TECHNICAL REPORT ARCCB-TR-93007

MANUFACTURE OF TITANIUM ALLOY CANNON COMPONENTS

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MARCH 1993

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
March 1993

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
MANUFACTURE OF TITANIUM ALLOY
CANNON COMPONENTS

5. FUNDING NUMBERS
PRON: M77F0034M71A

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Benet Laboratories, SMCAR-CCB-TL
Watervliet, NY 12189-4050

8. PERFORMING ORGANIZATION REPORT NUMBER
ARCCB-TR-93007

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Close Combat Armaments Center
Picatinny Arsenal, NJ 07806-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release: distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
This report contains the results of a two-year Manufacturing Methods and Technology project that addresses the machinability of titanium beta-C material. Because of the lack of machining data, the machinability evaluation was performed both in-house and by an independent laboratory. Testing was done mostly on hollow cylinders and included operations such as milling, turning, deep-hole boring, and bore finishing. A substantial database was developed and can be used to optimize the manufacture of titanium alloy components and to establish manufacturing costs.

14. SUBJECT TERMS
Titanium Beta-C, Milling, Turning, Deep-Hole Boring, Bore Finishing, Roller Burnishing, Honing, Skiving

15. NUMBER OF PAGES
73

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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BACKGROUND AND INTRODUCTION

The effectiveness of military ground combat units relies heavily on the mobility of its troops and weapons. Weapon designers, therefore, must consider weight an important feature for a good design. Some recent large caliber weapon designs have employed longer gun tubes to increase range, however, this has added to the weight problem. Since the gun tubes are made completely of steel, the added length increases weight. Metallurgists have, by extensive alloying, improved the strength of gun steels and effectively kept the weight down by allowing gun tubes to be designed with less material (tube wall thickness).

A new approach considered to reduce the tube's weight is to incorporate lightweight reinforcing jackets on longer tubes designed with thinner steel tube sections. Certain titanium alloys that possess favorable mechanical properties and weigh approximately 44 percent less than steel are currently being used by the aircraft industry where strength and lightweight characteristics are needed. Therefore, a high specific strength titanium beta-C alloy (3Al-8V-6Cr-4Zr-4Mo) was identified as a material with the correct properties for these lightweight reinforcing cylinders.

The introduction of titanium lightweight reinforcing jackets on large caliber gun tubes is a relatively new application in cannon designs. Consequently, this material requires special or different manufacturing approaches.

PROBLEM

The manufacture of large titanium beta-C lightweight cylinders requires appropriate manufacturing methods in addition to equipment capable of processing long, hollow cylinders. The manufacturing facility at the Watervliet Arsenal (Watervliet, NY) has the equipment and the experience to process long, hollow cylinders such as gun tubes, but has somewhat limited experience regarding the machining of similar components made of nonferrous materials.

Existing machining methods for titanium alloys are basically those practiced for the last twenty years. The machinability database now used allows the selection of operating conditions on aircraft-type titanium components, typically Ti-6Al-4V, which require extensive turning, end milling, face milling, drilling, reaming, tapping, sawing, and grinding operations. A machinability and processing database for long turning, deep-hole boring, and bore finishing of hollow cylinders made of high specific strength titanium beta-C alloy 3Al-8V-6Cr-4Zr-4Mo is nonexistent.

Many characteristics of this titanium material make it very difficult and expensive to machine. Usually, considerable stock must be removed from primary forms such as long, hollow cylindrical forgings. Titanium is also chemically reactive, and therefore, has a tendency to weld to cutting tools during machining. Tools experience cratering, chipping, notching, and premature failure, and they produce poor surface finishes. Because of titanium's low heat conductivity and abrasive nature, the temperature at the tool/work piece interface increases, adversely affecting tool life, and consequently, dimensional accuracy. The introduction of a titanium alloy to a facility that is experienced in steel processing presents manufacturing problems. The problems include the determination of proper tooling and methods of manufacture. Furthermore, in order to establish manufacturing costs and production parameters, a processing database would have to be established.

PROBLEM APPROACH

In order to develop the necessary machinability database for the manufacture of titanium beta-C alloy components, it was decided to perform actual testing on components made of this 3Al-8V-4Zr-4Mo titanium alloy and configured to resemble components that would be processed in production.

This project was divided into three phases. The first phase was an in-house effort to establish an immediate machining knowledge on the titanium beta-C alloy. This was necessary to provide preliminary machining information to support the manufacture of prototype titanium components for weapon development efforts. The initial testing consisted of face milling, turning, and some boring using high speed steel (HSS) and carbide tooling.

The second phase was a major machinability study (contract) by an independent engineering laboratory. The scope of work required the contractor to perform turning, deep-hole boring, and finishing operations on titanium beta-C alloy tubes (cylinders). The contractor was required to screen cutting tool material, establish machining parameters, determine tool life, develop processing methods, and actually manufacture components based on their results. All the work was compiled into a contractor report (ref 1).

The third phase was an in-house machinability and processing effort that consisted of deep-hole boring and bore finishing of nearly full-length titanium beta-C alloy cylinders. This effort employed commercial deep-hole boring and bore finishing tools to evaluate various carbide grades and insert geometries and also to develop processing data. This phase paralleled the independent laboratory testing contract (second phase) and allowed comparisons to be made between the two.

RESULTS

Phase I: Initial Tool Material Evaluation

Initially, tests were performed to ascertain the level of difficulty to machine the titanium beta-C alloy. Early test results showed that conventional steel cutting carbide grades (C-6 through C-8) did not provide two minutes of tool life. These grades chipped, notched, cratered, and wore severely during use. Most of the tool failure can be attributed to their titanium carbide content. The titanium alloy exhibited a chemical affinity to the high grades and had a tendency to immediately develop a built-up-edge (BUE) or chip welding during machining. Typically, the BUE condition may be minimized by increasing the cutting speed; however, because of titanium's low heat conductivity and abrasive characteristics, increasing the cutting speed simply accelerated tool failure.

Pure tungsten carbide cutting tools, typically C-2 grades, were tested, and they performed the best. Chemically, the pure tungsten carbide grades are not similar to the titanium carbide grades; however, not all C-2 grade equivalents performed equally, and significant performance differences were experienced. These included variability among the C-2 category grades made by the same manufacturer and differences between manufacturers.

Phase I: Lathe Turning Evaluation

This effort impacted on the manufacturing operations that supported the first prototype end item (long cylindrical, hollow sleeve) to be produced. Lathe turning and boring were the two major operations of concern. The objective was to identify cutting tools and a set of parameters that would produce the best machining conditions, tool life, chip control, and work piece accuracy. Although cutting tools that enhanced the machining of the titanium beta-C alloy were identified, they performed somewhat marginally with respect to tool life and machining time.

Additional information on the foregoing tests can be found in Reference 2.

Phase II: Machinability Contract

A contract was awarded to Metcut Research Associates, Inc., Cincinnati, OH, to conduct an extensive machinability and processing evaluation in deep-hole boring, bore finishing, and outside diameter

(OD) turning of hollow titanium 3Al-8V-6Cr-4Zr-4Mo cylinders. Since numerous parameters must be investigated, it was determined that testing this alloy in a controlled environment would be beneficial to the overall effort. This contract was devised to develop a database that would represent and encompass the state-of-the-art in commercial cutting tool materials, tooling applications, and optimum processing parameters. The results would be used in conjunction with the in-house effort as a process planning database for the manufacture of 9-foot long titanium alloy cylinders in a production operation. The results of this machinability contract can be found in Reference 1. This report summarizes the contractor's work consisting of controlled laboratory screening tests to determine the best cutting tool material, most effective cutting fluid, and tool geometry combinations. Then, based on these screening activities, the cutting speed, feed rate, and tool life relationships were explored and mathematically modeled to best describe the laboratory data and provide a statistical analysis on the "speed-feed-tool life relationship." In addition, the contractor structured the laboratory tests to produce conditions that would sustain tool life sufficient for machining 9-foot long titanium cylinders. As a result of the foregoing laboratory work, Reference 1 also addresses process development for manufacturing. The contractor was required to use the laboratory data and to develop a workable machining process applicable to the manufacturing environment. To do this, three cylinders, 3 feet long, were machined to specific requirements (see ref 1, Figure A) and were used as a vehicle to develop the processes and inadverently qualify the contractor's laboratory results.

Phase III: In-House Effort

In the third phase of this project, in-house machinability tests were performed, some of which overlapped the independent machinability effort briefly discussed in Phase II. Early in this project, it was concluded that two separate but related efforts would be beneficial. The contract with Metcut Research Associates, Inc., was to focus more on scientific analysis to develop a comprehensive database that would represent and encompass the state-of-the-art in cutting tool material, tooling applications, and optimum process parameters. The in-house effort, while concentrating on machining and processing methods, was to provide a vehicle in which in-house, first-hand experience was being developed along with establishing real-time data on components close to the potential production part.

In-house testing included conventional deep-hole rough and finish-boring, skiving, roller burnishing, and honing on 6-foot long titanium beta-C (Ti-3Al-8V-6Cr-4Zr-4Mo) cylinders. Although the end item was closer to 9 feet long, 6-foot long test parts were used to maximize the use of available material.

Figure 1 shows one of the 6-foot test cylinders with machined indicating and roller rest diameters (normally called spots) needed to set up and support the tube in the machine. One end of the tube was also counterbored with three different diameters concentric with the spots (Figure 2). These three counterbored diameters served as a pilot to guide each of the boring heads into the tube's inside diameter (ID) during the onset of the boring operation. However, normally in production, a separate pilot bushing is fixtured in front of the work piece, thus eliminating the need for a pilot counterbore diameter.

Standard commercial tools were used for the boring, skiving, and roller burnishing tests. Three boring heads were tested: a 5.000-inch diameter, a 5.200-inch diameter, and a 5.312-inch diameter. These boring heads were designed to accept interchangeable International Standards Organization (ISO) standard tool holders (Figure 3), so that various cutting tool insert geometries and lead angles could be tested. The tool holders were adjustable so that any diameter could be set to approximately 0.030 inch over or under the basic size of each head. These heads were also designed with a single tool holder using two carbide guide pads (Figure 4) as stabilizers.

One size (5.312-inch diameter) of both a skiving and roller burnishing head were used in the testing to produce the final finished bore diameter (Figures 31 and 35). Both of these heads were adjustable to approximately 0.030 inch diametrically, plus or minus the nominal dimension of 5.312 inches, to allow accurate bore sizing.

The machine available for this testing effort was a 1945 Le Blonde hollow spindle boring machine, with a 4-inch diameter and a 30-foot long boring bar (Figure 5). This machine is customarily used to manufacture prototype components. Since the time involved to complete such a testing program is substantial, the use of newer, modern production machinery was not possible because of mandatory production schedules.

The cutting fluid used for all boring operations was oil, per MIL-C-46149 (Grade 5), which has sulfur and chlorine additives. Oil was used to provide added lubricity to the boring head guide pads. By doing this, the benefit of better heat dissipation that water soluble coolants provide was sacrificed. Water soluble coolants were evaluated by Metcut (ref 1).

The material used for the testing was a titanium beta-C alloy with a chemical composition of Ti-3Al-8V-6Cr-4Zr-4Mo, solution treated and aged to a 160 Ksi yield strength and a Rockwell hardness of approximately Rc 45. The cylindrical tube forgings with the following dimensions were the rough configurations of the components:

Length	72 inches
OD	7 inches
ID	4.750 inches

The rough tube forgings had a substantial wall thickness variation caused by the forming operation. This meant the ID was not concentric with the OD by as much as 0.250 inch. Running spots were machined on the OD to be used for set up and indicating surfaces, as shown in Figure 1. The runout between the ID and OD was balanced so that stock was equally distributed while machining the running spots. Counterbores were machined concentric with the running spots (Figure 2) to allow the boring heads to enter the tube and stabilize via the guide pads prior to starting the boring cut. By machining the counterbores concentric with the running spots, the boring began with minimal runout. In many instances, the runout was 0.150 inch at various locations in the cylinder. During the testing, as the boring head moved through the tube, the runout would influence the heat to gradually follow the eccentric axis of the rough ID. As several boring passes were completed, the eccentricity gradually lessened.

Test Results

The actual testing was done in stages: first a 5.000-inch diameter bore, then a 5.200-inch diameter bore, and ultimately a 5.312-inch diameter bore were machined. A total of eight 6-foot long tubes were machined. All the cutting data were recorded and are listed in Tables 1 through 10 in the Appendix.

5.000-Inch Diameter Boring Tests

The first series of tests was conducted to evaluate the following:

1. Single-cutter boring head with two carbide guide pads.

2. SNMG--433 and 432 insert style.

3. 15-degree tool lead angle. Cartridge PTKNR-16CA-12.

4. Cutting tool inserts (company and grade):

Sandvik H-10A (C-2)
Sandvik 3015 (C-2)
Kennametal K-68 (C-2)
Kennametal K-313 (micrograin)
Sandvik H-20 (C-2)
Kennametal K-6 (C-2)
Valinite V1N (TiN coated)
Sandvik H-13A (C-2)

The tests were conducted under the following machining conditions:

Spindle speed	82 rpm
Cutting speed	107 sfm
Feed	0.005 ipr
Depth of cut	0.125 inch
Cutting fluid	Oil (MIL-C-46149 Grade 5)

Figures 6 and 7 show comparisons of the three tool inserts that performed best during this initial series of test cuts. Figure 6 shows the distance each tool traveled in the cut prior to failure. The Sandvik H-10A insert provided the best life under these conditions, with ten inches of bore length machined. Kennametal K-6 insert came in a close second with seven inches of bore machined, followed by Kennametal K-68 with six inches of bore machined. Similarly, Figure 7 charts the same inserts with respect to tool life (time), showing the H-10A grade lasted 24.4 minutes. In all cases, the tool life was a measure of how long the inserts cut until the tool failed, and in each case, the inserts broke catastrophically.

Based on these results, the 15-degree lead angle was suspected of causing the tools to break because heavy chatter was present during all machining from the beginning. To further evaluate the 15-degree lead angle, an attempt was made to stabilize the cut by reducing the feed to 0.0037 ipr, in effect reducing the chip load on the cutting edge. The severe chatter remained, and there was no measurable tool life change. Figures 8 and 9 show the results of this exercise. Actually, because of the catastrophic tool breakage, the foregoing machining parameters proved to be unacceptable to machine a 5.000-inch bore in the titanium cylinder, and the tool life of each insert grade tested is questionable, i.e., the tool life depicted in Figures 7 and 9 may not represent what each insert can actually do.

<u>45-Degree Lead Angle Change</u>

Since the 15-degree lead angle was unacceptable, the cutting tool lead angle was changed to 45 degrees by changing the tool holder to a PTSNR-16CA-12, which takes a triangular-shaped TNMG-style insert (Figure 10). All other machining conditions remained unchanged. Sandvik H-13A and 3015 triangular inserts were used in this testing. Again, vibration persisted during boring, causing the inserts to eventually break. Also, damage to the carbide guide pads became evident (Figure 11). However, cutting length and tool life were slightly improved, as shown in Figures 12 and 13. Figure 12 shows the H-13A insert bored 38 inches of tube, while the 3015 insert bored 21 inches of tube. However, consistency in tool performance could not be obtained, e.g., another H-13A insert also failed after 10.5 inches of boring depth. The tool breakage seemed to be caused by the heavy vibration, and the galling appeared to be created by the chips interfering with the carbide guide pads. Figure 13 compares the tool life of these inserts, showing that the H-13A insert had a tool life of 89 minutes while cutting 38 inches of bore, and in contrast, 24 minutes when boring the second time, thus demonstrating inconsistency. The 3015 insert lasted 49 minutes, boring 21 inches of the tube.

At this point, it was felt that the vibration was caused by the unbalanced cutting force of the single tool and by the chips lodged between the guide pads and the bore.

5.000-Inch Diameter Boring Tests Using the Boring Head Modified to Two Opposing Tool Holders and Two Guide Pads

The 5.000-inch diameter boring head was modified to accommodate two opposing tool holders to balance the cutting forces. An additional pocket was also added to relocate one of the guide pads, so that the two tools opposed each other, and the guide pads also opposed each other. Figure 14 shows a front view comparison of a single tool boring head and one with two opposing tools. Figure 15 shows a side view of the same two boring heads.

Boring resumed using the modified 5.000-inch diameter head with two Sandvik H-13A inserts. The spindle speed was set at 82 rpm, but the feed was increased to 0.0097 inch per revolution, which approximated the 0.005-inch feed per revolution used for the single-cutter design. The results were approximately the same as that experienced with the single tool boring head. Extreme vibration was still present. It was suspected that the carbide guide pads did not allow a smooth bearing action on the titanium alloy. Also, the speeds, feeds, chip interference, and the position of the guide pads may be contributing factors. Therefore, a decision was made to remove the carbide guide pads and bore without them. Beginning with a 5.010-inch diameter setting on the boring head, a total of 61 inches was bored without vibration. However, the bore diameter at the exit end of the tube measured 4.950 inches, which resulted from 0.060 inch of diametric wear on the inserts. At this point, it became apparent that the tool wear producing bore diameter reduction was causing the guide pads to operate in a severe interference condition. This situation was the contributing factor in the vibration problem and the subsequent damage to the guide pads (Figure 11).

In order to prevent the chips from flowing back to the boring head and interfering with the guide pads, a teflon ring was installed on the 5.000-inch diameter boring head (Figure 16). The guide pad seats were also modified to position the pads farther back on the head in an attempt to correct the chip interference problem. Again, Figures 14 and 15 show comparisons of the two boring heads, one with a single tool holder and two guide pads and the other with two tool holders, two guide pads, and a teflon ring for blocking the chips.

This modification was tested at the same 82-rpm spindle speed. The guide pads were again galled, and heavy vibration also occurred during boring. Therefore, the guide pads were removed, new inserts were installed (H-13A), and the remainder of the tube was bored using the same machining parameters. A total of 51 inches was bored without vibration resulting in a tool insert life of 19 minutes. However, the inserts wore 0.030 inch diametrically causing the teflon ring to also wear 0.030 inch diametrically. This confirmed that the carbide guide pads were causing the vibration by trying to move through an undersized bore. As the bore became smaller, the guide pads were building up heat from friction and approaching seizure, causing the boring operation to become progressively worse as the head advanced through the tube.

An analysis of the 5.000-inch boring tests yielded the following conclusions:

1. The 45-degree lead angle outperformed the 15-degree angle by a margin of 3 to 1 in boring length, as shown in Figures 6 and 12, and in tool life by comparing Figures 7 and 13.

2. The vibration experienced in this early testing seemed to be attributed to the carbide guide pads operating in an undersized bore. This was proven by removing the pads and boring without them. This was only possible when the boring head was modified to a two-cutter head, whereas the cutting tools balanced each other's radial cutting forces. Guide pads are needed with the single tool boring head.

Therefore, further testing on the larger heads will include boring using guide pads manufactured from other materials such as brass and hardened steel.

3. The feeds and spindle speeds used in the 5.000-inch boring tests were not considered optimum because of tool wear and repeated tool breakage. During testing of the larger boring heads, an attempt will be made to establish an optimum cutting speed which will allow successful boring of a complete 6-foot titanium tube without tool failure (breakage) or excessive wear causing the ID to be tapered.

5.200-Inch Diameter Boring Tests Using the Boring Head Modified to Two Opposing Tool Holders and Two Guide Pads

The 5.200-inch diameter boring head was modified to accommodate two opposing tool holders and two guide pads. A teflon ring was also added to the boring head to prevent the chips from flowing back and interfering with the guide pads, as previously shown in Figure 14. Figure 5 shows a side view of the modified 5.200-inch diameter boring head mounted in the boring bar of the machine.

In order to further investigate the effect of the guide pads, a decision was made to manufacture pads from different materials to see how they affected the performance of the boring heads. Pads were manufactured from hardened (Rc 50) tool steel and brass. The tests were conducted to evaluate the following:

1. Two-cutter boring heads.
2. SNMG-433 insert style.
3. Guide pads made of hardened steel and brass.
4. A teflon ring mounted on the head to prevent chips from flowing back.
5. 45-degree tool lead angle--tool holder PSSNR-16CA-12.

The tests were conducted under the following machining conditions:

Spindle speed	82 rpm
Cutting speed	112 sfm
Feed	varied
Depth of cut	0.100 inch

The cutting tools (inserts) tested (company and grade) were Sandvik H-13A (C-2) and Kennametal K-313 (micrograin). The carbide guide pads were replaced with brass for the initial boring passes to test the effects of the softer material as a stabilizer. The feed rate was also varied from 0.021 to 0.040 inch per revolution.

During this test, the best results were obtained using Sandvik H-13A inserts at the 0.021-inch feed rate, where 35 inches of bore was machined before the inserts failed, resulting in a tool life of 20 minutes. Increasing the feed rate had a negative effect on tool performance. For comparison purposes, using Sandvik H-13A inserts and a feed rate of 0.030 inch per revolution, 20.5 inches of bore was machined with a tool life of 8 minutes. Again using the Sandvik H-13A inserts, a feed rate of 0.40 inch per revolution produced 9 inches of machined bore, or a tool life of 2.7 minutes. When the H-13A inserts were replaced with two Kennametal K-313 inserts and all other parameters were the same, the results were identical. The results of this testing are illustrated in Figures 16 and 18, showing the length of cut and tool life, respectively.

The vibration and chatter, which were evident while boring with the carbide guide pads, did not occur when using the brass guide pad material, but the pads wore approximately 0.012 inch diametrically (Figure 19). However, the bore diameter size was within 0.001 inch indicating that the runout of the tube's ID was responsible for this wear. This suggests that the brass material is too soft to use as guide pads for boring this titanium alloy.

The brass pads were then replaced with AISI 4340 alloy steel pads hardened to Rc 50. Testing was conducted under the following conditions:

Spindle speed	60 rpm
Cutting speed	80 sfm
Feed	0.015 ipr
Depth of cut	0.100 inch

This phase of testing was not successful since heavy vibration and chatter began after seven inches of the bore was machined. The steel pads were severely galled and showed titanium deposits on their surface, as shown in Figure 20. This result was comparable to the previous boring trials using the carbide guide pads, but without an undersized bore. It is apparent that steel is not compatible with titanium, and therefore is not a good bearing material.

New brass pads were reassembled on the boring head and shimmed to make contact with the bore. Testing was conducted to evaluate the following:

1. Modified two-cutter boring head.

2. SNMG - 432 insert style.

3. Guide pads - brass.

4. Tool holder PSSNR-16CA-12, with a 45-degree lead angle.

The following machining parameters were used:

Spindle speed	40 rpm
Cutting speed	54 sfm
Feed	0.016 and 0.020 ipr
Depth of cut	0.100 inch

The cutting tools tested were Excello (Carbi-Tech) - XL-202 (TiN-coated) and Excello (Carbi-Tech) - E-6.

The Excello XL-202 insert successfully machined 54 inches of bore using the above machining parameters. This yielded a tool life of 84.37 minutes, as illustrated in Figures 21 and 22. A diametric measurement taken of the inserts after the boring pass revealed no reduction from the preset size of 5.207 inches. The bore finish was visibly good, and the ID measured within 0.001 inch for the complete 54 inches. A measurement taken of the brass guide pads revealed a diameter reduction of 0.022 inch. This was attributed to the runout of the bore, i.e., the rubbing of the harder titanium material on the brass pads caused the wear. However, as expected, some of the runout was removed without this boring pass.

Because of the improved success of boring at a reduced cutting speed, another attempt was made with the hardened steel guide pads to reassure that the faster cutting speed was not the determining factor for the failure. The same tooling and machining parameters were used as in the foregoing boring pass. This attempt was not successful, since vibration and chatter occurred immediately upon contact of the steel guide pads. Therefore, the steel guide pads were removed and the remaining 35 inches of tube was bored successfully without incident resulting in a tool life of 43.8 minutes (Figures 21 and 22). A measurement over both inserts was taken before and after the boring pass and found to be the same. The bore was also measured and found to be within 0.001 inch in the 35 inches bored.

As the test results improved, an attempt was made to bore a tube with an increased chip load by increasing the depth of cut to 0.450 inch, i.e., bore with a 5.200-inch diameter head without first boring with the 5.000-inch diameter boring head. The test was conducted to evaluate the following:

1. Two-cutter boring head.

2. SNMG-432 insert style.

3. 45-degree tool lead angle - PSSNR-16CA-12 tool holder.

4. Insert Excello - E-6 (C-2).

The test was conducted under the following machining conditions:

Spindle speed	40 rpm
Cutting speed	55 sfm
Feed	0.016 ipr
Depth of cut	0.225 inch

No guide pads were used because the two tools seemed to balance the cutting forces. Boring was successful for 60 inches, yielding a tool life of 93.75 minutes (Figures 21 and 22) with good chip control (chips breaking). Figure 23 shows chips produced during this boring test. At 60 inches, one insert failed, and when the head was retracted, the teflon ring was severely damaged and worn. The inserts were replaced, and with the worn teflon ring still in place, boring was again attempted without success. This indicated that the teflon ring acted as a guide bushing, much like the guide pads, and after it wore down, its guiding/stabilizing effect was eliminated. An analysis of the 5.200-inch boring tests yielded the following conclusions:

1. Soft guide pads could only be used on the two-cutter modified head, because the tool pressure from the single-cutter head wore down the pads, eliminating their stabilizing effect and causing a tapered bore.

2. The brass guide pads eliminated chatter and vibration because as a bearing surface, brass is more compatible with the titanium alloy, but wore substantially from abrasion caused by the ID runout.

3. The two-cutter modified head can bore without guide pads because the teflon ring helps to stabilize the boring head.

4. Boring length and tool life decreased as the feed was increased using the same cutting speed and depth of cut (Figures 17 and 18).

5. Boring results improved as the cutting speed was reduced.

6. The boring head tends to follow the runout of the bore, and consequently, causes significant wear to the guide pads.

7. Hardened steel is not a good guide pad material because it is not compatible with titanium.

5.312-Inch Diameter Boring Tests

Because results improved by reducing the cutting speed, testing of the 5.312-inch boring head was conducted using the original single tool design with two carbide guide pads. The first series of tests was conducted to evaluate the following:

1. Single-cutter boring head--two carbide wear pads.

2. SNMG-432 insert style.

3. 45-degree tool lead angle--PSSNR-16CA-12 tool holder.

The tests were conducted under the following machining conditions:

Spindle speed	40 rpm
Cutting speed	54 sfm
Feed	0.008 and 0.015 sfm
Depth of cut	0.056 inch

The cutting tools tested were Sandvik H-13A (C-2), Kennametal K-313 (micrograin), and Excello (Carbi-Tech) E-6 (C-2).

Fifty-three inches of the tube was bored using a Sandvik H-13A square insert. The insert was indexed at 26 inches, not because of visible wear, but because the head began to vibrate. The feed was varied from 0.006 to 0.012 inch in an attempt to stop the vibration, but was unsuccessful. A Kennametal K-313 insert was then tested. This is a micrograin grade with a larger chip breaker. However, vibration continued, and the test was terminated. The K-313 insert was then replaced with an Excello (Carbi-Tech) E-6, which is a C-2 grade. The remaining 16 inches of tube was bored producing good chips virtually without incident. Figures 24 and 25 compare the three inserts with respect to cutting length and tool life, respectively.

A tube was then prepared with a 5.312-inch counterbore to accommodate the largest boring head without first boring with the smaller 5.000-inch and 5.200-inch diameter heads. This was done to increase the chip load to 0.285 inch, via depth of cut, but using the same spindle speed and cutting feed. This series of tests was conducted to evaluate the following:

1. Single-cutter boring head.

2. TNMG - 332 and 333 insert style.

3. 45-degree tool lead angle - PTSNR-16CA-12 tool holder.

The cutting tools material tested were Kennametal K-313 (micrograin), Excello (Carbi-Tech E-6 (C-2)), and Carbaloy E-48 (C-2).

The test was conducted under the following conditions:

Spindle speed	40 rpm
Cutting speed	55 sfm
Feed	0.010 ipr
Depth of cut	0.285 inch

The best results were obtained from the Excello E-6 insert, where 52 inches of tube was bored with a tool life of 130 minutes followed by the Carbaloy E-48 insert, where 48 inches of tube was bored with a tool life of 120 minutes. Figure 26 charts each tool with respect to cutting length, and Figure 27 compares their respective tool life in minutes. Figure 28 shows chips produced during this phase of testing while boring with the Excello E-6 carbide insert. The curled chips are those produced at the beginning of the cut. As the tool wore, the material began to fragment into smaller chips. An analysis of the 5.312-inch boring tests resulted in the following conclusions:

1. The single-cutter and two carbide wear pad designed boring head is effective once an optimum cutting speed is established.

2. The optimum cutting speed is 55 sfm.

3. The optimum feed rate is from 0.008 to 0.010 ipr.

4. Carbide as a material for guide pads will last approximately 130 minutes (it is not the best, but it is better than brass and teflon because of its hardness).

5. Runout accelerates guide pad deterioration.

6. The heavier depth of cut does not seem to affect the performance of the boring head at these speeds and feeds.

Boring Tests Using High Speed Steel Tooling

One of the titanium cylinders was prepared with a 5.318-inch counterbore to test the performance of HSS tooling in boring the titanium alloy. A wood packed reamer body, Figure 29, was used during this testing phase. The wood is turned to a diameter slightly larger than the pilot counterbore (or cutter diameter) so that it interferes with the ID as it advances through the tube during boring. This provides stability to the boring head. The tooling used for this test was Braecut M44 HSS and ground with a 45-degree lead angle.

The initial test was run under the following conditions:

Spindle speed	17 rpm
Cutting speed	23 sfm
Feed	0.010 and 0.020 ipr
Depth of cut	0.285 inch

Three attempts were made to bore this material. At best, four inches of bore length was machined producing a tool life of less than 20 minutes. Vibration and chatter began to occur almost immediately once the tools made contact with the bore. Upon retracting the boring head, the tools were badly worn, as shown in Figure 30, requiring complete reconditioning. The spindle speed of 17 rpm or a cutting speed of 23 sfm was the slowest the machine would run, therefore, adjustments could not be made to reduce the cutting speed. The next two boring attempts were made with similar poor results when adjustments were made in the *feed rate only.* This was done by first doubling the feed to 0.020 ipr and then reducing the feed to 0.007 ipr. An analysis of the boring tests using high speed tooling resulted in the following conclusions:

1. The cutting speed of 23 sfm was too high resulting in rapid tool failure.

2. In order to bore this material using HSS tooling, the cutting speed must be reduced to less than 10 sfm, and the feed rate must be less than 0.005 inch per revolution. This would make it costly and impractical to machine with HSS.

Operation: Bore finishing tests were conducted on two tubes to establish a uniform bore size and finish throughout the full length of the tube and make the bore void of tool marks. The tubes would later be used for roller burnishing and honing tests. Tests were conducted using the following equipment:

1. Single-cutter boring head with two carbide guide pads.

2. TNMG-333 insert style.

3. 45-degree tool lead angle - PTSNR-16CA-12 tool holder.

The cutting tool used for bore finishing tests was Excello (Carbi-Tech) E-6 (C-2).

Tests were conducted using the following conditions:

Spindle speed	40 rpm
Cutting speed	55 sfm
Feed	0.010 ipr
Depth of cut	0.005 inch

Bore finishing was done in one complete pass, and in both instances, the machined bores were tapered approximately 0.002 inch smaller at the exit end of the tube and had a surface finish averaging 70 rms.

Skiving

Skiving is a process of bore finishing by incorporating cutting tools designed with a very slight lead angle of 9 degrees from the axial plane of the bore (81 degrees from the perpendicular). This tool geometry produces better finishes than conventional boring and is commonly used for rapid finish machining alloy and low carbon steel cylinders, e.g., hydraulic cylinders. The cutting action can be described as shaving the material compared to conventional boring using steeper lead angles. The skiving head used for this testing phase was designed with two diametrically opposed cutting tools mounted on individual cartridges which, as an assembly, produced a floating "knife." The "knife" is collapsed at the end of the skiving process so that the head can be retracted without marking the machined surface. The body of the head is equipped with four guide pads made of a proprietary material closely resembling delrin or nylon. The pads are equally spaced around the periphery of the body and serve as stabilizers during the skiving process. The inserts are preset to the desired cutting diameter and the "knife" is allowed to float. This floating action allows the tools to center to the bore diameter and equalize the depth of cut. Figures 31, 32, and 33 show the skiving head used for this testing.

The basic diameter of the skiving head is 5.312 inches, but it is adjustable to approximately 0.030 inch above and below the basic diameter. This allows fine adjustments to be made to control bore sizing. The skiving tests were performed on tubes bored with the 5.312-inch boring head. Since the skiving process is common for low carbon and alloy steels, the only inserts available for the skiving operation were S-2 type (Sandvik), P-20 (C-6 grade equivalent) carbides that are specifically designated for steels. The skiving tests were conducted under the following conditions:

Spindle speed	40 rpm
Cutting speed	54 and 30 sfm
Feed	0.020 and 0.040 ipr
Depth of cut	0.007 inch

The skiving tests showed that the tool inserts were only adequate for short distances between 12 to 20 inches, or a tool life not exceeding 15 minutes. When adjustments were made by increasing the feed to 0.040 ipr and lowering the cutting speed to 30 sfm, no measurable improvement was observed. The inserts' cutting edge wore to a point where a 0.003-inch taper was produced in the cylinder. The finish in the tubes prior to skiving averaged 150 rms. The skiving operation improved the bore finish to an average of 85 rms. In contrast, the bore finishing operation produced finishes of 70 rms and held the diametric size to within 0.002 inch throughout the full 72 inches of cylinder length.

Figure 34 shows chips produced during the skiving operation on the titanium beta-C cylinders. Some of the chips were curled with smooth edges indicating they were produced by a sharp insert. As the inserts wore, the chips became ragged along the edges and eventually broke away in smaller pieces without curling. A visual inspection of the bore after skiving revealed changes in the surface finish appearance as the head advanced through the cylinder. This corresponded to the profilometer inspection of the bore showing that the finish became rougher as the instrument advanced downbore.

An analysis of the skiving operation concluded the following:

1. The tooling (inserts) available for the process failed rapidly disallowing a favorable evaluation.

2. Test results indicate that skiving may be a potential finishing operation if proper C-2 carbide grades are used.

Roller Burnishing

A roller burnishing head, shown in Figure 35, was tested on two of the titanium tubes. The first tube was previously bore-finished and inspected with a portable profilometer. The average surface finish recorded was 70 rms. The roller burnishing head was pulled through the tube at a feed rate of two inches per minute with a spindle speed of 20 rpm. Profilometer readings taken after roller burnishing showed no improvement to the bore finish. The second tube had been skived first and had an average finish of 85 rms. The roller burnishing head was pulled through the tube at a feed rate of three inches per minute with a spindle speed of 44 rpm. Profilometer readings again indicated no measurable improvement in the finish of the bore. An analysis of the roller burnishing testing resulted in the following conclusions:

1. The titanium material appears to be too tough to be deformed by roller burnishing.

2. Roller burnishing is not a practical process to improve the bore finish on this titanium beta-C material.

Honing

The honing tests were conducted on the same tubes that were roller-burnished because they were relatively uniform in size. Prior to honing, the surface finish of each tube was measured with a portable profilometer at 12-inch intervals throughout the full length of the bore and recorded. The ID was also measured with a dial bore gage at 12-inch intervals throughout the full length of the tube and recorded. Both tube profiles are shown in Figures 37 and 39.

Tube #1 was honed using stones designated as A-240-V6S, which is a 240-grit aluminum oxide sulfurized stone (Figure 36). The honing head held twelve stones (1/2 inch by 1/2 inch by 6 inches). The bar rotational speed was set at 105 rpm, and the traverse speed was set at 45 feet per minute. One set of stones was adequate enough to remove 0.005 to 0.006 inch of stock from the bore at a stock removal rate of 0.0003 inch per minute. The finish was improved from 70 to 12 rms (Figure 37).

Tube #2 was honed using stones designated as C320-L7-VX, which is a 320-grit silicone carbide sulfurized stone (Figure 38). The honing head was loaded with twelve stones (1/2 inch by 1/2 inch by 6 inches). The bar rotational speed was set at 105 rpm, and the traverse speed was set at 45 feet per minute. One set of stones was adequate to remove 0.003 to 0.005 inch of stock from the bore at a stock removal rate of 0.0005 inch per minute. The finish was improved from 80 to 18 rms (Figure 39).

An analysis of the honing tests resulted in the following:

1. A comparison of stock removal rates between the silicone carbide and aluminum oxide honing stones shows the silicone carbide has a slightly higher metal removal rate, i.e., 0.0003 inch per minute for the aluminum oxide compared to 0.0005 inch per minute for the silicone carbide. Courser stones are needed to increase the metal removal rates.

2. The finish was improved favorably in both tubes and proved that a fine finish is attainable in this material. The degree of finish obtained is relative to the grit of the honing stones, therefore, to obtain an even better finish, finer grit stones would have to be used.

PROCESS PLAN FOR BORE FINISHING FULL LENGTH TITANIUM BETA-C COMPONENTS

Based on the machinability test results, a process plan was developed to establish manufacturing costs to produce full length (9-foot long) titanium beta-C components.

The following process plan covers bore finishing of 9-foot long cylinders to a 5.310 ± 0.001-inch ID with a 16-rms surface finish.

Rough material configuration:

Length - 9 feet (108 inches)
OD - 7 inches
ID - 4.750 inches

First Operation

Load the cylinder in the hollow spindle lathe and indicate the bore at both ends to 0.010 inch total indicator reading (TIR). Turn three 6 ± 0.062-inch long spots on the OD of the cylinder, one at each end and one at the center to 6.800 ± 0.005-inch diameter. Use C-2 grade carbide with 45-degree lead and 5-degree negative rake angles.

Machining Parameters	Operation Time
Spindle speed - 30 rpm Cutting speed - 55 sfm Feed - 0.010 ipr	1 hour 30 minutes

Second Operation

Set up the cylinder in the hollow spindle boring machine with the roller rest located at the center spot. Indicate the turned spots at both ends of the tube to within 0.001 inch TIR. Adjust the rollers to support the cylinder at the center spot maintaining 0.001 inch TIR. Using a guide bushing to start a two-cutter boring head, cylinder to 5.200 ± 0.005-inch diameter.

Tooling

1. Two-cutter boring head with fiber (micarta) guide pads.

2. 45-degree tool lead and 5-degree negative rake angles.

3. C-2 grade carbide inserts.

Machining Parameters	Operation Time
Spindle speed - 42 rpm Cutting speed - 55 sfm Feed - 0.016 ipr Cutting fluid - emulsifiable chlorinated soluble oil	2 hours 40 minutes

Change to a 5.300-inch diameter, two-cutter boring head with fiber (micarta) guide pads. Using the same cutting tool inserts and tool holders and a guide bushing to start the boring head, finish bore to 5.300 ± 0.002-inch diameter.

Machining Parameters	Operation Time
Spindle speed - 40 rpm Feed - 0.016 ipr	2 hours 48 minutes

Third Operation

Load the cylinder and clamp in the yoke fixture on the honing machine. Load the honing head with a minimum of twelve silicone carbide stones designated as C320-L7-VX. Hone the cylinder to 5.305 ± 0.001-inch diameter with a 16-rms surface finish.

Machining Parameters	Operation Time
Bar speed - 105 rpm Traverse speed - 45 fpm	45 minutes

Composite of Operations:

First Operation:	turn spots -	1 hour 30 minutes
Second Operation:	rough bore -	2 hours 40 minutes
	finish bore -	2 hours 48 minutes
Third Operation:	hone -	45 minutes

Total Operation Time Per Cylinder: 7 hours 43 minutes

CONCLUSIONS AND RECOMMENDATIONS

Machinability tests conducted both in-house and by Metcut demonstrated that machining the titanium beta-C alloy is difficult, but not impossible. Comparatively, Metcut's and the in-house results show distinct similarities and discrepancies. Metcut's report stated that the 150-sfm cutting speed was most effective, however, our tests concluded that 55 sfm was optimum. Metcut also indicated that reducing the cutting speed reduced the tool life, and we demonstrated that reducing the cutting speed actually increased the tool life. In addition, Metcut stated that increasing the depth of cut decreased the tool life, and in-house results showed that a depth of cut over 0.100 inch had no significant impact on the tool life. These discrepancies are attributed to the depth of cut under which testing was performed. Metcut's work centered around an 0.050-inch depth of cut, which can be classified as a finish-machining parameter. Therefore, based on this, Metcut's work identifies a distinct pattern of change as machining parameters approach rough-machining conditions. Our work was concentrated around rough-machining conditions and identified a totally different trend as machining conditions became more severe. At the finish-machining stage, there is a tendency for tool life to drop when the cutting speed is reduced and similarly, when the depth of cut is increased. However, after a 0.100-inch depth of cut, the trend is reversed when the cutting speed is increased, and it is stable when the depth of cut is increased. Logically, looking at both situations, it is concluded that finish-machining and rough-machining must be approached separately. Therefore, 150 sfm is appropriate for finish-machining, and once the depth of cut reaches or exceeds the finish cut stage (0.100 inch), the cutting speed must be kept at 55 sfm.

Although the cutting speed and depth of cut at finish- and rough-machining conditions affected tool life differently, the effect of feed (ipr) in both cases was the same. Increasing feed decreases tool life, therefore, tool life drops off linearly. Both Metcut and in-house tests concluded that a feed range of 0.003 to 0.008 ipr would be optimal.

The boring tests performed by Metcut utilized a two-cutter boring head. Metcut states their boring head used "fiber (micarta type) guide pads instead of carbide" because, "titanium alloys have a strong tendency to weld or seize against tungsten carbide at normal machining temperatures" (ref 1, p. 31). This statement is partially incorrect because the American Heiler boring head did have four TiN-coated carbide bearing pads located in line with the two cutters. Micarta guide pads were also present, but were used to guide the body of the boring head in back of the cutters. Basically, their head simulated our modified two-cutter boring head, and the carbide affinity was similar to what was experienced in-house.

Metcut's report also fails to specifically comment on the results of the boring operation. Therefore, it is difficult to show a relationship between the in-house boring test and theirs. However, having the opportunity to witness their test, recollection serves that the "124 fpm" (sfm) speed worked best, and the results were somewhat better than in-house tests. This was mainly because the Beohringer machine was more rigid and provided better control of the operation.

Our in-house test, after considerable speed adjustments, demonstrated that the single-cutter and two-cutter heads can be used adequately. In both cases, 55 sfm was the best cutting speed and the carbide guide pads lasted approximately 130 minutes. The exercise with alternate guide pad materials did not substantiate replacing carbide.

Another significant consideration is the difference in the equipment used in each of these separate efforts. The machine used for the in-house testing was a 1945 Le Blonde hollow spindle boring lathe with a 4-inch diameter and a 30-foot long boring bar. Metcut's boring tests were conducted on a visibly newer and more rigid 40 horsepower Beohringer Model V 800 Trepanning machine. This machine, with its shorter boring bar, higher pressure coolant system, and more rigid construction, contributed to significantly better boring results.

Metcut's testing of a 15-degree versus a 45-degree tool lead angle proved that the 45-degree lead produced greater tool life. This conclusion was verified by the in-house testing where the tool life increased from 38 minutes (15-degree tool) to 89 minutes by using the 45-degree tool with the same machining parameters. This was attributed to the thinning of the chip by distributing the material over a longer cutting edge, thus, in effect, reducing the chip load.

Metcut's comparison of negative versus positive tool rake angles showed that for a tool life level of 30 minutes, a negative tool had a 19 percent higher cutting speed than a positive tool. The ISO tool holders used for the in-house boring tests were designed to hold the inserts at a 5-degree negative tool rake. In-house boring tests did not include cutting with positive tool rake angles.

Metcut tested two cutting fluids against cutting this titanium beta-C alloy dry. The two cutting fluids were Trim-Sol (an emulsifiable heavy duty chlorinated soluble oil) and Mobilmet 235 (a semi-synthetic). Results showed that a one-third increase in tool life was possible by using Trim-Sol, as opposed to cutting dry (ref 1). The cutting fluid used by Metcut for the ID boring operation was Garia-T, which is a sulfo-chlorinated oil.

All of the boring and skiving tests performed in-house were conducted with cutting oil, per MIL-C-46149, Grade 5, which has similar sulfur/chlorine additives. In both cases, this cutting oil was used to add lubricity to the boring head guide pads while sacrificing better heat dissipation that the water soluble fluids provide. Emulsifiable heavy duty chlorinated soluble oils such as Trim-Sol are recommended for boring this titanium beta-C material when using two-cutter heads, because the two cutters balance the cutting pressure and alleviate the pressure on the guide pads. This fluid, because it is blended with water, provides better heat dissipation, and consequently, better tool life.

However, for boring, this titanium beta-C material with a single-cutter head, sulfo-chlorinated oil, such as the Garia-T oil used by Metcut or the oil per MIL-C-46149, Grade 5, used in-house is recommended. The single-cutter head requires guide pads harder than the material being bored so that the boring head will be stabilized and the bore size will be maintained. These guide pads are subject to a great deal of radial pressure, and thus, need fluid with added lubricity to reduce some of the friction generated by their interaction with the bore. The sulfur and chlorine additives help prevent the chips from welding to the tool while cutting.

The inserts that performed best in the boring tests on this titanium beta-C material are listed below in priority order:

1. Excello E-6 (C-2) - uncoated - supplied by Carbi-Tech
2. Excello XL-202 (C-2) - TiN-coated - supplied by Carbi-Tech
3. Carbaloy E-48 (C-2) - uncoated - supplied by General Electric
4. Sandvik H-13A (C-2) - uncoated - supplied by Sandvik
5. Sandvik 3015 (C-2) - aluminum oxide-coated - supplied by Sandvik

The coated carbide inserts performed somewhat comparable to the uncoated type. Their performance, however, is attributed more to their substrate material, which, in each of these cases, is a C-2 grade. For example, the two Excello inserts listed above are the same except for the TiN coating. The performance of the uncoated insert was somewhat equal, and therefore, it is concluded that the coatings do not enhance tool performance when cutting this titanium beta-C material. In comparison, the carbide inserts used during the in-house testing showed similar trends to those results presented in Metcut's report (ref 1).

Metcut's three best performers were aluminum oxide-coated, C-2 grades, and TiN-coated carbides, in order of priority. Both test results on tool performance were very close in most cases, whereas any of the identified best performers could surpass the others on any given cut. Therefore, the group of best performers used during the in-house testing are concluded to be similar to those tested by Metcut and are recommended for boring this titanium beta-C material.

Braecut brand M44 HSS was tested both in-house and by the contractor. The in-house testing consisted of boring with a two-cutter head at a 0.280-inch depth of cut. Using a cutting speed of 23 sfm and a feed rate of 0.010 ipr, a tool life of less than 20 minutes was attained. Figure 2 and Table II of Reference 1 show that during single-point turning tests, a tool life of 420 minutes was attained by using a cutting speed of 30 sfm, a feed rate of 0.003 ipr, and a depth of cut of 0.050 inch. The poor results of the in-house testing may be attributed to both the heavier depth of cut, which was five times as great, and the feed rate, which was three times as great as the Metcut tests. It is suspected that when cutting this material with HSS, any increase to the depth of cut, feed rate, and/or cutting speed has a very detrimental effect on tool life. This is substantiated by Metcut's report, where an increase in the feed rate from 0.003 to 0.005 ipr reduced the tool life from 420 minutes to 180 minutes. In addition, changing the cutting speed from 30 to 50 sfm and using the same feed rate of 0.003 ipr reduces the tool life from 420 minutes to 28 minutes.

It is concluded that if HSS tooling is used to machine this titanium beta-C material, in order to obtain a reasonable tool life, the recommended machining parameters are a cutting speed of less than 30 sfm, a feed rate of 0.003 ipr, and a depth of cut no greater than 0.050 inch.

Skiving tests were performed in-house only, therefore, no comparisons can be made with Metcut. The only carbide inserts available for this testing were those designated for use on steels equivalent to a C-6 grade. Although skiving did improve the surface finish, the tools were rapidly resulting in a taper of 0.003 inch. It is concluded that skiving could be used successfully to finish bores on titanium beta-C material if inserts made of C-2 carbide grades are used. However, further testing is needed.

Roller burnishing was only performed during in-house testing and did not improve the surface finish at all. The titanium beta-C material is too tough and resists deformation. This process is not recommended for finishing bores made of this material.

Honing tests were performed on this titanium beta-C material both in-house and by Metcut to demonstrate the feasibility of this process for improving the surface finish of the bores. The in-house honing tests were conducted with both 240-grit aluminum oxide and 320-grit silicone carbide honing stones. The aluminum oxide stones removed stock at a rate of 0.0003 inch per minute, improving the surface finish from 70 to 12 rms. The silicone carbide stones removed stock at a rate of 0.0005 inch per minute, improving the surface finish from 80 to 18 rms. Similarly, the honing tests performed by Metcut reported that 150-grit aluminum oxide and 220-grit cubic boron nitride stones were used. The stock removal rates of 0.0003 to 0.0005 inch per minute were essentially the same as our in-house tests, and the surface finish was improved from 164 to 10 rms.

Therefore, the in-house and Metcut honing tests were comparable, since the stock removal rates and surface finish improvements were similar. Any of the honing stones used in either of these efforts are recommended to hone titanium beta-C material. Both of these testing efforts proved that honing is a viable, although slow, means of improving the surface finish of the inside diameter of titanium beta-C cylinders. Courser stones have to be tested to improve the stock removal rates. To improve the finish even further, finer stones would have to be used, but it is expected that the stock removal rates would decrease as the finish improved.

Finally, the cubic boron nitride stones used by Metcut are more expensive then the standard aluminum oxide and silicone carbide stones, but they have a significantly slower wear rate; therefore, they would require less changing and may be more cost-effective.

In conclusion, most of the data compiled during both testing efforts is comparable. It would not be economically feasible to test every type and grade of tool under every criteria. Therefore, the testing followed a course of pursuing positive changes in the parameters in a direction that shows favorable results. For example, the tool inserts were failing catastrophically in relatively short distances during initial boring tests. Adjustments were made to the cutting speed and feed rate until tool performance improved. Finer adjustments were then made to improve tool performance further, so that optimal conditions could be achieved. Also, variations in depth of cut and double-cutter heads versus single-cutter heads were also tested to observe how these changes affected the process.

The test data recorded herein and in Reference 1 can be used as a process planning tool to machine titanium beta-C material. It should take the costly, time-consuming guesswork out of choosing appropriate tooling and machining parameters needed to machine a titanium component to a reasonable degree of accuracy with good surface integrity and a reasonable tool life.

REFERENCES

1. Metcut Research Associates, Inc., "Final Report on Turning and Boring Machinability Tests on Titanium Beta C Tubes," ARDEC Contractor Report ARCCB-CR-90012, Metcut Research Associates, Inc., Cincinnati, OH, April 1990.

2. Alex Wakulenko, "Manufacturing of Titanium Alloy Cannon Components," ARCCB-TR-88009, Benet Laboratories, Watervliet, NY, February 1988.

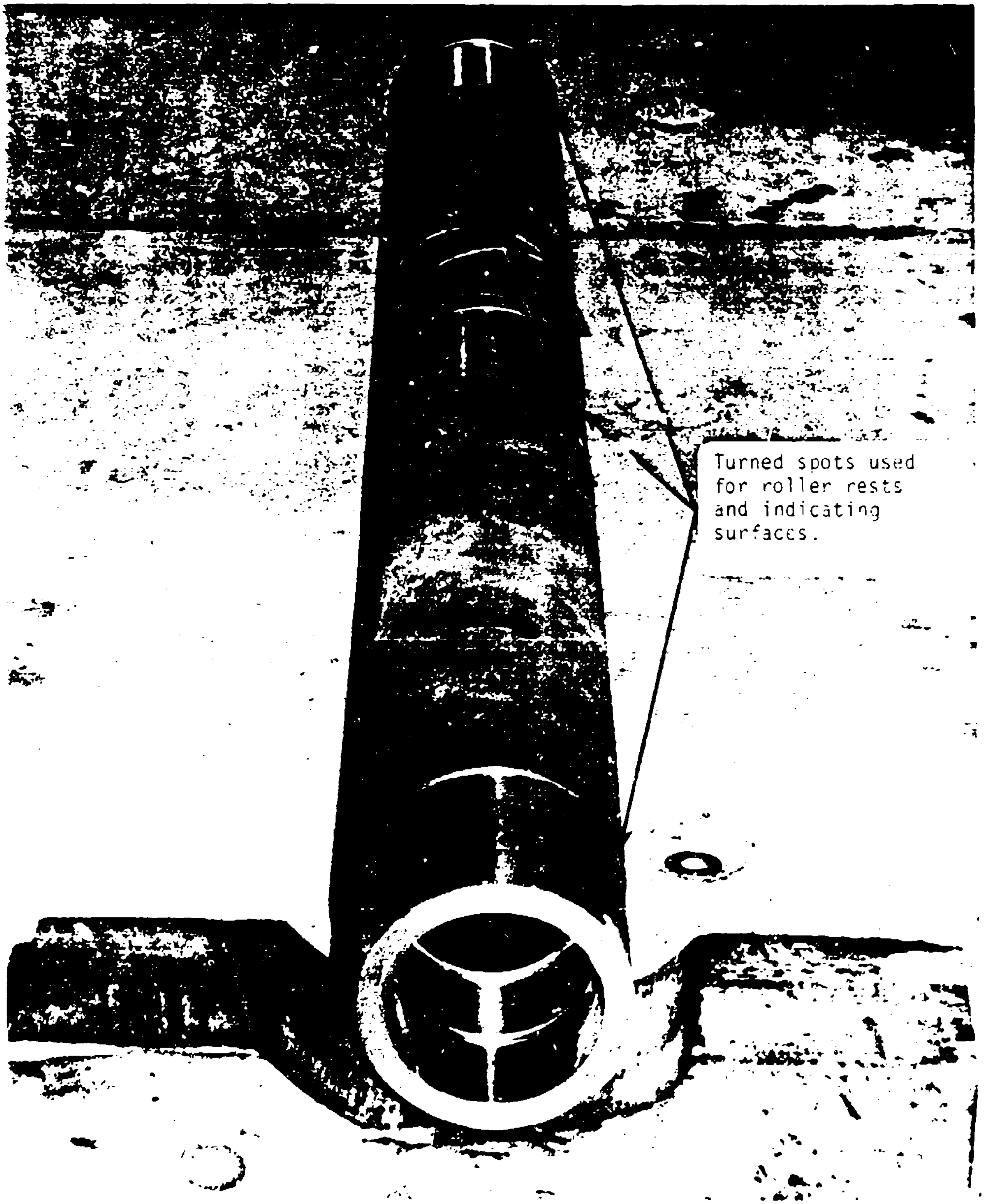


Figure 1. Titanium beta-C forged alloy cylinder pre-machined for test boring.

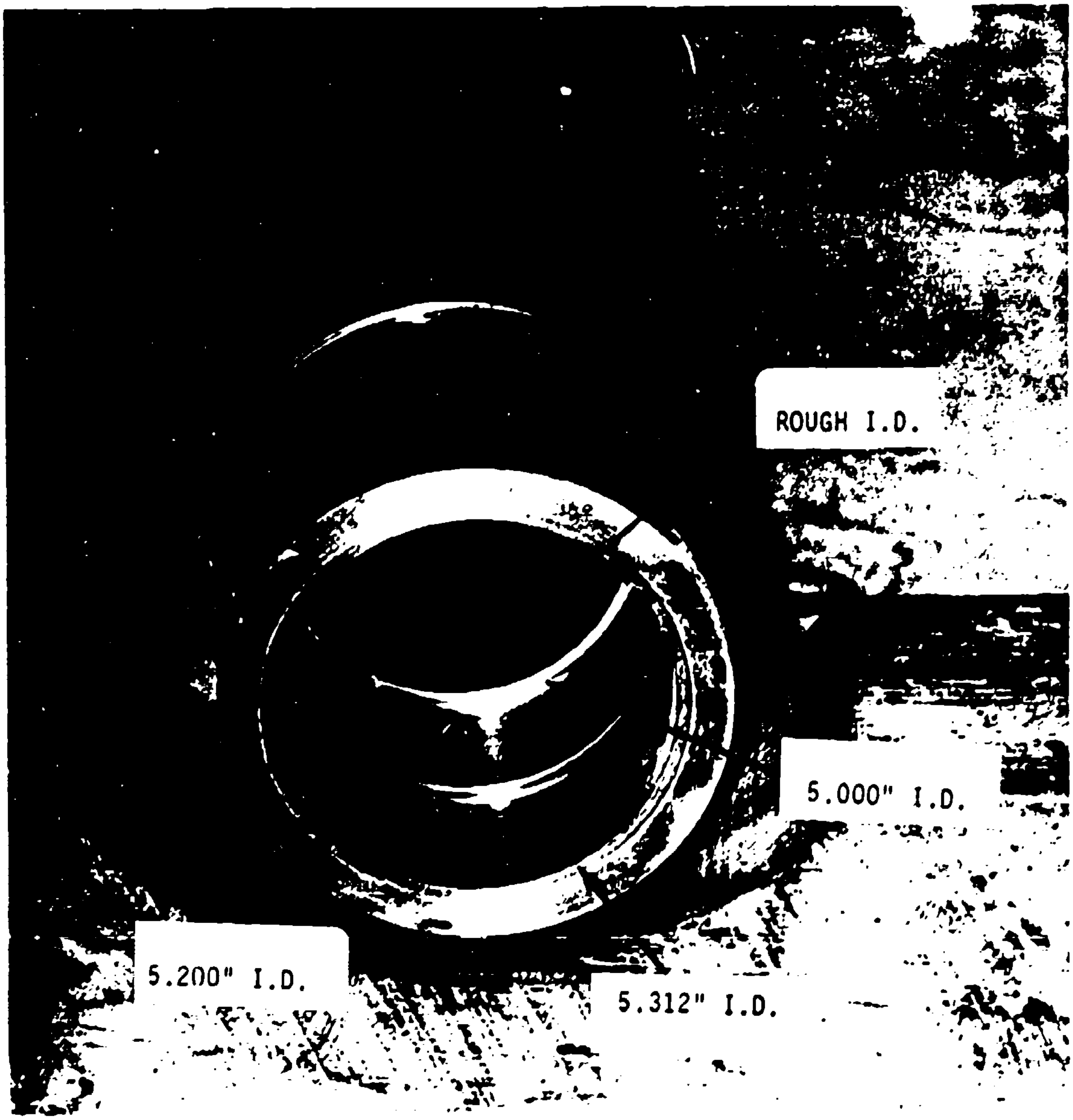


Figure 2. Titanium beta-C test cylinder counterbored to accommodate boring heads.

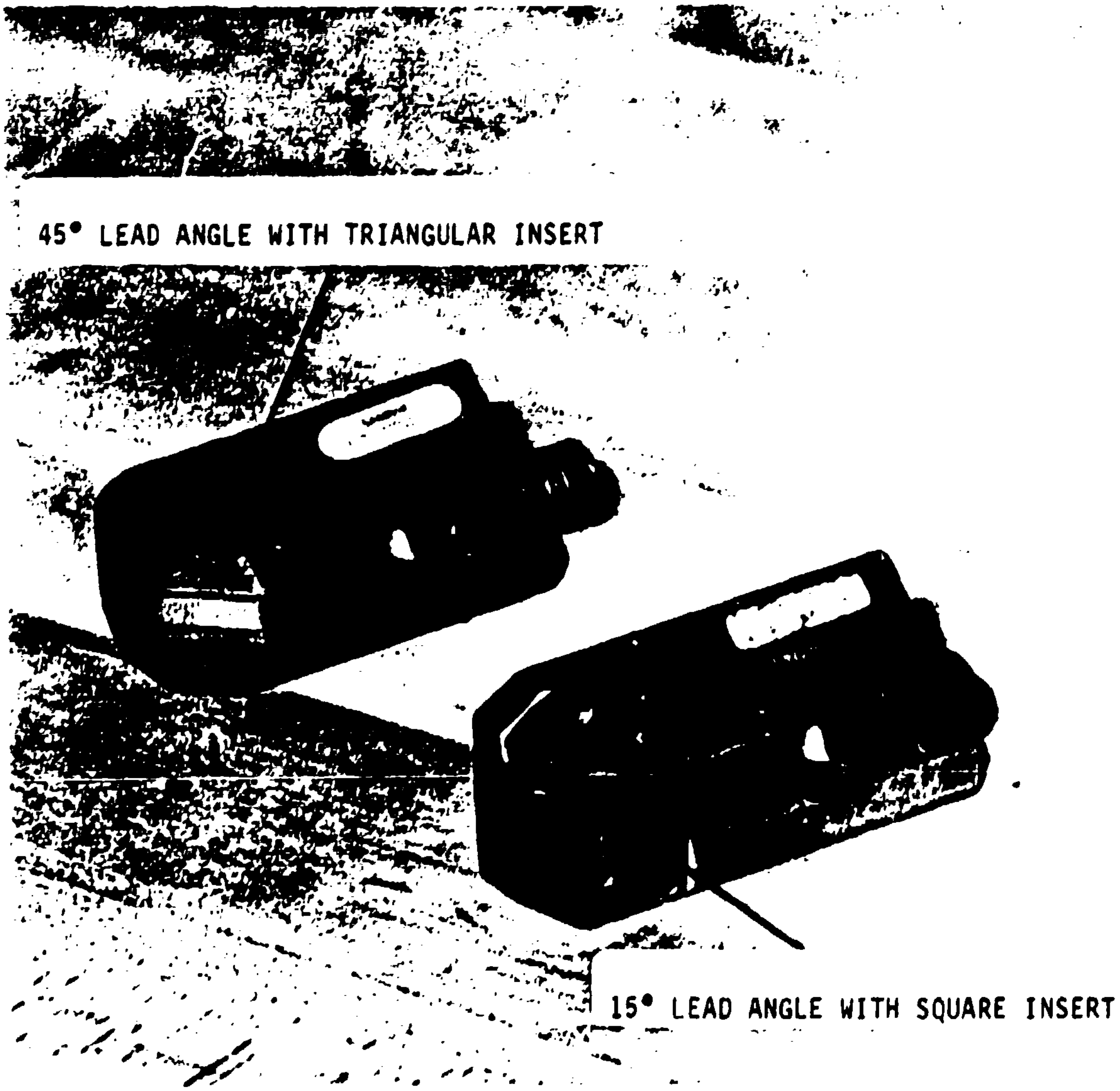


Figure 3. ISO standard boring head tool holders.

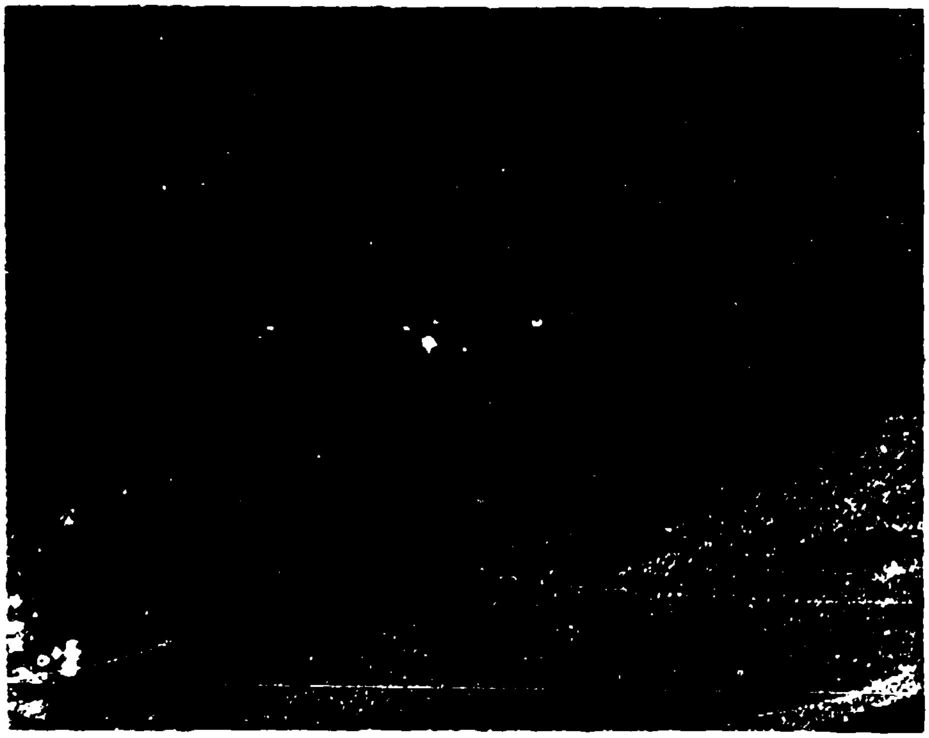


Figure 4. Carbide guide pad used to stabilize deep-hole boring head.

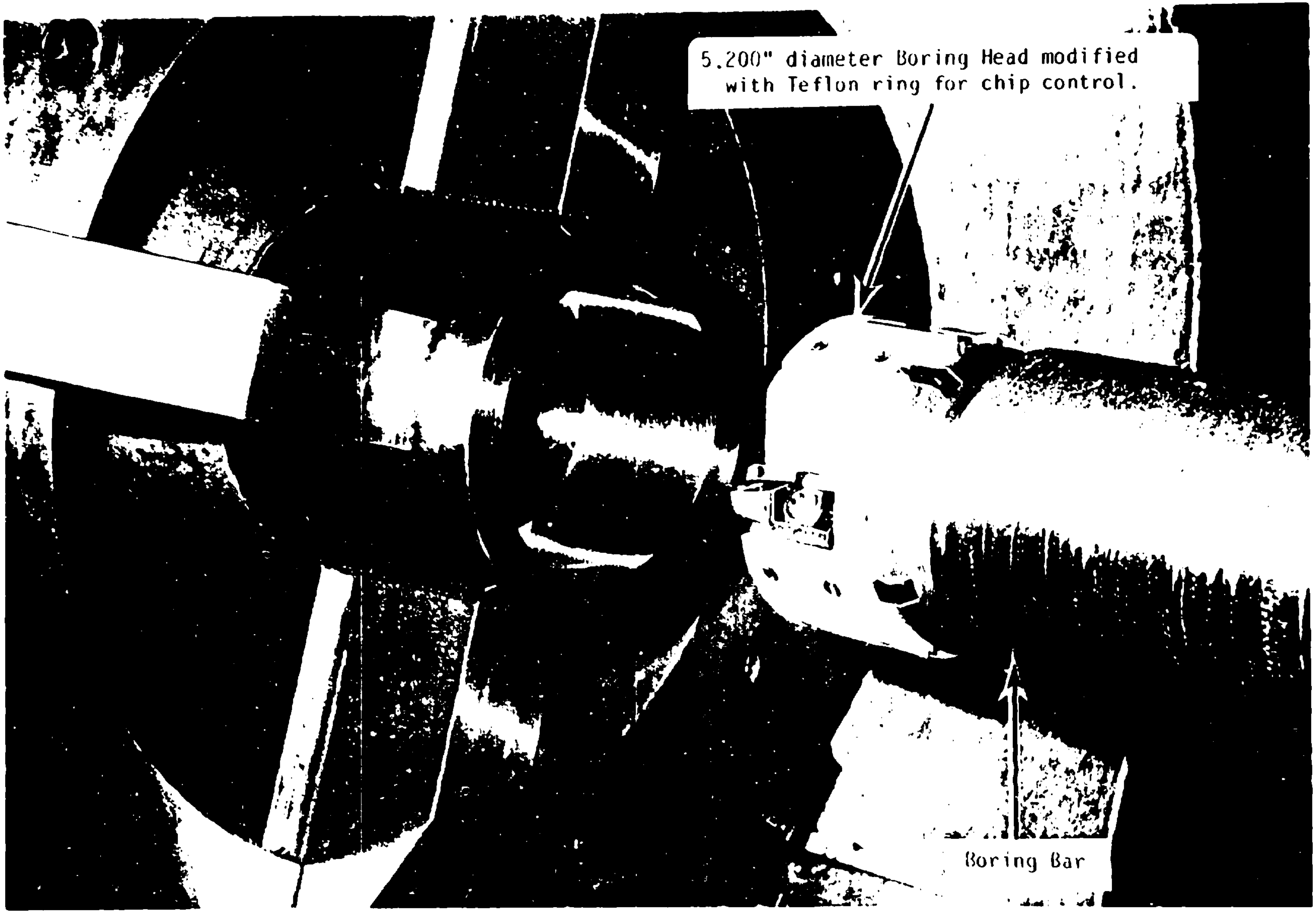


Figure 5. Titanium beta-C cylinder secured in Le Blonde hollow spindle boring machine chuck.

BORING TITANIUM Beta-C Alloy

INSERT EVALUATION

CUTTING LENGTH

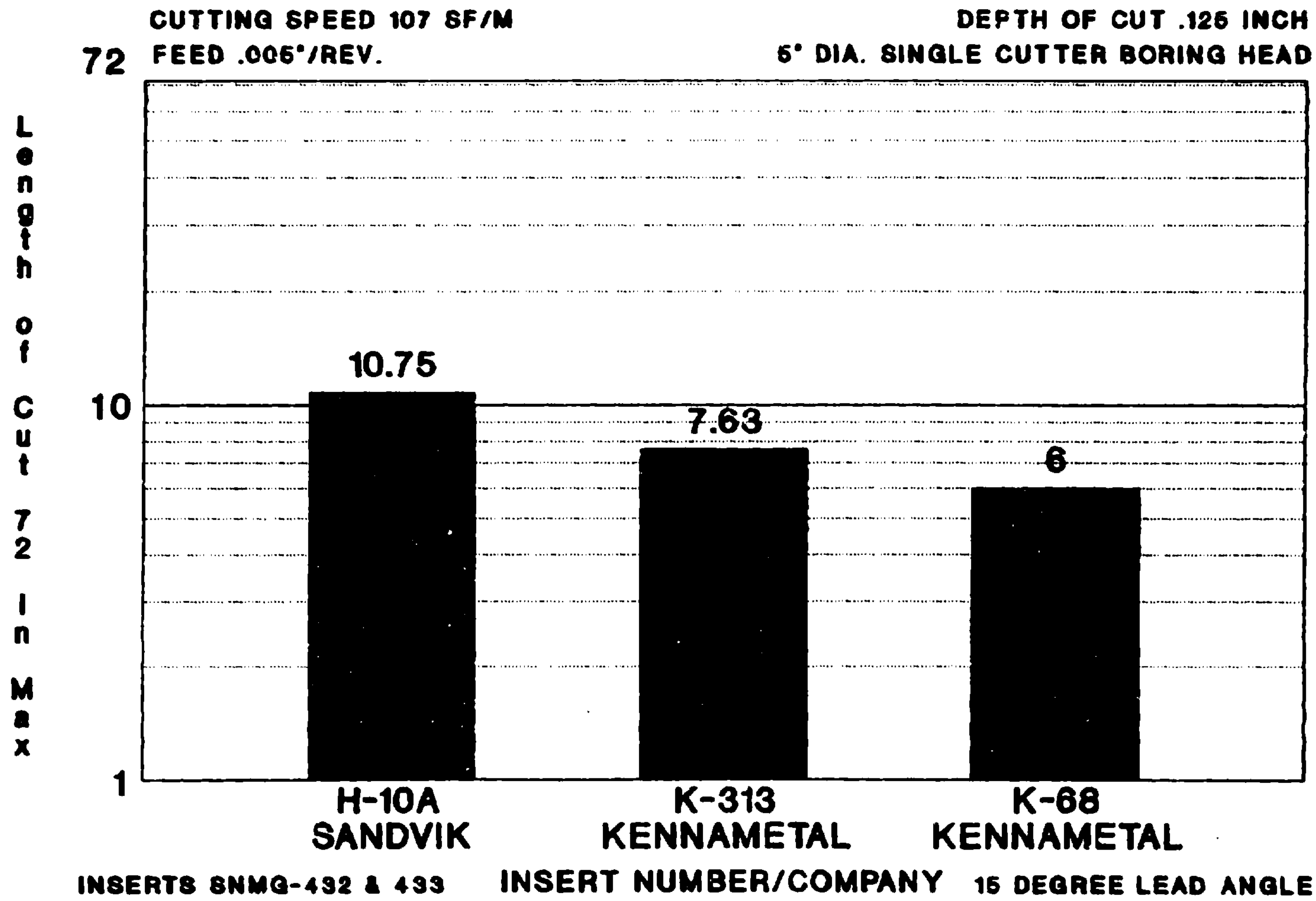


FIGURE 6

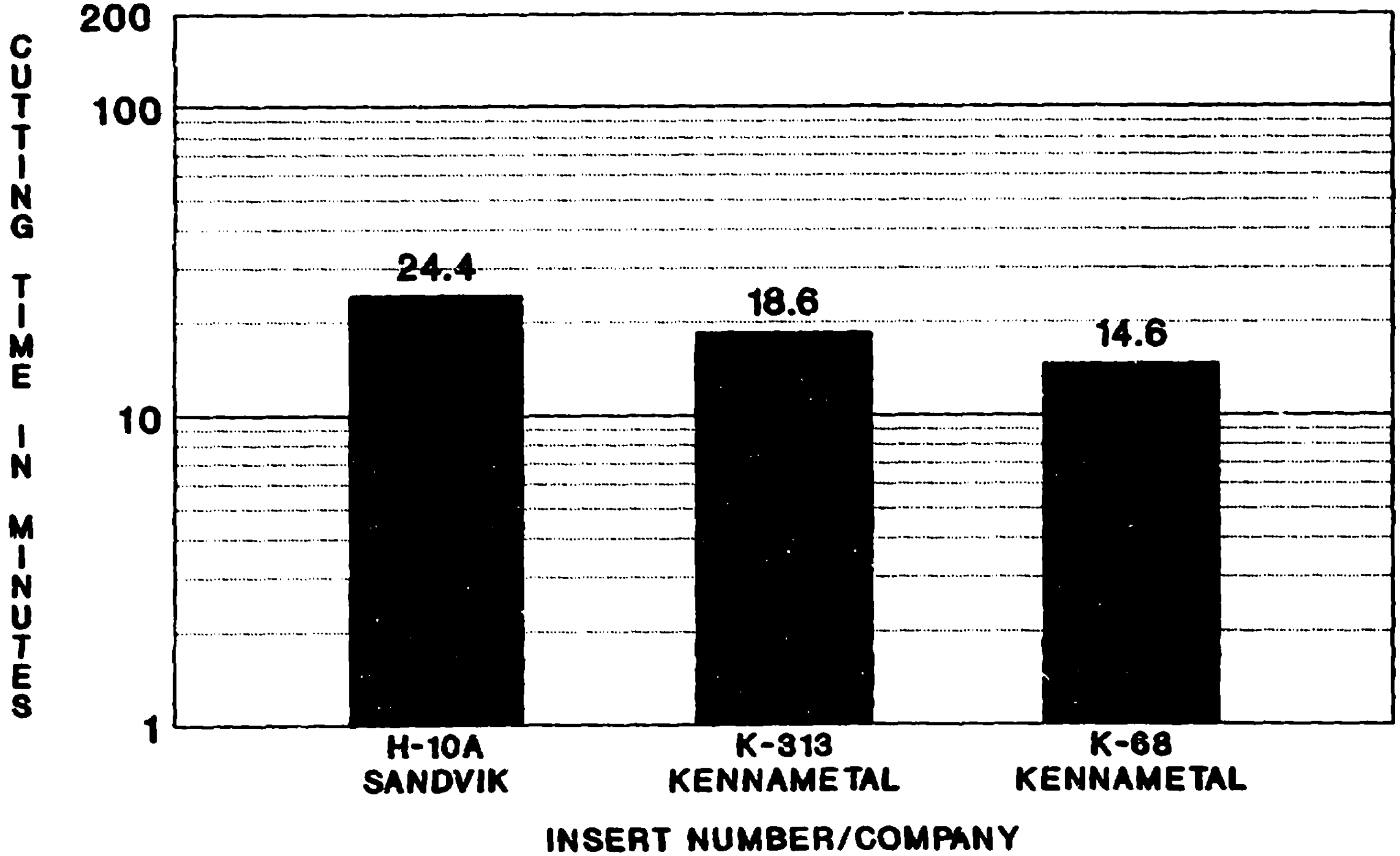
BORING TITANIUM BETA-C ALLOY

INSERT EVALUATION

INSERT TOOL LIFE

CUTTING SPEED 107 SFM — DEPTH OF CUT .125 INCH

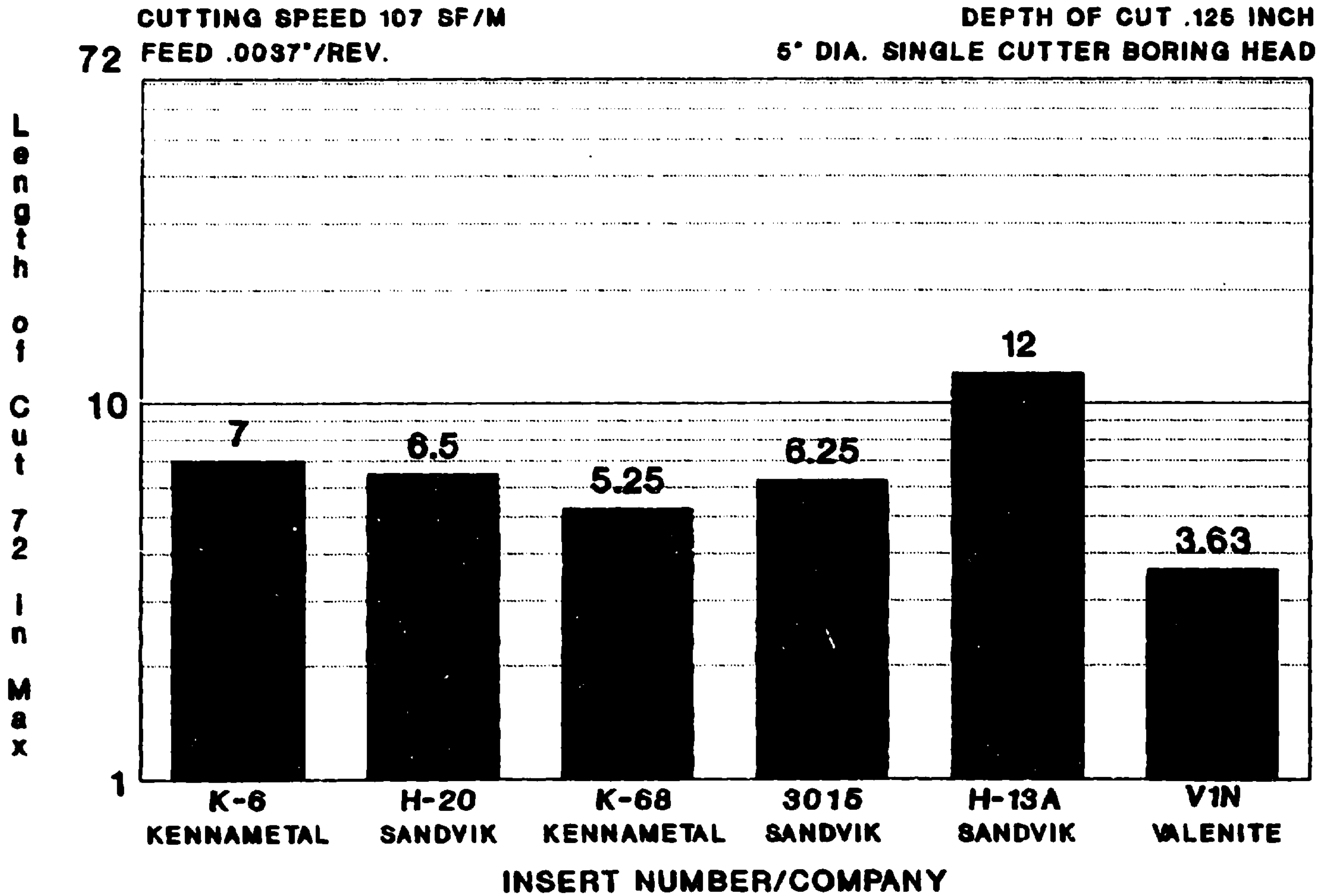
FEED .005"/REVOLUTION — 5" DIA. SINGLE CUTTER BORING HEAD



INSERTS SNMG-432 & 433 — 15 DEGREE LEAD ANGLE

FIGURE 7

BORING TITANIUM Beta-C Alloy
INSERT EVALUATION
CUTTING LENGTH

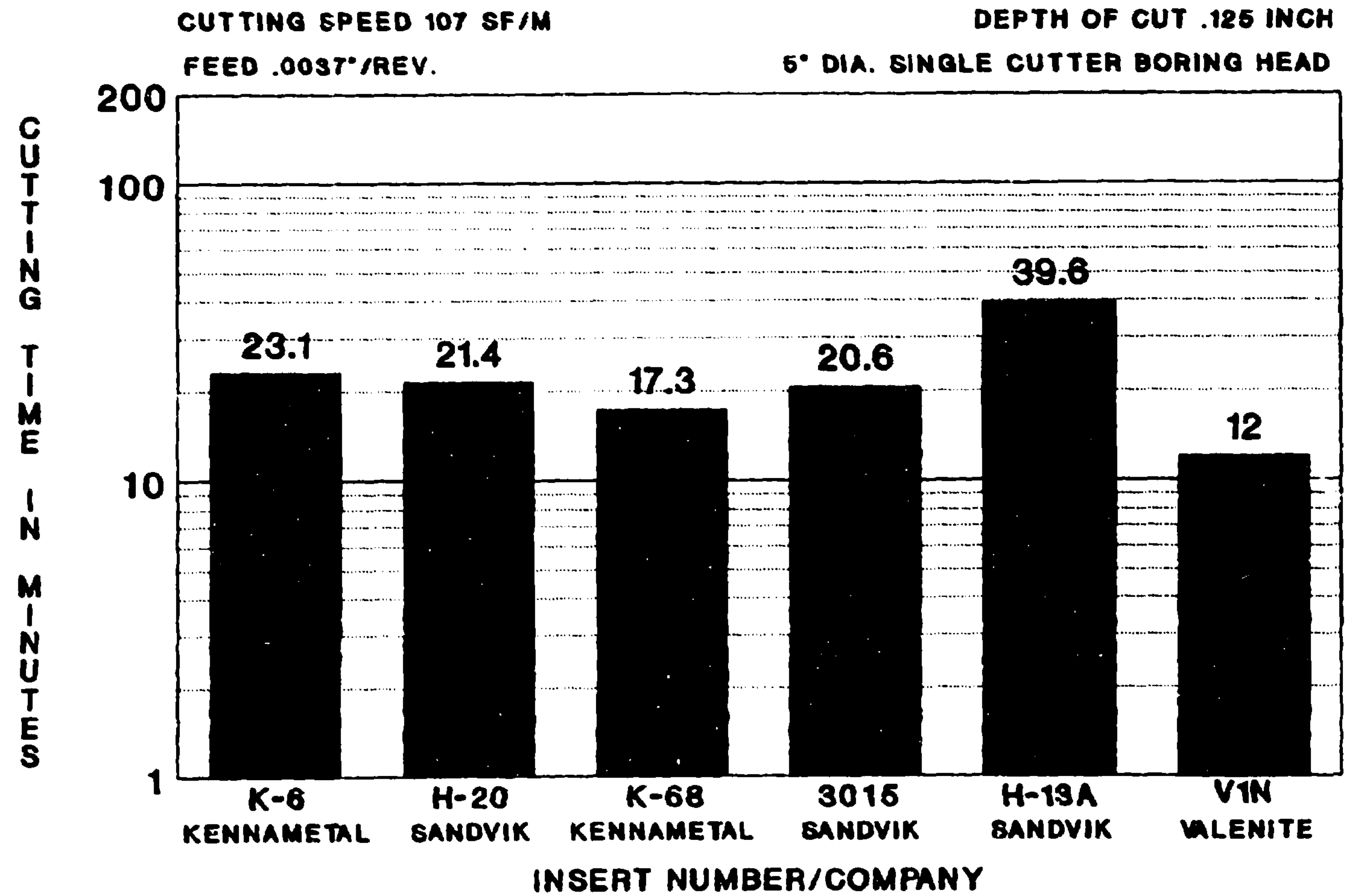


INSERTS SNMG-432 & 433

FIGURE 8

15 DEGREE LEAD ANGLE

BORING TITANIUM Beta-C Alloy
INSERT EVALUATION
INSERT TOOL LIFE



INSERTS SNMG-432 & 433

FIGURE 9

15 DEGREE LEAD ANGLE

Figure 10. ISO standard deep-hole boring head tool holder with 45-degree lead angle and triangular insert.

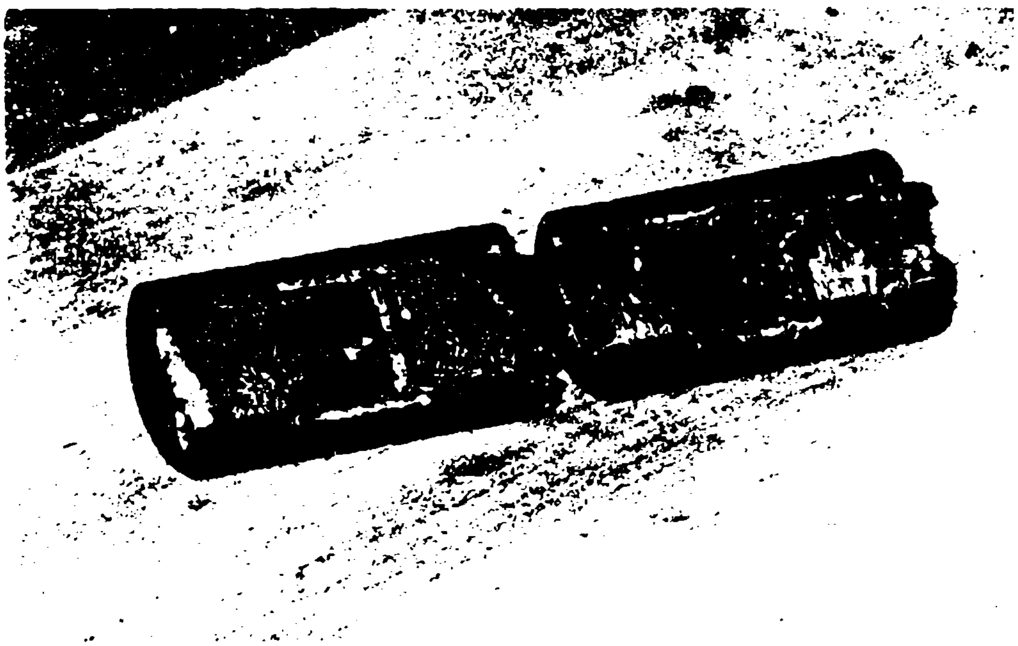


Figure 11. Carbide guide pads destroyed while boring titanium beta-C alloy at 107 sfm and feed rate of 0.005 ipr.

BORING TITANIUM Beta-C Alloy

INSERT EVALUATION

CUTTING LENGTH

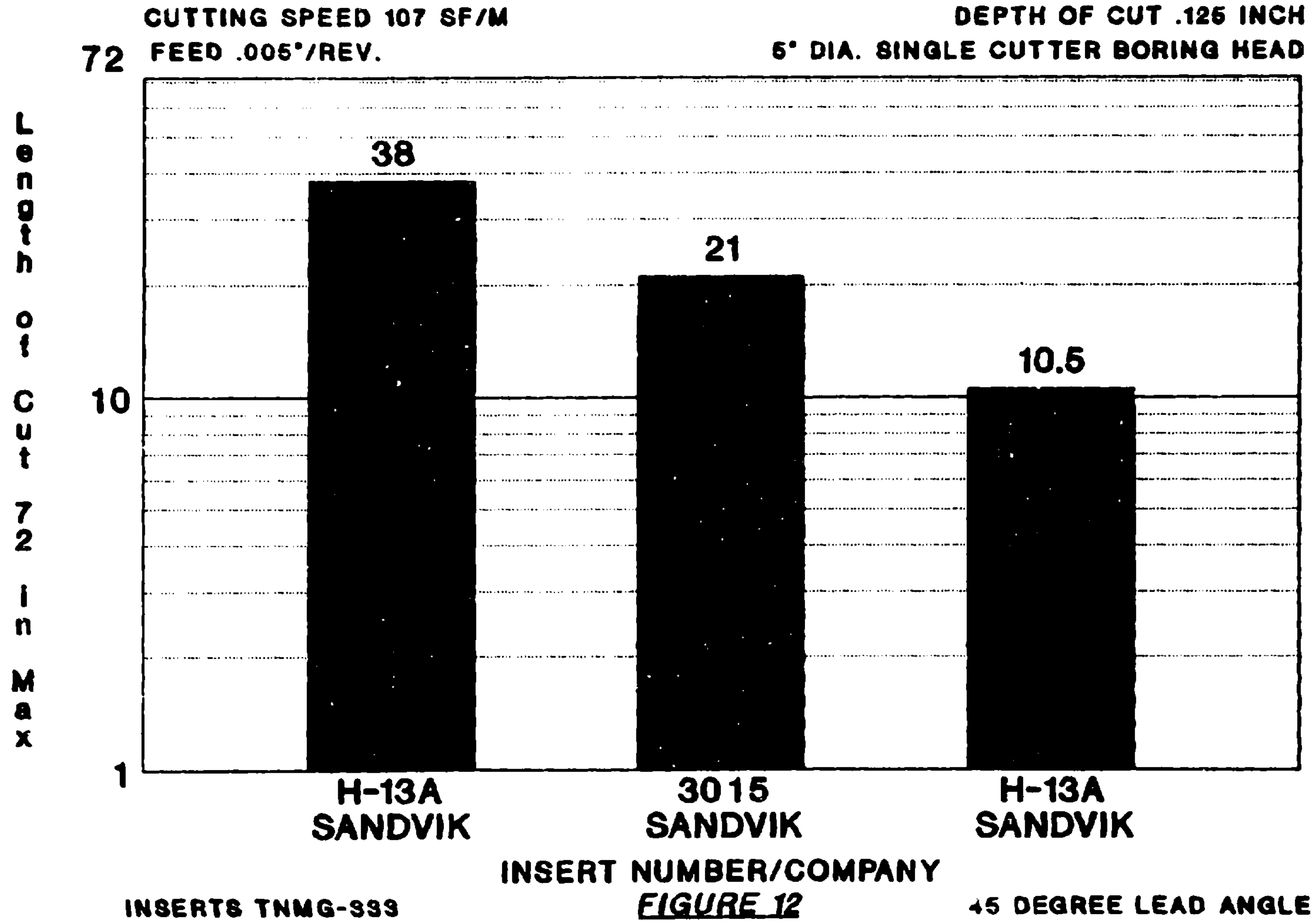
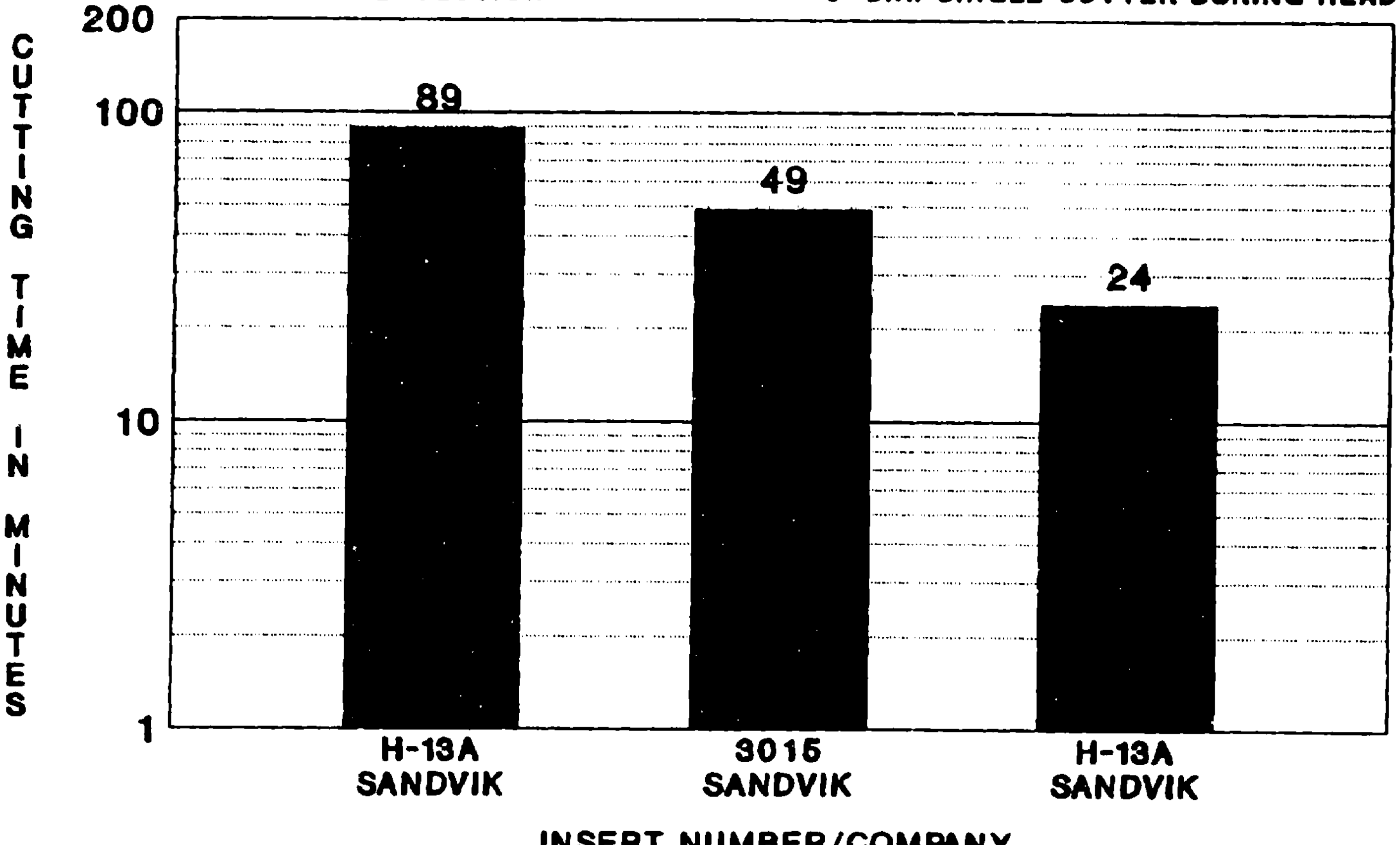


FIGURE 12

BORING TITANIUM BETA-C ALLOY
INSERT EVALUATION
INSERT TOOL LIFE

CUTTING SPEED 107 SFM
FEED .006"/REVOLUTION

DEPTH OF CUT .125 INCH
5" DIA. SINGLE CUTTER BORING HEAD



INSERTS TNMG-333

FIGURE 13

45 DEGREE LEAD ANGLE

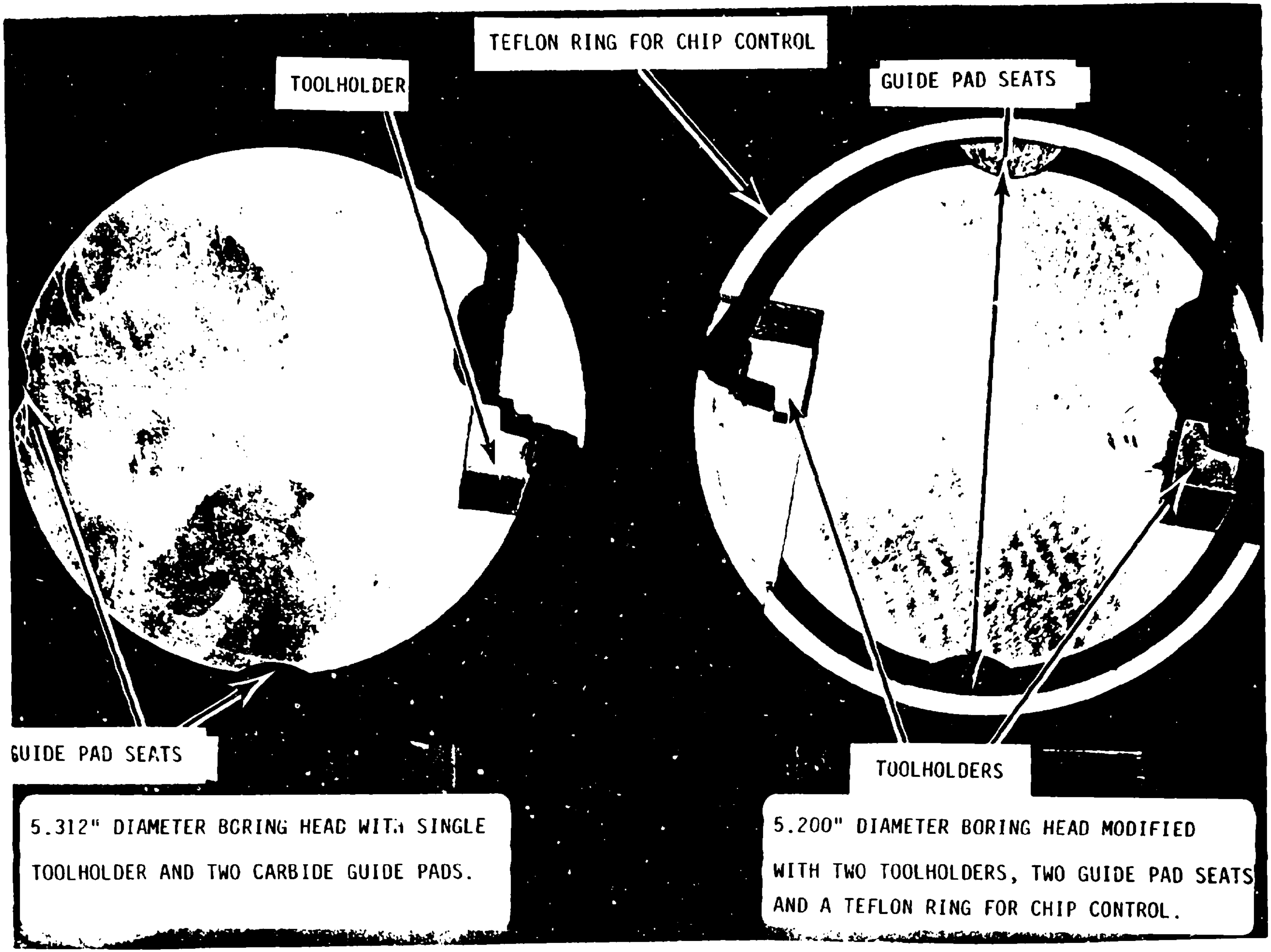


Figure 14. Front view of deep-hole boring heads.

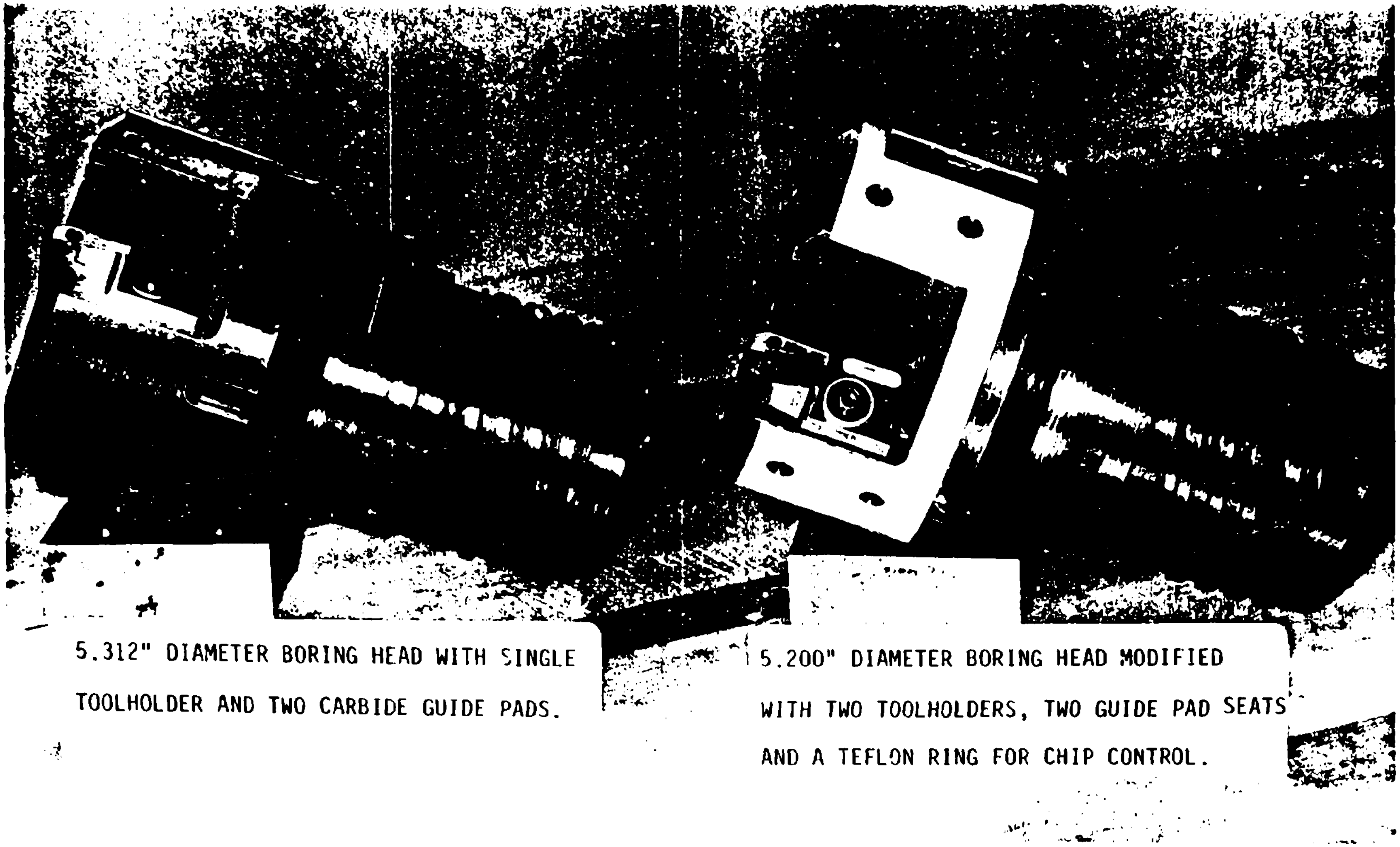


Figure 15. Side view of deep-hole boring heads.

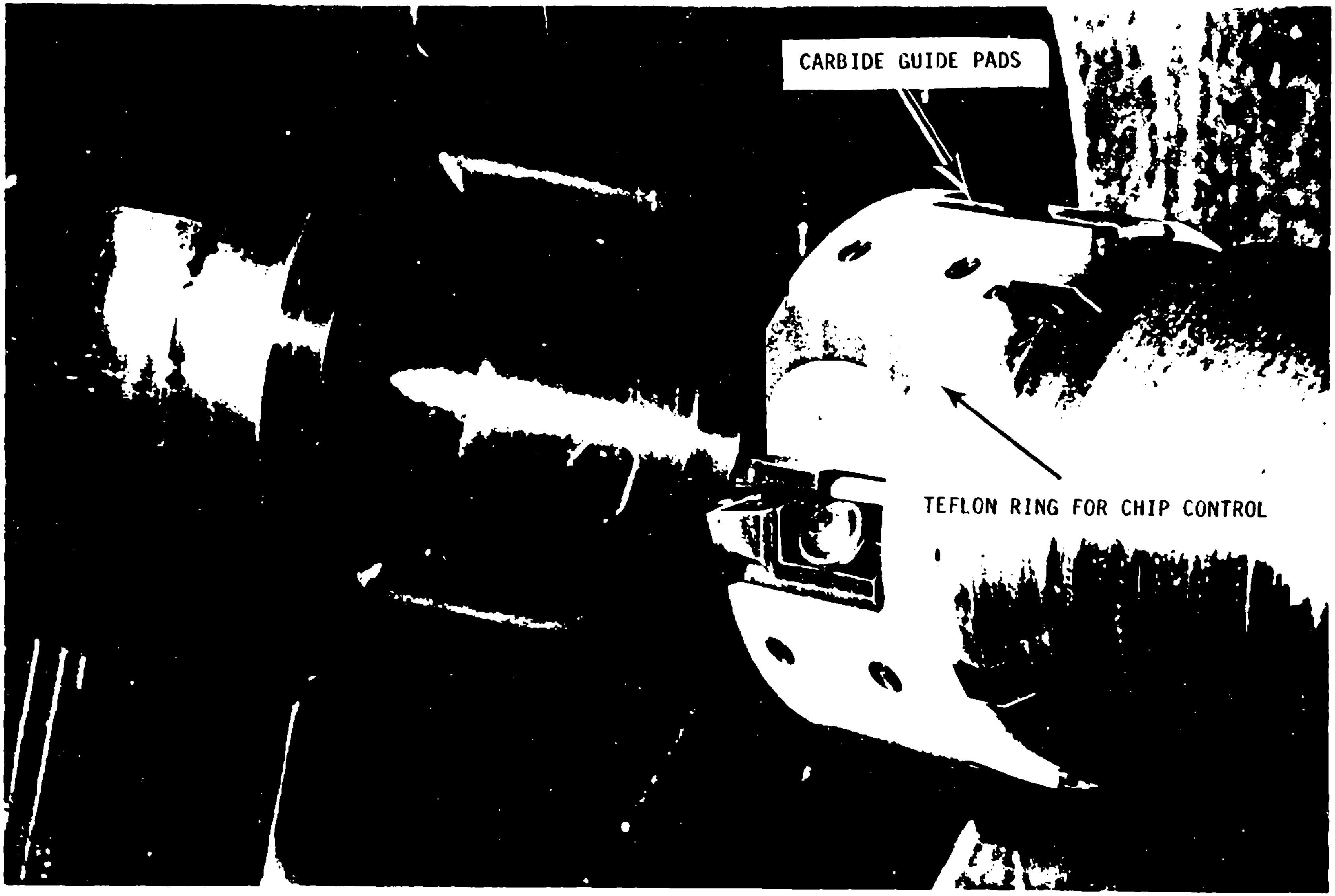


Figure 16. Titanium beta-C alloy tube secured in hollow spindle chuck and 5.200-inch diameter modified boring head mounted in boring bar.

BORING TITANIUM Beta-C Alloy
INSERT EVALUATION
CUTTING LENGTH

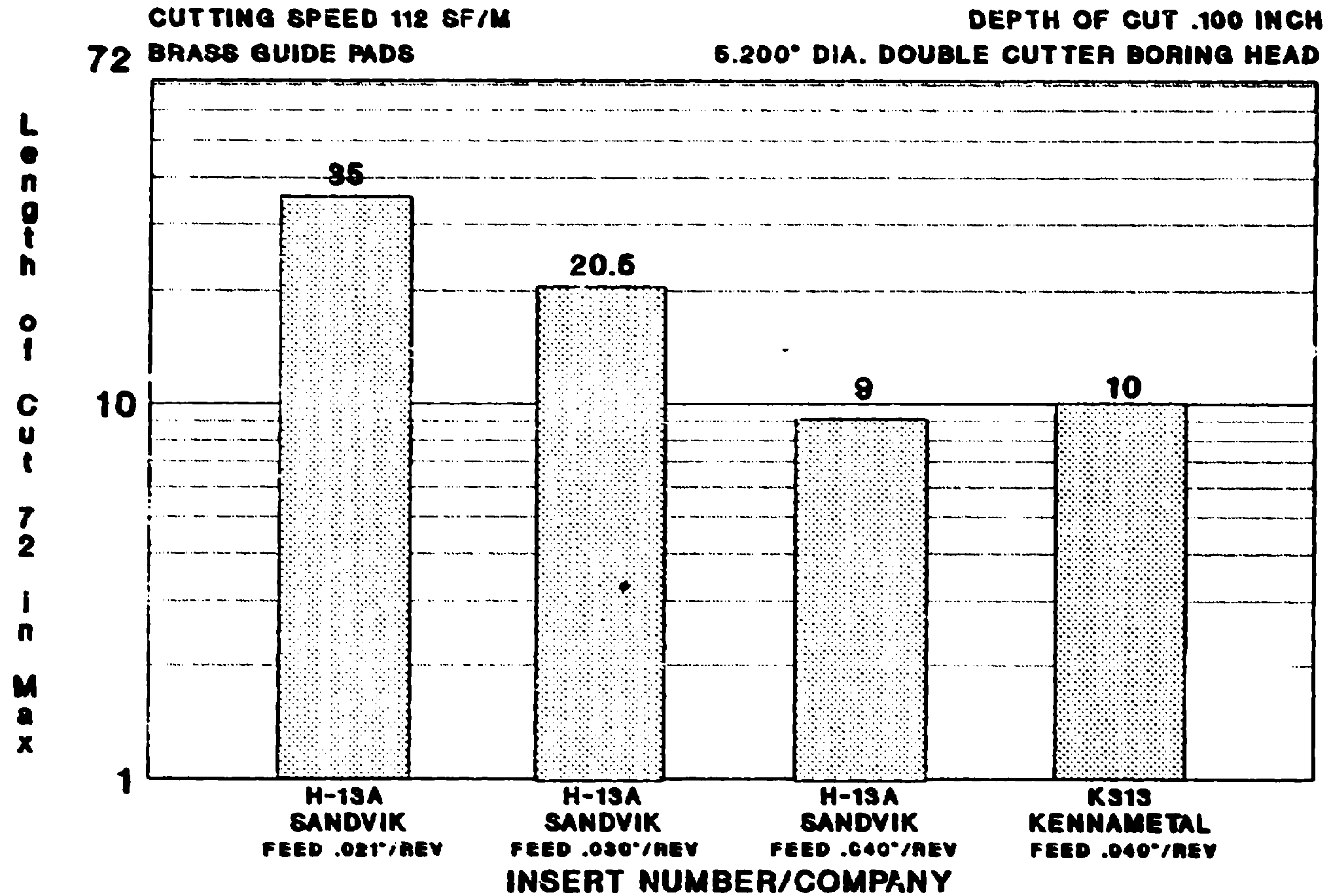
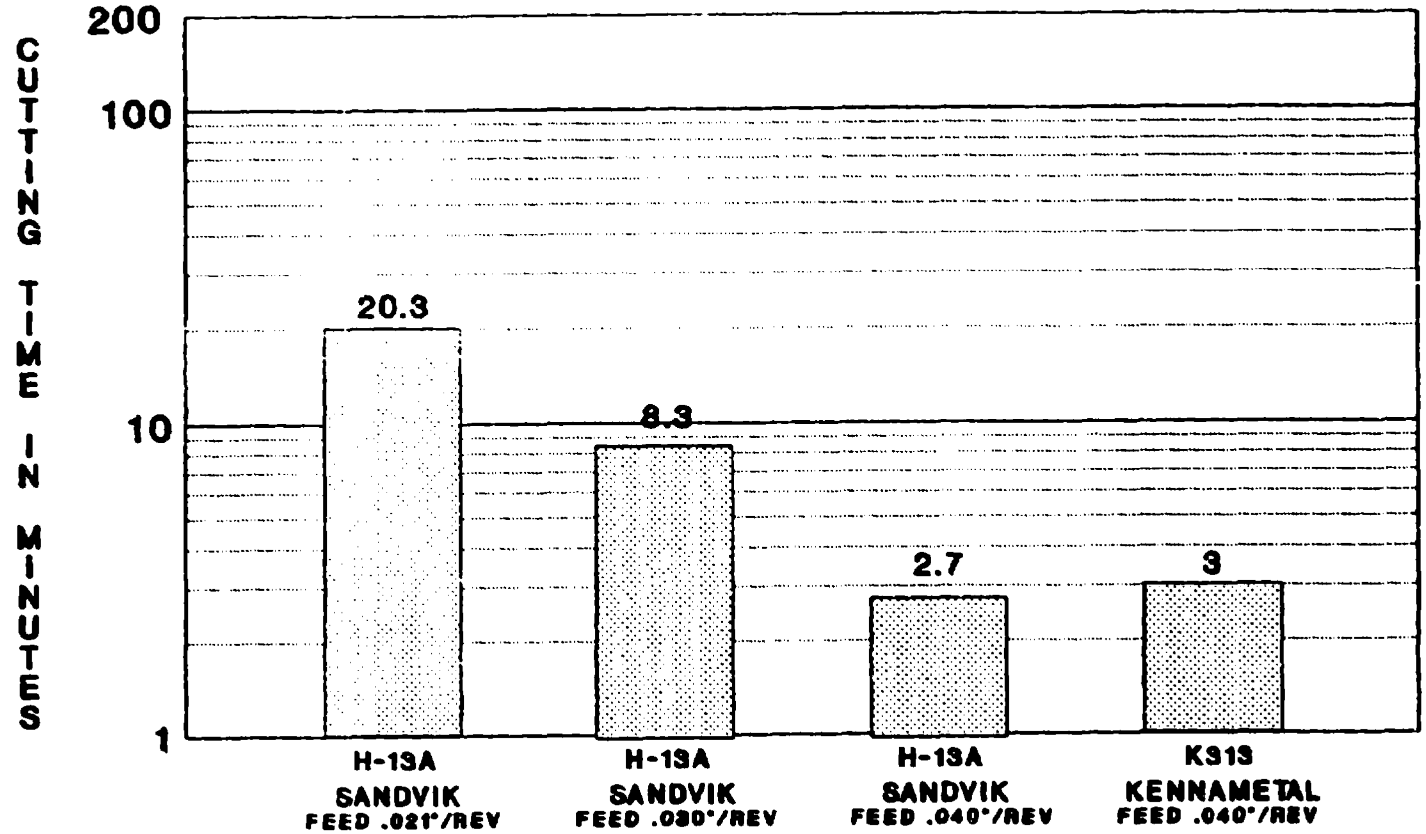


FIGURE 17

BORING TITANIUM BETA-C ALLOY
INSERT EVALUATION
INSERT TOOL LIFE

CUTTING SPEED 112 SF/M
BRASS GUIDE PADS

DEPTH OF CUT .100 INCH
5.200" DIA. DOUBLE CUTTER BORING HEAD



INSERTS SNMG-433

45 DEGREE LEAD ANGLE

FIGURE 18

Figure 19. Brass guide pads.

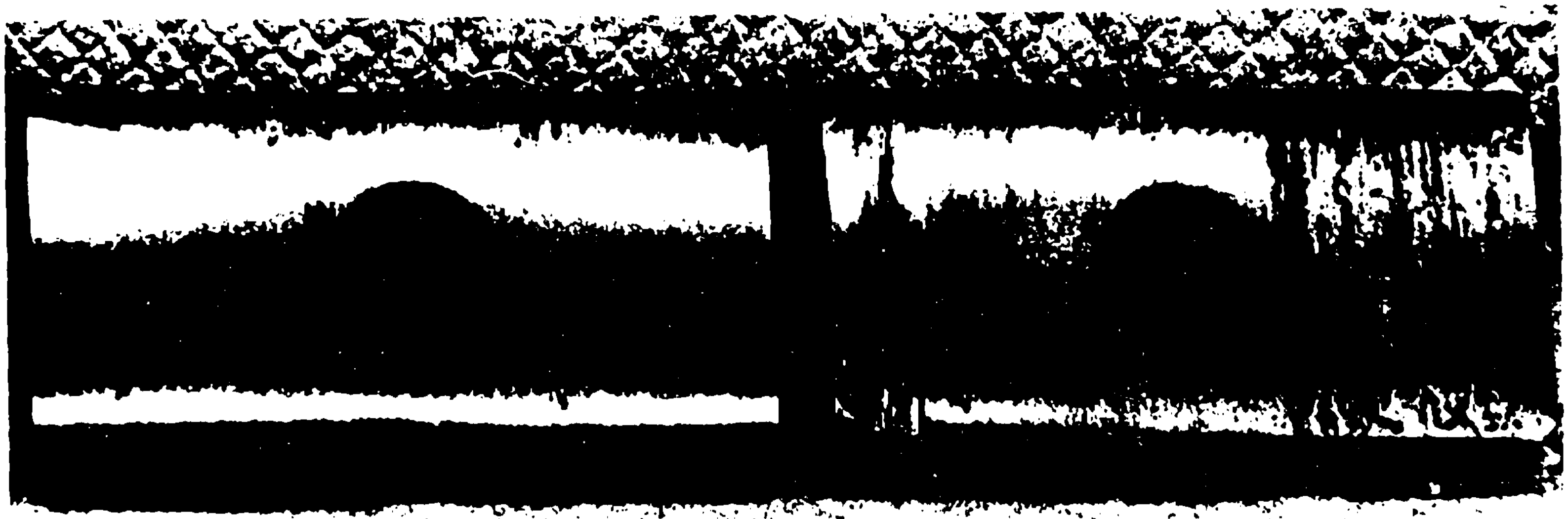
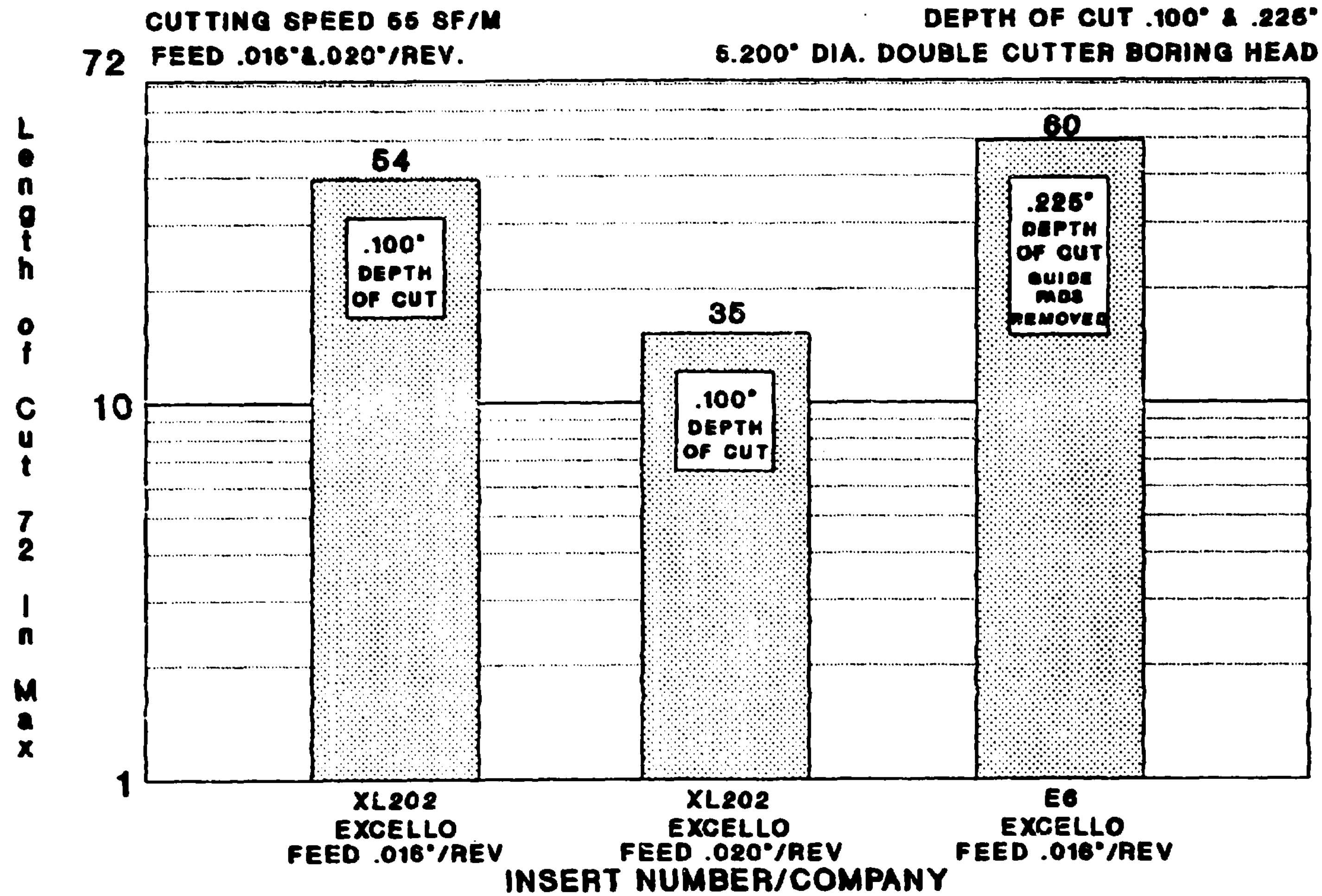


Figure 20. Hardened steel guide pads showing galling from boring titanium beta-C alloy.

BORING TITANIUM Beta-C Alloy

INSERT EVALUATION

CUTTING LENGTH



INSERTS SNMG-432 *FIGURE 21* 45 DEGREE LEAD ANGLE

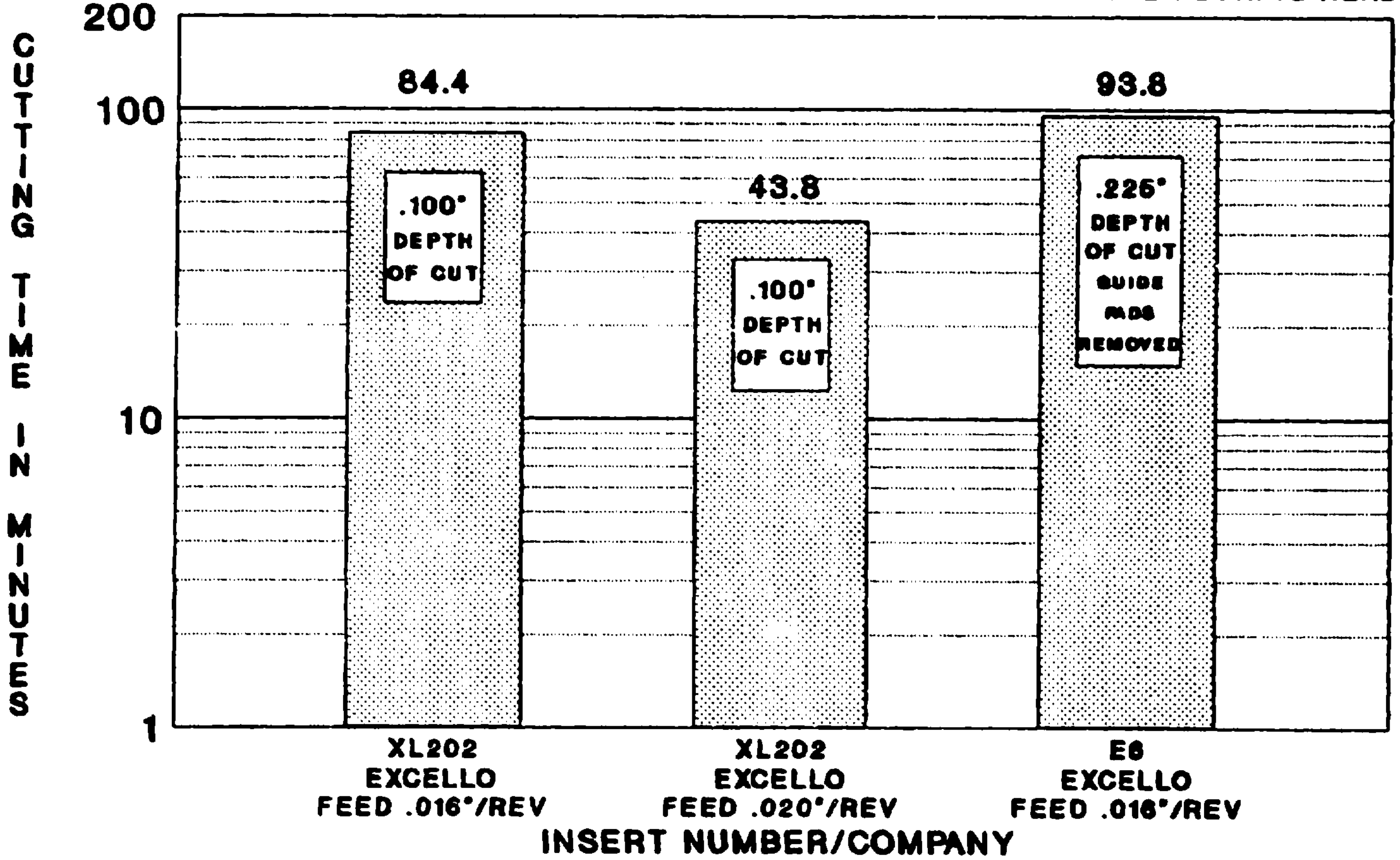
BORING TITANIUM BETA-C ALLOY
INSERT EVALUATION
INSERT TOOL LIFE

CUTTING SPEED 55 SFM

FEED .016"&.020"/REV

DEPTH OF CUT .100" & .225"

5.200" DIA. DOUBLE CUTTER BORING HEAD



INSERTS SNMG-432

FIGURE 22

45 DEGREE LEAD ANGLE

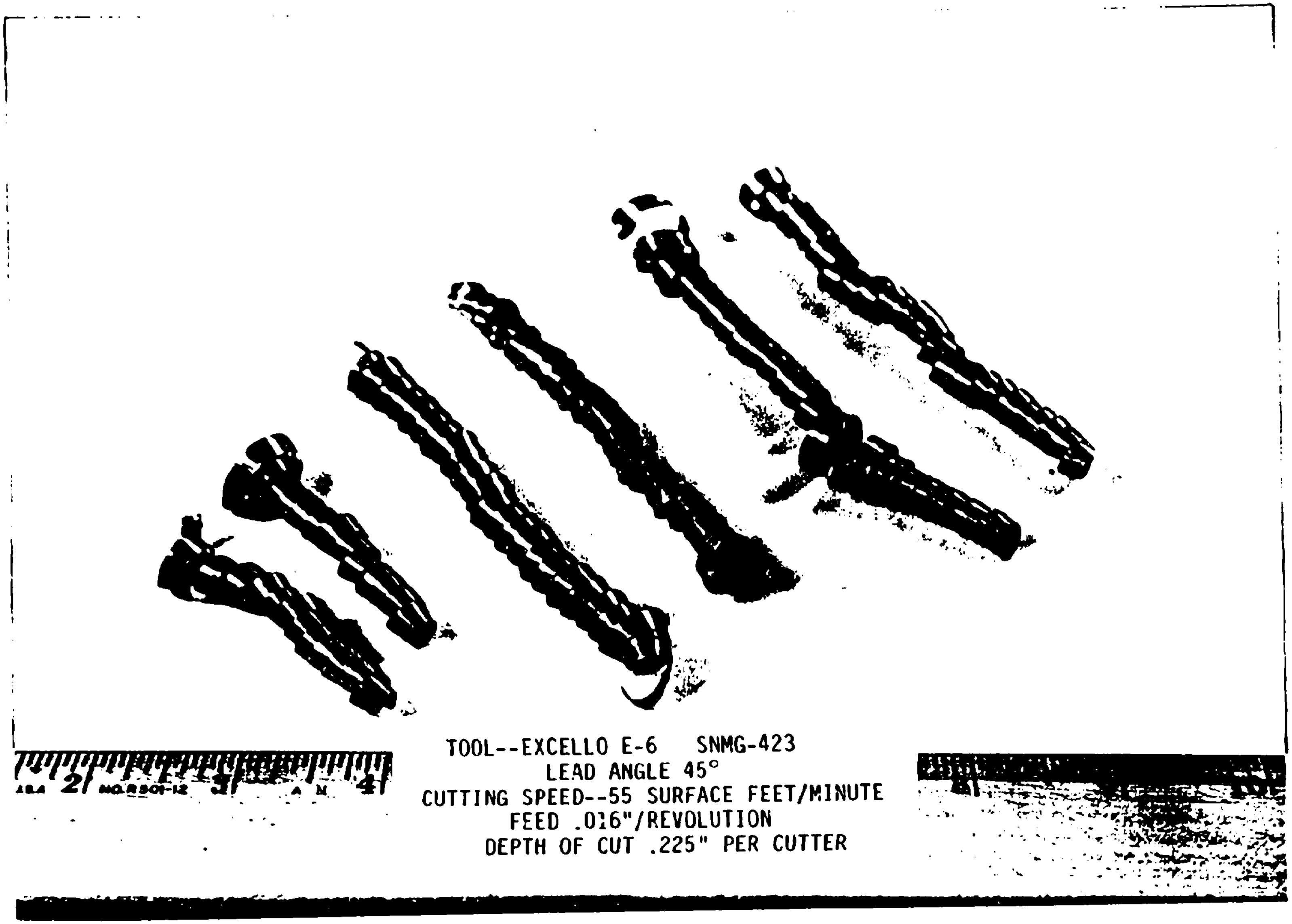
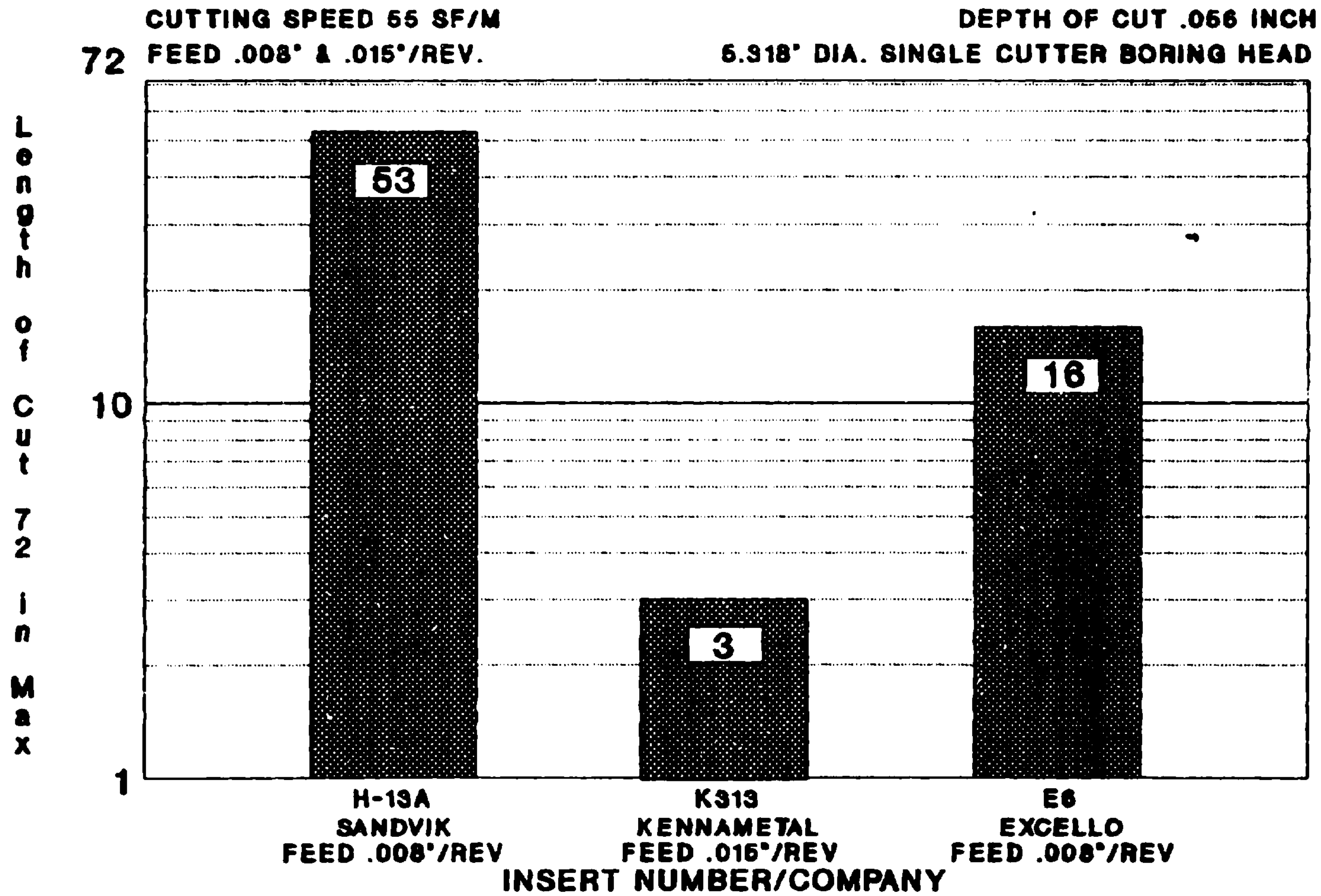


Figure 23. Chips produced during boring operation on titanium beta-C alloy with 5.200-inch diameter boring head and two tool holders.

BORING TITANIUM Beta-C Alloy
INSERT EVALUATION
CUTTING LENGTH



INSERTS SNMG-432

FIGURE 24

45 DEGREE LEAD ANGLE

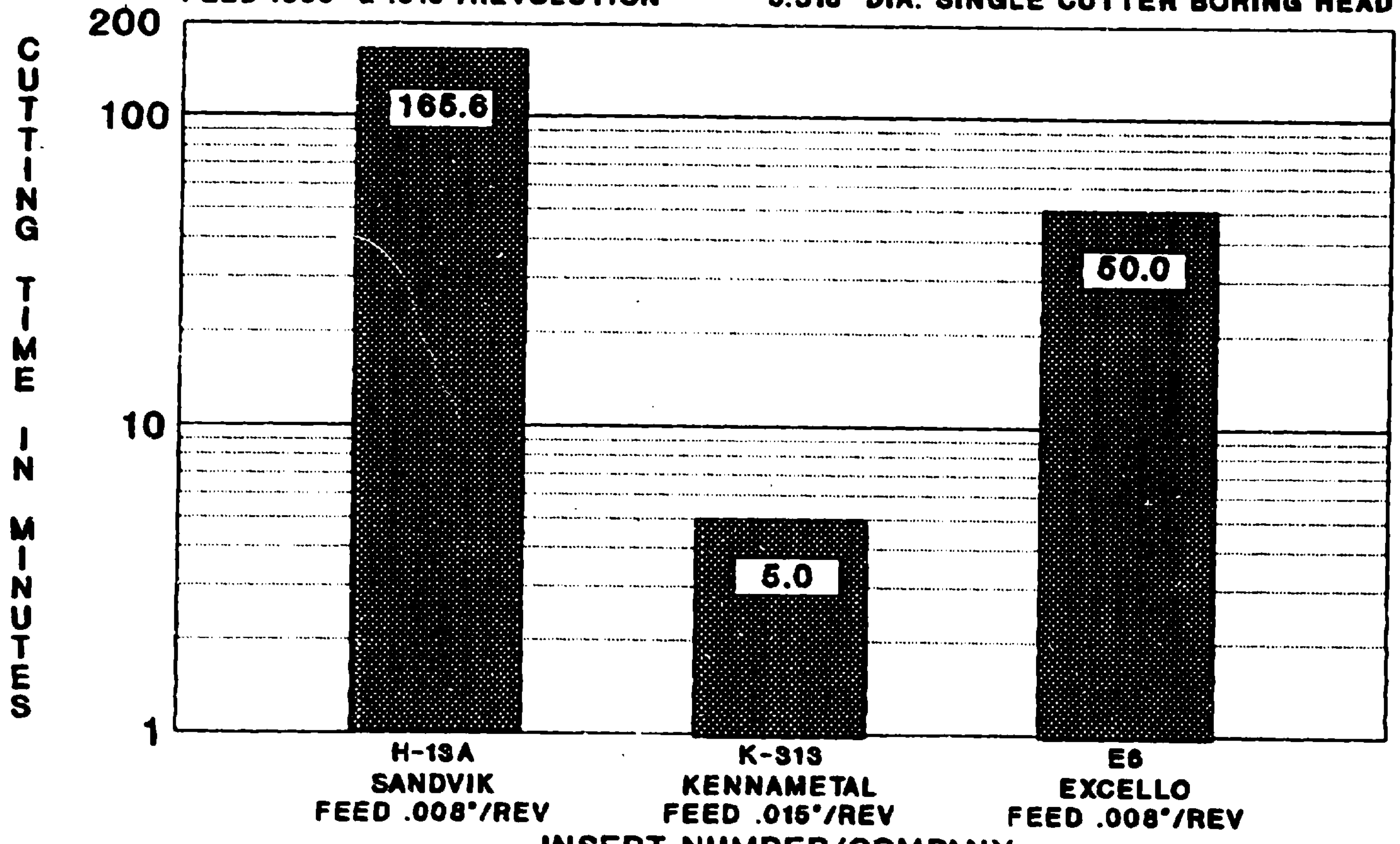
BORING TITANIUM BETA-C ALLOY
INSERT EVALUATION
INSERT TOOL LIFE

CUTTING SPEED 55 SFM

FEED .008" & .015"/REVOLUTION

DEPTH OF CUT .056 INCH

5.318" DIA. SINGLE CUTTER BORING HEAD



INSERTS SNMG-432

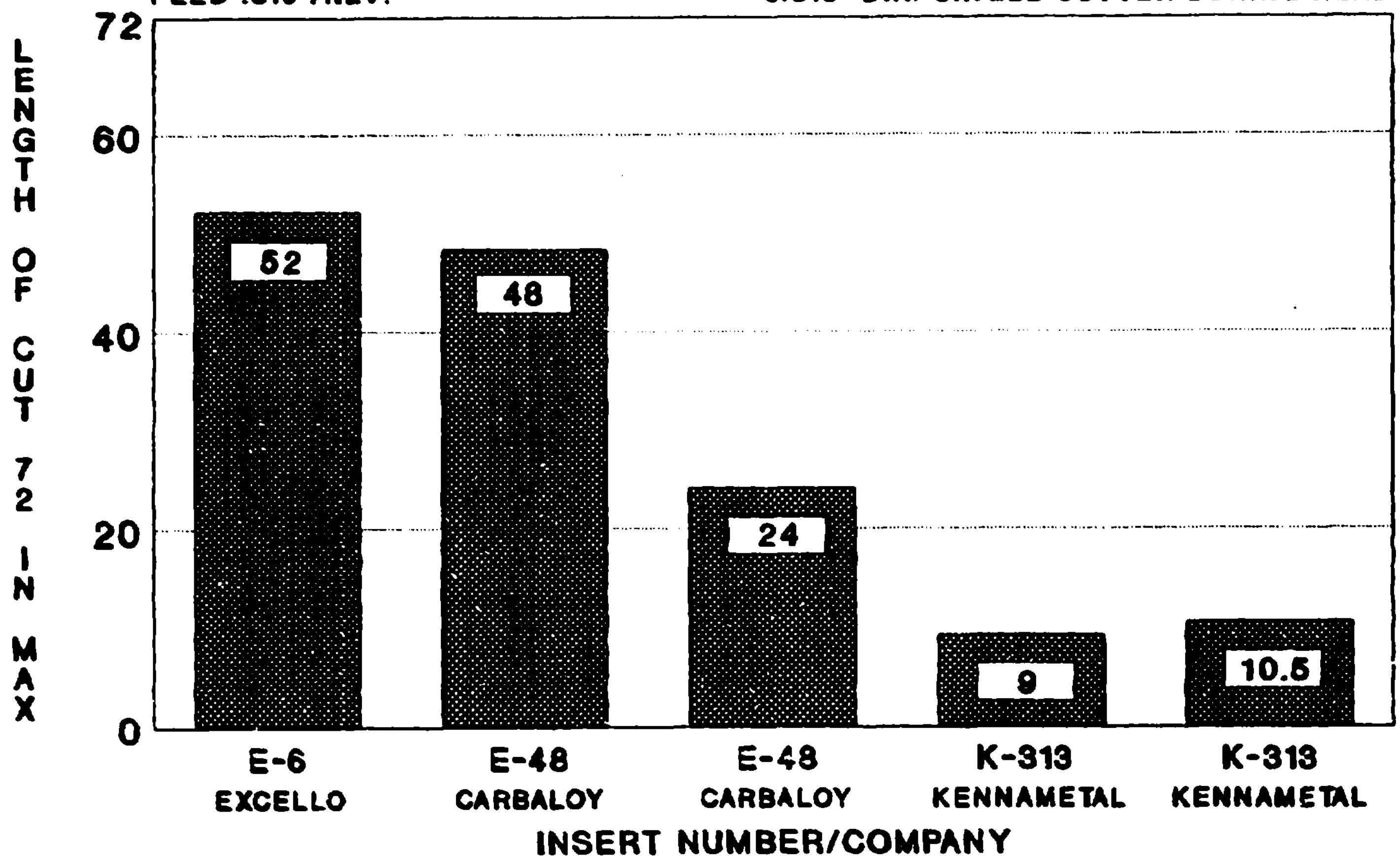
FIGURE 25

45 DEGREE LEAD ANGLE

BORING TITANIUM BETA-C ALLOY
INSERT EVALUATION
CUTTING LENGTH

CUTTING SPEED 55 SF/M
FEED .010"/REV.

DEPTH OF CUT .285"
5.318" DIA. SINGLE CUTTER BORING HEAD

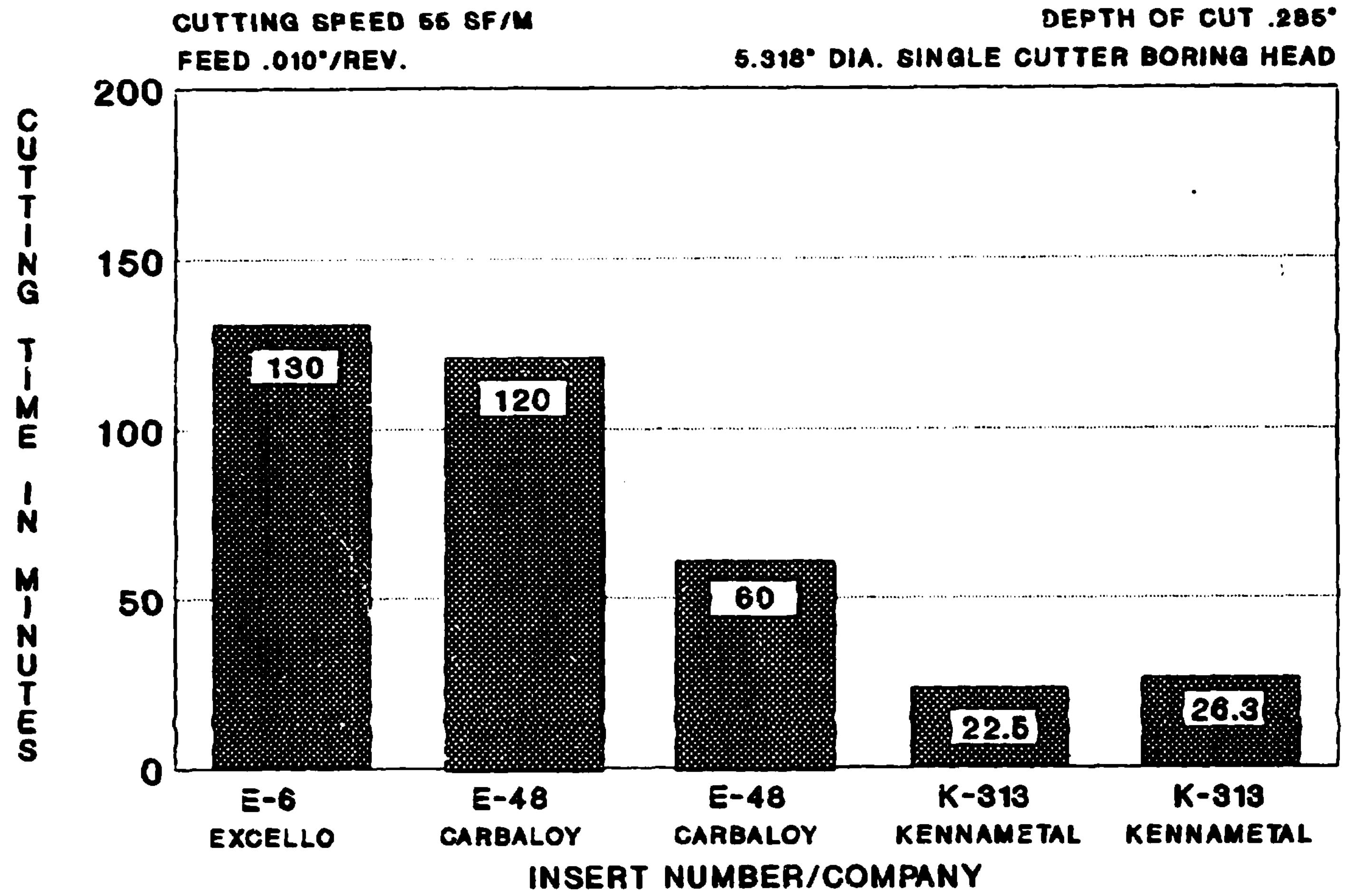


INSERT TYPE TNMG - 333

FIGURE 26

45 DEGREE LEAD ANGLE

BORING TITANIUM BETA-C ALLOY
INSERT EVALUATION
INSERT TOOL LIFE



INSERT TYPE TNMG - 333 | *FIGURE 27* | 45 DEGREE LEAD ANGLE

TOOL--EXCELLO E-6 TNMG-333-E
LEAD ANGLE 45°
CUTTING SPEED--55 SURFACE FEET/MINUTE
FEED .010"/REV
DEPTH OF CUT .570"

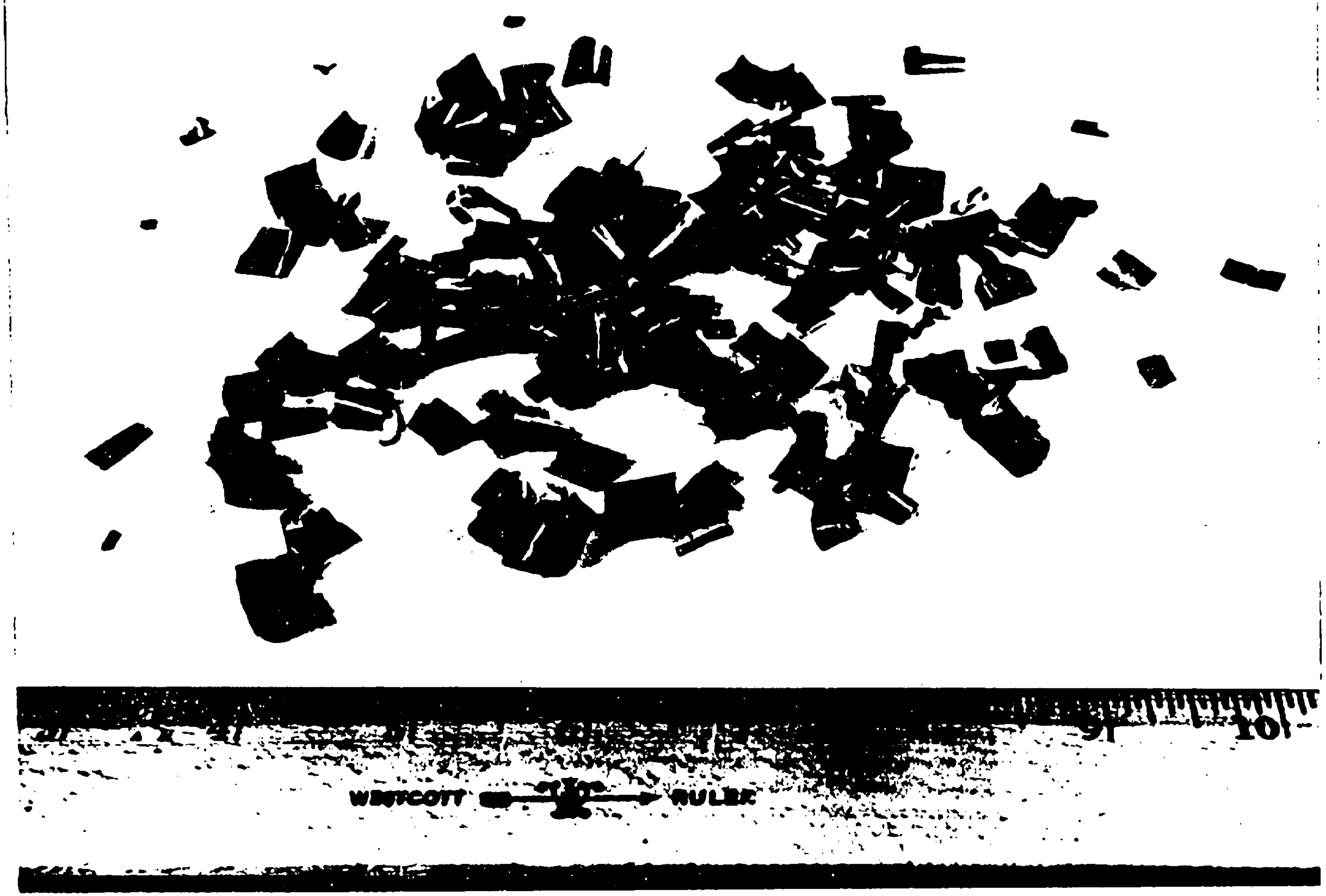


Figure 28. Chips produced while boring titanium beta-C material using 5.312-inch diameter single tool boring head with two carbide guide pads.

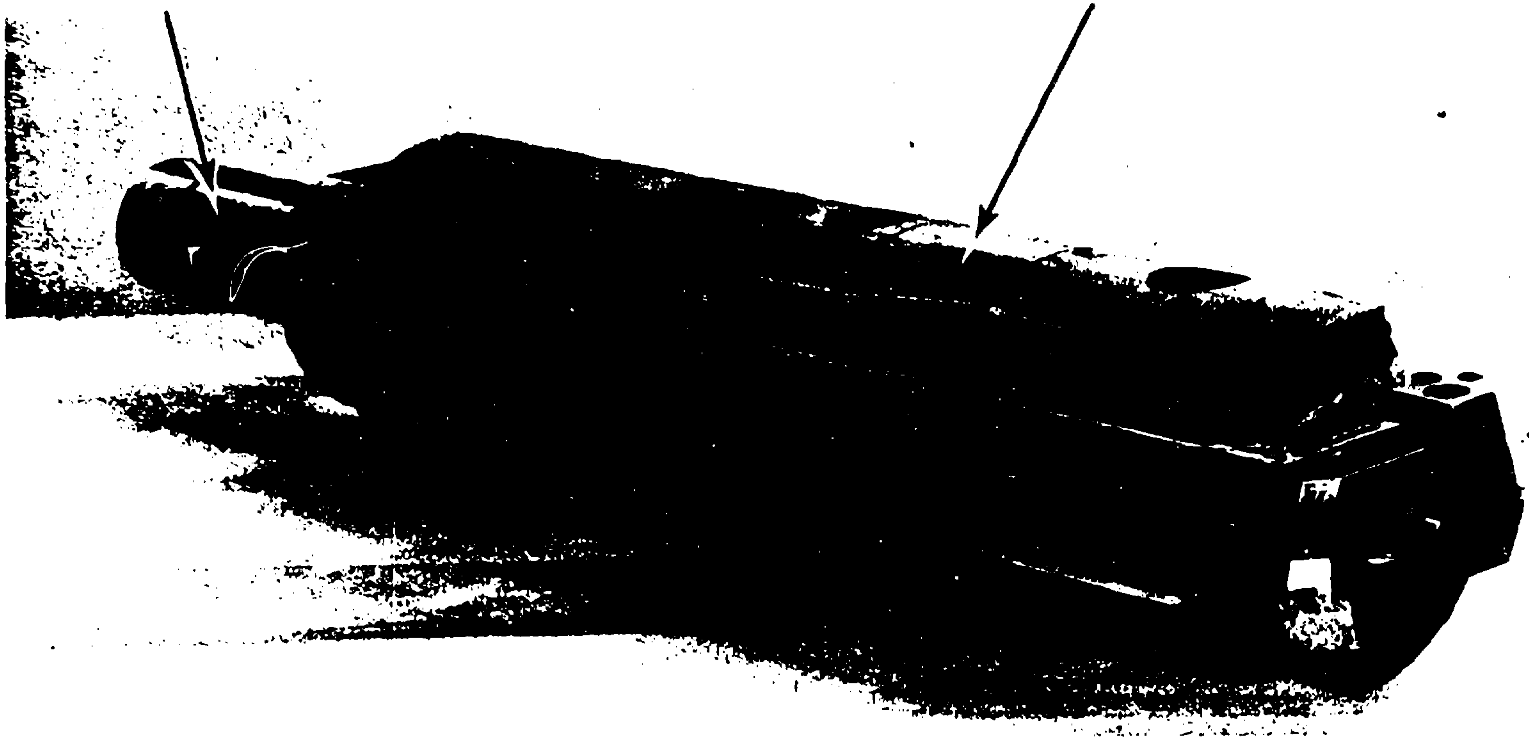


Figure 29. Wood packed reamer.

Figure 30. Wood packed reamer showing Bracut high speed steel tools worn from boring titanium beta-C material.

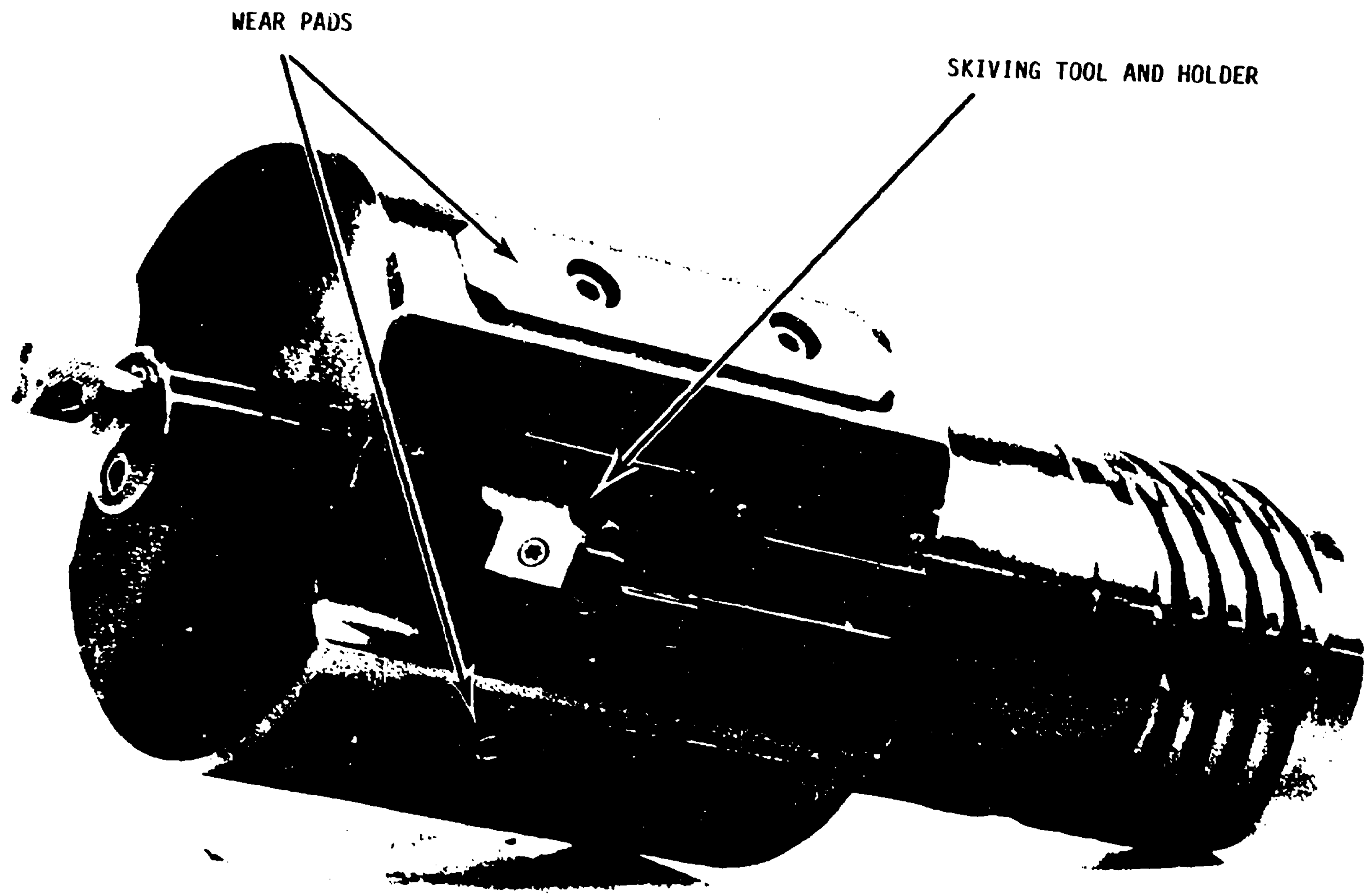


Figure 31. Skiving head.

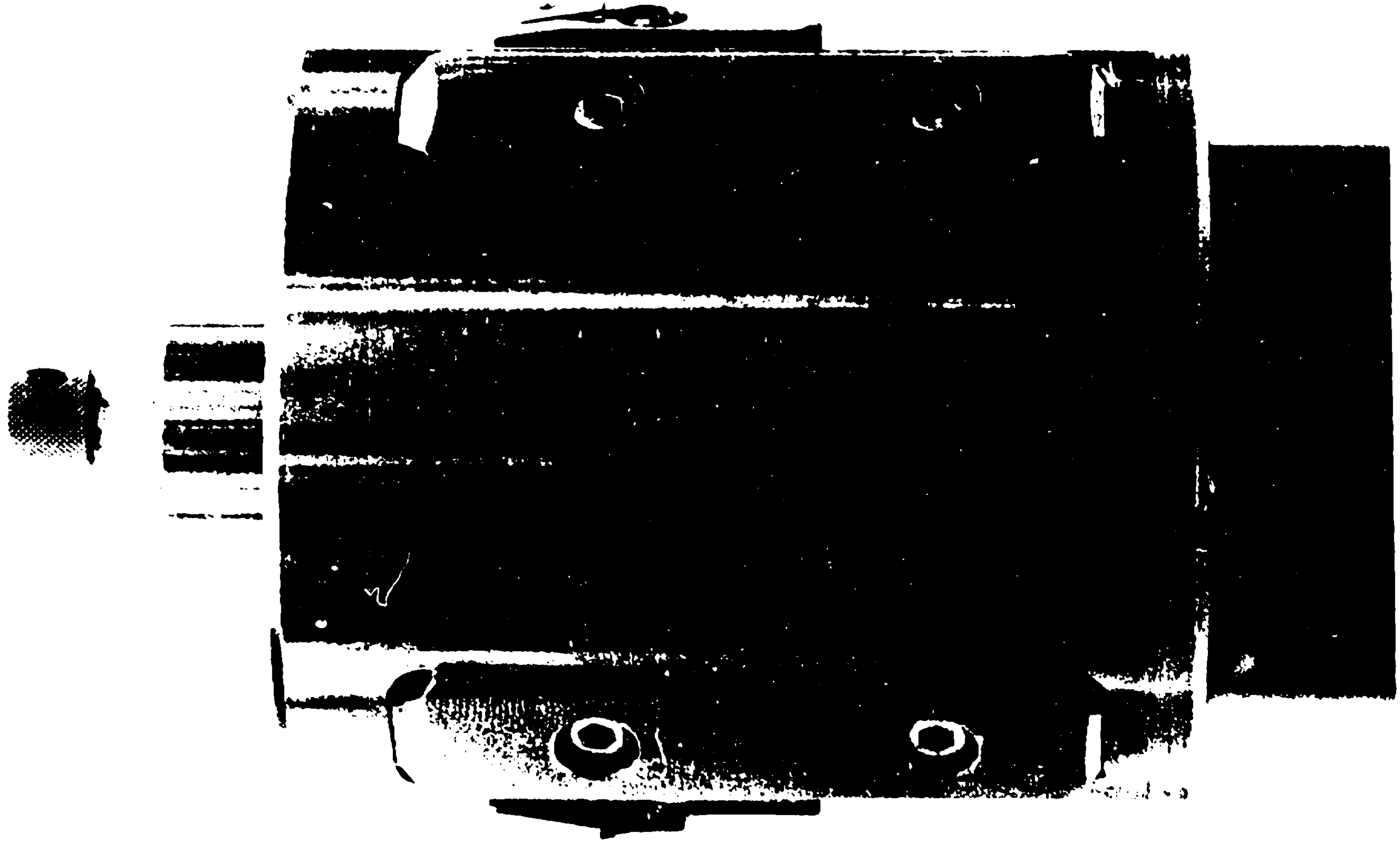


Figure 32. Side view of skiving head.

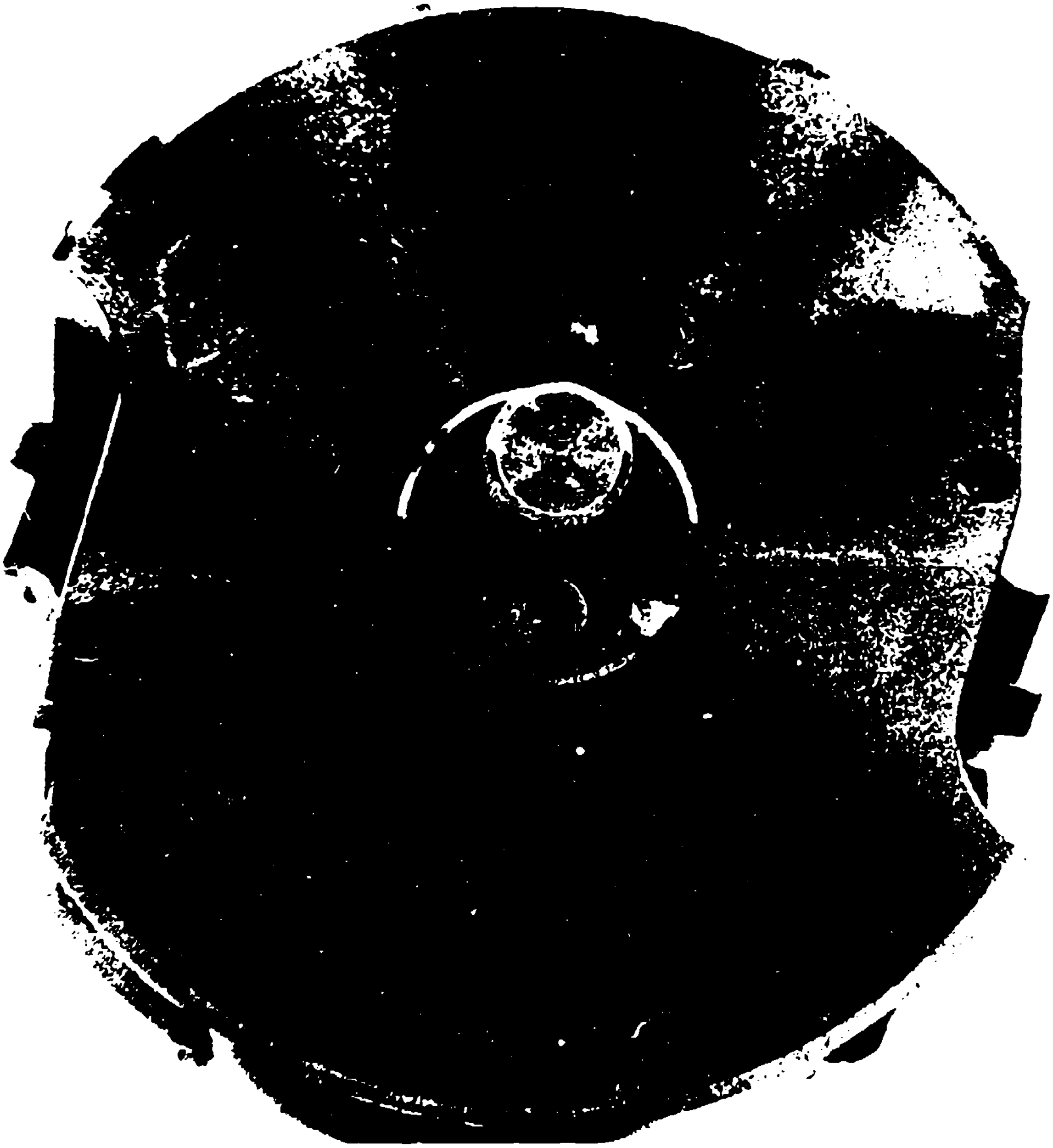


Figure 33. Front view of skiving head.

Figure 34. Chips produced from skiving operation on titanium beta-C cylinder.

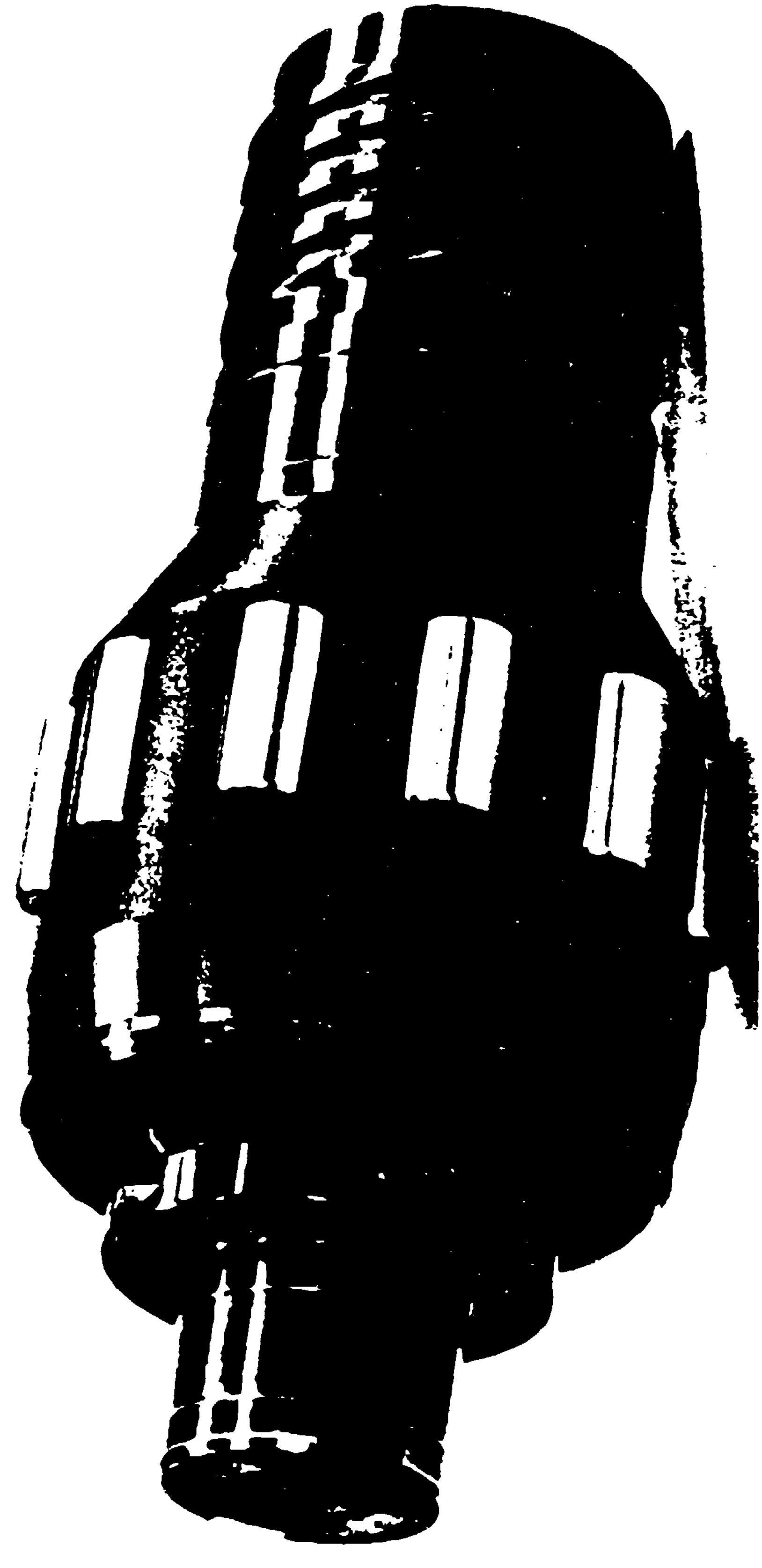


Figure 35. Side view of roller burnishing head.

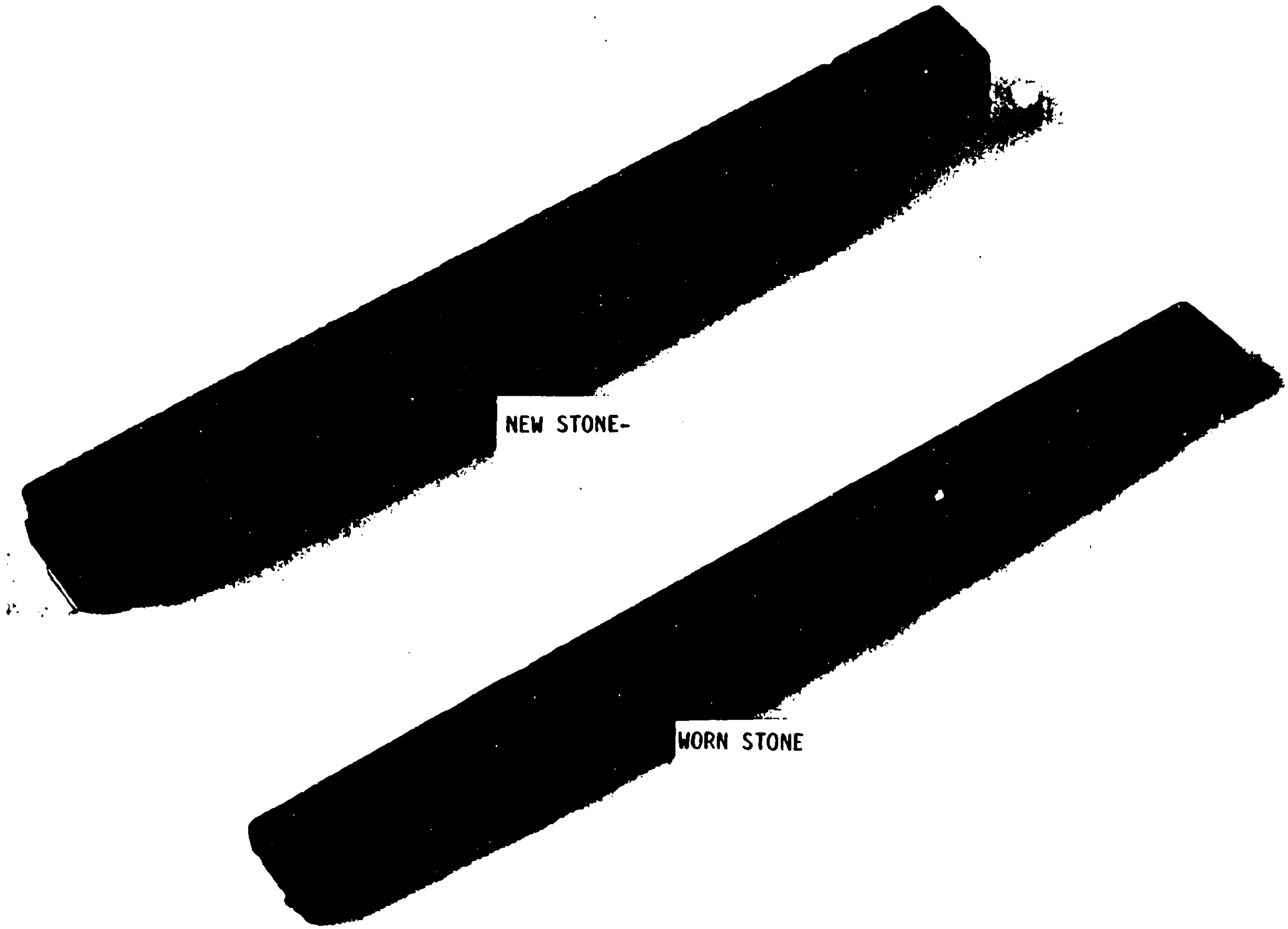
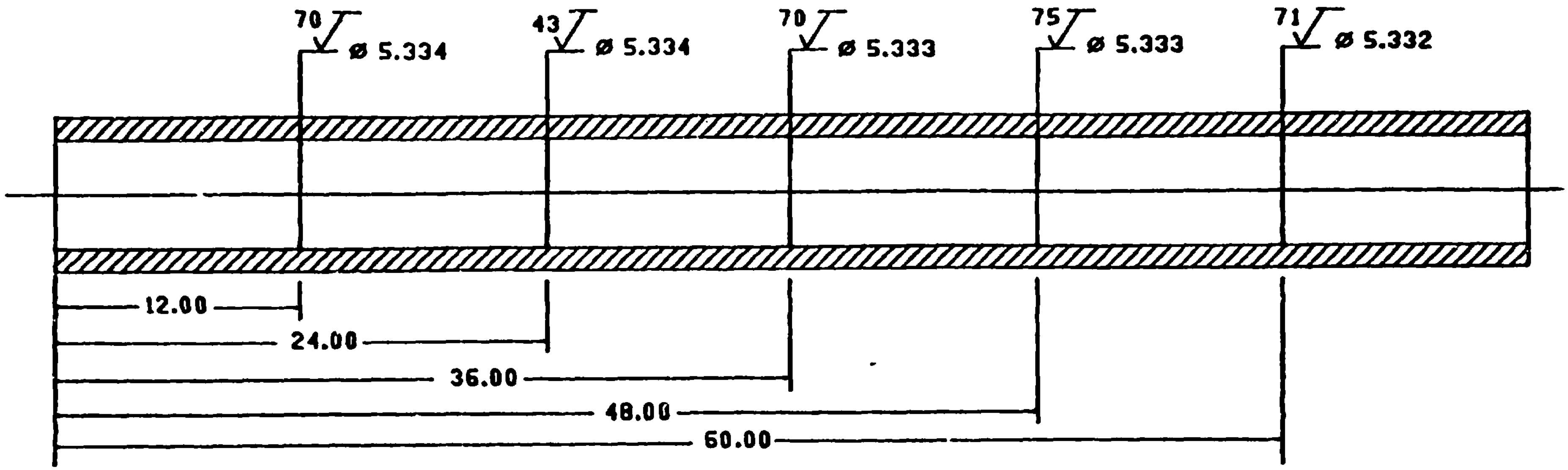
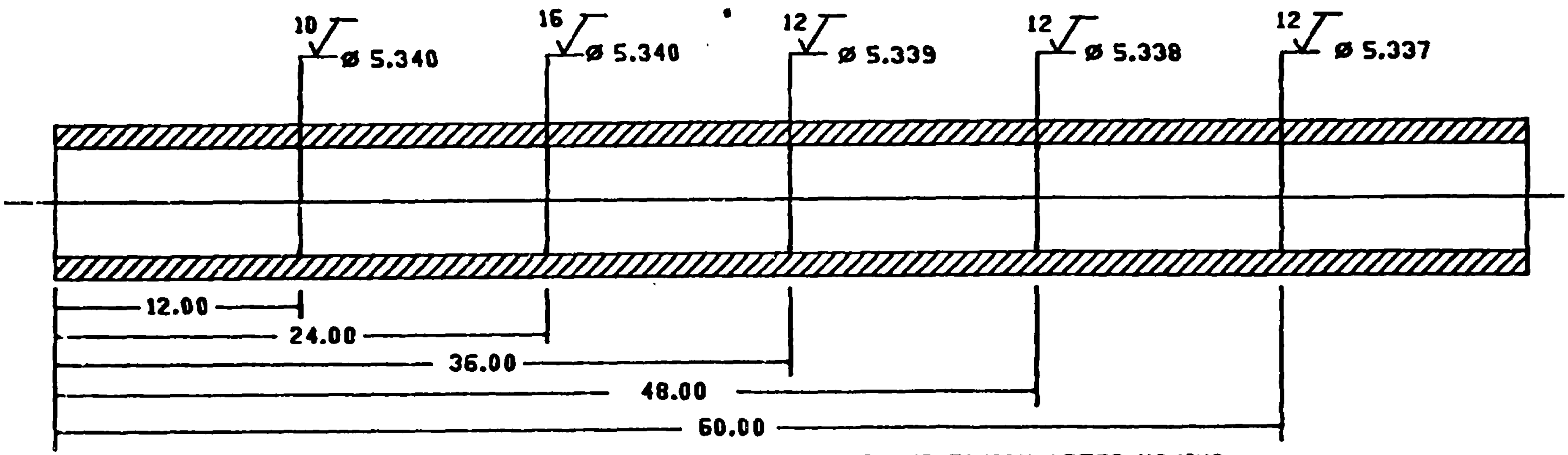


Figure 36. Aluminum oxide honing stones (A-240-V6S).



TUBE NO. 1 FINISH BORED THEN ROLLER BURNISHED SHOWING INSIDE DIAMETERS MEASURED WITH DIAL BORE GAGE AND FINISH CHECKED WITH PORTABLE PROFILOMETER



TUBE NO. 1 SHOWING INSIDE DIAMETERS AND FINISH AFTER HONING

MACHINABILITY TESTING OF TITANIUM BETA-C ALLOY TUBES

Figure 37. Tube profile before and after honing.

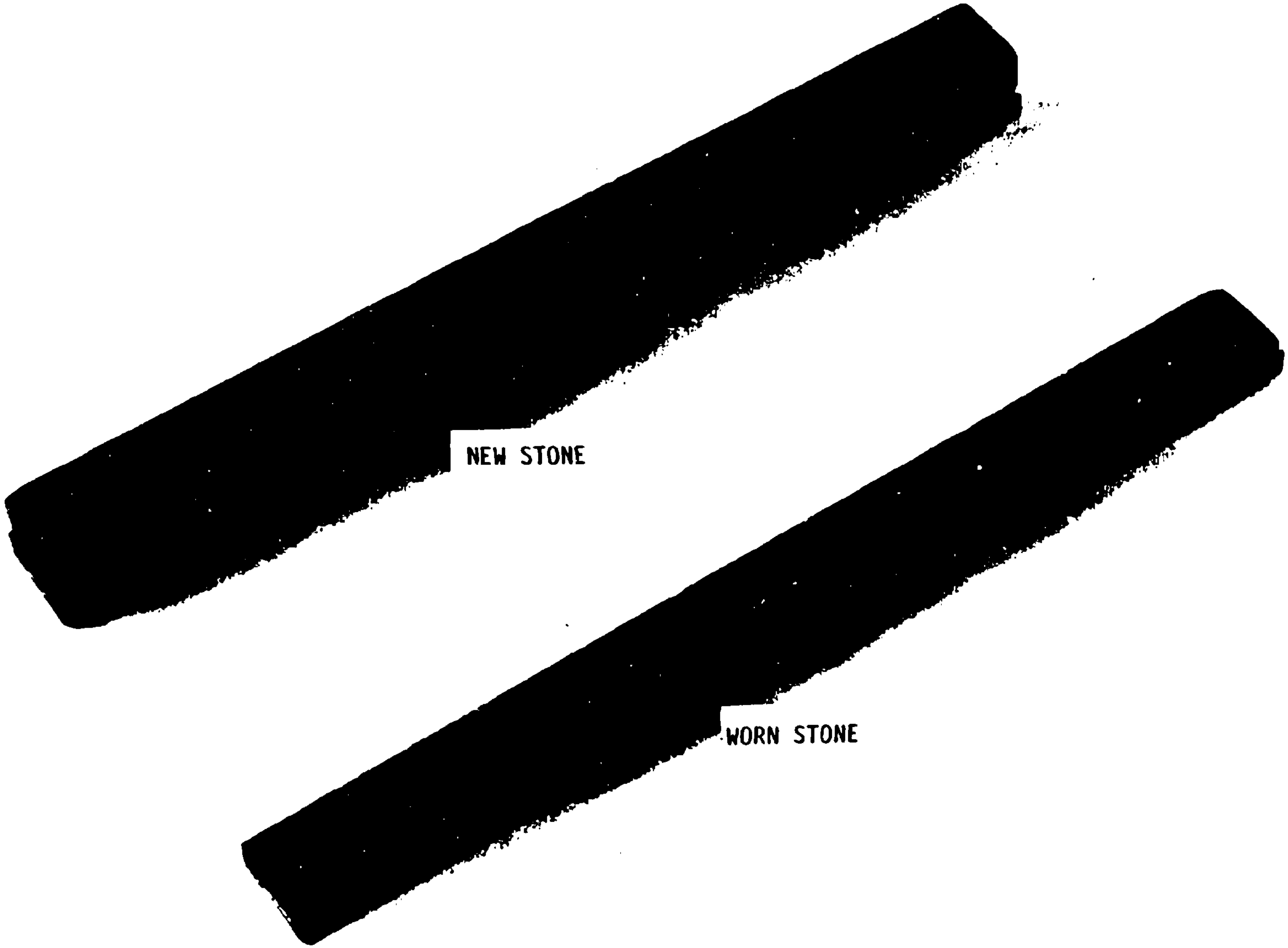


Figure 38. Silicone carbide honing stones (C320-L7-VX).

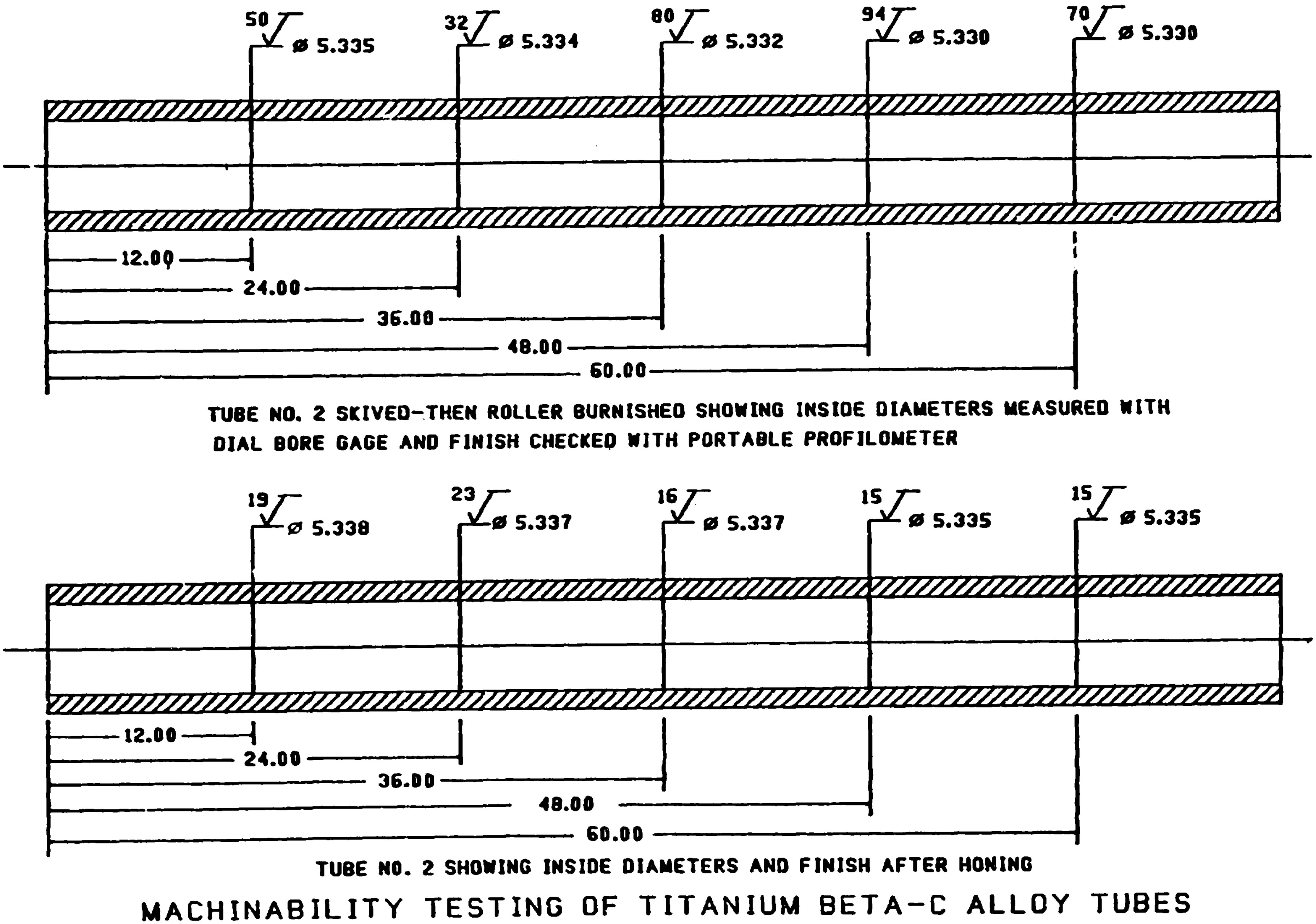


Figure 39. Tube profile before and after honing.

APPENDIX

Machinability Testing of Titanium 38-06-44 Alloy

MACHINABILITY TESTING OF TITANIUM 38-06-44 ALLOY

TUBE NUMBER 1

INSERT TYPE	GRADE	MANUFACTURER	CHIPBREAKER	LEAD ANGLE	RPM	FEED (IPR)	SURFACE FEED	BORING TOOL DIA.	LENGTH OF CUT	COMMENTS
SNMG-433	H10A	SANDVIK	FACTORY	15	61	.005	80	5.000	3"	STOPPED DUE TO BORING BAR HOLDER RUBBING ON BORE
SNMG-433	H10A	SANDVIK	FACTORY	15	82	.005	107	5.000	10 3/4"	INSERT EDGE BROKE
SNMG-433	3015	SANDVIK	FACTORY	15	82	.005	107	5.000	5/8"	INSERT NOTCHED AT D.O.C. STOPPED DUE TO NOISE
SNMG-432	K68	KENNAMETAL	FACTORY	15					0	DID NOT RUN
SNMG-433	H10A	SANDVIK	FACTORY	15	52	.005	68	5.000	0	DID NOT RUN
SNMG-432	K313	KENNAMETAL	FACTORY	15	82	.005	107	5.000	7 5/8"	INSERT BROKE
SNMG-4?2	K68	KENNAMETAL	FACTORY	15	82	.005	107	5.000	6"	INSERT BROKE
SNMA-433	H20	SANDVIK	NONE	15	82	.0037	107	5.000	6 1/2"	INSERT BROKE
SNMA 433	H20	SANDVIK	SHOP GROUND	15	82	.0037	107	5.000	2 1/4"	SEVERE CHIP WELD ON INSERT. STOPPED TEST
SNMG-432	K6	KENNAMETAL	FACTORY	15	82	.0037	107	5.000	7"	INSERT WORN BUT NOT BAD. CHIP BUILD UP ON PADS
SNMG-432	VIN	VALENITE	FACTORY	15	82	.0037	107	5.000	1 5/8"	TIN COATED. INSERT SLIGHTLY WORN. SEVERE VIBRATION
*	*	*	*	SAME INSERT EDGE * SAME PARAMETERS					2"	SAME RESULTS. SEVERE VIBRATION
SNMG-433	3015	SANDVIK	FACTORY	15	82	.0037	107	5.000	0	BLACK OXIDE COATED. INSERT BROKE IMMEDIATELY
*	*	*	*	SAME INSERT EDGE * SAME PARAMETERS					1 1/4"	SEVERE VIBRATION. BACKED OUT
*	*	*	*	SAME INSERT EDGE * SAME PARAMETERS					5"	6 1/4 TOTAL. NO BREAK JUST SEVERE VIBRATION/ NOISE
SNMG-432	K68	KENNAMETAL	FACTORY	15	82	.0037	107	5.000	5 1/4"	INSERT BROKE
SNMG-432	H13A	SANDVIK	FACTORY	15	82	.0037	107	5.000	2 3/4	SLIGHT INSERT FAILURE. BACKED OUT FOR EXCESS CHIPS
*	*	*	*	SAME INSERT EDGE * SAME PARAMETERS					9 1/4"	12" TOTAL. SLIGHT INSERT WEAR. 5.000" DIA THROUGH
TNMG-333	3015	SANDVIK	FACTORY	45	82	.0037	112	5.200	34"	VERY LITTLE INSERT WEAR. INDEXED ANYWAY
TNMG-333	3015	SANDVIK	FACTORY	45	82	.0037	112	5.200	13 1/4"	INSERT BROKE (CHATTER)
TNMG-333	3015	SANDVIK	FACTORY	45	82	.0037	112	5.200	12 1/4"	EXCESS PAD CHATTER w/ CHIP BUILDUP. MODERATE WEAR, INDEX INSERT
TNMG-333	3015	SANDVIK	FACTORY	45	82	.0037	112	5.200	12 1/2"	NO WEAR ON INSERT. BORE FINISHED

5.200" BORE FINISHED   FINISHED DIA. AT START- 5.1885"   FINISHED DIA. AT TUBE END- 5.170"

TABLE 1

MACHINABILITY TESTING OF TITANIUM 38-06-44 ALLOY

TUBE NUMBER 2

INSERT TYPE	GRADE	MANUFACTURE	CHIPBREAKER	LEAD ANGLE	RPM	FEED (IPR)	SURFACE FEED	BORING TOOL DIA.	LENGTH OF CUT	COMMENTS
TNMG-333	H13A	SANDVIK	FACTORY	45	82	.005	107	5.000	28"	LOWER GUIDE PAD BROKE OFF. EXCESS VIBRATION. INSERT NOT BAD
*	*	*	*	SAME INSERT EDGE * SAME PARAMETERS					10"	REAR PAD BROKE OFF. SEVERE VIBRATION. 38" TOTAL. FINISH EXCELLENT
TNMG-333	3015	SANDVIK	FACTORY	45	82	.005	107	5.000	14"	SEVERE VIBRATION. BACKED OUT & RETRIED
*	*	*	*	SAME INSERT EDGE * SAME PARAMETERS					7"	21" TOTAL. INSERT EDGE BROKE OFF
TNMG-333	H13A	SANDVIK	FACTORY	45	82	.005	107	5.000	10 1/2"	SEVERE CHIP GALL ON PADS & ADAPTOR. VIBRATION CAUSED INSERT BREAK
TNMG-333	H13A	SANDVIK	FACTORY	45	82	.005	107	5.000	2 1/2"	TUBE FINISHED
5.000" BORE FINISHED FINISHED DIA. AT START- 4.975 FINISHED DIA. AT TUBE END- 5.008										
ENTIRE FINISH RUINED BY CARBIDE PADS. LAST 20" VERY POOR DUE TO GALLING UP										
TNMG-333	H13A	SANDVIK	FACTORY	45	82	.005	112	5.210	9"	PADS GALLED UP. INSERT FAILED
SNMG-432	K6	KENNAMETAL	FACTORY	45	82	.005	112	5.210	9 1/2"	INSERT BROKE
ROUND	065N	SANDVIK	FACTORY	N/A	82	.005	112	5.210	0	INSERT BROKE IMMEDIATELY
TNMG-333	H13A	SANDVIK	FACTORY	45	82	.005	112	5.210	16 1/2"	INSERT HAD LITTLE WEAR. HOLDER CRACKED & BROKE
ROUND	065N	SANDVIK	FACTORY	N/A	82	.005	112	5.210	0	INSERT BLEW APART. PAD BROKE OFF.
TNMG-333	H13A	SANDVIK	FACTORY	45	82	.005	112	5.210	2 1/2	HOLDER BROKE.

TESTS SUSPENDED PENDING RE-TOOLING 5.2000" BORE HALF COMPLETE.

TABLE 2

MACHINABILITY TESTING OF TITANIUM 38-6-44 ALLOY

TUBE NUMBER 3

BORING

INSERT TYPE	GRADE	MANUFACTURER	CHIPBREAKER	LEAD ANGLE	RPM	FEED (IPR)	SURFACE FEED	TOOL DIA.	LENGTH OF CUT	COMMENTS
			MODIFIED HEAD. TWO (2) CUTTERS.			**DIVIDE FEED RATE (IPR) BY TWO FOR CHIP LOAD PER CUTTER**				
TNMG-333	H13A	SANDVIK	FACTORY	45	82	*.0097**	107	5.010	1"	SEVERE GALLING ON PADS. SLIGHT WEAR ON INSERTS. TORQUE ON BAR.
*	*	*	*	SAME INSERT EDGE * SAME PARAMETERS					2"	TOP PAD DESTROYED. EXTREME GALLING ON PADS. EXTREME VIBRATION.
TNMG-333	H13A	SANDVIK	FACTORY	45	82	*.0190**	107	5.010	61"	PADS REMOVED. (1) INSERT BROKE. 2nd INSERT HAD MODERATE WEAR.
						5.000" BORE FINISHED. FINAL SIZE 4.950".				
TNMG-433	H13A	SANDVIK	FACTORY	45	82	*.0329**	107	5.065	69"	FINAL SIZE 5.000". (1) INSERT BROKE. 2nd HAD MODERATE WEAR.

TUBE NUMBER 4

BORING

INSERT TYPE	GRADE	MANUFACTURER	CHIPBREAKER	LEAD ANGLE	RPM	FEED (IPR)	SURFACE FEED	TOOL DIA.	LENGTH OF CUT	COMMENTS
						MODIFIED HEAD. TWO (2) CUTTERS.				**DIVIDE FEED RATE (IPR) BY TWO FOR CHIP LOAD PER CUTTER**
TNMG-333	3015	SANDVIK	FACTORY	45	82	*.0320**	107	5.007	15"	TUBE RUNOUT .180". PADS MOVED BACK & TEFLON ADDED. PADS STILL GALLED UP. INSERTS NOTCHED AT DEPTH OF CUT.
TNMG-333	H13A	SANDVIK	FACTORY	45	82	*.0320**	107	5.007"	51"	PADS REMOVED. TEFLON WORE .030". INSERTS WORE .030". RUNOUT REMAINED IN FINISHED TUBE. SMALL PIECE TEFLON BROKE OFF.
						MODIFIED HEAD 2 CUTTERS (5.200) BRASS WEARPADS				
SNMG-433	H13A	SANDVIK	FACTORY	45	82	*.0210**	112	5.207"	35"	INSERTS (2) BROKE. CHECK SIZE 5.208 (6" FROM END OF TUBE) BRASS PADS WORE - .012. TEFLON RING 5.190.
SNMG-433	H13A	SANDVIK	FACTORY	45	82	*.0300**	112	5.207"	20 1/2"	INSERTS (2) BROKE. BRASS PADS AND TEFLON RING DID NOT CHANGE.
SNMG-433	H13A	SANDVIK	FACTORY	45	82	*.0400**	112	5.207"	9"	INSERTS (2) BROKE. PADS, RING DID NOT CHANGE.
SNMG-433	K313	KENNAMETAL	FACTORY	45	82	*.0400**	112	5.207"	10"	BORED THROUGH. 1ST INSERT BROKE BEFORE EXITING. 2ND CUT THROUGH. BRASS PADS WORN AFTER INSERT BROKE.

TABLE 3

MACHINABILITY TESTING OF TITANIUM 38-06-44 ALLOY

TUBE NUMBER 3

BORING

INSERT TYPE	GRADE	MANUFACTURER	CHIPBREAKER	LEAD ANGLE	RPM	FEED (IPR)	SURFACE FEED	TOOL DIA.	LENGTH OF CUT	COMMENTS
MODIFIED HEAD. TWO (2) CUTTERS. *DIVIDE FEED RATE (IPR) BY TWO FOR CHIP LOAD PER CUTTER*										
CHANGED TUBE. REPLACE PADS WITH HARDENED STEEL										
SNMG-433	K313	KENNAMETAL	FACTORY	45	60	.015*	80	5.207"	11"	CONTINUOUS CHIP. VIBRATION AND CHATTER BEGAN AT 7", CHIPS INTERFACED WITH PADS. RETRACT BAR. PADS GALLED. RESUME BORING AT 9". VIBRATION BEGAN PRIOR TO FULL CUT. RETRACT BAR, PADS GALLED WITH CHIPS.
SNMG-433	K313	KENNAMETAL	FACTORY	45	60	.030*	80	5.207"		RESUME BORING AT 9". VIBRATION BEGAN PRIOR TO FULL CUT. RETRACT BAR, PADS GALLED WITH CHIPS.
REMOVE STEEL PADS, SHIM WORN BRASS PADS TO 5.208 DIA.										
SNMG-432	XL202	EXCELLO COATED	FACTORY	45	40	.016*	54	5.207"	54	BORED THROUGH COMPLETE. INSERTS INTACT. MEAS. OVER INSERTS 5.207 (NO WEAR). MEAS. OVER BRASS PADS (SHIMMED) 5.185 (.022 WEAR) REMOVED SOME RUNOUT AT TUBE END.

TUBE NUMBER 2

BORING

INSERT TYPE	GRADE	MANUFACTURER	CHIPBREAKER	LEAD ANGLE	RPM	FEED (IPR)	SURFACE FEED	TOOL DIA.	LENGTH OF CUT	COMMENTS
USE TUBE THAT HAD BEEN BORED 36" DEEP TO 5.200 DIA. BORE WITHOUT PADS TO CLEAN OUT ROUGH BORE AND ESTABLISH COUNTERBORE DEPTH, RETRACT, ROTATE INSERT, ADD HARDENED STEEL PADS										
SNMG-432	XL202	EXCELLO (COATED W/TiN)	FACTORY	45	40	.030*	54	5.206"	1 1/4"	VIBRATED. RETRACT BAR. PADS LOST .002 FROM 5.200 TO 5.198.
SNMG-432	XL202	EXCELLO (COATED W/TiN)	FACTORY	45	40	.020*	54	5.206"	35"	REMOVED STEEL PADS. (PADS DO NOT SEEM PRACTICAL WITH 2 CUTTERS PERHAPS BECAUSE OF THEIR LOCATION). BORED WITHOUT PROBLEMS.
CHANGE TO 5.312 BORING HEAD WITH SINGLE CUTTER AND 2 CARBIDE PADS.										
SNMG-432	H-13A	SANDVIK	FACTORY	45	40	.008	54	5.318"	53"	VARIED FEED FROM.0065"/REV TO .012 WHEN VIBRATION STARTED 26" IN BORE. ROTATED INSERT. CONTINUE TO 53". VIBRATION - STOP CHECK.
SNMG-432	K-313	KENNAMETAL	FACTORY	45	40	.015	54	5.318"	3"	TRIED THIS INSERT BECAUSE OF THE LARGER CHIP BREAKER AREA FOR EASIER CHIP FLOW. NOT SUCCESSFUL. VIBRATION. STOP.
SNMG-432	E-6	EXCELLO	FACTORY	45	40	.008	54	5.318"	10"	BORING GOOD. GOOD CHIP. INTERMITTENT VIBRATION-CLEARS ITSELF. STOP, END OF WORK SHIFT.
SNMG-432	E-6	EXCELLO	FACTORY	45	40	.008	54	5.318	6"	COMPLETED BORING FROM PREVIOUS DAY. NO VIBRATION. FINISH GOOD. RUNOUT .011 IMPROVES EACH BORING PASS. CHECK I.D. - .018 TOOL VIBRATED OUT OF SEAT.

TABLE 4

MACHINABILITY TESTING OF TITANIUM 38-06-44 ALLOY

SKIVING

TO SET UP FOR SKIVING - ADAPTOR REQUIRED MODIFICATION FOR CUTTING OIL AS SKIVING HEAD DOES NOT ALLOW OIL TO FLOW THROUGH. HOLES WERE DRILLED AROUND PERIMETER OF ADAPTOR FACE (4) WITH PIPE THREADS. FITTINGS WITH COPPER TUBING WERE ATTACHED TO ALLOW OIL TO FLOW ON TO SKIVING CUTTERS AND CARRY CHIPS FORWARD. TOOL MADE TO TRIP SKIVING TOOLS TO RETRACT HEAD.

INSERT TYPE	GRADE	MANUFACTURER	CHIPBREAKER	LEAD ANGLE	RPM	FEED (IPR)	SURFACE FEED	TOOL DIA.	LENGTH OF CUT	COMMENTS
ATTACH SKIVING HEAD TO BORING BAR. SET CUTTERS TO 5.326.										
S-2	P-20	SANDVIK	FACTORY	SKIVING	40	.020*	54	5.326"	11 1/2"	NO PROBLEMS. STOP, TRIP TOOLS, RETRACT HARD TO CHECK FINISH AND TOOL INSERTS. FINISH VERY GOOD. INSERTS MEASURE 5.324 (-.002 DIA.) INDEX INSERTS.
S-2	P-20	SANDVIK	FACTORY	SKIVING	40	.020*	54	5.326"	32"	STOP, RETRACT, INSERTS WORN. FINISH LOOKS GOOD.
S-2	P-20	SANDVIK	FACTORY	SKIVING	20	.040*	30	5.326"	28"	CHECKED BORE, TAPERED 0/3. TOOL INSERTS WORN. FINISH GOOD. LEAVE HEAD EXTENDED, THROUGH TUBE. PROPOSE REVERSING SKIVING HEAD TO CUT BACK
THROUGH										TUBE TO ELIMINATE TAPER.
ROTATE INSERT, REVERSE FEED TO PULL BAR BACK THROUGH TUBE TO POSSIBLY ELIMINATE TAPER.										
S-2	P-20	SANDVIK	FACTORY	SKIVING	20	.040*	30	5.326"	24"	CHIP WAS GOOD UNTIL 24" INTO BORE, THEN CHANGED. STOP & RETRACT BAR (FORWARD) INSERT WASHED OUT.
CHANGE FEED DIRECTION TO BORE FORWARD TO TRY TO ELIMINATE SIZE DIFFERENTIAL IN TUBE.										
S-2	P-20	SANDVIK	FACTORY	SKIVING	20	.040*	30	5.326"	20"	STOP TO INSPECT INSERT. INSERT GOOD. MOVE BAR TO 18". RESUME SKIVING.
S-2	P-20	SANDVIK	FACTORY	SKIVING	20	.040*	30	5.326"	16"	STOP, CHECK INSERT. WORN OR WASHOUT. ROTATE TO NEW EDGE.
S-2	P-20	SANDVIK	FACTORY	SKIVING	20	.040*	30	5.326"	36"	SKIVED TUBE COMPLETE. CHECKED DIA. OVER INSERTS
S-2	P-20	SANDVIK	FACTORY	SKIVING	20	.040*	30	5.326"	72"	BORED TUBE COMPLETE WITH SKIVING HEAD TO CLEAN UP TAPER.

TABLE 5

ROLLER BURNISHING

SET ROLLER BURNISHING HEAD TO ID OF TUBE AT OPPOSITE END. BACK OFF .005 BY USING LINE INDICATOR ON FACE FOR POSSIBLE TAPER IN TUBE.
REMOVE SKIVING HEAD - MOUND ROLLER BURNISHING HEAD AT OPPOSITE END TO PULL THROUGH TUBE.
PULL ROLLER BURNISHING HEAD THROUGH TUBE AT 2"/MIN AT 20
RPM. FINISH SEEMED TO IMPROVE BUT COULD BE FROM HEAD WEIGHT AND NOT ACTUALLY ROLLER BURNISHING. WILL SPEAK
WITH SUPPLIER FOR NEXT ATTEMPT. LEAVE THIS TUBE IN MACHINE AND PREPARE 2-6' TUBES FOR BORING. ONE FOR WOOD PACKED REAMER, THE SECOND FOR BORING WITH FEWER
HEADS, THAT IS ELIMINATE THE 5" HEAD AND BORE WITH 5.200 FIRST. THREE TUBES WHICH WERE BORED TO 5.200 ID WILL BE FINISH BORRD TO 5.318, THEN SKIVING AND ROLLER
BURNISHING WILL BE RESUMED.
SPOKE TO SUPPLIER ABOUT ROLLER BURNISHING HEAD. HE ASSURED THAT THE HEAD WOULD COLLAPSE IF PRESSURE IS TOO GREAT THEREFORE, HEAD WILL NOT BE DAMAGED IF SET
TOO LARGE. A SECOND ATTEMPT AT ROLLER BURNISHING THE TUBE LEFT IN THE MACHINE WAS UNSUCCESSFUL AS THE HEAD WAS SET TO INTERFACE OR SIZED TO END OF TUBE. MACHINE
SET AT 44 RPM AND 3"/MIN FEED RATE (APPROXIMATELY .070"/PER REVOLUTION). ROLLS COLLAPSE.

SET ROLLER BURNISHING HEAD TO INTERFERE WITH I. D.- HEAD COLLAPSES. RESET UNTIL GAP IN LOCK SCREW MAINTAINS SAME DISTANCE. RUN THRU TUBE AT 44 RPM-3" PER MINUTE
FEED RATE. SEEMED TO ROLL SURFACE BUT UNABLE TO EVALUATE. (WILL MANUFACTURE SET RING FOR NEXT ATTEMPT.)

MACHINABILITY TESTING OF TITANIUM 38-06-44 ALLOY

TUBE NUMBER 5

BORING

INSERT TYPE	GRADE	MANUFACTURER	CHIPBREAKER	LEAD ANGLE	RPM	FEED (IPR)	SURFACE FEED	TOOL DIA.	LENGTH OF CUT	COMMENTS
CHANGE TUBE TO FIRST OF FOUR PREPARED WITH 5.318 IN. COUNTERBORE. USE SINGLE TOOL BORING HEAD WITH 2 CARBIDE GUIDE PADS. .570" DIAMETRIC STOCK REMOVAL.										
TNMG-332	K-313	KENNAMETAL	FACTORY	45	40	.010	55	5.318	9 "	INTERMITTENT VIBRATION. INSERT TIP BROKEN. ROTATE TIP.
TNMG-332	K-313	KENNAMETAL	FACTORY	45	40	.010	55	5.318	10 1/2 "	VIBRATION CONTINUES. STOP RETRACT TOOL. INSERT BROKEN. CHANGE INSERT.
TNMG-333E	E-6	EXCELLO (UNCOATED)	FACTORY	45	40	.010	55	5.318	38"	CHIPS CURL AND BREAK. NO VIBRATION . STOP. END OF SHIFT.
TNMG-333E	E-6	EXCELLO (UNCOATED)	FACTORY	45	40	.010	55	5.318	14"	USED SAME TOOL FROM PREVIOUS DAY'S BORING CUT. RESUME BORING. FINISH TUBE LAST 10". CHIPS BRAKE. NO VIBRATION.
CHANGE TO SKIVING HEAD										
SKIVING										
S-2	P-20	SANDVIK	FACTORY	SKIVING	32	.020	44	5.327	24"	HONED INSERT CUTTING EDGE PRIOR TO SKIVING OPERATION.STOPPED TO CHECK TOOL AFTER 24" CUT. TOOL SEEMED TO BE O.K RESUME SKIVING.
S-2	P-20	SANDVIK	FACTORY	SKIVING	32	.020	44	5.327	2"	BEGAN TO MAKE NOISE IMMEDIATELY AS IF MATERIAL WAS WORK HARDENED STOP, RETRACT BAR. TOOL WORN BADLY.
REMOVE SKIVING HEAD - REPLACE WITH BORING HEAD										
BORING										
SINGLE TOOL WITH 2 CARBIDE WEAR PADS										
TNMG-333E	E-6	EXCELLO	FACTORY	45	40	.010	55	5.335	72"	BORE COMPLETE TO IMPROVE FINISH. .010" DIA. STOCK REMOVAL
CHANGE TO ROLLER BURNISHING HEAD										
ROLLER BURNISHING										
SET ROLLER BURNISHING HEAD. SET MACHINE SPINDLE SPEED TO 22 RPM, BAR FEED AT 2.618" PER MINUTE. RUN BURNISHING HEAD THROUGH COMPLETE TUBE, 72". FINISH SEEMED TO BE IMPROVED. I.D. DID NOT CHANGE.										

TABLE 7

MACHINABILITY TESTING OF TITANIUM 38-06-44 ALLOY

TUBE NUMBER 6

BORING

INSERT TYPE	GRADE	MANUFACTURER	CHIPBREAKER	LEAD ANGLE	RPM	FEED (IPR)	SURFACE FEED	TOOL DIA.	LENGTH OF CUT	COMMENTS
			LOAD ANOTHER TUBE- INSTALL 5.312"DIA. BORING HEAD WITH SINGLE TOOL AND 2 CARBIDE WEAR PADS. STOCK REMOVAL .570" DIAMETRICAL							
TNMG-333	E-48	CARBALOY	FACTORY	45	40	.010	55	5.323	48"	DEVELOPED VIBRATION DURING BORING. STOP, RETRACT BAR. INSERT BROKEN. REPLACE.
TNMG-333	E-48	CARBALOY	FACTORY	45	40	.010	55	5.323	24"	NO VIBRATION FOR FIRST 6," THEN PADS HEATED UP AND VIBRATION CONTINUED THROUGHOUT REMAINDER OF TUBE, APPROXIMATELY 18"
TNMG-333	E-6	EXCELLO	FACTORY	45	40	.010	55	5.333	72"	BORED TUBE COMPLETE TO IMPROVE FINISH..010" DIA. STOCK REMOVED.

ROLLER BURNISHING

CHANGE TO ROLLER BURNISHING HEAD. SET HEAD FOR .005" INTERFERENCE. SET MACHINE AT 22 RPM AND 2.616" FEED PER MINUTE. CHECKED I.D. BEFORE AND AFTER WITH PORTABLE PROFILOMETER . FINISH REMAINED THE SAME.

ATTEMPTED TO ROLLER BURNISH A SECOND TIME SETTING THE HEAD TO 5.340" DIA. FINISH REMAINED THE SAME AS DID THE DIA. ROLLERS COLLAPSED.

TUBE NUMBER 7

BORING

MODIFIED HEAD. TWO (2) CUTTERS. **DIVIDE FEED RATE (IPR) BY TWO FOR CHIP LOAD PER CUTTER**

LOAD NEW TUBE INTO MACHINE. ATTEMPT TO BORE WITH INCREASED CHIP LOAD BY USING THE 5.200" HEAD WITHOUT BORING FIRST WITH THE 5.000" HEAD. THE 5.200" HEAD HAD BEEN MODIFIED TO A TWO CUTTER HEAD AND A TEFLON RING ATTACHED TO THE BODY OF THE BORING HEAD. GUIDE PADS WERE ALSO REMOVED.

INSERT TYPE	GRADE	MANUFACTURER	CHIPBREAKER	LEAD ANGLE	RPM	FEED (IPR)	SURFACE FEED	TOOL DIA.	LENGTH OF CUT	COMMENTS
SNMG-432	E-6	EXCELLO (UNCOATED)	FACTORY	45	40	.016*	55	5.200	60"	BORING WAS VERY SUCCESSFUL REMOVING .450" OF STOCK FROM THE I.D. WITH THE CHIPS CURLING AND BREAKING FOR 60". ONE INSERT APPARENTLY BROKE CAUSING HEAVY VIBRATION .STOPPED AND RETRACTED BAR. FOUND THE TEFLON RING HAD BROKEN ALSO ALONG WITH THE INSERT. REMOVED THE RING AND REPLACED THE INSERT.
			MADE ANOTHER ATTEMPT AT BORING WITHOUT THE TEFLON RING WITHOUT SUCCESS. VIBRATION BEGAN IMMEDIATELY AND INSERT BROKE. CHANGED BACK TO 5.000" BORING HEAD.							
SNMG-432	E-6	EXCELLO (UNCOATED)	FACTORY	45	40	.016*	55	5.000	12"	BORED COMPLETE WITHOUT INCIDENT, LAST 12". CHANGED BORING HEAD BACK TO 5.200" DIA.
SNMG-432	E-6	EXCELLO (UNCOATED)	FACTORY	45	40	.016*	55	5.200	12"	BORED REMAINDER OF STOCK FROM TUBE, LAST 12".
			CHANGE TO 5.312" DIA. BORING HEAD WITH SINGLE CUTTER AND 2 CARBIDE WEAR PADS.							
TNMG-433	E-6	EXCELLO (UNCOATED)	FACTORY	45	40	.016	55	5.326	12"	HEAVY VIBRATION BEGAN ALMOST IMMEDIATELY. INSERT FAILED 12" IN BORE. FEED TOO HEAVY. STOP, INDEX TOOL.
TNMG-433	E-6	EXCELLO (UNCOATED)	FACTORY	45	40	.010	55	5.326	18"	BEGAN TO VIBRATE 30" INTO BORE. STOP RETRACT BAR, CHANGE INSERT TO SANDVIK H-13.
TNMG-433	H-13A	SANDVIK	FACTORY	45	40	.010	55	5.326	21"	BORED THROUGH 20" OK UNTIL VIBRATION BEGAN AND INSERT BROKE. STOP RETRACT BAR. BAR STOPPED WHILE RETRACTING. PULLEY BROKE. TESTS SUSPENDED FOR MACHINE REPAIR.

TABLE 8

MACHINABILITY TESTING OF TITANIUM 38 06-44 ALLOY

MACHINE REPAIRED AND READY FOR USE

TUBE NUMBER 8

WOOD PACKED REAMER BORING

REMOVED BORED TUBE. LOAD TUBE PREPARED FOR WOOD PACKED REAMER. COUNTERBORED FROM ROUGH TO 5.318" DIA.

INSERT TYPE	GRADE	MANUFACTURER	CHIPBREAKER	LEAD ANGLE	RPM	FEED (IPR)	SURFACE FEED	TOOL DIA.	LENGTH OF CUT	COMMENTS
H.S.S.		BRAECUT	TOOLROOM	45	17	.010	23	5.318	4"	AFTER A SHORT DISTANCE BEGAN TO CHATTER BADLY AND HAD TO STOP. RETRACTED BAR , TOOLS BADLY WORN. REMOVED REAMER AND HAVE TOOLS RE-SHARPENED AND RE-SET TO SIZE. IT WAS SUGGESTED THAT INCREASING THE FEED MAY HELP.
H.S.S.		BRAECUT	TOOLROOM	45	17	.020	23	5.318	3"	VIBRATION BEGAN AGAIN AFTER A SHORT DISTANCE. STOPPED AND RETRACTED BAR. TOOLS BADLY WORN AGAIN. HAVE HEAD RE-WORKED.
H.S.S.		BRACUT	TOOLROOM	45	22	.007	30	5.318	2 3/4"	BEGAN TO VIBRATE AND TOOLS FAILED. TERMINATE WOOD PACKED REAMER BORING TEST.

HONING TESTS

CHOSE TWO TUBES FOR HONING TESTS. ONE WAS PROCESSED BY SKIVING THEN ROLLER BURNISHING, THE OTHER WAS BORED COMPLETE WITH A FINISH BORING PASS. BOTH TUBES WERE CHECKED AND PROFILES RECORDED WITH RESPECT TO SIZE AND FINISH, THE RANGES OF WHICH WERE SIMILAR. INSIDE DIAMETERS RANGED FROM 5.330" TO 5.335" AND FINISHES RANGED FROM 32 TO 100 RMS. ONE TUBE WAS HONED USING ALUMINUM OXIDE STONES, THE OTHER WAS HONED USING SILICONE CARBIDE STONES.

TUBE #1 - HONED USING 12, A- 240-V6S ALUMINUM OXIDE STONES.

BAR SPEED - 105 RPM.

TRAVERSE SPEED - 45 FEET PER MINUTE.

STOCK REMOVAL RATE - .0003" PER MINUTE.

FINISH WAS IMPROVED FROM 65 TO 12 RMS.

TUBE #2 - HONED USING 12, C-320-L7-VX SILICONE CARBIDE STONES.

BAR SPEED - 105 RPM.

TRAVERSE SPEED - 45 FEET PER MINUTE.

STOCK REMOVAL RATE - .0005" PER MINUTE.

FINISH WAS IMPROVED FROM 65 TO 18 RMS.

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