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C-84 – Reactors-Special Features of Aircraft Reactors

AEC RESEARCH AND DEVELOPMENT REPORT

COMPATIBILITY TESTS OF MATERIALS FOR USE IN BEARINGS, SEALS, AND VALVES IN FUSED FLUORIDE SALTS AT 1200°F

W. C. Tunnell

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AIRCRAFT REACTOR ENGINEERING DIVISION

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CONTENTS

COMPATIBILITY TESTS OF MATERIALS FOR USE IN BEARINGS, SEALS, AND VALVES IN FUSED FLUORIDES AT 1200°F

W. C. Tunnell

ABSTRACT

A series of tests were made for selecting combinations of materials compatible for possible use in journal bearings, face seals, and valve seats operating in fused fluoride salts at 1500°F. The test apparatus was designed to impose on the test specimen conditions similar to those that will be encountered in starting journal bearings and face seals from rest or in opening valves which have been seated for a considerable time. These conditions are considered to be those most likely to cause damage to the working surfaces.

Thirty-six combinations of ten different materials were tested in fused fluoride salts at 1200°F with the use of an apparatus consisting of a pin sliding against a rotating plate under a fixed load. The following combinations of materials showed sufficient promise to warrant further testing at higher temperatures:

Kennametal 151A vs Adamas A	Kennametal 151A vs Carboloy 608
Adamas A vs Kennametal 138A	Kennametal 151A vs Kennametal 151A
Kennametal 151A vs Norbide B_4C	Kennametal 151A vs High-Density Graphite

MATERIALS REQUIREMENTS

A basic requirement of materials used for pump journal bearings, face-type shaft seals, and valve seats in contact with fused fluoride salts at high temperatures is corrosion resistance. In addition the materials must resist wear, galling, and self-welding under severe operating conditions. Therefore screening tests were developed to ascertain the design limitations that materials might impose on the Aircraft Reactor Test, in which a fused salt mixture is to be circulated at 1500°F. The selected corrosion-resistant materials were screened for compatibility under conditions that simulated, in a general way, the operation of journal bearings, face-type seals with boundary lubrication, or valve seats under load in fused fluoride salts at 1200 to 1500°F.

It was originally planned that the materials would be given a preliminary screening test at 1200°F, that those proving to be compatible would then be further tested at 1350 and 1500°F, and that any material proving to be compatible at 1500°F would be tested as actual bearing pump and valve components. However, tests at 1200°F were the only ones performed, because the work was stopped by higher priority projects.

SELF-WELDING AND FRICTION EFFECTS

In considering materials for high-temperature application, it is recognized that any formed, smooth surface has microscopic asperities. Also, it has been reliably demonstrated that two such surfaces in intimate sliding contact will generate sufficient heat to cause welding and shearing of these minute asperities as they come in contact under the extreme unit pressures, or that the asperities will shear without welding, or that they will slide "up and over" each other and create frictional forces, metal transfer, and/or surface damage. A similar condition exists in a valve poppet and seat, and it is intensified when the assembly is subjected to a high temperature with high unit pressures at the minute contact points; that is, a "weld" forms through diffusion bonding of the metals. When the valve is to be opened, the welds must be broken; surface damage and metal transfer result. Some metal combinations apparently resist diffusion bonding, or welding, but such resistant combinations can be determined only through tests. In a study of the friction of metals the conclusion has been that the magnitude of the frictional forces and the extent and type of surface damage caused by sliding are determined primarily by the relative physical properties of the two sliding surfaces.[1] In particular, the behavior is very dependent upon the relative hardnesses of the sliding surfaces, and, if the sliding speed is high, the relative softening or melting points are quite important.

Properly designed, hydrodynamically lubricated bearings operate with a thin layer of the lubricant separating the two sliding surfaces, except in cases of extreme loads or of starting and stopping under load, when the thin film may be destroyed or interrupted and metal-to-metal contact may occur. The bearing then operates in what is called a "boundary region" of lubrication, and an analysis of the friction developed becomes complicated. The phenomena involved cannot be explained by any presently known lubrication theory. Surface finish and the chemical and physical properties of the sliding surfaces become critical in this situation, and hardnesses, shear strengths, and melting points of the materials are important.

TEST APPARATUS

The test apparatus, which was modified from apparatus previously used for testing seals, consisted of an Inconel sump tank, an Inconel operating pot, and a concentric spindle shaft and sliding shaft arrangement inserted in the operating pot and externally supported by ball bearings (Fig. 1). The $2\frac{3}{4}$-in. specimen plate was rotated in the operating pot and was held against a $\frac{1}{2}$-in.-dia stationary pin specimen. The contact pressure of the plate on the pin could be adjusted by an external spring. The surface of the plate specimen was lapped flat, to within three light bands, and the end of the stationary pin specimen was ground to a $\frac{1}{2}$-in.-radius cylindrical surface so that theoretical line contact between the specimens could be obtained. The pin was mounted so that contact would occur at a mean radius of 1 in. from the center of the plate. The mean sliding speed (7.4 fps) used by Vail at KAPL[2] was selected for use in these tests. At the specified sliding speed of 7.4 fps, the plate rotated at 850 rpm.

The test apparatus was calibrated (tests Nos. 1 and 2) by use of acetylene tetrabromide (1.1–2.2 TEB) as the liquid, a Graphitar 14 plate, and an

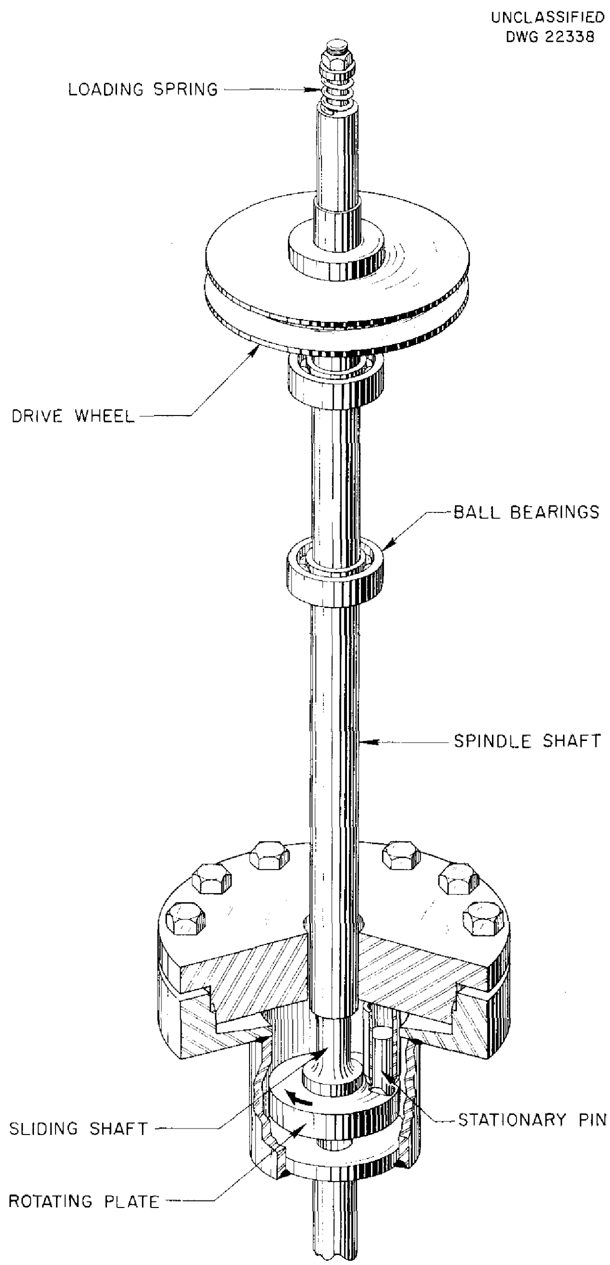


Fig. 1. Bearing Materials Compatibility Tester.

Inconel pin. Contact pressure was applied in varying steps until, with a 10-lb load on the load spring and an initial Hertz stress of about 15,000 psi, the hydrodynamic film was interrupted and a boundary lubricated condition existed. With the load requirement established, a series of six correlation tests (tests Nos. 3 through 8, Appendix B) were conducted in which type 416 stainless steel plates were used in combination with six different

[1] F. P. Bowden and D. Tabor, *The Friction and Lubrication of Solids*, p 78, Clarendon Press, Oxford, 1950.

[2] D. B. Vail, *Compatibility of Materials in Liquid Metal*, KAPL-589 (Aug. 18, 1951).

pin materials: babbit, die steel, high-speed tool steel, Stellite 6, Stellite Star J, and Superoilite. The fluid used was regular-grade Texaco Regal "A" oil, without additives, which has a viscosity of 40 to 44 SSU at 210°F. The correlation tests were run at room temperature and were each of 2-hr duration. The results were in reasonable agreement with the KAPL data for the same material combinations.

A pin-wear classification guide (Fig. 2) was prepared by taking cuts of known amounts off the wearing nose of an unused test pin and then photographing the pin. The photographs provided a reference to which photographs of the tested pins could be compared to determine visually the extent of wear.

SELECTION OF MATERIALS

An examination of work by Vail[3] with sodium and sodium-potassium alloy at temperatures up to 950°F and recommendations made by the Materials Chemistry Section and the Ceramics Department of ORNL were used as the basis for selecting materials. Samples of materials that were expected to be corrosion resistant were obtained and were exposed to the fluoride salt in static capsule or seesaw tests[4] for 100 hr. The materials selected and the results of the corrosion tests are presented in Table 1.

TEST PROCEDURE

The test specimens were cleaned with alcohol and then slowly heated to 1200°F in a purging stream of dry, pure helium. After the operating pot and specimens were heated, a fluoride mixture at 1200°F was introduced into the pot and brought to the level-control probe. The rotation of the submerged plate specimen was started, and the system temperature was allowed to come to equilibrium at 1200°F. Contact was then established between the pin and plate specimens, with a 10-lb contact load being applied for 120 min, during which time the specimens remained submerged in the molten fluoride salt. The load was released, and the fluoride mixture was allowed to drain back into the sump pot and freeze. The system was allowed to cool to room temperature under a helium atmosphere before the specimens were removed for examination. Photographs were taken of the pin and the plate after each run (see Appendix C), and enlargements were made of the pin-surface and plate-surface photographs to show the wear pattern.

A Faxfilm replica was also made of each plate and pin. The process consisted in applying a clear solvent to the surface to be recorded, pressing a piece of soluble plastic tape against the solvent and surface, allowing a few seconds for reaction and drying, and then mounting the tape in slides for projection.

A sample of the fluoride was recovered after each run, and a spectrographic analysis was made, with special emphasis given to the constituents of the compatibility specimens. There was no increase of metal content, except in the case of the oxides, which were recognized as being soluble in the fluoride.

CRITERIA FOR RATING MATERIALS

The compatibility of pairs of materials operating in contact with each other was established as a relative measure of resistance to mechanical damage, such as wear, galling, and self-welding. For the purpose of classifying materials according to test results, arbitrary group standards were established, as follows:

Group A – Only slight wear on the narrow-band pin specimen; no spalling of either specimen; no galling or smearing tendency; no appreciable change in surface flatness of the plate; no change in surface finish, except an improvement (polishing or superfinishing); no appreciable reduction in hardness as indicated by the Rockwell hardness tester; and no evidence of erosion or corrosion by spectrographic or visual means.

Group B – Slight wear indications on either specimen; no spalling; no smearing or metal pickup; slight scoring and surface roughening; no appreciable reduction in Rockwell hardness; no evidence of erosion or corrosion by spectrographic or visual means.

Group C – More extensive wear than on specimens of Group B; some possible roughening of either surface or of both; some metal pickup, smearing, scoring, or spalling readily apparent; no evidence of erosion or corrosion by spectrographic or visual means.

[3] D. B. Vail, *Compatibility of Materials in Liquid Metal, Second Report*, KAPL-1021 (Jan. 5, 1954).

[4] A. deS. Brasunas, *A Simplified Apparatus for Making Thermal Gradient Dynamic Corrosion Tests*, ORNL CF-52-3-123 (March 13, 1952).

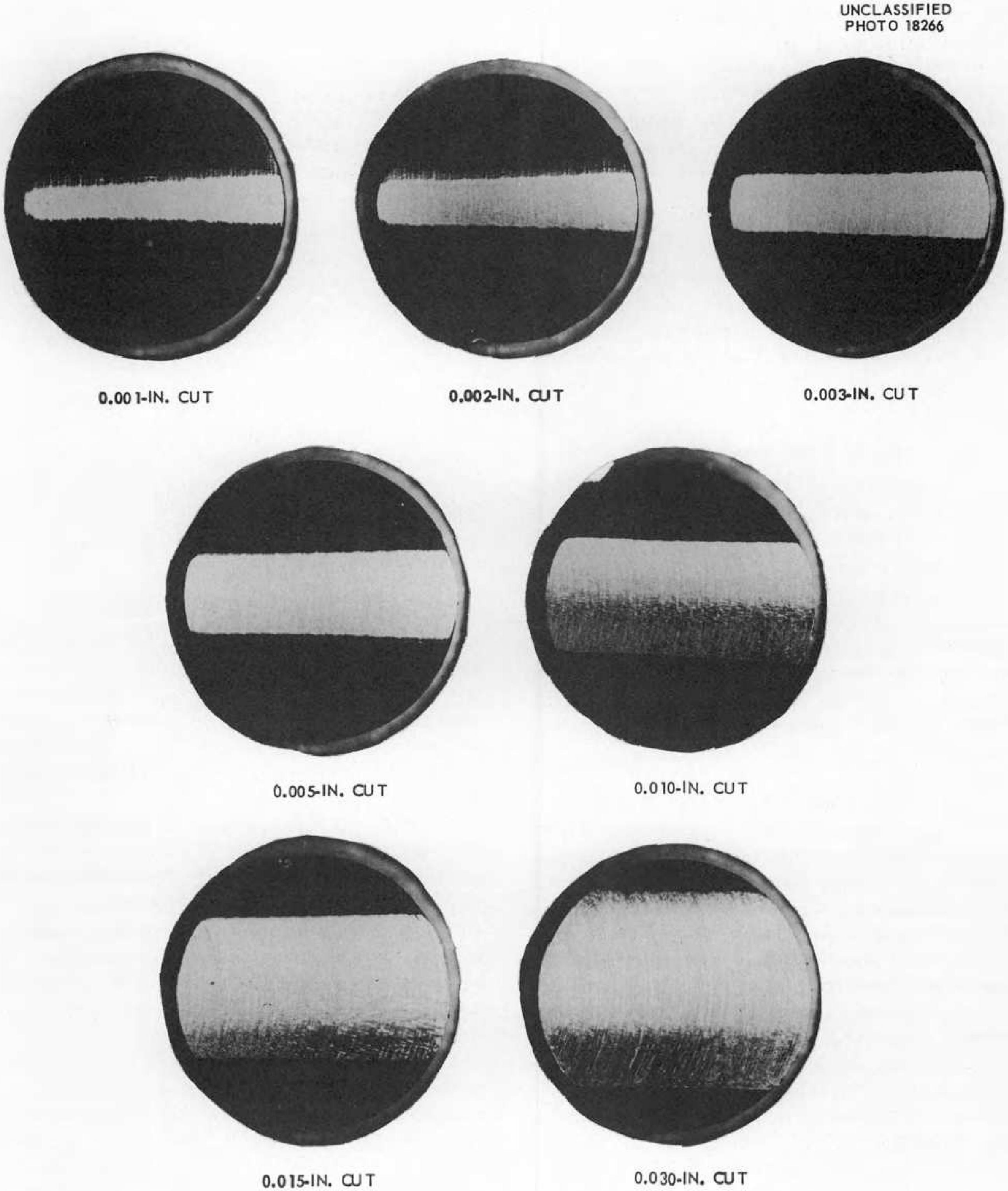


Fig. 2. Pin-Wear Classification Guide. Machine cuts of various amounts on an Inconel pin specimen.

Group D — Excessive wear of either specimen; metal pickup; scoring or smearing; roughening of surfaces; reduction in hardness; deterioration of surface finish; corrosion or erosion readily apparent.

EVALUATION OF RESULTS

From the post-test photographs (presented in Appendix C), a very clear indication of the compatibility of the test materials was obtained. Wear, smearing, or metal buildup, galling or self-welding, spalling, and cracking are all identifiable in the photographs. The extent of pin wear may be observed by comparison of the test photograph with Fig. 2. The hardness readings and the spectrographic analyses were effective in indicating the compatibility of the specimens.

The test data, presented in Tables 2 and 3, showed that, in general, pairs of unlike materials were more compatible than pairs of like materials. Thirty-six combinations of ten different materials were tested, and the following were considered suitable for further testing at higher temperature:

Kennametal 151A vs Adamas A
Adamas A vs Kennametal 138A
Kennametal 151A vs Norbide B_4C
Kennametal 151A vs Carboloy 608
Kennametal 151A vs Kennametal 151A
Kennametal 151A vs High-Density Graphite

The repetition of various tests showed that the results were reproducible and indicated that the test apparatus and methods used were consistent and reliable.

No single property or combination of properties, such as surface finish, hardness, or chemical composition, was found which was characteristic of the best materials. It is felt that tests of additional combinations of carbides would be productive and that tests of available borides, nitrides, and silicides would greatly increase the chances of finding ideal combinations of materials for the desired applications.

CONCLUSIONS AND RECOMMENDATIONS

From the results obtained at 1200°F it is concluded that several of the combinations of materials tested were sufficiently compatible under the conditions imposed on them to warrant further testing at 1350 to 1500°F, as was originally planned (see "Materials Requirements"). Therefore the following recommendations are made:

1. Resume the compatibility screening tests reported herein and test additional promising combinations of carbides, as well as combinations of borides, nitrides, and silicides, which also offer promise.
2. Run a series of tests on the screened combinations at 1350 and 1500°F, successively screening and retaining the most promising.
3. Test the material combinations which show promise at 1500°F as journal bearings, face seals, and valve seats in apparatus designed to simulate operation in an actual reactor circuit.

ACKNOWLEDGMENT

The work of D. B. Vail of the Knolls Atomic Power Laboratory (reports KAPL-589 and - 021) on the compatibility of materials in sodium and in NaK was of considerable value in the initial selection of materials to be tested. It was also used to check and to validate the calibration of the apparatus used.

The data presented herein were obtained by P. G. Smith and J. W. Kingsley of ORNL and by W. K. Stair, consultant, the University of Tennessee.

TABLE 1. CONDITIONS AND RESULTS OF CORROSION TESTS OF SELECTED ALLOYS, CERMETS, AND CERAMICS IN FUSED FLUORIDE SALTS

Fluoride Salt Mixtures Used:
1. $NaF\text{-}ZrF_4\text{-}UF_4$ (50-46-4 mole %)
2. $NaF\text{-}ZrF_4\text{-}UF_4$ (46-50-4 mole %)
3. $NaF\text{-}ZrF_4\text{-}UF_4$ (53.5-40-6.5 mole %)
4. $NaF\text{-}KF\text{-}LiF\text{-}UF_4$ (10.9-43.5-44.5-1.1 mole %)

Manufacturer	Material Identification	Typical Composition (wt %)	Fluoride Salt Mixture Used (see above)	Type of Test[a]	Depth of Attack (mils)	Comments	Corrosion Reference
Adamas Carbide Corp.	AA	97 WC–3 Co	1	Seesaw	0	Hot zone, 1500°F; cold zone, 1328°F	*b*
	A	94 WC–6 Co	1	Seesaw	0	Hot zone, 1490°F; cold zone, 1355°F	*b*
	66	60 WC–12 Co–28 TaC	1	Seesaw	1	Hot zone, 1500°F; cold zone, 1319°F	*b*
Borolite Corp.	$MoSi_2$	Nickel-bonded	3	Seesaw	0		*c*
	SiC		3	Static	0		*d*
	TiB_2		3	Seesaw	2		*d*
	ZrB_2		3	Seesaw	2		*d*
Carboloy Dept., General Electric Co.	44A	94 WC–6 Co	2	Static	0		*e*
	55A	87 WC–13 Co	2	Static	0		*e*
	608	83 Cr_3C_2–2 WC–15 Ni	2	Static		Some surface roughening	*e*
			1	Seesaw	4	Attack on exposed surface	*f*
	779	91 WC–9 Co	2	Static	0	Some evidence of spalling	*e*
	907	74 WC–6 Co–20 TaC	2	Static	0	Some evidence of spalling	*e*
	X350S	98 Cr_3C_2–2 WC	1	Seesaw	0	Specimen extremely brittle	*f*
The Carborundum Company	BN		3	Static	2 to 5		*d*
	Mo_2B 501		3	Seesaw	16		*d*
Electro Metallurgical Company	Cr_3C_2		3	Static	0	Cr_3C_2 particles did not appear well bonded in as-received condition	*d*
	Si_3N_4		3	Static	2 to 5		*d*
	TiC		3	Static	0	TiC particles did not appear to be formed or bonded as well as could have been	*d*

TABLE 1. (continued)

Manufacturer	Material Identification	Typical Composition (wt %)	Fluoride Salt Mixture Used (see above)	Type of Test[a]	Depth of Attack (mils)	Comments	Corrosion Reference
Electro Metallurgical Company	ZrC		3	Static	Penetrated	Small incipient cracks in ZrC particles throughout specimen	*d*
Firth Sterling, Inc.	FS 27	43 TiC–50 Ni–7 Cr_3O_2	1	Seesaw	2 to 5		*e*
Haynes Stellite Company	1	46 Co–31 Cr–13 W–1 Ni–3 Fe–2.45 C	1	Static	10		*e*
	3	46 Co–31 Cr–13 W–3 Ni–3 Fe–2.45 C	4	Static	6		*e*
			2	Static	29		*e*
	6	56 Co–30 Cr–5 W–3 Ni–3 Fe–1.25 C	1	Static	15		*e*
	12	56 Co–31 Cr–8 W–2 Fe–1.35 C	1	Static	13		*e*
	19	52 Co–31 Cr–10 W–3 Fe–1.8 C	4	Static	2		*e*
			2	Static	29		*e*
	21	65 Co–25 to 30 Cr–4.5 to 6.5 Mo–2 Fe–1.5 to 3.5 Ni–0.2 C	1	Static	5		*e*
	25	40 Co–20 Cr–15 W–10 Ni–3 Fe–1 Mo–0.1 C	4	Static	0		*e*
			1	Static	5		*e*
	40	13.5 Cr–4.5 Fe–4 Si–1 Co–3.2 B–Bal Ni	1	Static	5		*e*
	41	12 Cr–4.5 Fe–4 Si–1 Co–2.25 B–Bal Ni	1	Static	23		*e*
	Hastelloy B	63 Ni–28 Mo–6 Fe–1 Cr	4	Static	5		*e*
			1	Static	5		*e*
	Hastelloy C	55 Ni–17 Mo–16 Cr–6 Fe–4 W–7 to 10 Si	4	Static	2		*e*
			1	Static	1		*e*

TABLE 1. (continued)

Manufacturer	Material Identification	Typical Composition (wt %)	Fluoride Salt Mixture Used (see above)	Type of Test[a]	Depth of Attack (mils)	Comments	Corrosion Reference
Haynes Stellite Company	Hastelloy D	83 Ni–4 Ca–1 Fe–1 Cr	1	Static	1.5		*e*
Kennametal, Inc.	138A	65 TiC–20 Co–15 $NbTiTaC_3$	1	Seesaw	0.5 to 1	May have been slight attack on binder	*g*
	150A	80 TiC–10 Ni–10 $NbTiTaC_3$	1	Seesaw	4		*f*
			3	Seesaw	0		*c*
			3	Seesaw	0		*d*
	151A	70 TiC–20 Ni–10 $NbTiTaC_3$	1	Seesaw	1 to 2		*f*
			1	Seesaw	6	Blisters on surface	*c*
			3	Seesaw	0		*d*
			3	Seesaw	0		*d*
	152B	64 TiC–30 Ni–6 $NbTiTaC_3$	1	Seesaw	2		*f*
			1	Seesaw	4 to 7	Erratic attack	*c*
			3	Seesaw	0		*d*
			3	Seesaw	0		*d*
	153B	54 TiC–40 Ni–6 $NbTiTaC_3$	1	Seesaw	3	Uniform attack above TiC particle surface	*g*
	161B	? TiC–? Ni–? Mo	1	Seesaw	0	Only 208°F temperature differential on capsule	*g*
	162B	64 TiC–25 Ni–5 Mo–6 $NbTiTaC_3$	1	Seesaw	9	Portions of surface appeared to be plated	*f*
			3	Seesaw	0		*d*
			3	Seesaw	0		*d*
	D4675	97.5 WC–2.5 Co	1	Seesaw	1	Slight subsurface voids	*c*
			3	Seesaw	0		*d*
	Metamic LT-1	77 Cr–23 Al_2O_3	1	Seesaw		Completely penetrated	*h*
Norton Company	Norbide B_4C		3	Static	5	One side of specimen showed unidentified phase 14 mils deep	*d*

TABLE 1. (continued)

Manufacturer	Material Identification	Typical Composition (wt %)	Fluoride Salt Mixture Used (see above)	Type of Test[a]	Depth of Attack (mils)	Comments	Corrosion Reference
ORNL Ceramics Laboratory	SiC-Si						
Sintercast Corp. of America	1	50 TiC–50 Co-base binder	1	Seesaw	0.5 to 2	Random penetration, voids between TiC and binder	*g*
	4	48 TiC–52 Co-base binder	1	Seesaw	1	Possible phase change within particle	*g*
	5	48 TiC–52 Ni-base binder	1	Seesaw	0		*g*
	8	48 TiC–52 Ni-base binder	1	Seesaw	2	Some TiC without binder observed; not attacked	*g*
	10	47 TiC–53 Ni-base binder	1	Seesaw	5	Some attack on binder; TiC particles separated	*g*
Vascoloy-Ramet Corp.	EE	80 WC–10 TiC–10 Co	1	Seesaw	0	Hot zone, 1500°F; cold zone, 1346°F	*b*
	EH	54 WC–40 TiC–6 Co	1	Seesaw	0	Hot zone, 1500°F; cold zone, 1445°F	*b*
	2A3	89 WC–11 Co	1	Seesaw	0	Hot zone, 1500°F; cold zone, 1328°F (55 hr only)	*b*
	2A7	95.5 WC–4.5 Co	1	Seesaw	0	Hot zone, 1500°F; cold zone, 1355°F; spalling to a depth of 1 to 1.5 mils	*b*
Unidentified	TiN		3	Static	2		*d*
	Copper		4	Static	0	Negligible attack	*i*
	Graphite		4	Static	0	Negligible attack	*i*
	Graph-i-tite		1	Static	2		*d*
			3	Static	2		*d*

NOTE: See following page for references.

[a]Static tests: specimen submerged in fluoride salt sealed in Inconel capsule for 100 hr at 1500°F. Seesaw test: tilting Inconel capsule filled with fluoride salt; temperatures of specimen end (hot zone) and other end (cold zone), as specified; tests of 100-hr duration.

[b]Memorandum, D. C. Vreeland to W. D. Manly, *Results of Corrosion Tests with Various Tungsten Carbide Cermets* (Nov. 25, 1953).

[c]Data presented at conference at ORNL, May 25, 1954, by ORNL Metallurgy Division representatives.

[d]Personal communication from W. H. Cook.

[e]Memorandum, D. C. Vreeland to W. D. Manly, *Summary of Corrosion Resistance of Some Hard Facing Alloys, Cermets, and Ceramics in Various Media* (Dec. 22, 1953).

[f]Memorandum, E. E. Hoffman to W. D. Manly, *Cermets Seesaw Tested in Fluoride #30 in Inconel Containers.*

[g]Memorandum, W. H. Cook to W. D. Manly, *Dynamic Testing of Some Nickel-Base Bonded and Cobalt-Base Bonded Litanium Carbide Specimens in Fluoride #30* (April 20, 1954).

[h]Memorandum, D. C. Vreeland to W. D. Manly, *Results of Corrosion Tests with Metamic LT-1 Cermet* (Nov. 24, 1953).

[i]D. C. Vreeland, E. E. Hoffman, and L. D. Dyer, *Met. Quar. Prog. Rep. Oct. 31, 1952*, ORNL-1437, p 25.

TABLE 2. SUMMARY OF DATA OF MATERIALS COMPATIBILITY TEST

Test No.	Pin Identification	Plate Identification	Pin Hardness*		Pin Wear Resistance	Plate Hardness		Plate Surface Finish**		Metal Pickup, Spalling, and Galling Resistance	Remarks	Group Classification
			Before Test	After Test		Before Test	After Test	Before Test	After Test			
1	Inconel	Graphitar 14									Calibration run for load requirement using TEB	
2	Copper	Graphitar 14									One-hour operation, 10-lb load, room temperature TEB	
3	Babbit	Type 416 stainless steel			Good			18–20	18	Good	Correlation test in oil, 2 hr at 850 rpm, room temperature	
4	Ontario die steel	Type 416 stainless steel			Poor			18–20	150–160	Poor	Correlation test in oil, 2 hr at 850 rpm, room temperature	
5	Stellite 6	Type 416 stainless steel			Poor			18–24	175–225	Poor	Correlation test in oil, 2 hr at 850 rpm, room temperature	
6	Stellite Star J	Type 416 stainless steel			Poor			20–28	125–150	Poor	Correlation test in oil, 2 hr at 850 rpm, room temperature	
7	High-Speed tool steel	Type 416 stainless steel			Poor			24–32	160	Poor	Correlation test in oil, 2 hr at 850 rpm, room temperature	
8	Superoilite	Type 416 stainless steel			Good			16–24	30–35	Fair	Correlation test in oil, 2 hr at 850 rpm, room temperature	
9	Inconel	Graphitar 14			Good						Friction test, 18°F temperature rise in oil	

*Hardness determined on Rockwell Hardness Tester. This machine was not available for use from the beginning of investigation.

**Surface finish determined by use of The Brush Development Co. Profilometer in μin. rms.

TABLE 2. (continued)

Test No.	Pin Identification	Plate Identification	Pin Hardness* Before Test	Pin Hardness* After Test	Pin Wear Resistance	Plate Hardness Before Test	Plate Hardness After Test	Plate Surface Finish** Before Test	Plate Surface Finish** After Test	Metal Pickup, Spalling, and Galling Resistance	Remarks	Group Classification
10	Inconel	Graphitar 14			Good						Operation for 20 hr, 10-lb load, oil, room temperature	
11	Inconel	Graphitar 14			Good					Good	First test using fuel No. 30, metal buildup on pin	C
12	Carboloy 608	Kennametal 135A					71 R_c	4			Excessive metal buildup preventing contact	
13	Kennametal 138A	Kennametal 138A					71 R_c				Excessive metal buildup preventing contact	
14	Inconel	Graphitar 14			Good					Good	Temperature calibration; pin 38°F cooler than liquid	C
15	Carboloy 608	Kennametal 151A						10–12			Metal buildup investigation; Ni plate pot, Inconel sump	
16	Carboloy 608	Kennametal 151A					70 R_c	10			Metal buildup investigation; type 316 stainless steel pot, Inconel sump	
17	Carboloy 608	Kennametal 151A					72 R_c	7–10			Metal buildup investigation; Ni pot, Ni sump	
18	Carboloy 608	Kennametal 151A					71 R_c	7–10			Metal buildup investigation; Inconel pot, Inconel sump	

*Hardness determined on Rockwell Hardness Tester. This machine was not available for use from the beginning of investigation.

**Surface finish determined by use of The Brush Development Co. Profilometer in μin. rms.

TABLE 2. (continued)

Test No.	Pin Identification	Plate Identification	Pin Hardness*		Pin Wear Resistance	Plate Hardness		Plate Surface Finish**		Metal Pickup, Spalling, and Galling Resistance	Remarks	Group Classification
			Before Test	After Test		Before Test	After Test	Before Test	After Test			
19	Carboloy 608	Kennametal 151A		65 R_c	Fair		70 R_c	6–7	6–7	Good	Slight taper wear on pin; plate alignment good	C
20	Kennametal 151A	Adamas A		72 R_c	Good		79 R_c	5–7	2–3	Good	Corner wear on misaligned pin; plate wear good	B
21	Adamas A	Adamas A	77 R_c	78 R_c	Fair	78 R_c	78 R_c	7–10	16–18	Fair	Like materials expected to wear; plate may be warped	C
22	Carboloy 608	Adamas A	70 R_c		Fair	79 R_c	72 R_c	5–7	7–8	Good	Good pin pattern; plate may be warped	C
23	Adamas A	Kennametal 151A	79 R_c		Good	73 R_c	66 R_c	5–7	5–7	Good	Good wear patterns; slight material buildup	B
24	Adamas A	Kennametal 138A	79 R_c		Good	73 R_c		4–5	4–5	Good	Good wear pattern; very slight buildup	B
25	Adamas A	Norbide B_4C	73 R_c		Excellent			8–10	15–20	Fair	Plate scored and excessive spalling	C
26	Kennametal 151A	Kennametal 138A						5–7			Specimens reground before photos made; data destroyed	?
27	ARE moderator BeO	Adamas A				72 R_c		5–7	Surface scale		Pin reacted with fuel; no contact existed	D
28	Adamas A	High-Density Graphite	65		Good			10–12		Fair	Good wear pattern; some material buildup	C

*Hardness determined on Rockwell Hardness Tester. This machine was not available for use from the beginning of investigation.

**Surface finish determined by use of The Brush Development Co. Profilometer in μin. rms.

TABLE 2. *(continued)*

Test No.	Pin Identification	Plate Identification	Pin Hardness* Before Test	Pin Hardness* After Test	Pin Wear Resistance	Plate Hardness Before Test	Plate Hardness After Test	Plate Surface Finish** Before Test	Plate Surface Finish** After Test	Metal Pickup, Spalling, and Galling Resistance	Remarks	Group Classification
29	ARE moderator BeO	ARE moderator BeO						15–18			Pin and plate reacted; fuel plate cracked	D
30	Adamas A	Kearfoot Al_2O_3	70					15–18			Plate reacted with fuel; plate cracked	D
31	Adamas A	Graphitar 14	71	57	Good			3–5		Fair	Good wear pattern; some material buildup	
32	Carboloy 608	Carboloy 608	58	64	Fair	61 R_c	72 R_c	1–2	2–3	Good		
33	Carboloy 608	Norbide B_4C	58 R_c		Fair			2–3		Poor	Material buildup; plate misaligned; smearing	D
34	Carboloy 608	Kennametal 138A	59 R_c	70 R_c	Fair	59 R_c		1–2		Good	Pin and plate wear pattern even and concentric	C
35	Adamas A	Norbide B_4C		68	Good			2–3		Good	Dry run; inert atmosphere; 900°F noted even though no heat had been applied	C
36	Kennametal 151A	Norbide B_4C	56	67	Good			2–3		Fair	Some scoring of plate; pin wear good	B
37	Kennametal 151A	Carboloy 608	57	68	Good	61		1–2		Good	Only slight scoring of plate; pin wear very good	B
38	Kennametal 151A	Kennametal 151A	58	66	Good	61		1–2		Good	Slight scoring; may be warping of plate; pin wear even	B

*Hardness determined on Rockwell Hardness Tester. This machine was not available for use from the beginning of investigation.
**Surface finish determined by use of The Brush Development Co. Profilometer in μin. rms.

TABLE 2. (continued)

Test No.	Pin Identification	Plate Identification	Pin Hardness*		Pin Wear Resistance	Plate Hardness		Plate Surface Finish**		Metal Pickup, Spalling, and Galling Resistance	Remarks	Group Classification
			Before Test	After Test		Before Test	After Test	Before Test	After Test			
39	Kennametal 151A	Graphitar 14	57	53	Fair			5–6		Fair	Spalling of plate; material buildup	C
40	Kennametal 151A	High-Density Graphite	56	66	Good			50–60		Good	Slight scoring of plate; even wear pattern	B
41	Carboloy 608	Graphitar 14	50	70	Fair			5–7		Good	Some smearing on pin; plate wear good	C
42	Carboloy 608	High-Density Graphite	58	68	Fair			50–60	40–50	Good	Slight wear on plate; pin pattern even	C
43	Norbide B_4C	Adamas A			Fair	72	79	1–2	1–2	Good	Pin misaligned; high stress on plate but no wear	C
44	Norbide B_4C	Norbide B_4C			Fair			2–3	40–50	Fair	Pin spalled and worn; little plate wear; material buildup	D
45	Norbide B_4C	Carboloy 608			Fair	60	70	4–5	4–5	Good	Pin spalled; misaligned plate; wear uneven	C
46	Norbide B_4C	Kennametal 151A			Good	59	71	1–2	1–2	Good	Plate misaligned or warped; high stress; no wear	C
47	Norbide B_4C	Kennametal 138A			Good	58	72	1–2	2–3	Good	Pin and plate wear even; slight spalling of pin	C
48	Kennametal 138A	Adamas A	59	58	Fair	72	71	1–2	4–5	Fair	Some smearing and plate may have warped	C

*Hardness determined on Rockwell Hardness Tester. This machine was not available for use from the beginning of investigation.

**Surface finish determined by use of The Brush Development Co. Profilometer in μin. rms.

TABLE 2. (continued)

Test No.	Pin Identification	Plate Identification	Pin Hardness*		Pin Wear Resistance	Plate Hardness		Plate Surface Finish**		Metal Pickup, Spalling, and Galling Resistance	Remarks	Group Classification
			Before Test	After Test		Before Test	After Test	Before Test	After Test			
49	Kennametal 138A	Norbide B_4C	60	71	Good			2–3	100–150	Poor	Plate scored and smeared	
50	Kennametal 151A	Inconel	53	65	Poor	84 R_B	84 R_B	4–5	200–225	Poor	Pin worn excessively; plate roughened but showed little wear	D
51	Adamas A	Inconel	57	77		84 R_B		4–5				
52	Kennametal 151A	Inconel	58	66		84 R_B		4–5				
53	Adamas A	Inconel	70					4–5				
54	Kennametal 138A	Kennametal 138A	61			59		2–3				
55 (?)												

*Hardness determined on Rockwell Hardness Tester. This machine was not available for use from the beginning of investigation.

**Surface finish determined by use of The Brush Development Co. Profilometer in μin. rms.

TABLE 3. RESULTS OF SPECTROGRAPHIC ANALYSIS OF THE FLUORIDE AFTER VARIOUS TESTS

Test No.	Specimen Materials	Impurities in Fluoride Mixture (wt %)*								
		Al	B	Co	Cr	Fe	Ni	Si	Ti	W
					Sump Pot No. 1					
39	TiC-Ni and graphite	<0.1	<0.01	<0.05	<0.05	<0.05	<0.05	<0.01	<0.05	<0.2
32	Cr_3C_2	<0.01 T	<0.05	<0.05	0.2	<0.05	0.1	<0.05	<0.02	<0.1
45	B_4C and Cr_3C_2	<0.01 T	<0.05	<0.05	0.05	<0.05	<0.05	0.2	<0.02	<0.1
46	B_4C and TiC-Ni	<0.05 T	ND	<0.05	0.1	<0.5 T	<0.05	<0.05	<0.05	<0.1
48	TiC-Co and WC	0.1	T	<0.05	0.2	<0.05	0.05	0.2	<0.05	<0.1
					Sump Pot No. 2					
40	TiC-Ni and High-Density Graphite	<0.1	<0.01	<0.1	<0.1 T	0.1	<0.5 T	0.02	<0.01	<0.2
41	Cr_3C_2 and graphite	<0.1	<0.001	<0.1	<0.1	<0.05 T	<0.05	<0.01	<0.01	<0.2
42	Cr_3Cr and High-Density Graphite	<0.1 T	<0.05	<0.05	0.1	0.5	<0.05	0.05	<0.02	<0.1
44	B_4C	0.01, <0.01	<0.05 P	<0.05	0.2, <0.05	0.2, <0.05	<0.05 T	<0.05	<0.02	<0.1
47	B_4C and TiC-Co	0.05	ND	<0.05	0.2	<0.05	<0.05	<0.05	<0.05	<0.1
49	TiC-Co and B_4C	0.05	ND	<0.05	0.2	<0.05	<0.05	<0.05	<0.05	<0.1
50	TiC-Ni and Inconel	0.1	ND	<0.05	0.2	0.05	<0.05 0.2	<0.05	<0.05	<0.1
51	WC and Inconel	<0.05	ND	<0.05	0.2	<0.05	<0.05		<0.02	<0.1

*T indicates a trace detected; P indicates element present; ND indicates not detected.

APPENDIX A

INDEX FOR TESTS OF VARIOUS PIN AND PLATE COMBINATIONS

INDEX FOR TESTS OF VARIOUS PIN AND PLATE COMBINATIONS

Key: For test number for pin material, read across
For test number for plate material, read down

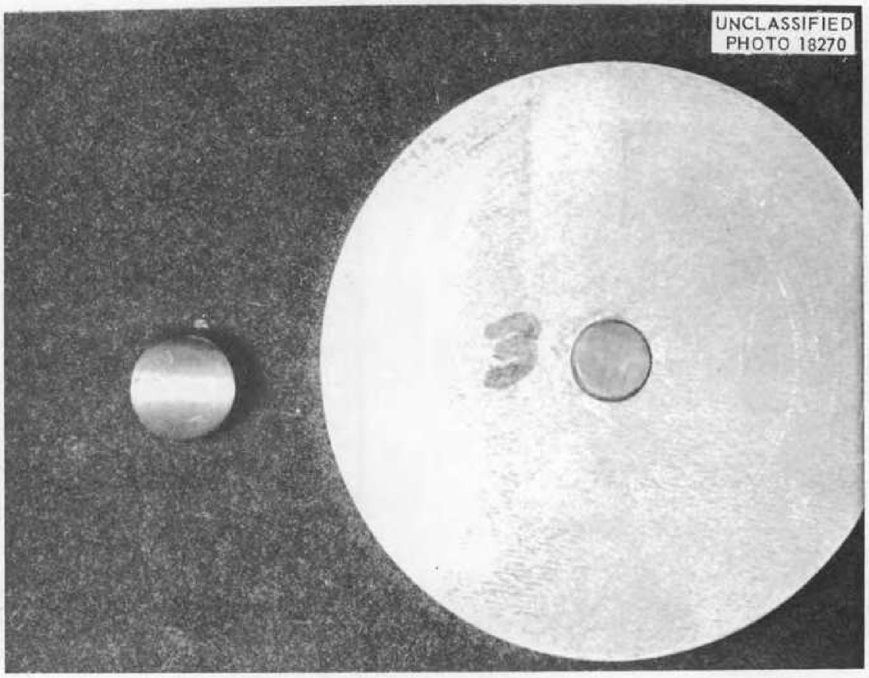
Pin Material	Vendor Identification	Plate Material and Vendor Identification									
		WC Adamas Grade A	Cr_3C_2 Carboloy 608	TiC + Co Kennametal 138A	TiC + Ni Kennametal 151A	B_4C Norton Norbide	Graphitar 14	High-Density Graphite	Inconel	BeO ARE Moderator*	Al_2O_3 Kearfoot Alumina*
WC	Adamas Grade A	Test 21		Test 24	Test 23	Tests 25, 35	Test 31	Test 28	Tests 51, 53		30
Cr_3C_2	Carboloy 608	Test 22	Test 32	Test 34	Tests 16, 17, 18, 19	Test 33	Test 41	Test 42			
TiC + Co	Kennametal 138A	Test 48				Test 49			55		
TiC + Ni	Kennametal 151A	Test 20	Test 37	Test 26**	Test 38	Test 36	Test 39	Test 40	Tests 50, 52		
B_4C	Norton Norbide	Test 43	Test 45	Test 47	Test 46	Test 44					
BeO*	ARE Moderator	27								29	
	Inconel						Tests 11,** 14**				

*Material eliminated because of lack of corrosion resistance.
**Photographs not included.

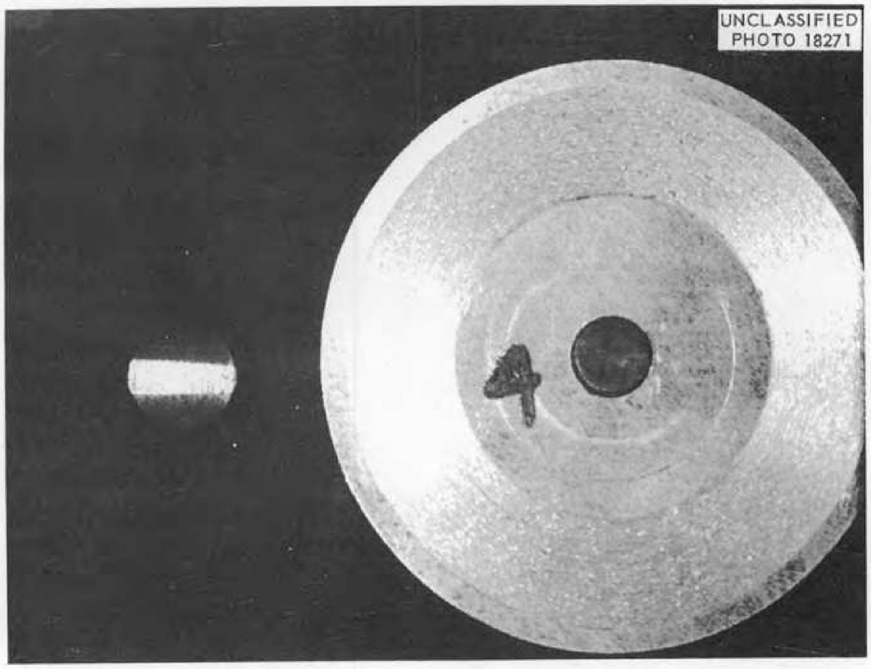
APPENDIX B

MATERIAL COMPATIBILITY TESTS – CORRELATION SERIES

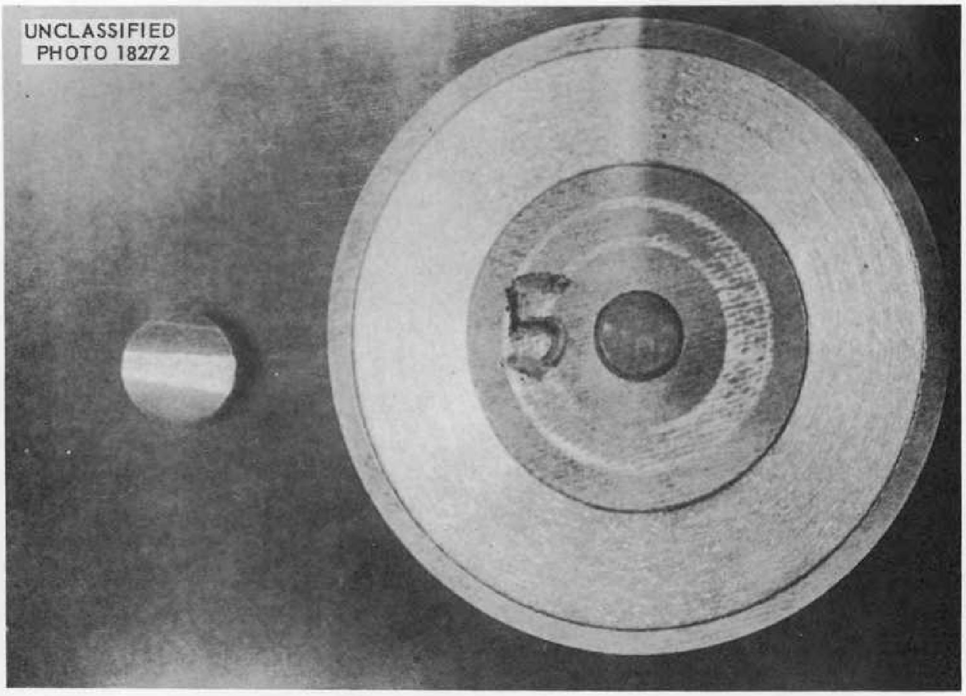
Tested in Texaco Regal "A" oil at room temperature, under 10-lb load, at 850 rpm for 2 hr.



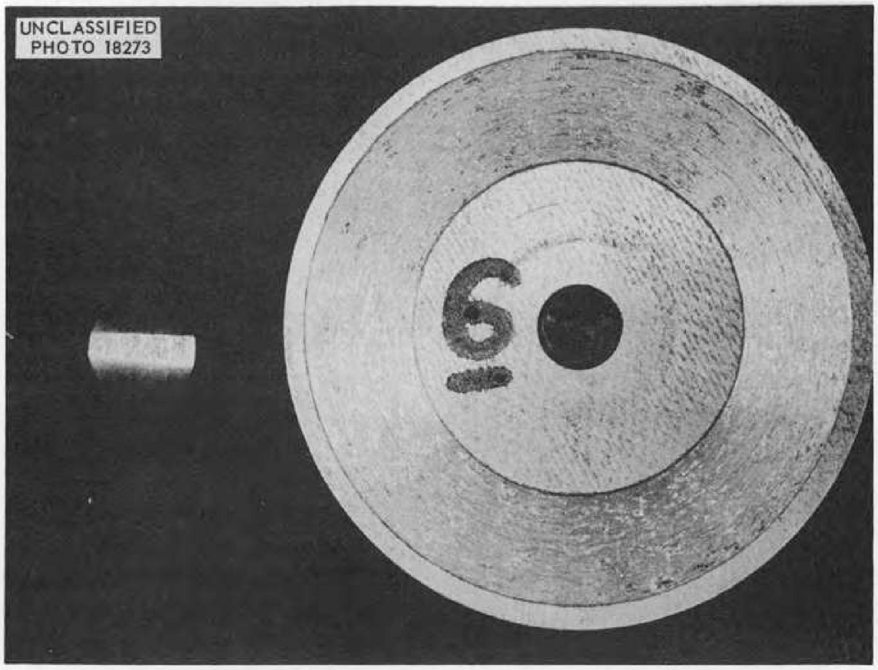
Test No. 3. Pin: Copper, Hard Drawn
Plate: Type 416 Stainless Steel, Ground Finish



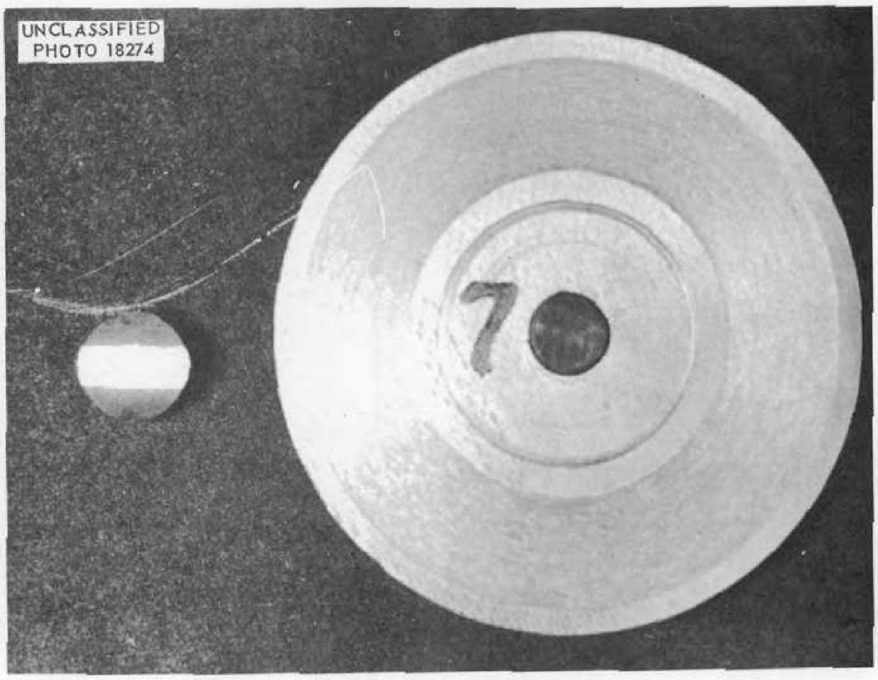
Test No. 4. Pin: Ontario Die Steel, As-Received
Plate: Type 416 Stainless Steel, Ground Finish



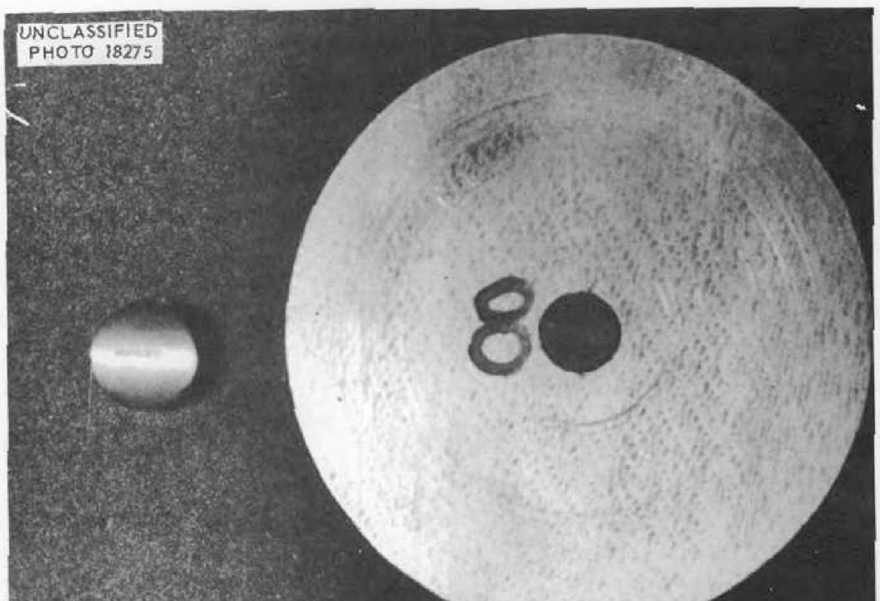
Test No. 5. Pin: Stellite 6
Plate: Type 416 Stainless Steel, Ground Surface



Test No. 6. Pin: Stellite Star J
Plate: Type 416 Stainless Steel, Ground Surface



Test No. 7. Pin: High-Speed Tool Steel (Type 6-6-2)
Plate: Type 416 Stainless Steel, Ground Surface



Test No. 8. Pin: Superoilite
Plate: Type 416 Stainless Steel, Ground Surface

APPENDIX C

PHOTOGRAPHIC RECORD OF WEAR PATTERNS

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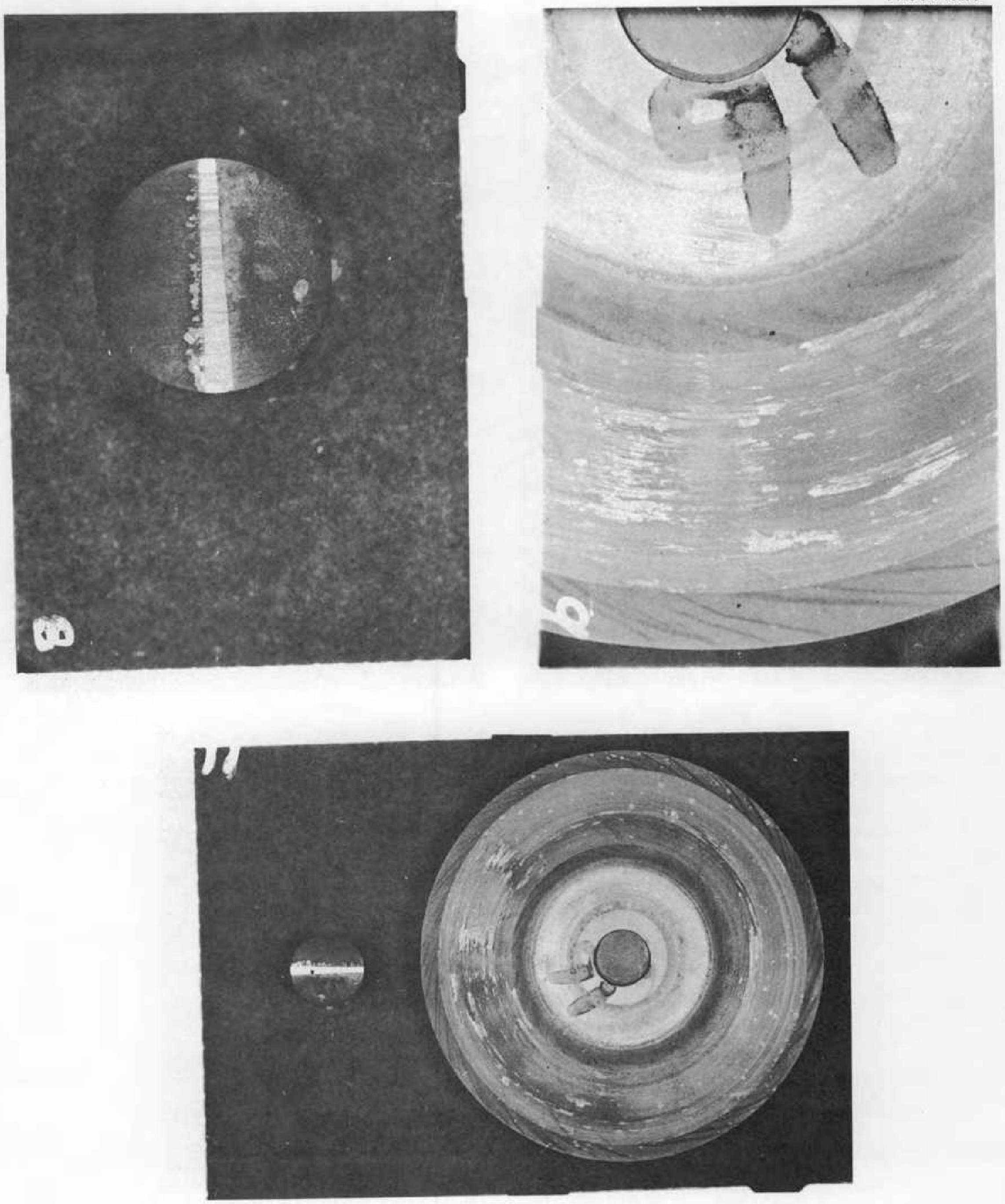
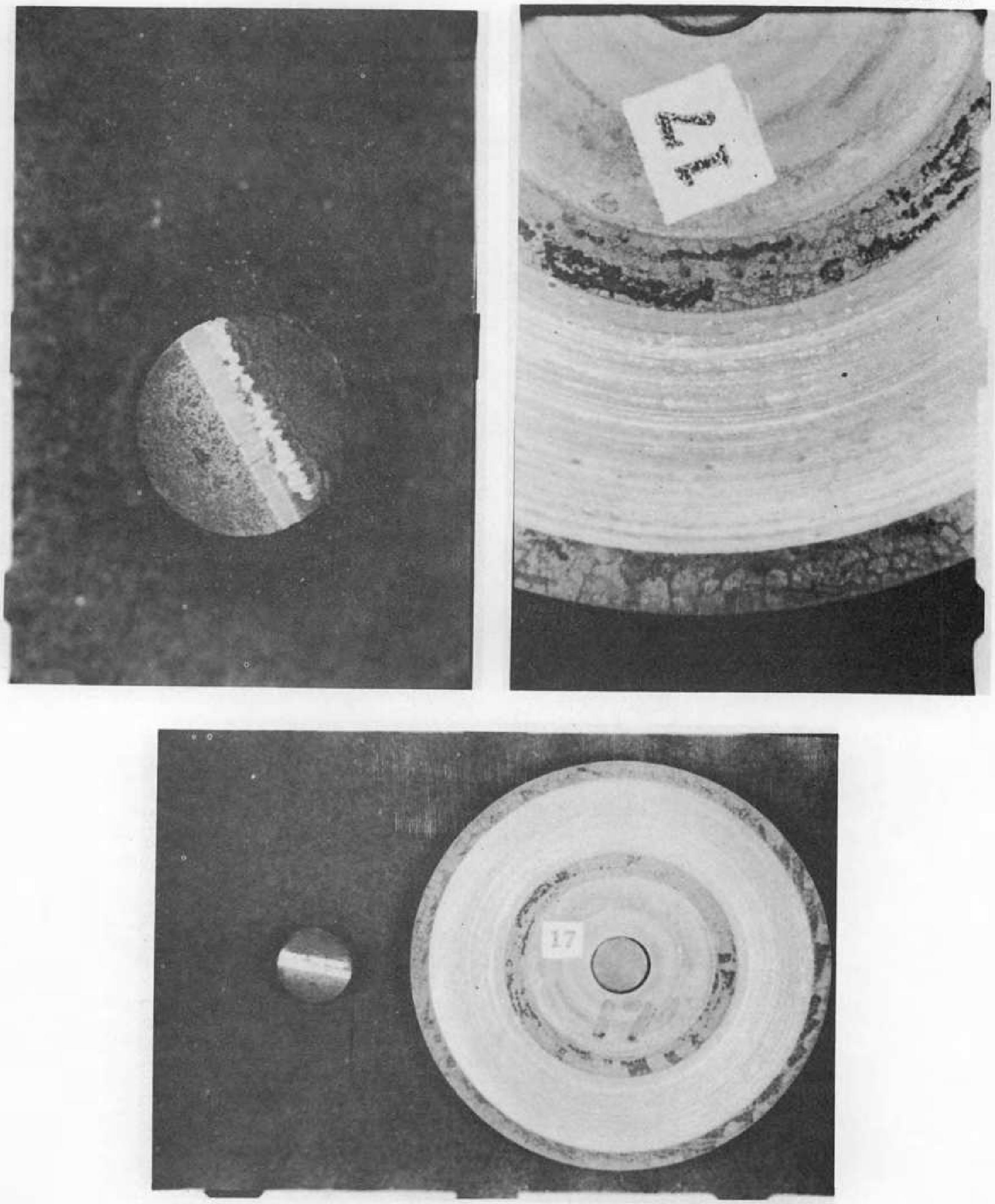
PHOTO 18276



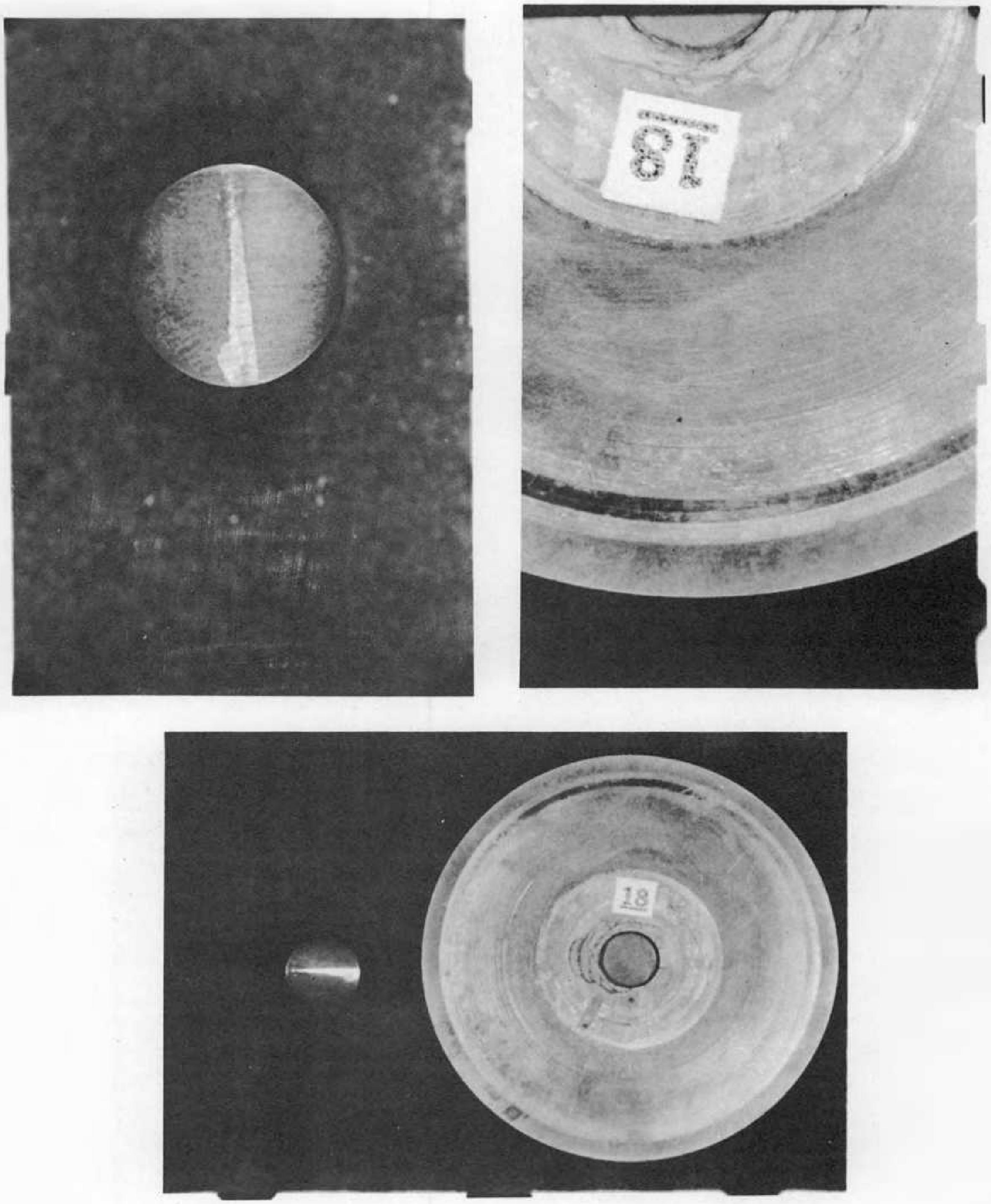
Test No. 16. Pin: Carboloy 608, Cr_3C_2
Plate: Kennametal 151A, TiC + Ni
Pot: Type 316 Stainless Steel
Sump: Inconel
Note Material Buildup on Pin

UNCLASSIFIED
PHOTO 18277



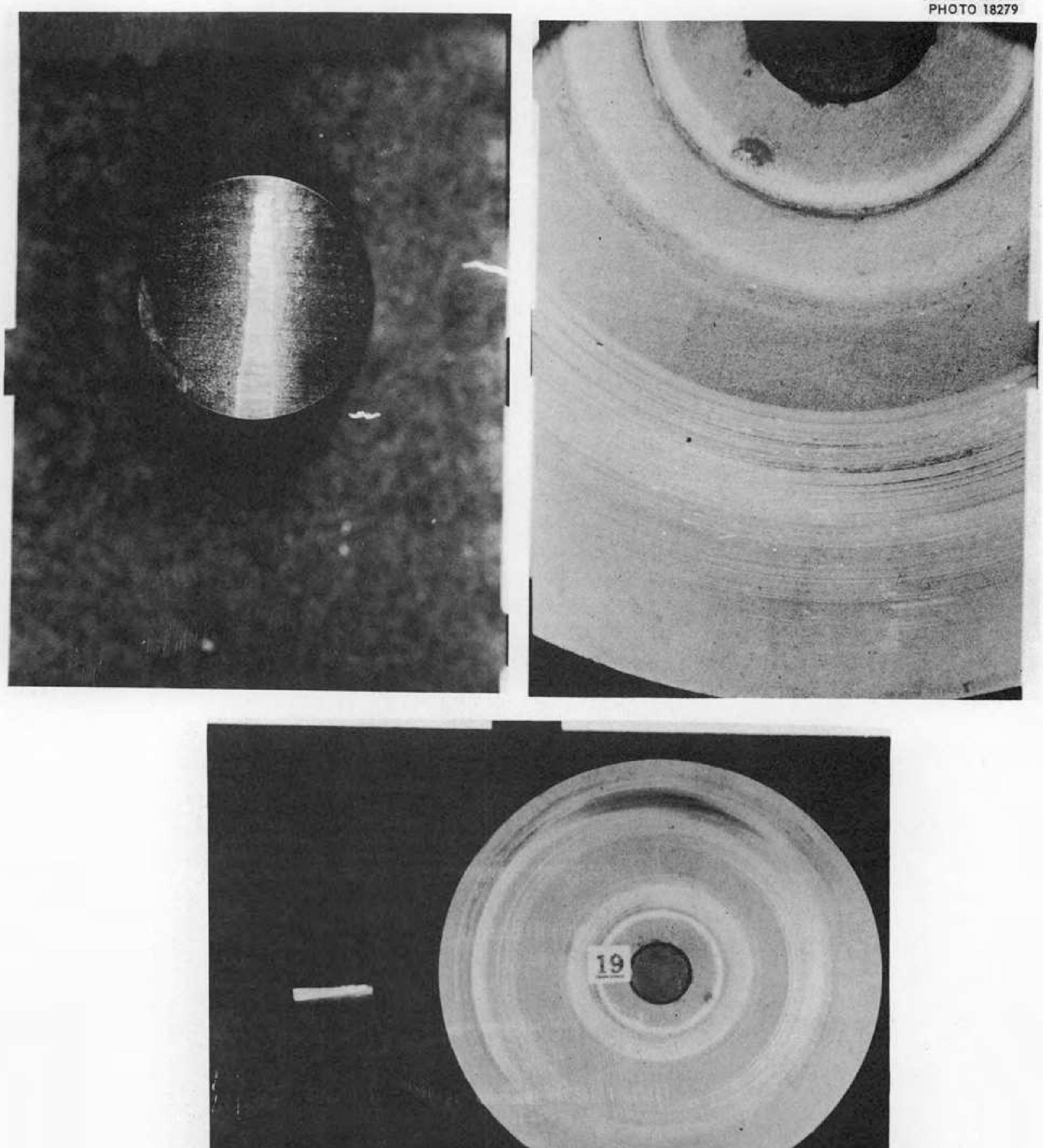
Test No. 17. Pin: Carboloy 608, Cr_3C_2
Plate: Kennametal 151A, TiC + Ni
Pot and Sump: Nickel
Note Material Buildup on Pin

UNCLASSIFIED
PHOTO 18278



Test No. 18. Pin: Carboloy 608, Cr_3C_2
Plate: Kennametal 151A, TiC + Ni
Pot and Sump: Inconel
Note Small Amount of Material Buildup on Pin

UNCLASSIFIED
PHOTO 18279



Test No. 19. Pin: Carboloy 608, Cr_3C_2
Plate: Kennametal 151A, TiC + Ni

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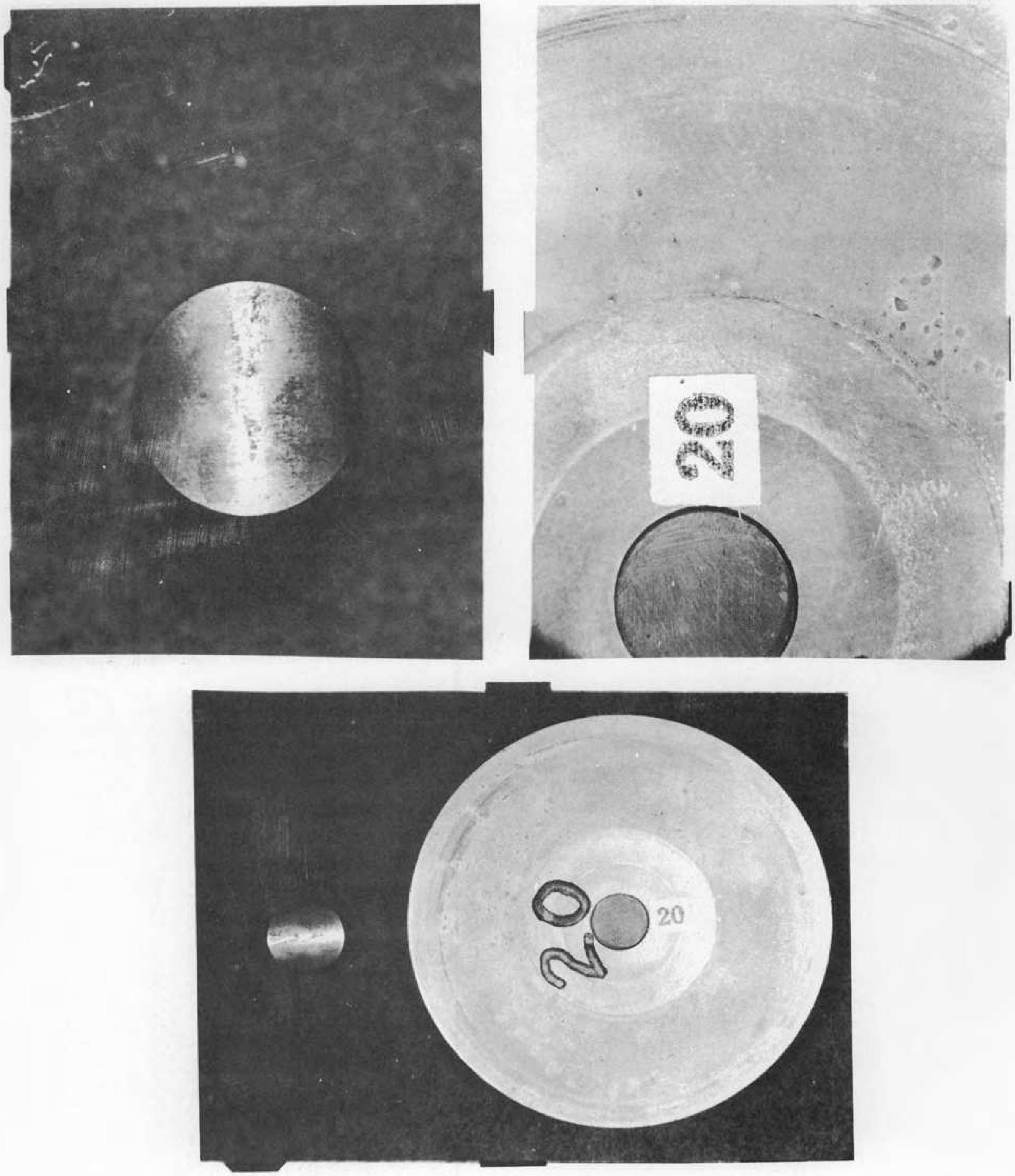
PHOTO 18280



Test No. 20. Pin: Kennametal 151A, TiC + Ni
Plate: Adamas Grade A, WC

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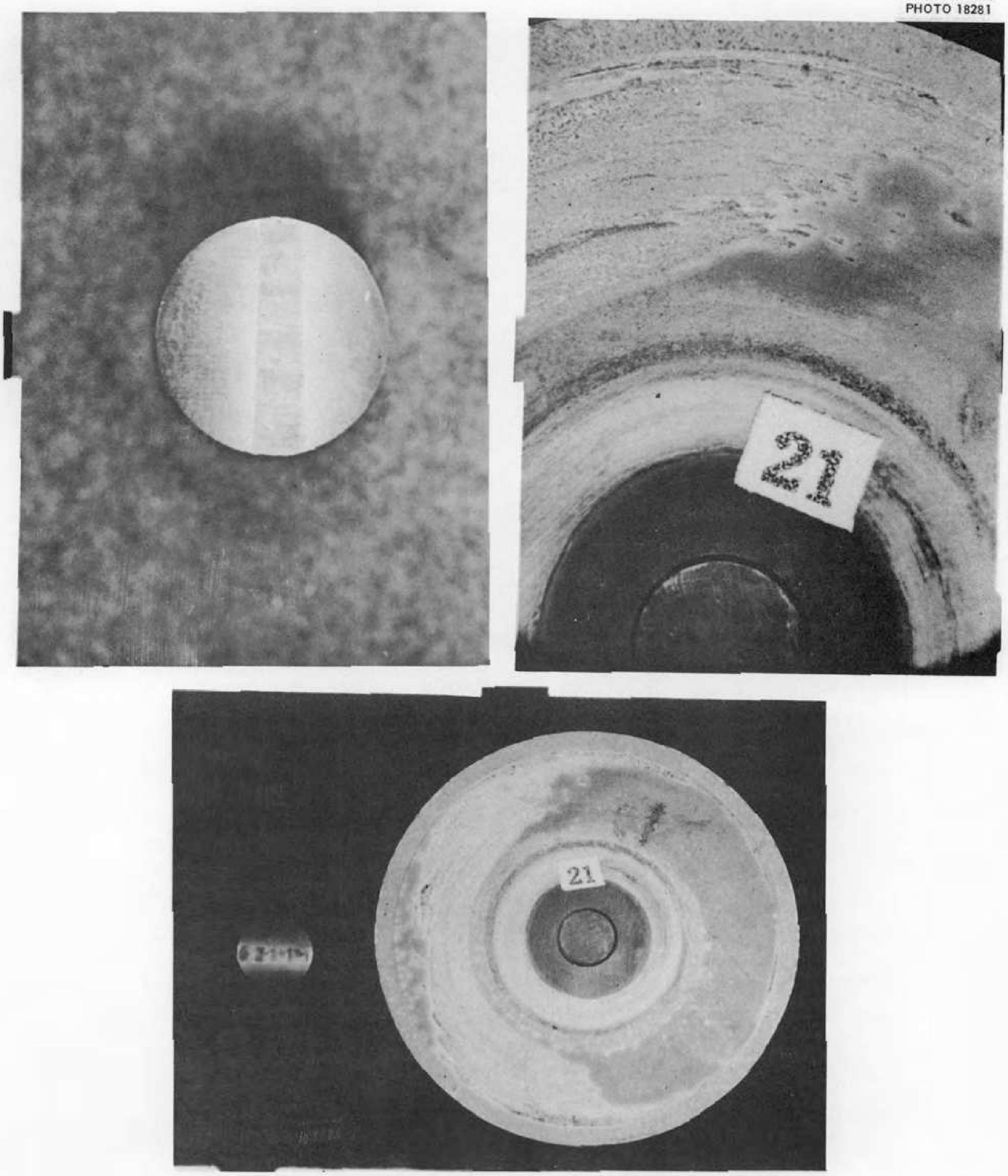
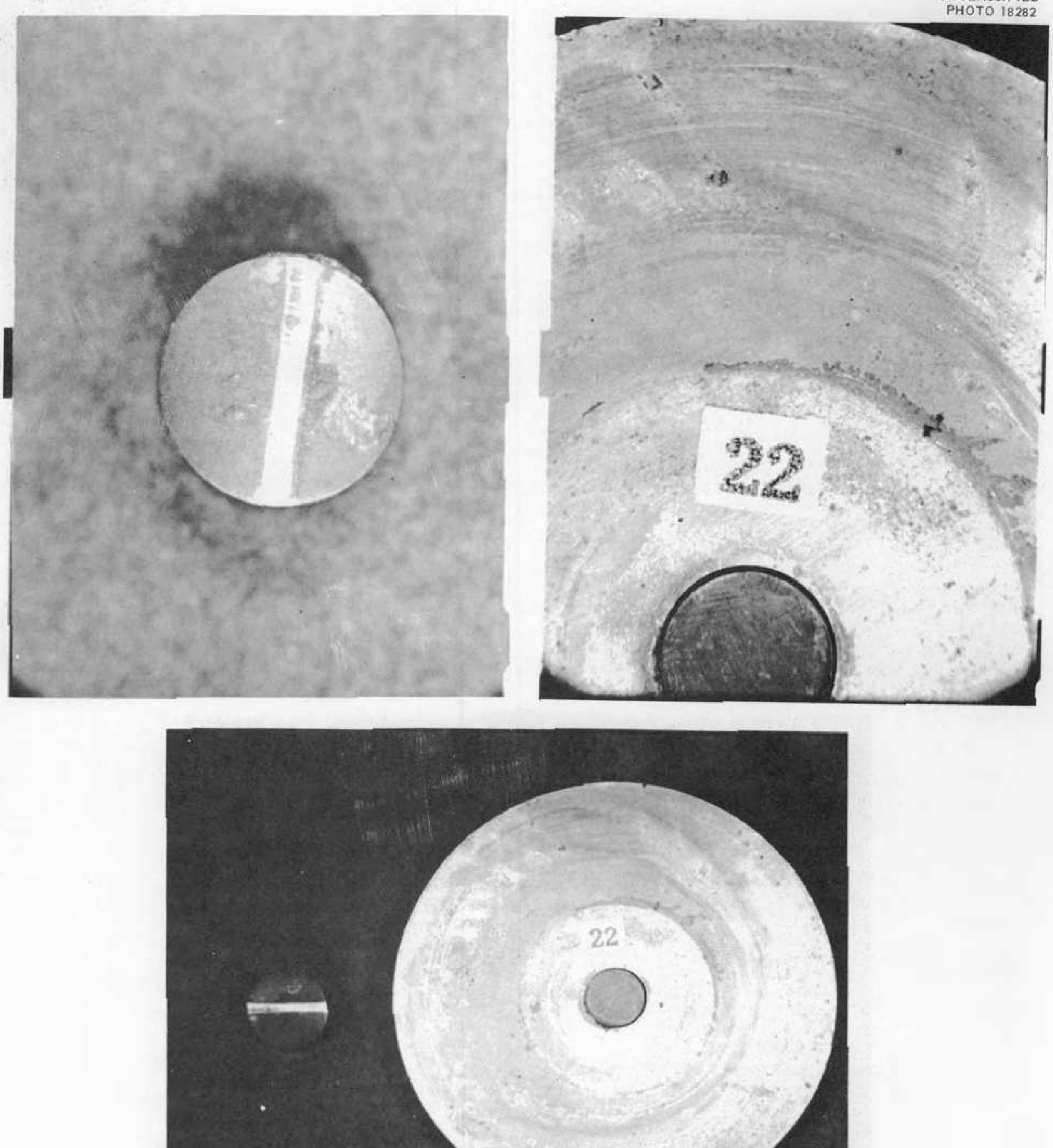
PHOTO 18281



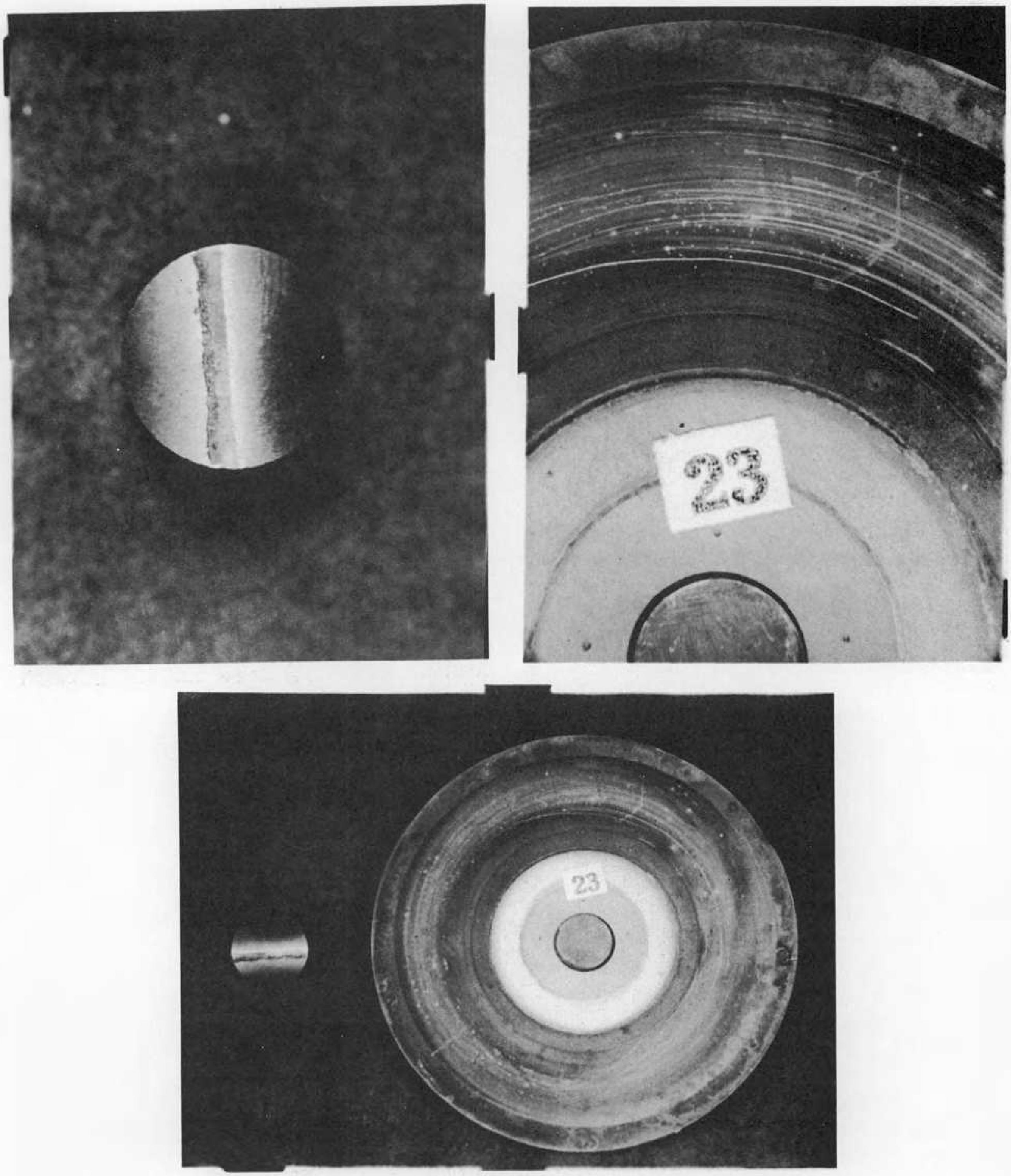
Test No. 21. Pin: Adamas Grade A, WC
Plate: Adamas Grade A, WC

UNCLASSIFIED
PHOTO 18282



Test No. 22. Pin: Carboloy 608, Cr_3C_2
Plate: Adamas Grade A, WC

UNCLASSIFIED
PHOTO 18283



Test No. 23. Pin: Adamas Grade A, WC
Plate: Kennametal 151A, TiC + Ni

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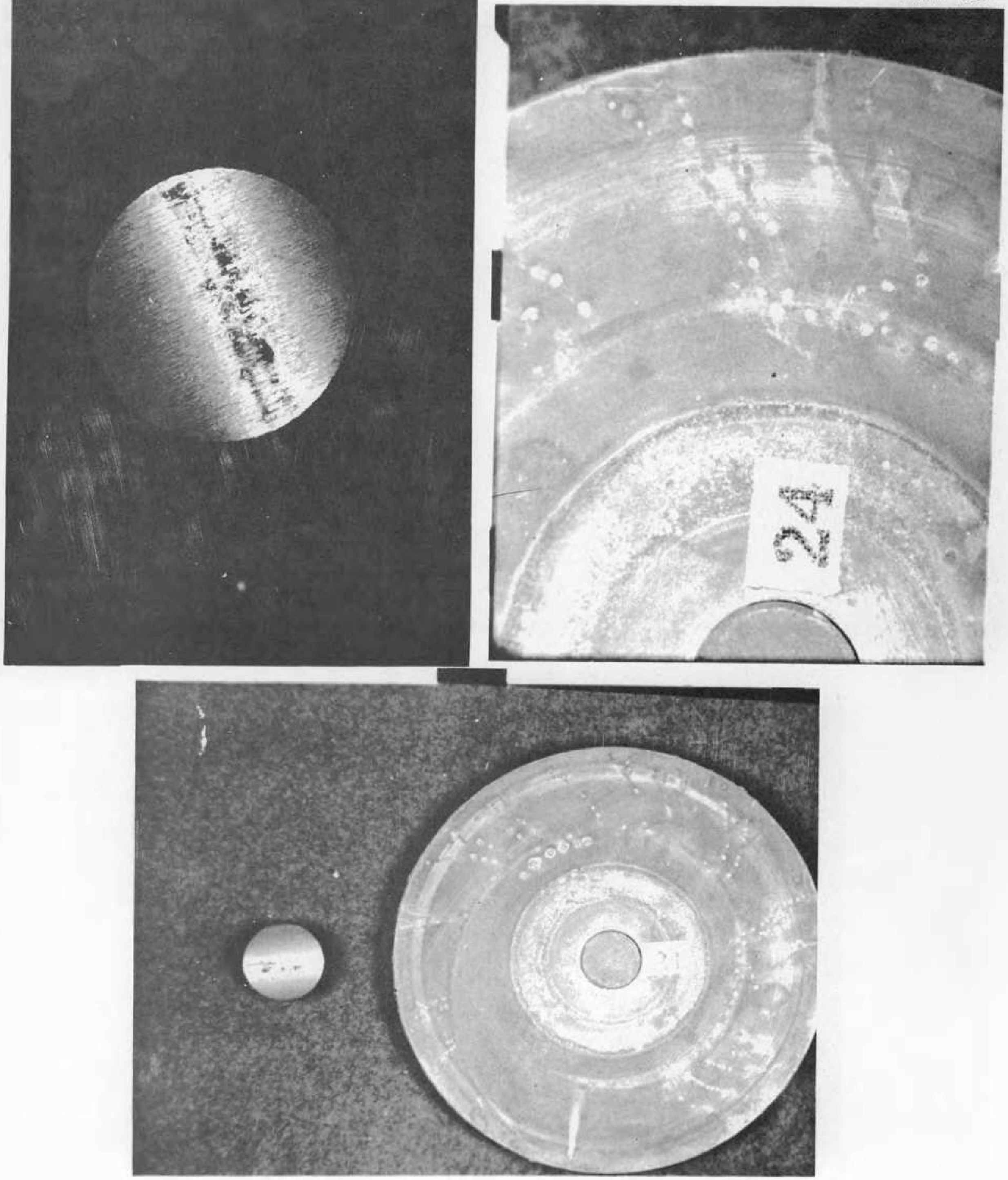
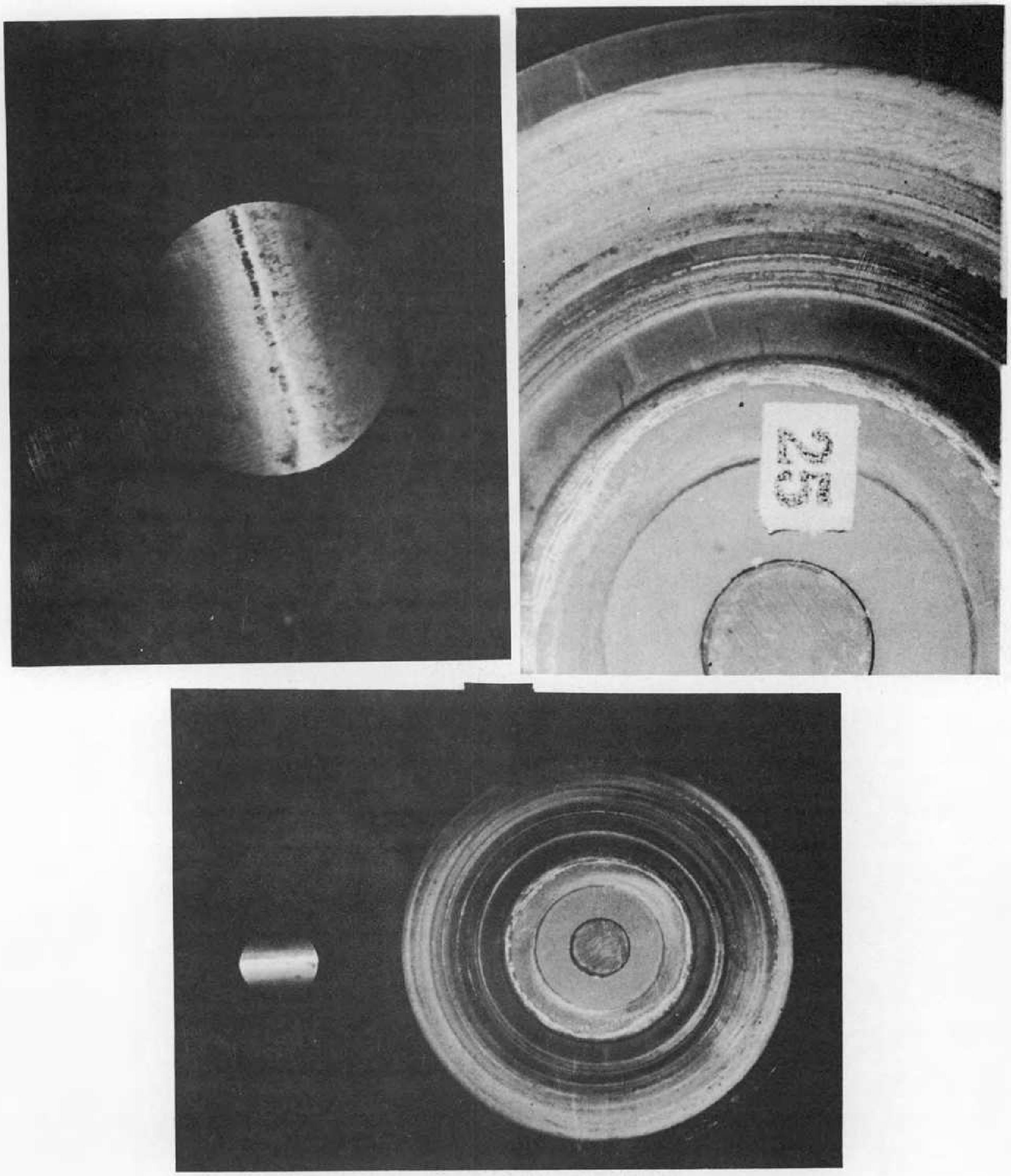
PHOTO 18284



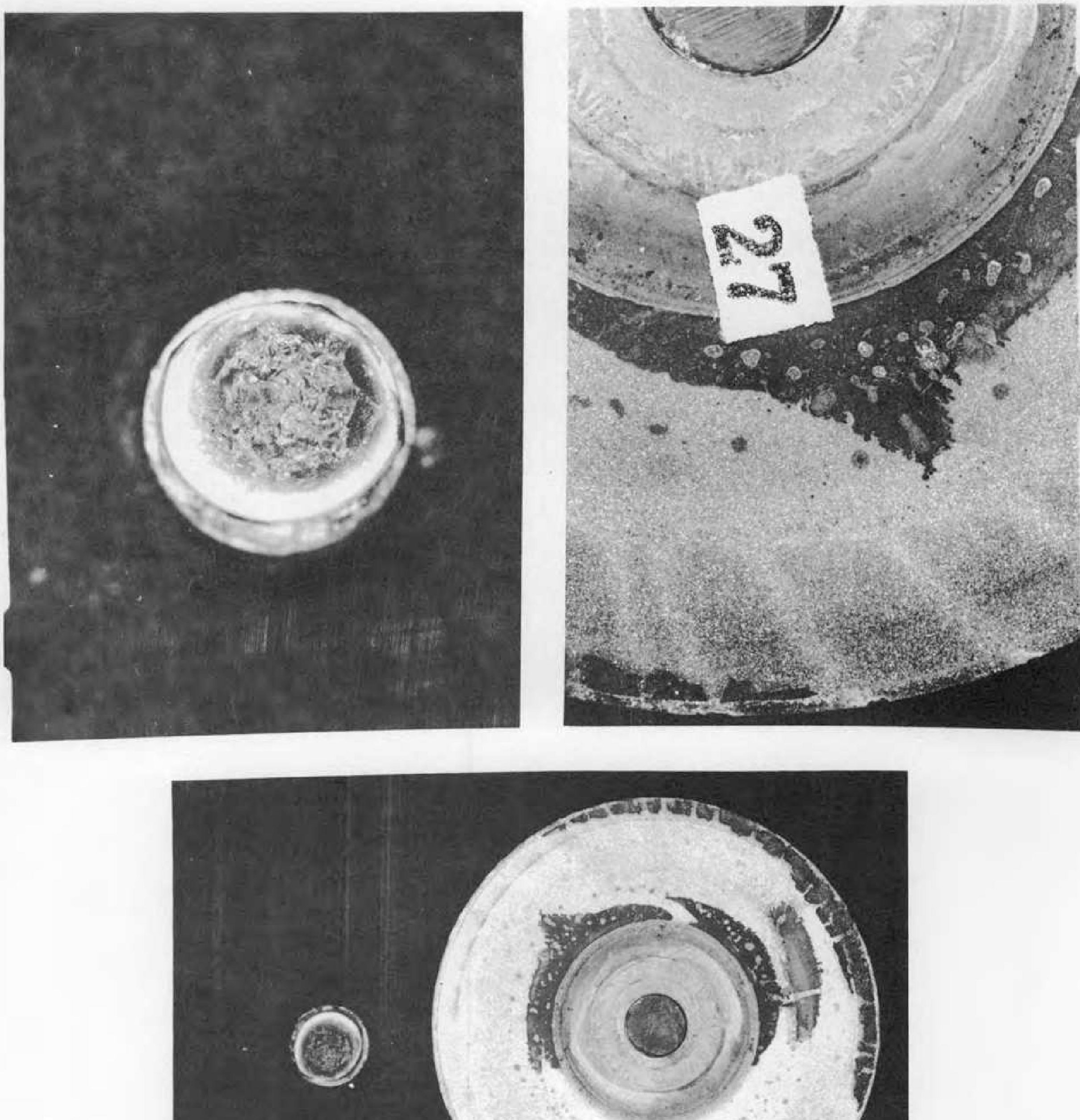
Test No. 24. Pin: Adamas Grade A, WC
Plate: Kennametal 138A, TiC + Co

UNCLASSIFIED
PHOTO 18285



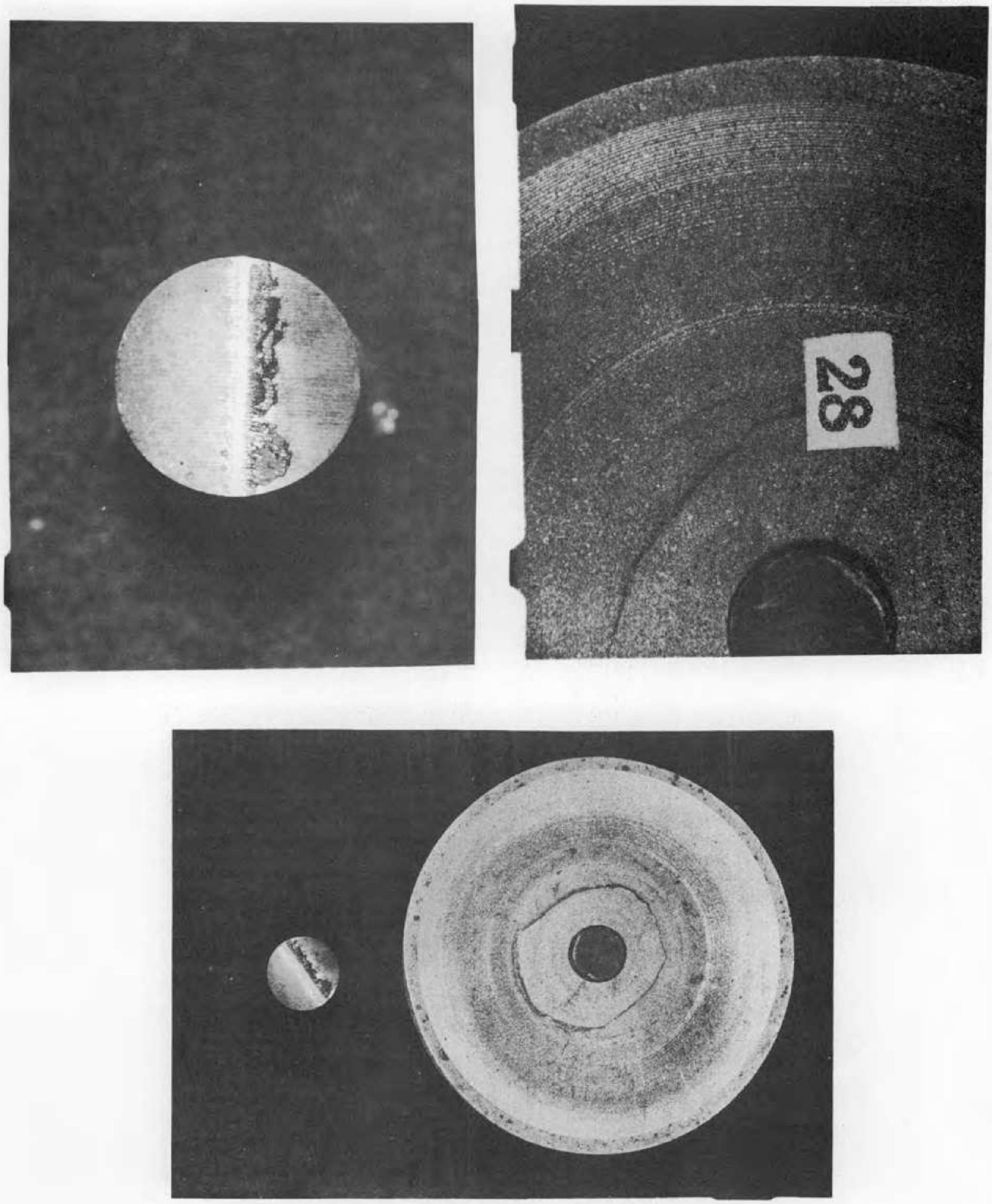
Test No. 25. Pin: Adamas Grade A, WC
Plate: Norton Norbide, B_4C

UNCLASSIFIED
PHOTO 18286



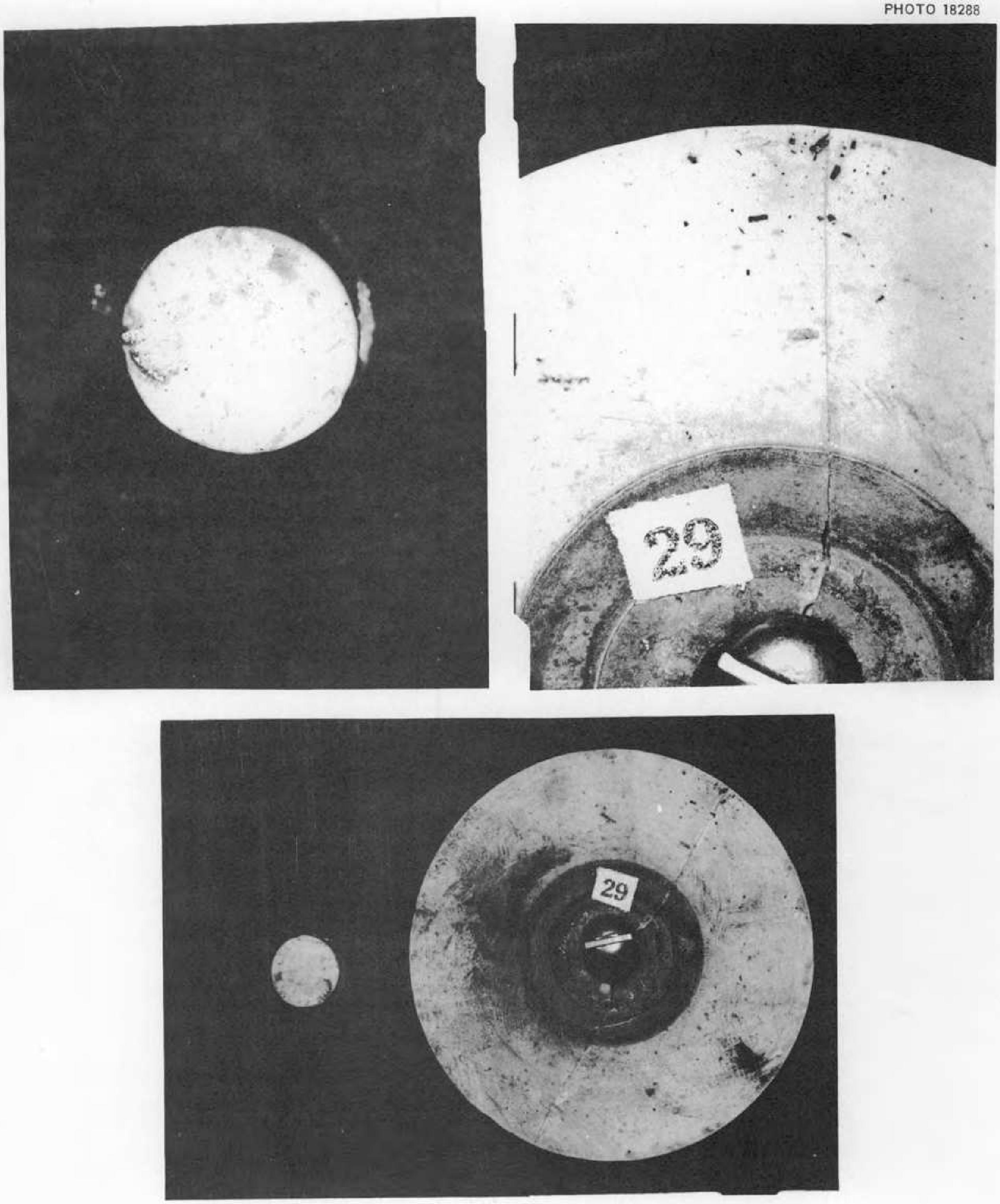
Test No. 27. Pin: ARE Moderator BeO
Plate: Adamas Grade A, WC

UNCLASSIFIED
PHOTO 18287



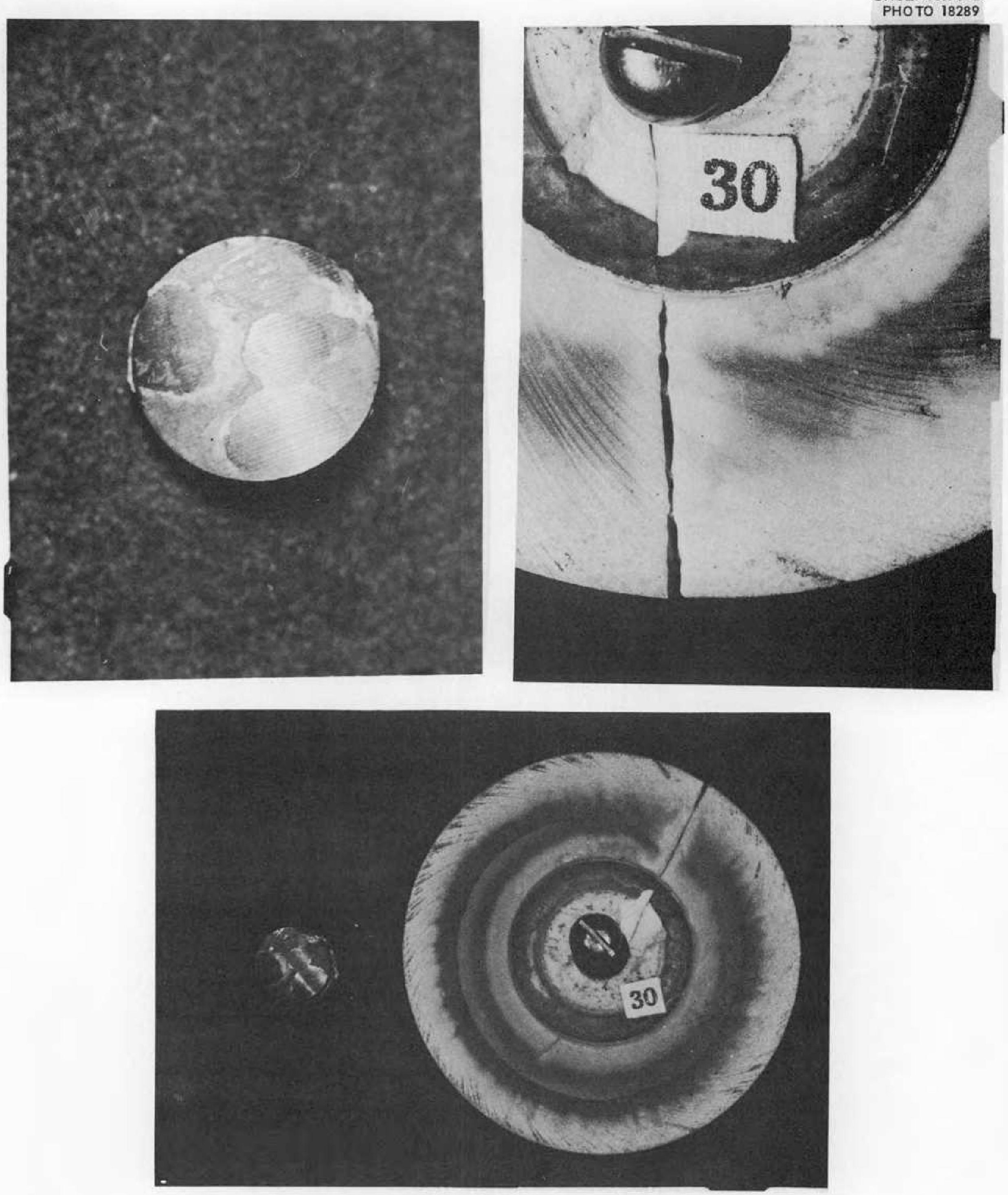
Test No. 28. Pin: Adamas Grade A, WC
Plate: High-Density Graphite

UNCLASSIFIED
PHOTO 18288



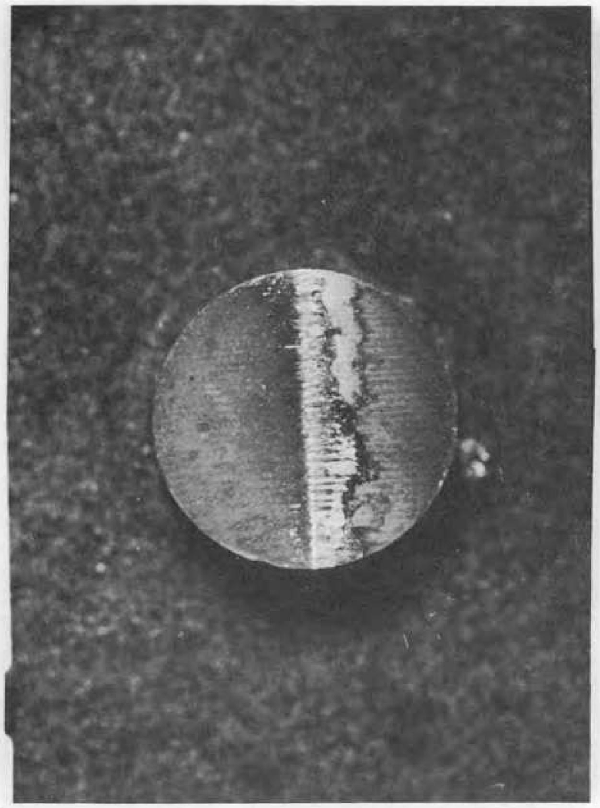
Test No. 29. Pin: ARE Moderator BeO
Plate: ARE Moderator BeO

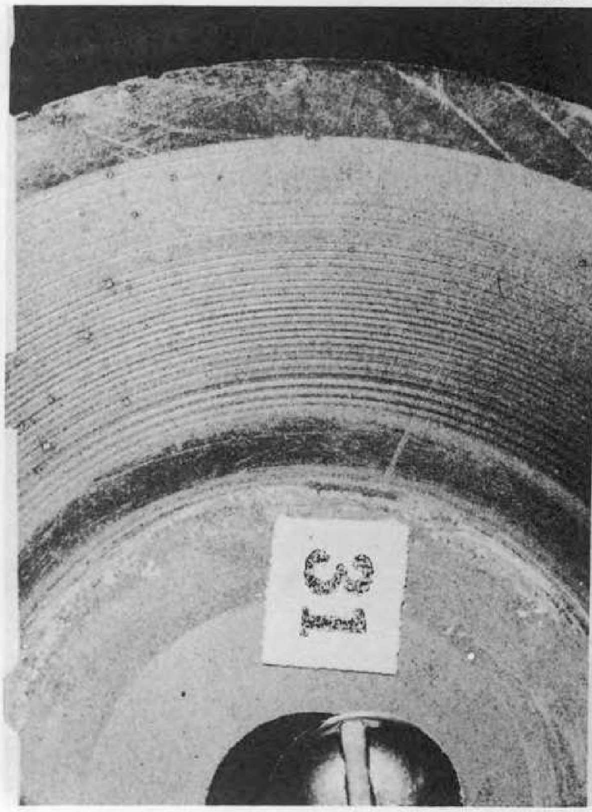
UNCLASSIFIED
PHOTO 18289

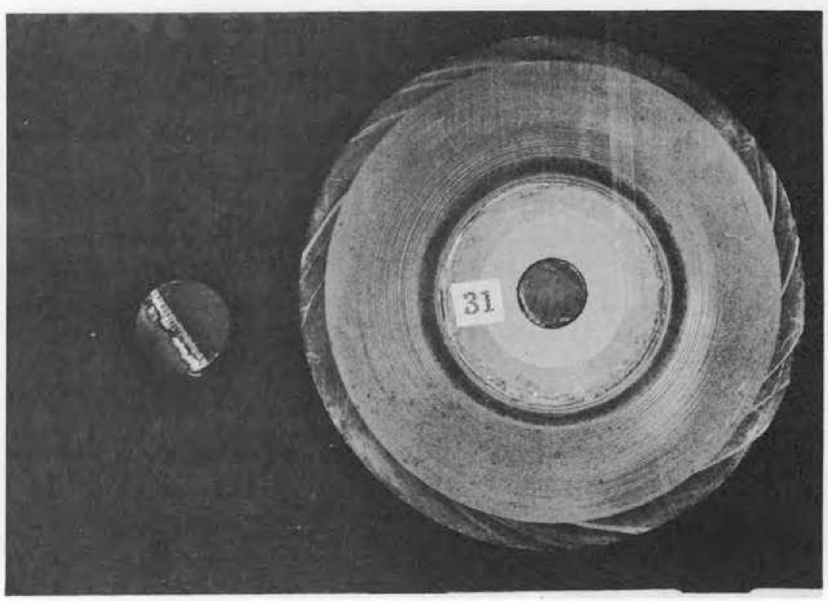


Test No. 30. Pin: Adamas Grade A, WC
Plate: Kearfoot Alumina, Al_2O_3

UNCLASSIFIED
PHOTO 18290

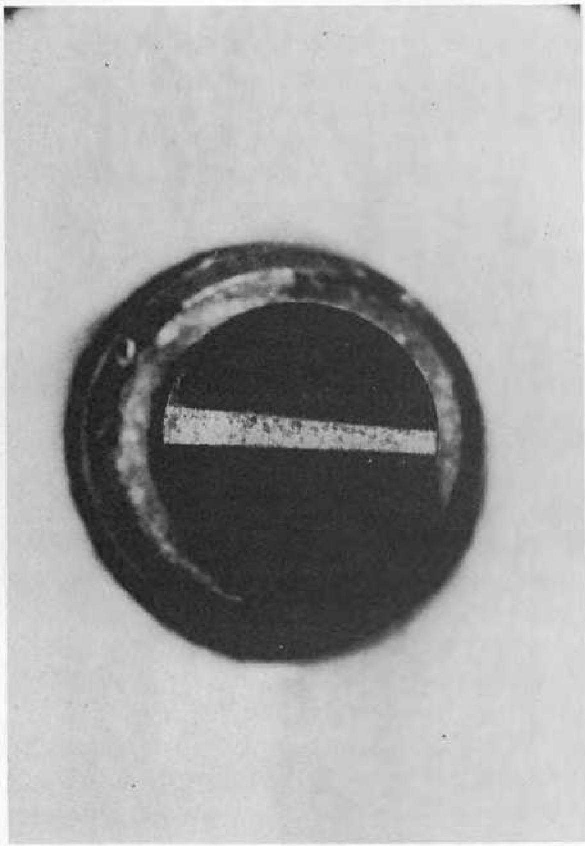


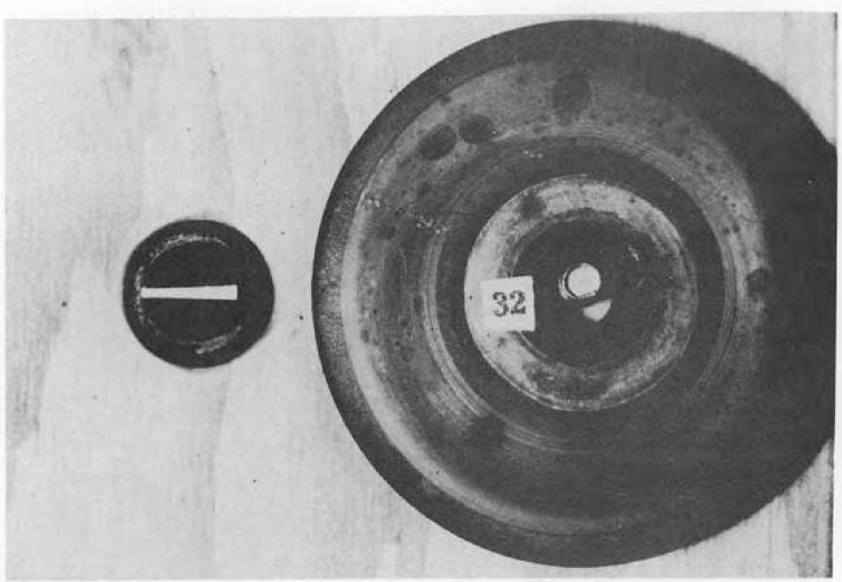




Test No. 31. Pin: Adamas Grade A, WC
Plate: Graphitar 14

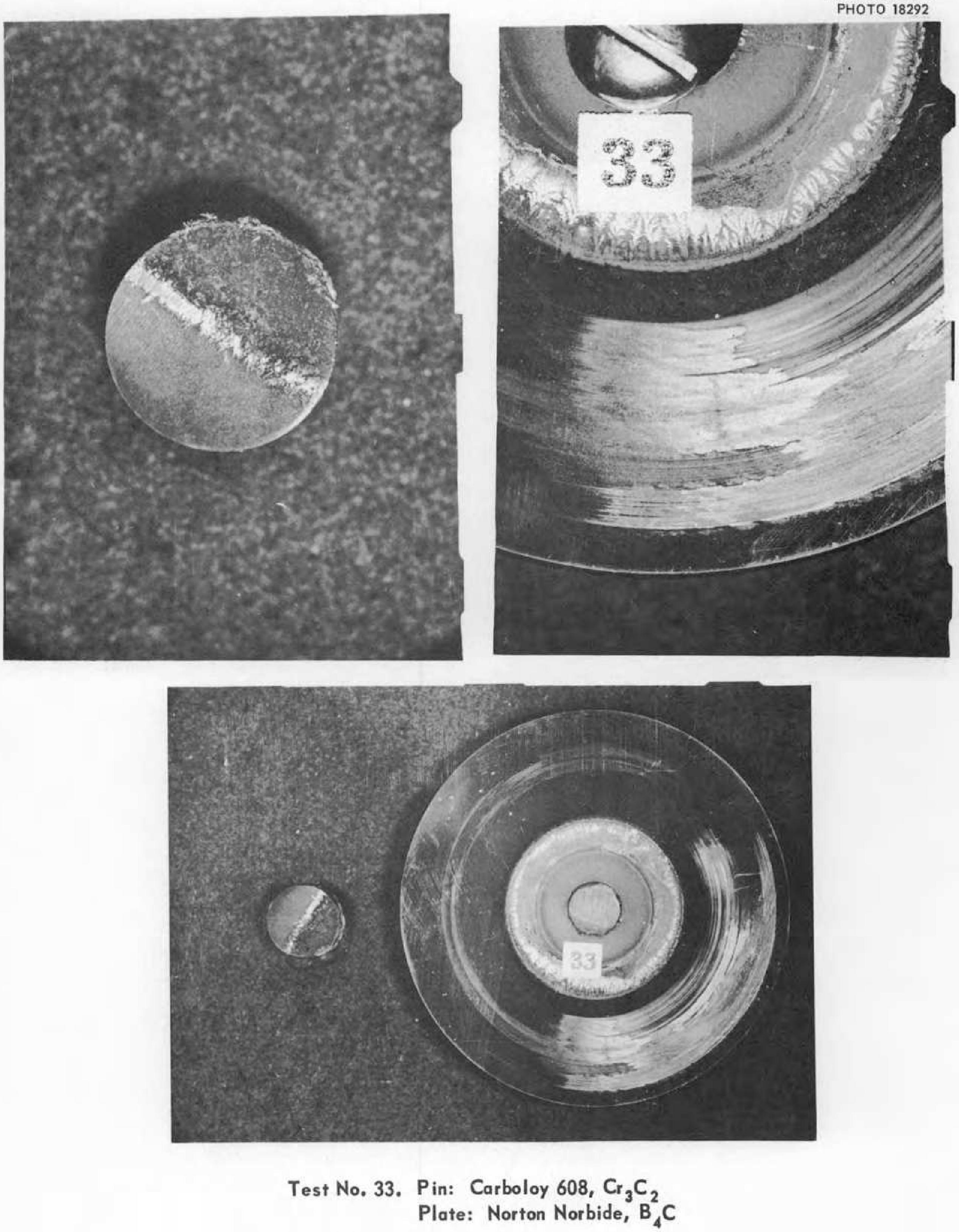
UNCLASSIFIED
PHOTO 18291





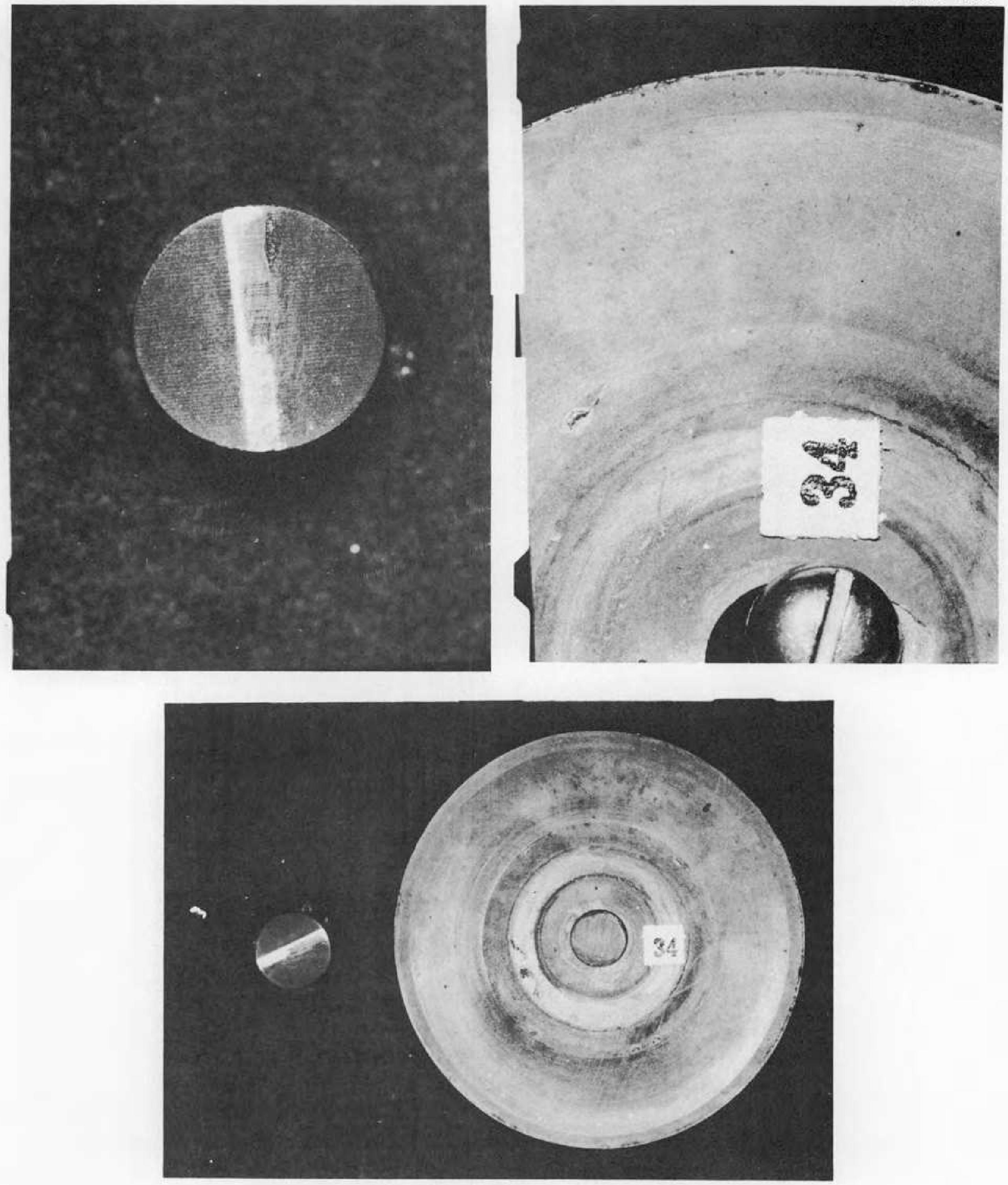
Test No. 32. Pin: Carboloy 608, Cr_3C_2
Plate: Carboloy 608, Cr_3C_2

UNCLASSIFIED
PHOTO 18292



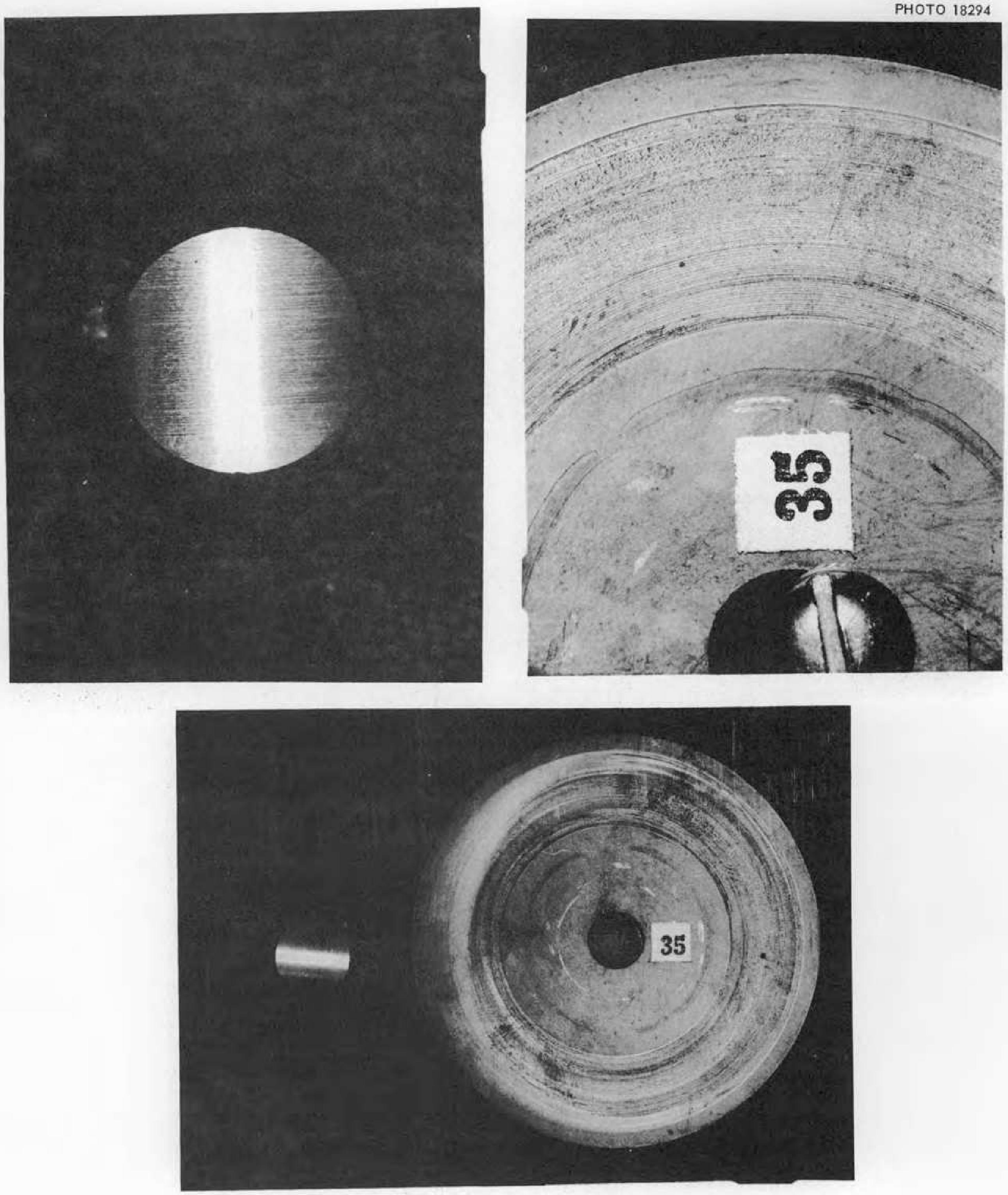
Test No. 33. Pin: Carboloy 608, Cr_3C_2
Plate: Norton Norbide, B_4C

UNCLASSIFIED
PHOTO 18293



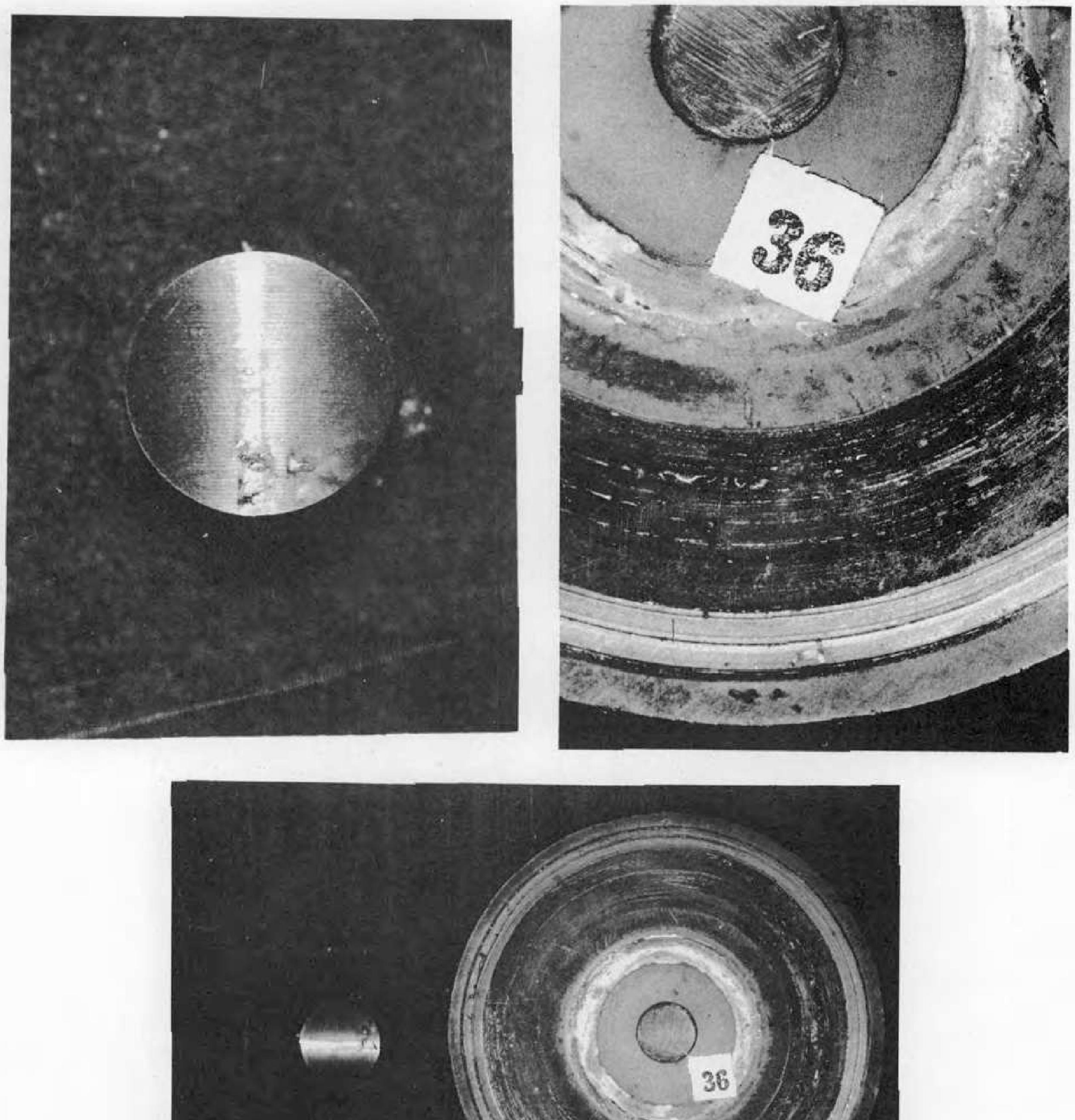
Test No. 34. Pin: Carboloy 608, Cr_3C_2
Plate: Kennametal 138A, TiC + Co

UNCLASSIFIED
PHOTO 18294



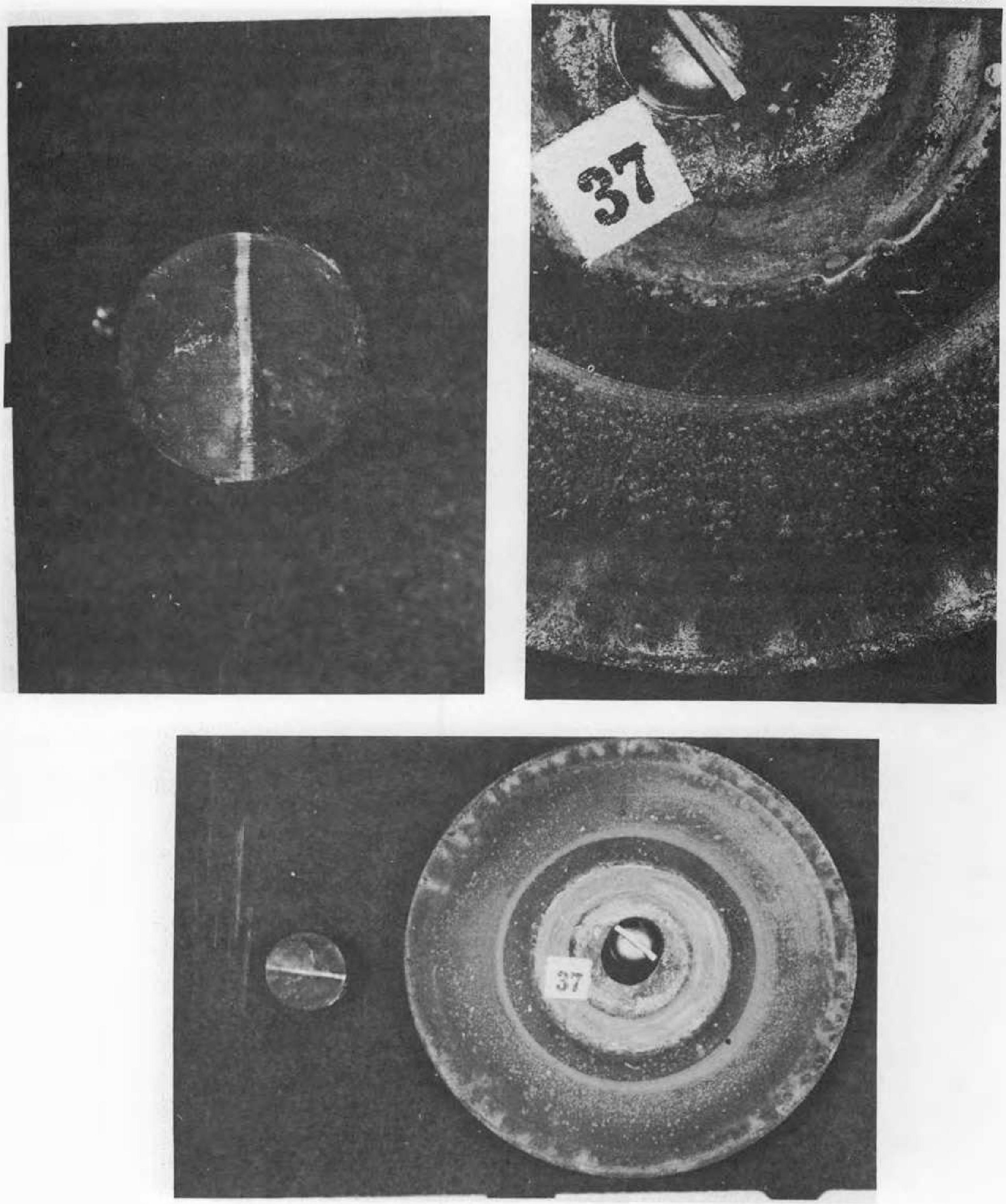
Test No. 35. Pin: Adamas Grade A, WC
Plate: Norton Norbide, B_4C

UNCLASSIFIED
PHOTO 18295



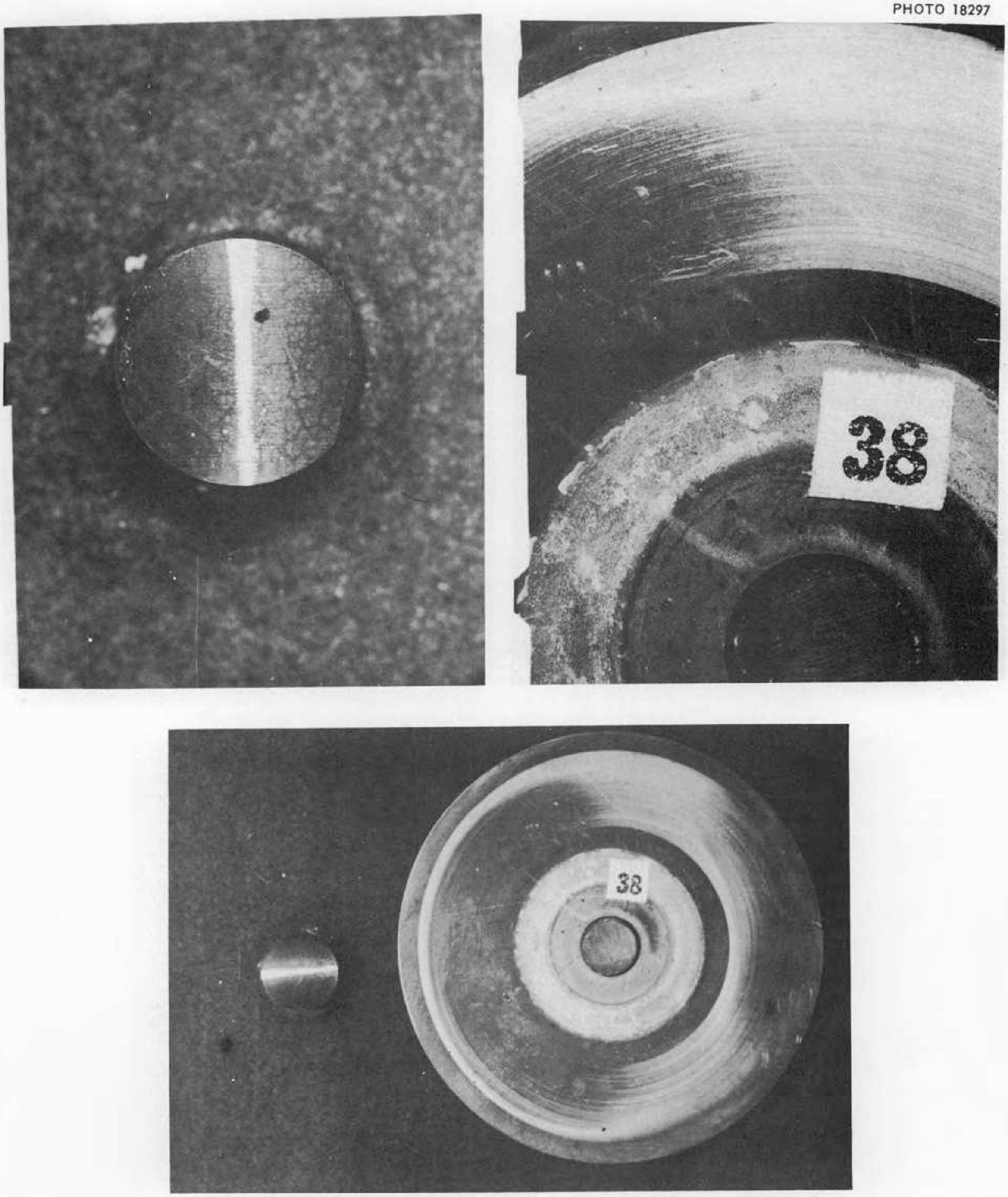
Test No. 36. Pin: Kennametal 151A, TiC + Ni
Plate: Norton Norbide, B_4C

UNCLASSIFIED
PHOTO 18296



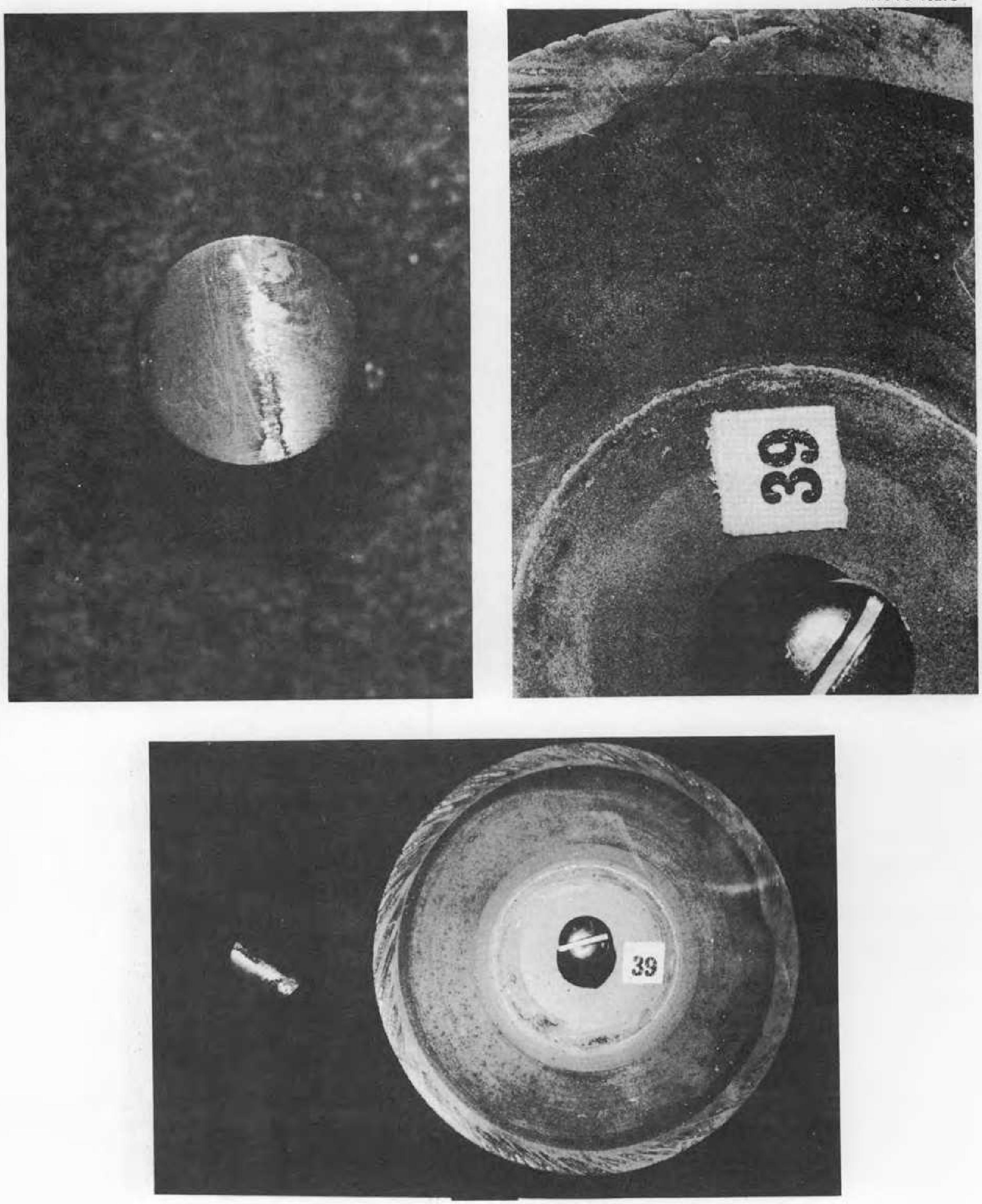
Test No. 37. Pin: Kennametal 151A, TiC + Ni
Plate: Carboloy 608, Cr_3C_2

UNCLASSIFIED
PHOTO 18297



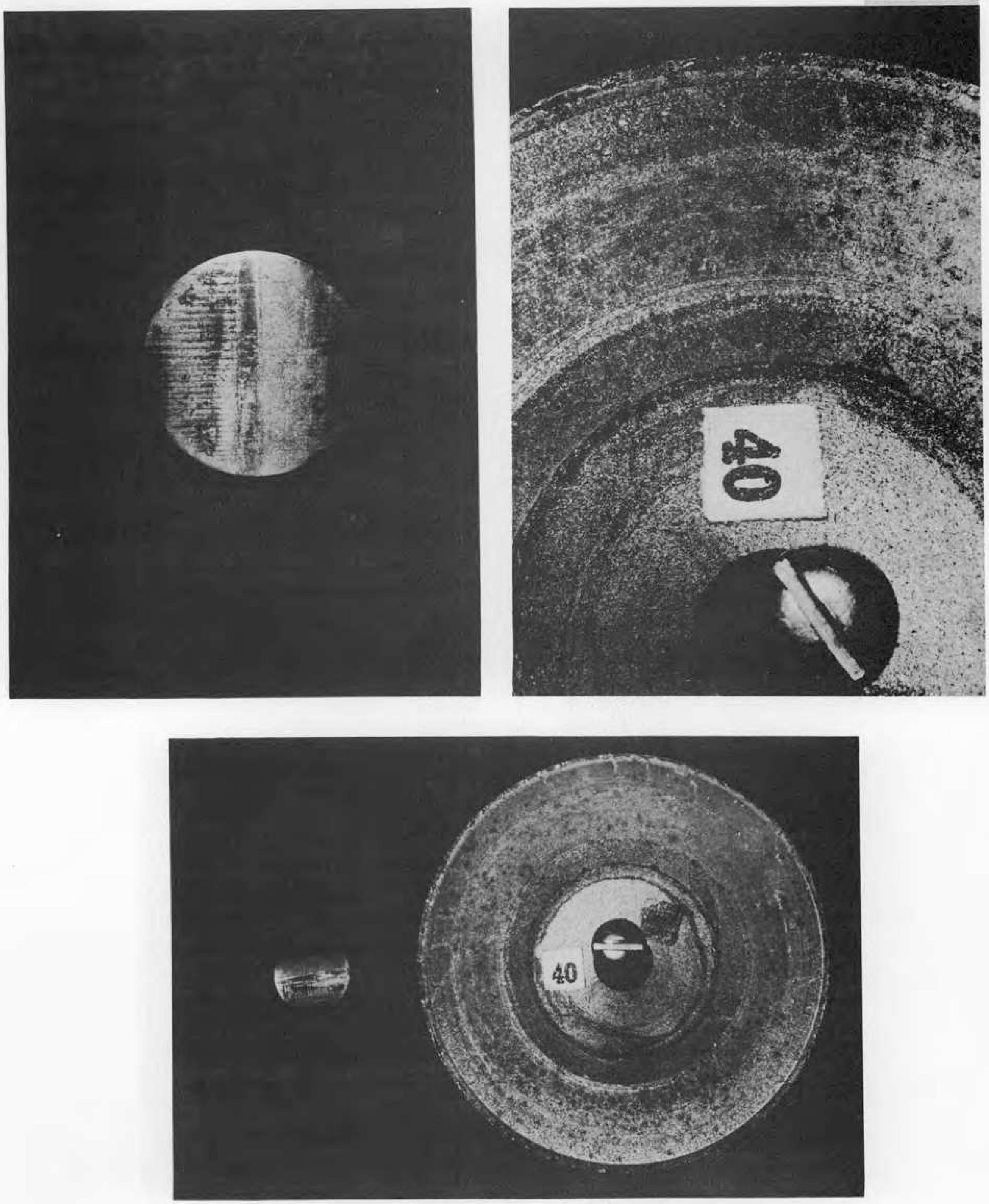
Test No. 38. Pin: Kennametal 151A, TiC + Ni
Plate: Kennametal 151A, TiC + Ni

UNCLASSIFIED
PHOTO 18298



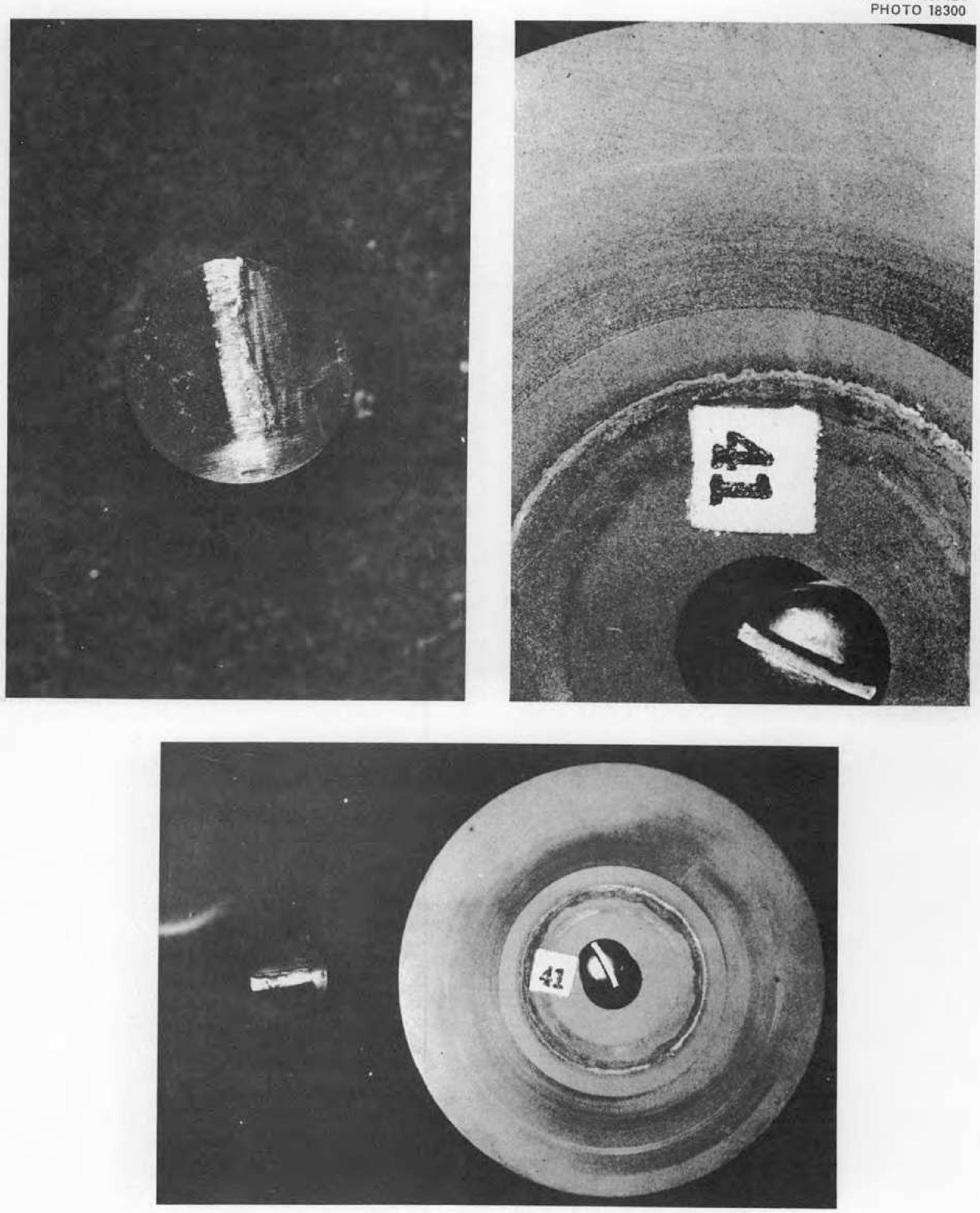
Test No. 39. Pin: Kennametal 151A, TiC + Ni
Plate: Graphitar 14

UNCLASSIFIED
PHOTO 18299



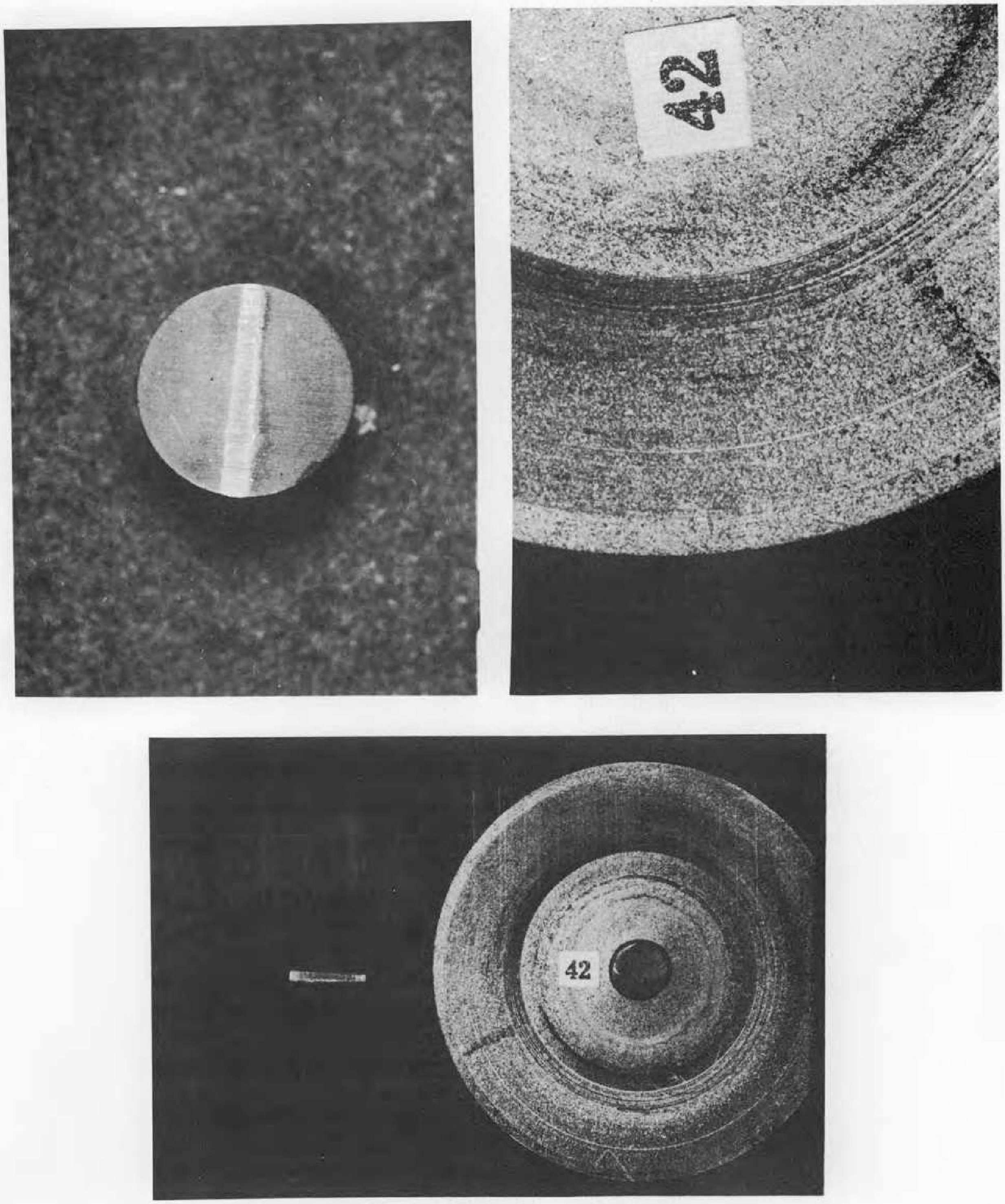
Test No. 40. Pin: Kennametal 151A, TiC + Ni
Plate: High-Density Graphite

UNCLASSIFIED
PHOTO 18300



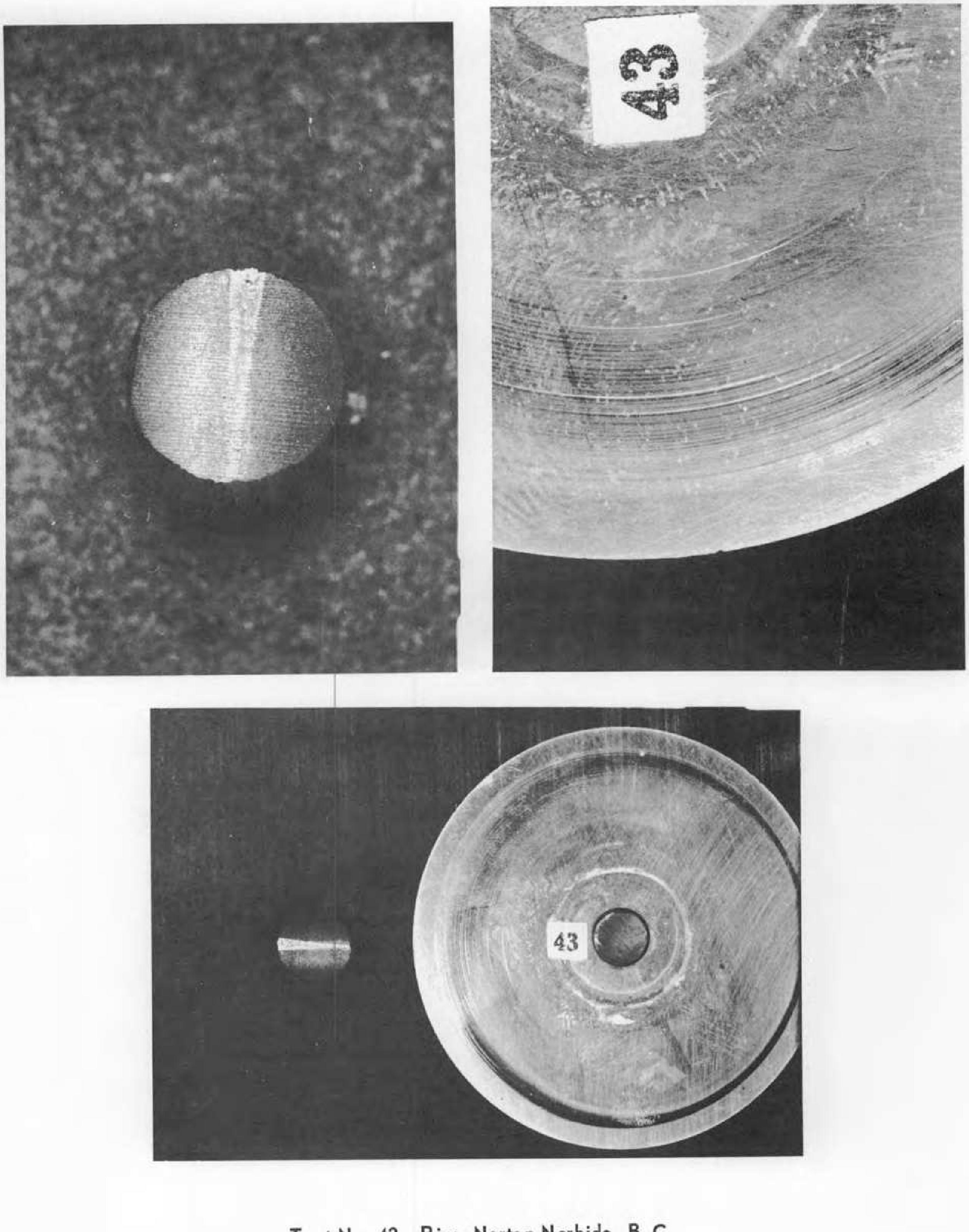
Test No. 41. Pin: Carboloy 608, Cr_3C_2
Plate: Graphitar 14

UNCLASSIFIED
PHOTO 18301



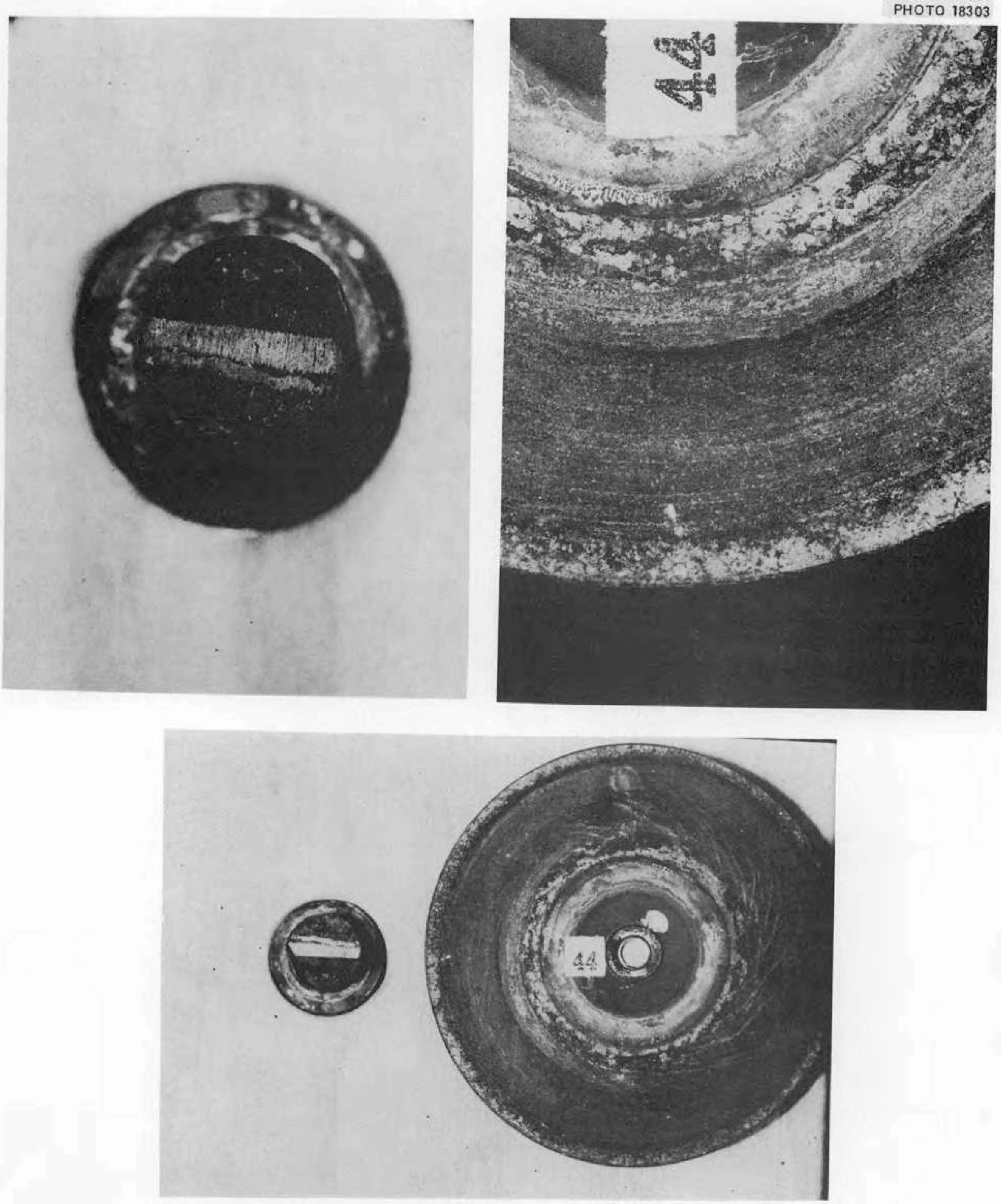
Test No. 42. Pin: Carboloy 608, Cr_3C_2
Plate: High-Density Graphite

UNCLASSIFIED
PHOTO 18302



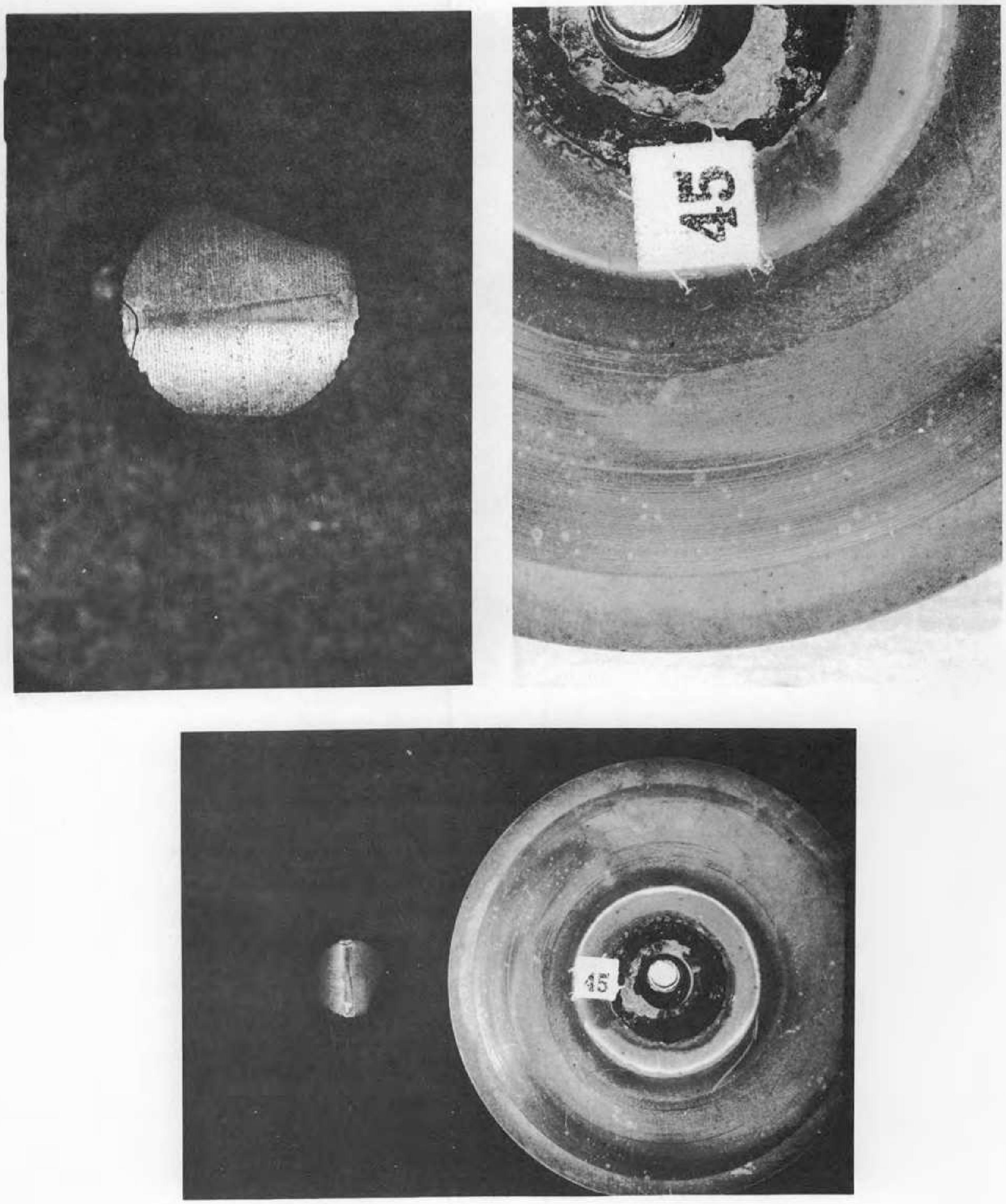
Test No. 43. Pin: Norton Norbide, B_4C
Plate: Adamas Grade A, WC

UNCLASSIFIED
PHOTO 18303



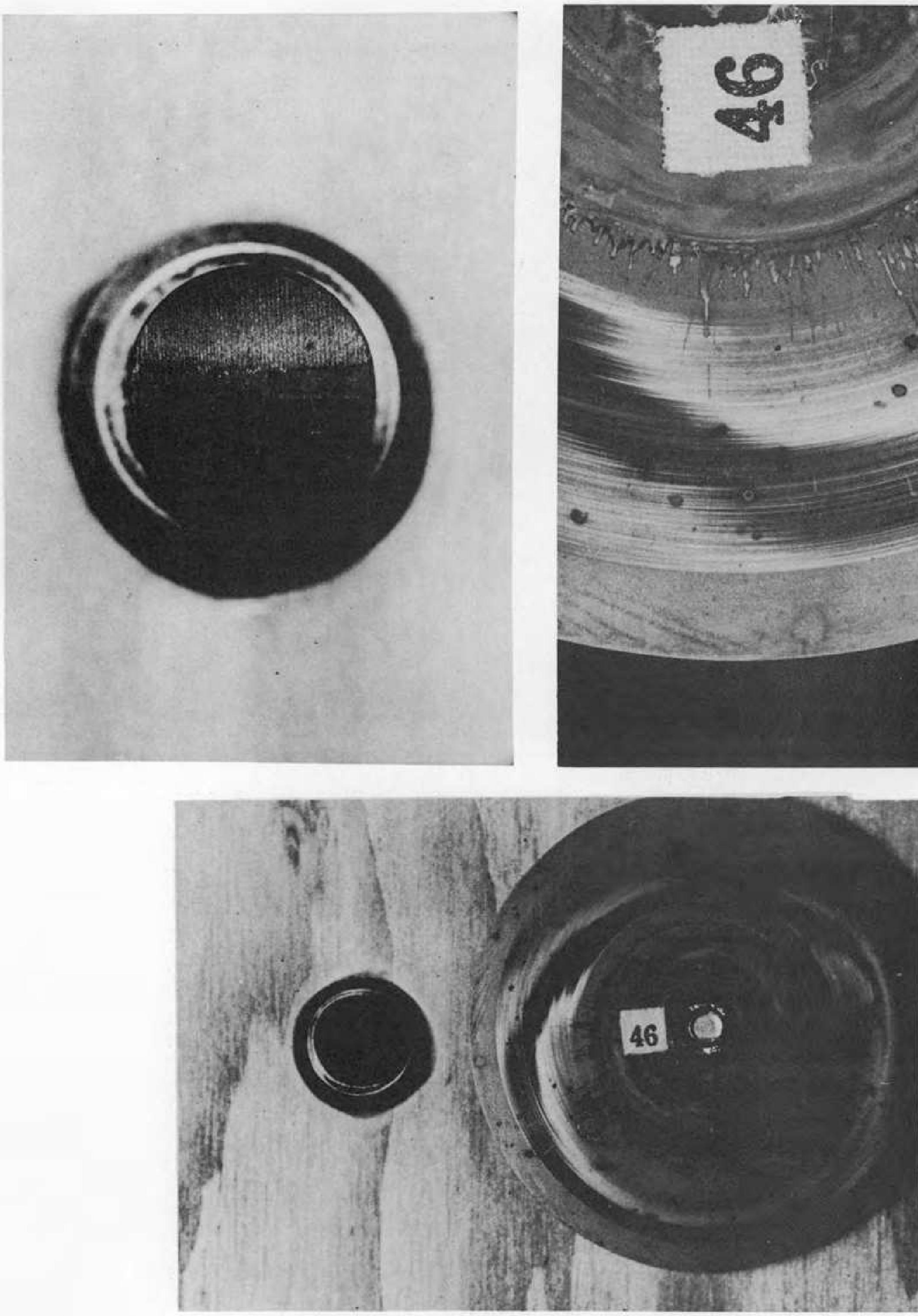
Test No. 44. Pin: Norton Norbide, B_4C
Plate: Norton Norbide, B_4C

UNCLASSIFIED
PHOTO 18304



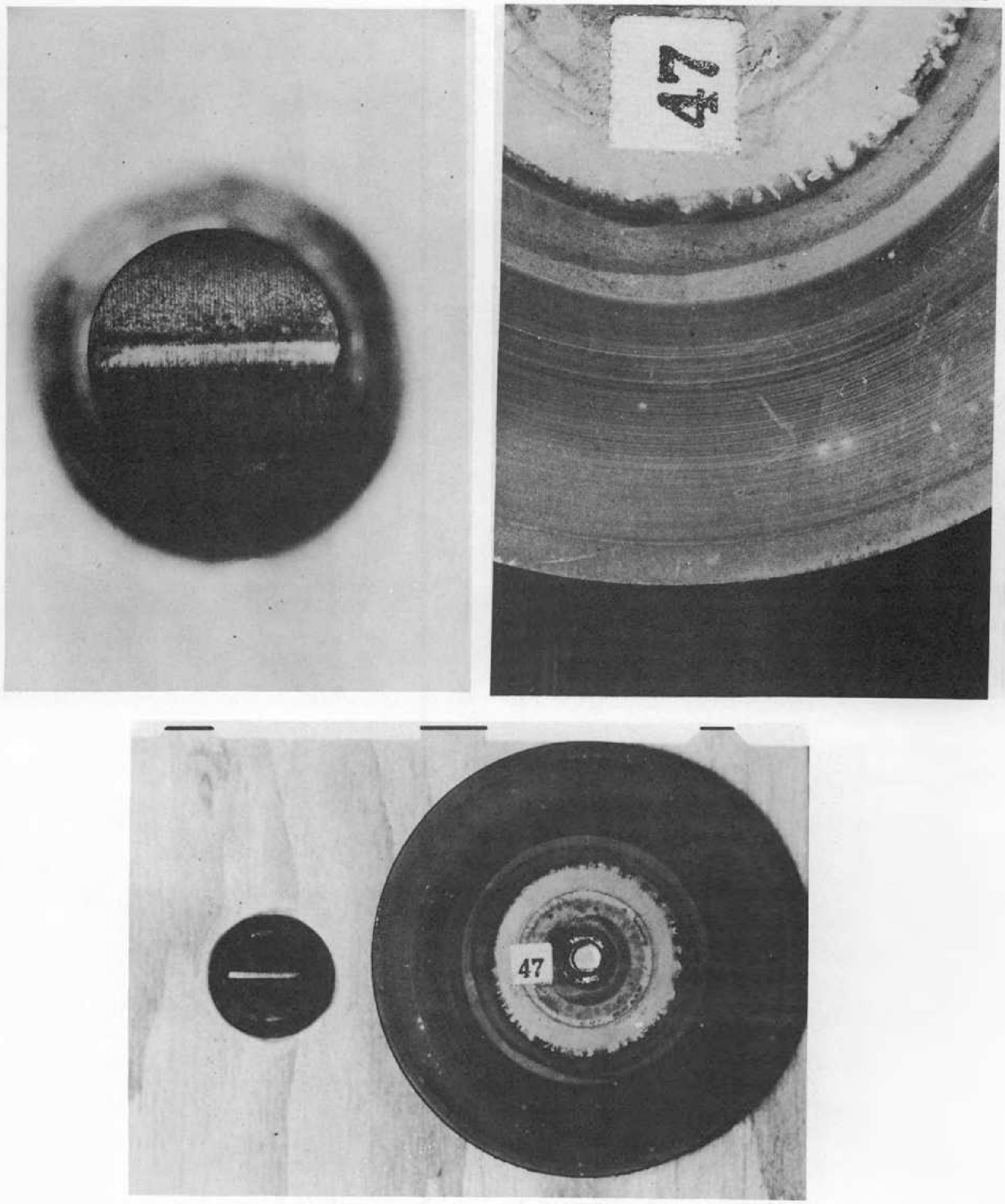
Test No. 45. Pin: Norton Norbide, B_4C
Plate: Carboloy 608, Cr_3C_2

UNCLASSIFIED
PHOTO 18305



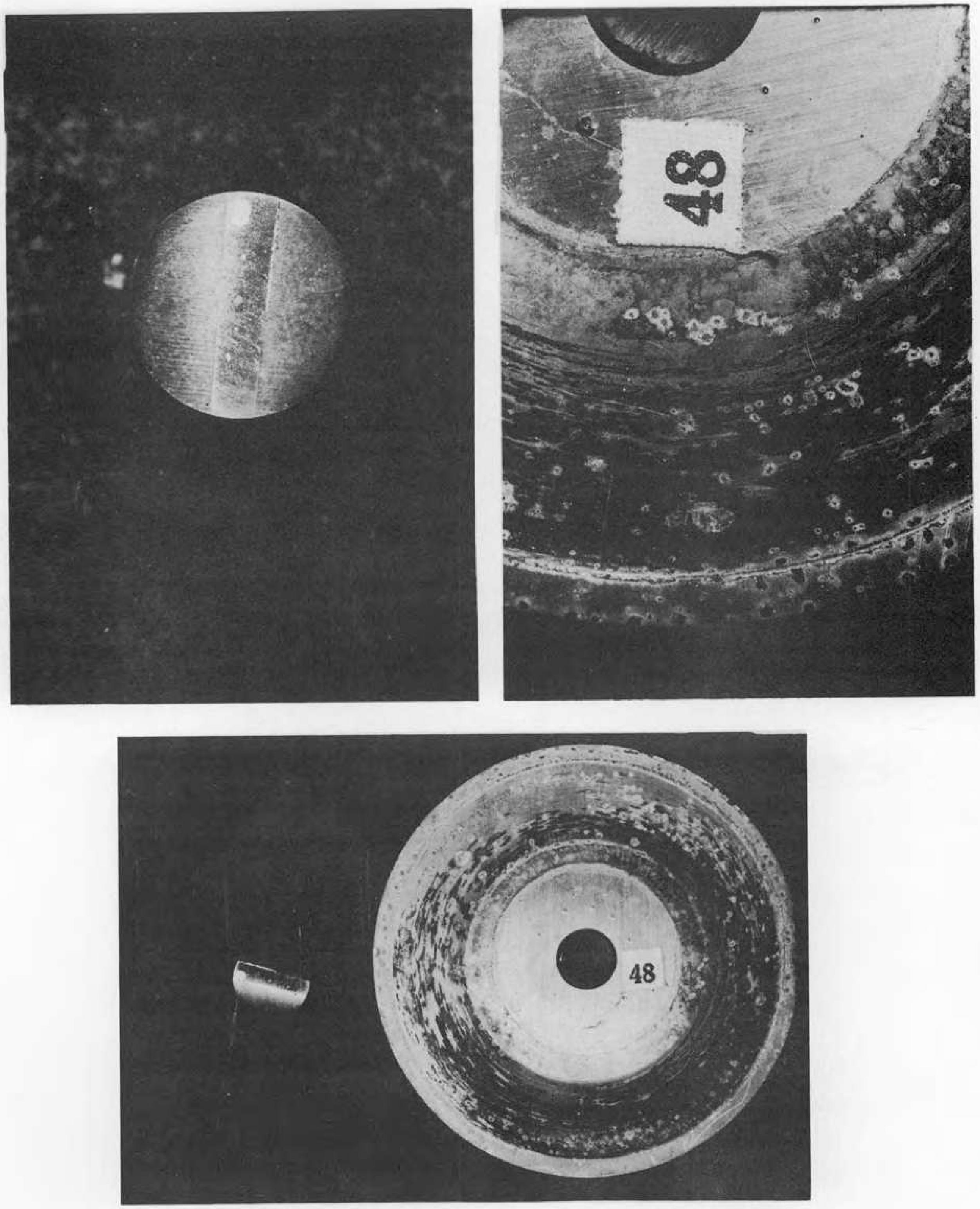
Test No. 46. Pin: Norton Norbide, B_4C
Plate: Kennametal 151A, TiC + Ni

UNCLASSIFIED
PHOTO 18306



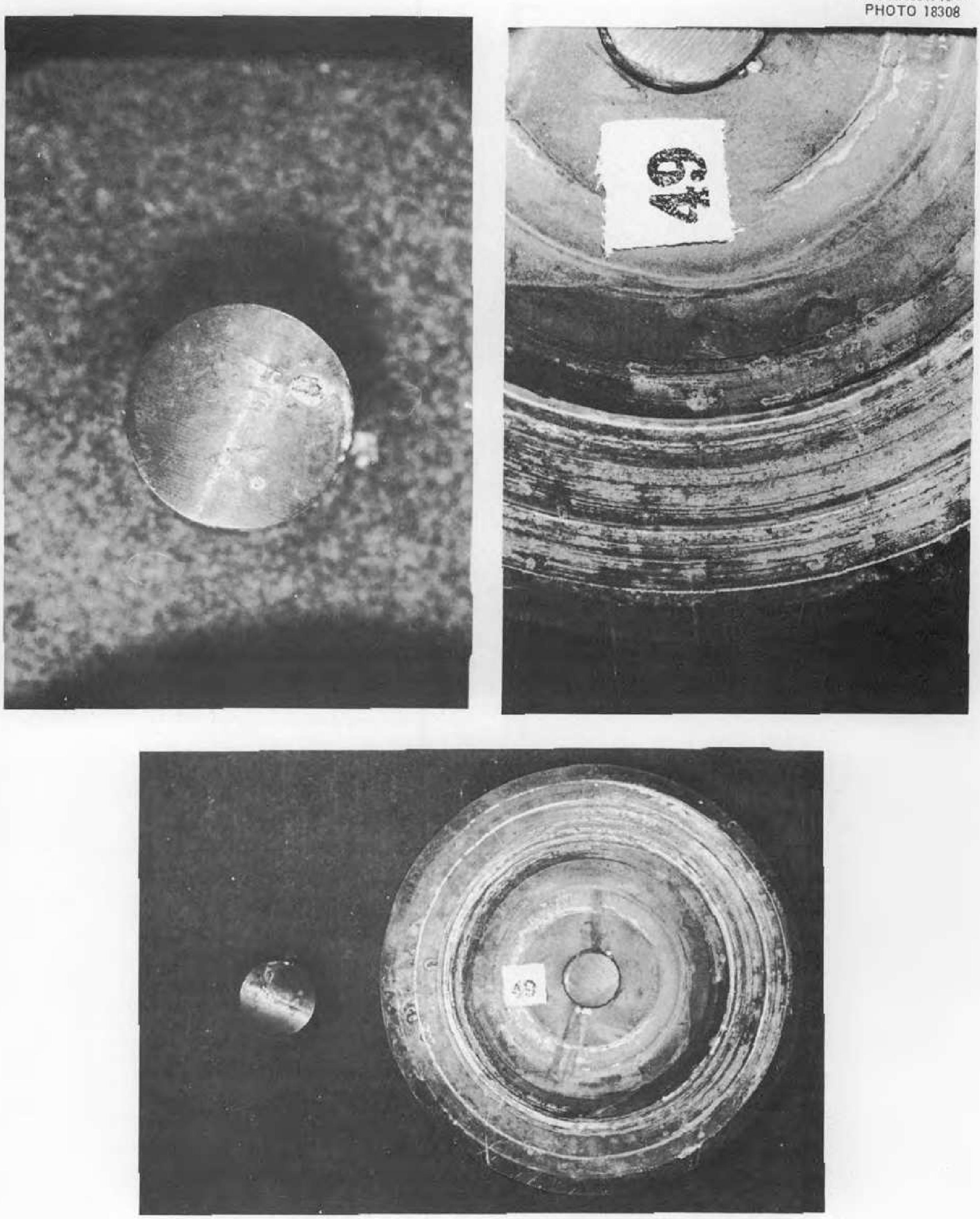
Test No. 47. Pin: Norton Norbide, B_4C
Plate: Kennametal 138A, TiC + Co

UNCLASSIFIED
PHOTO 18307



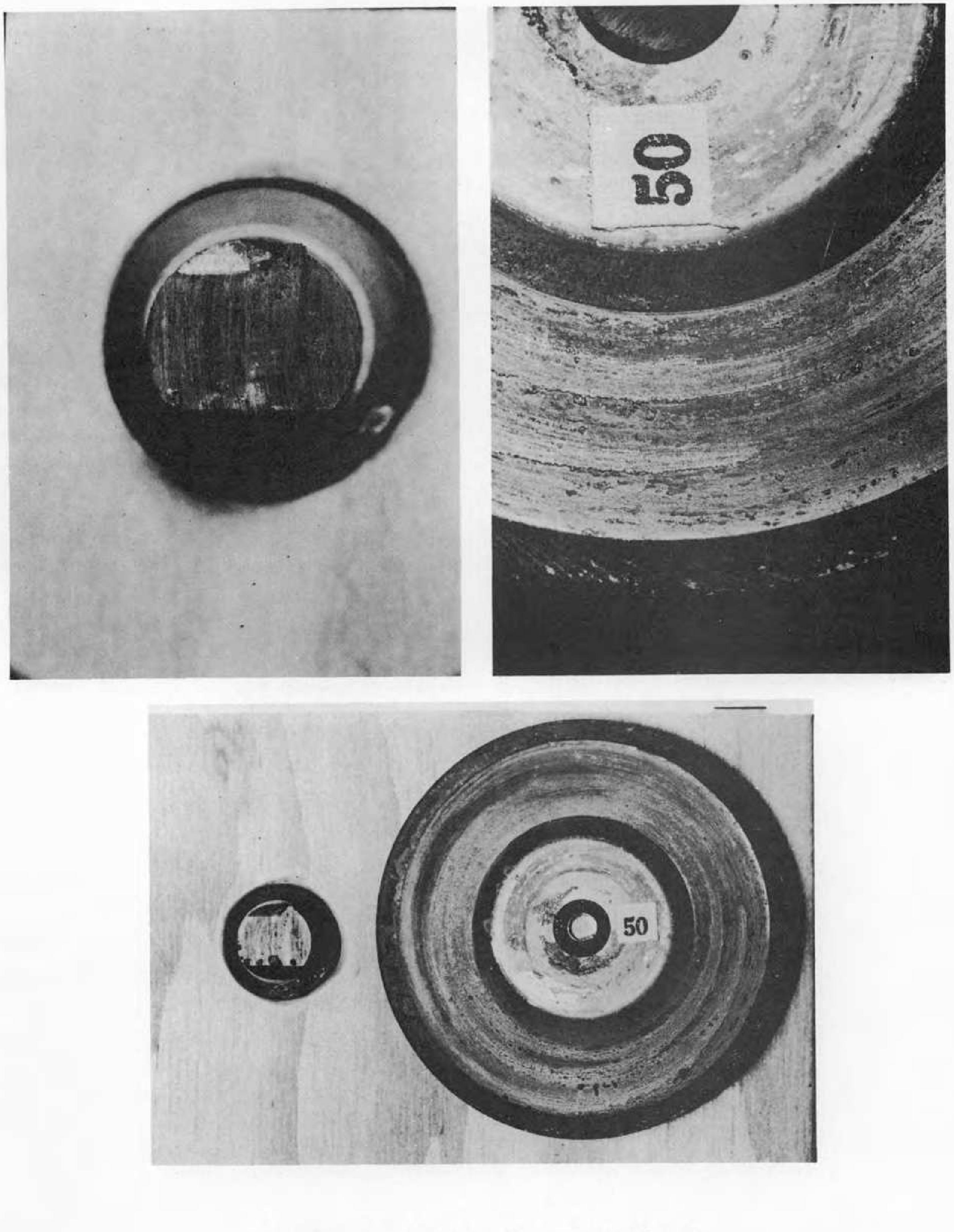
Test No. 48. Pin: Kennametal 138A, TiC + Co
Plate: Adamas Grade A, WC

UNCLASSIFIED
PHOTO 18308



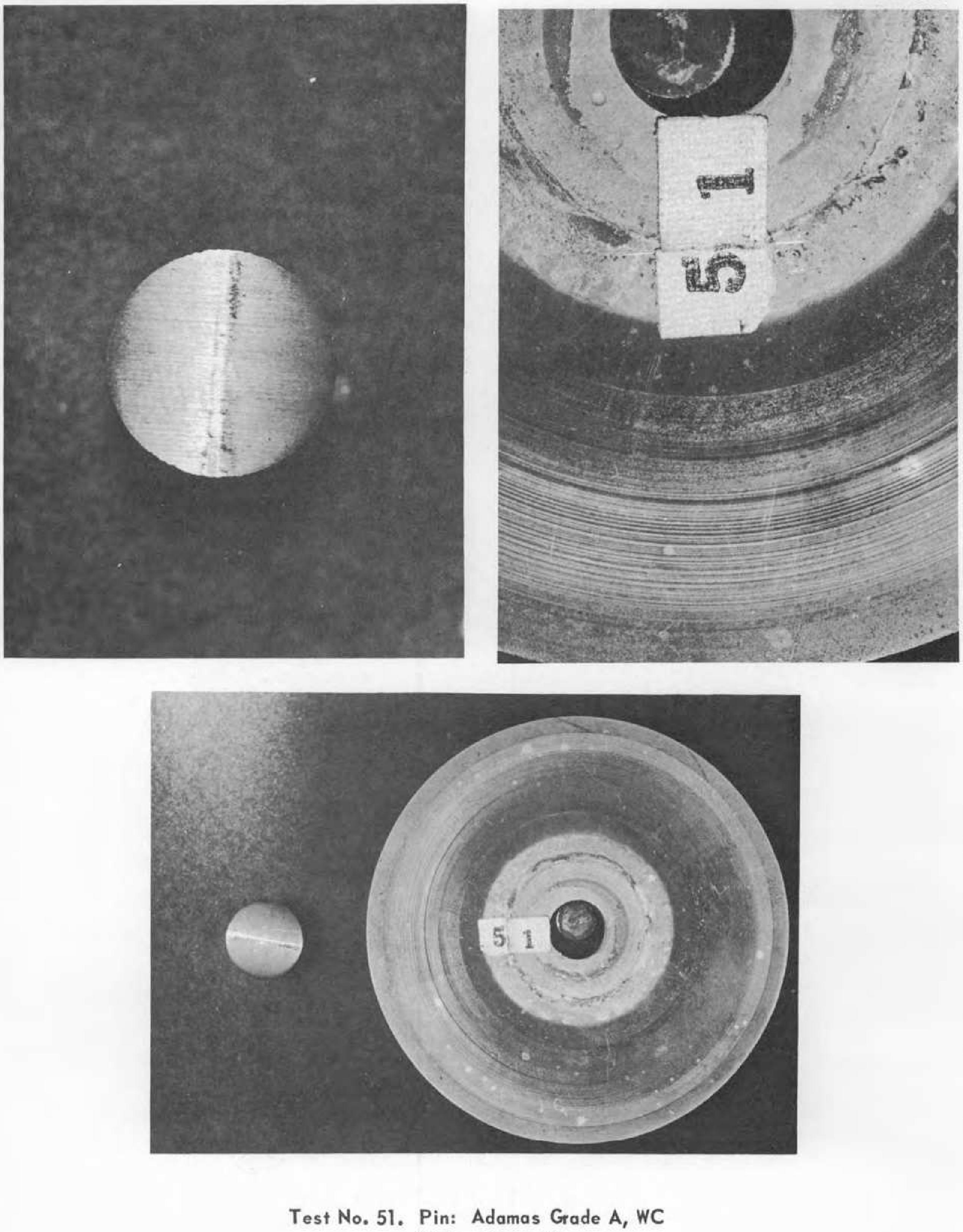
Test No. 49. Pin: Kennametal 138A, TiC + Co
Plate: Norton Norbide, B_4C

UNCLASSIFIED
PHOTO 18309



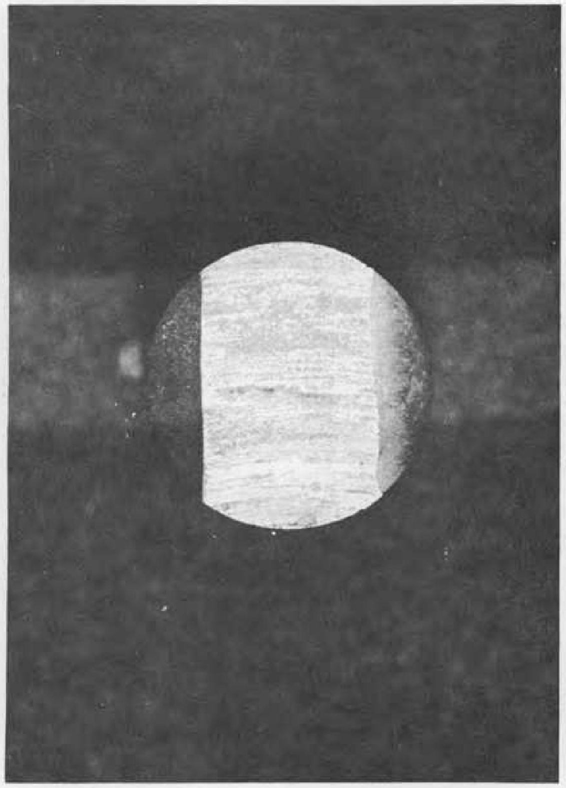
Test No. 50. Pin: Kennametal 151A, TiC + Ni
Plate: Inconel

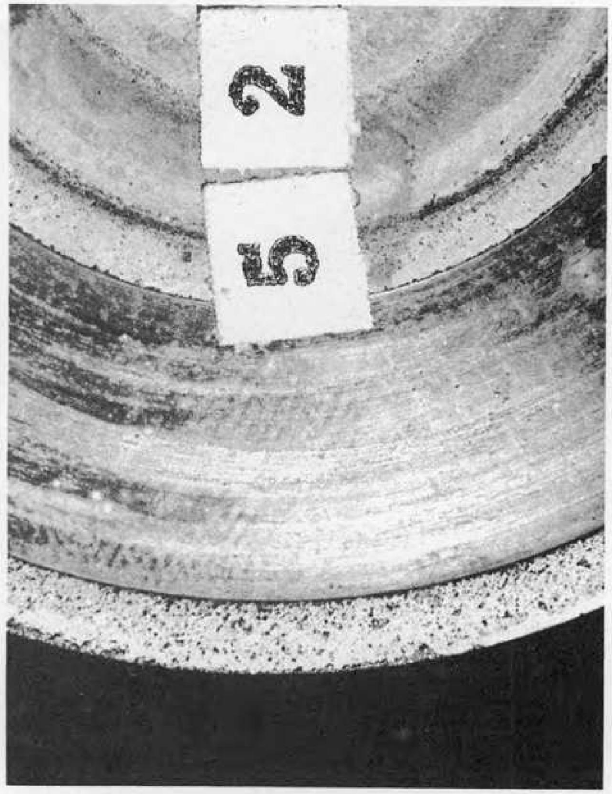
UNCLASSIFIED
PHOTO 18310

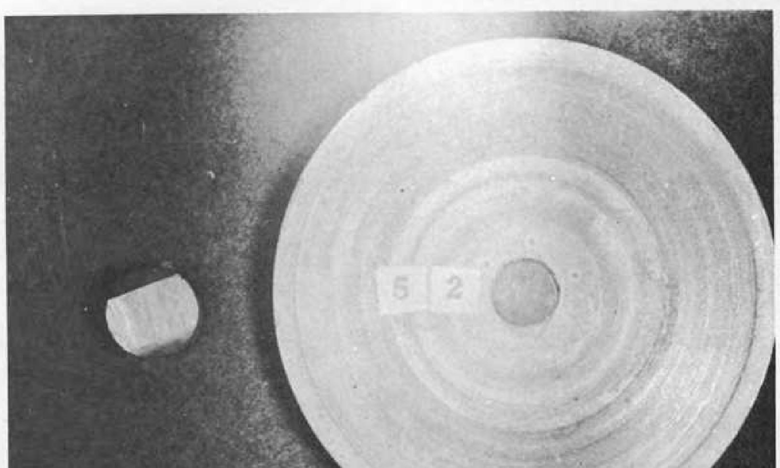


Test No. 51. Pin: Adamas Grade A, WC
Plate: Inconel

UNCLASSIFIED
PHOTO 18311

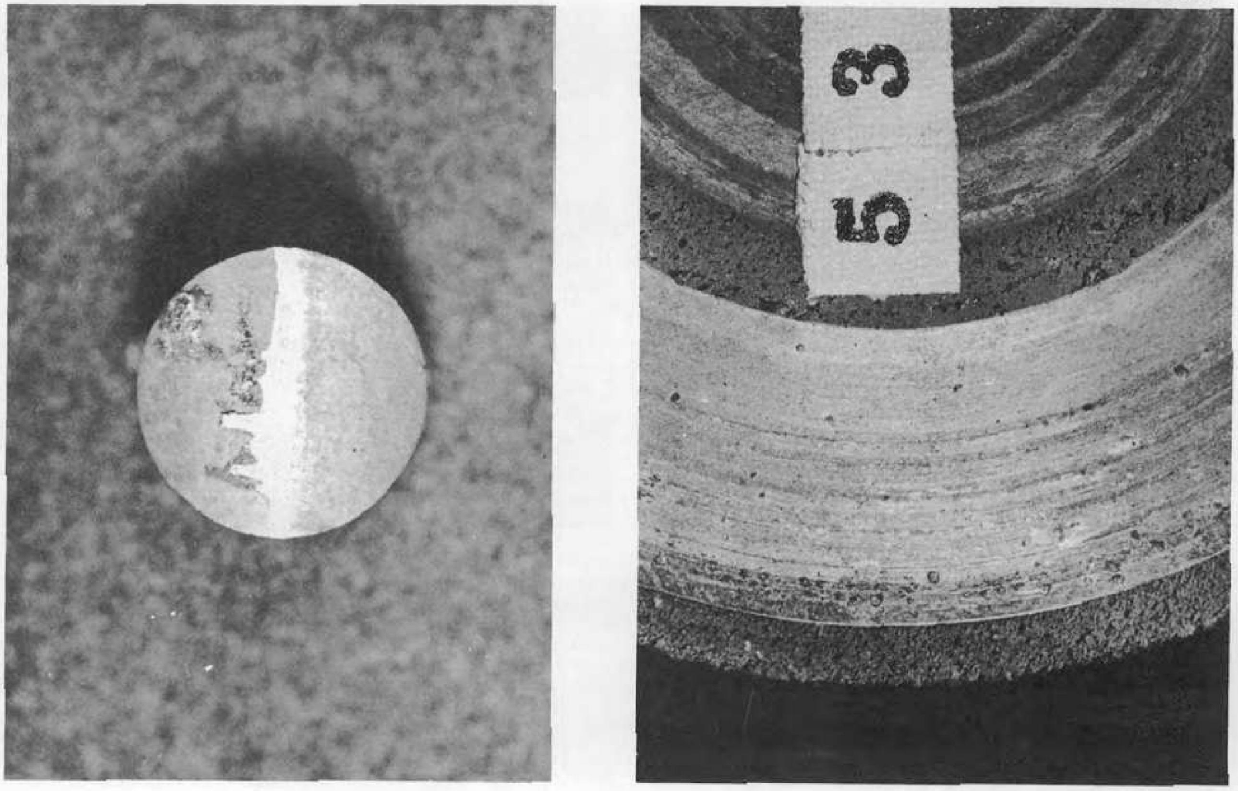






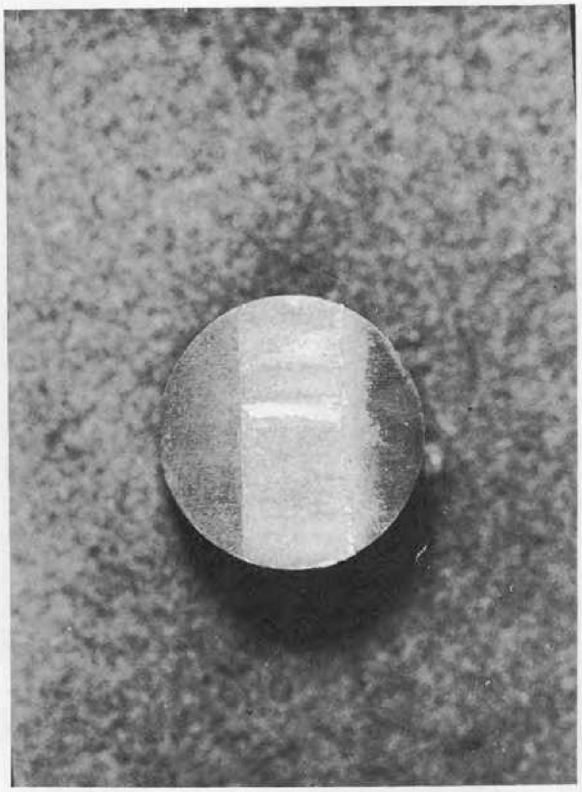
Test No. 52. Pin: Kennametal 151A, TiC + Ni
Plate: Inconel

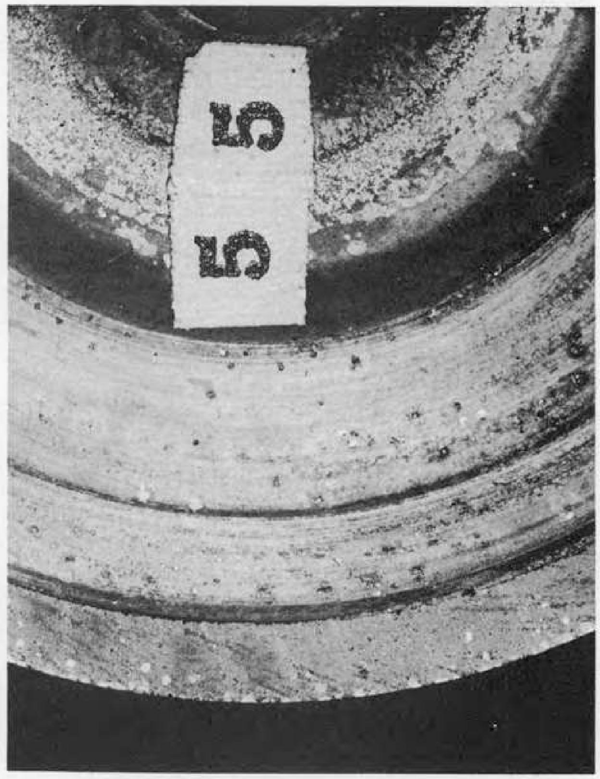
UNCLASSIFIED
PHOTO 18312

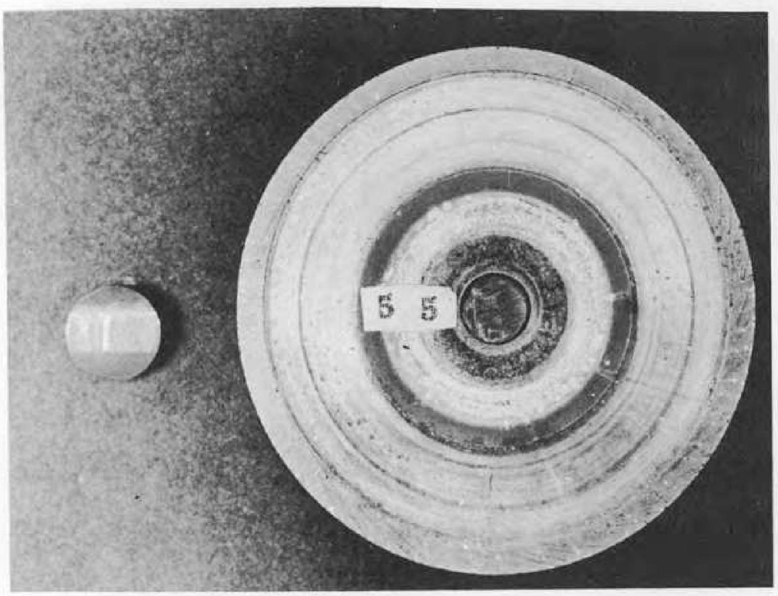


Test No. 53. Pin: Adamas Grade A, WC
Plate: Inconel

UNCLASSIFIED
PHOTO 18313







Test No. 55. Pin: Kennametal 138A, TiC + Co
Plate: Inconel