritic porosity in base of projectile made from Roblin Steel product, picral etch (100X)

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