SOLID FILM LUBRICATED CUTTING TOOLS

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The effect of solid film lubricants on tool life was investigated under the Navy Manufacturing Technology (MT) Program. Various solid lubricant formulations were evaluated in tapping and drilling oeprations on a laboratory device designed to measure the tapping efficiency of cutting fluids. The metallurgy of the workpieces studied included AISI 1020 and 4130 steels, 7075-T6 aluminum, 17-4 PH stainless steel, L-605 cobalt base alloy and Ti-6Al-4V alloy.

(continued)

The solid film lubricant was applied to high speed steel taps and drills and evaluated by measuring the torque developed or the number of holes the cutting tool could produce. Base line studies on uncoated cutting tools with and without the use of cutting fluid were also performed. Under the experimental conditions of this program no substantial benefit could be achieved.

S U M M A R Y

INTRODUCTION

The use of solid lubricants (MoS_2, graphite, etc.) in the form of a coating to reduce wear of both metallic and non-metallic components is widely recognized. Their ability to carry high loads and function in extreme environments offers a decided advantage over conventional liquid or grease lubricants. One area of application for solid lubricants which has received very limited attention involves machine tools. The fabrication and rework of military aircraft weapons systems requires a significant amount of metal removal operations and as such cutting tools are extensively utilized. The application of any concept which could extend the life of these tools and/or make such operations less time consuming would result in the achievement of significant cost savings both in materials and manpower. In addition, if the material removal process could be performed without the use of a cutting fluid added advantages would be realized, e.g., a saving of petroleum products which are in short supply, fewer problems in complying with OSHA regulations and the elimination of metalworking fluid handling/disposal processes.

With these goals in mind, a program was established at the Naval Air Development Center (NAVAIRDEVCEN) under the auspices of the Navy Manufacturing Technology (MT) program. The objective of this program was to establish manufacturing guidelines covering the application of solid film lubricants to cutting tools aimed at extending tool life, improving quality of work and/or increasing the production rate. This effort was to include procurement of test equipment, establishing a data base for current methods, evaluation of various coatings and the initiation of industry/government evaluations of the most promising coatings.

RESULTS

The following is a general summary of the major findings resulting from this program under the experimental conditions established.

1. The use of solid film lubricated taps and drills without cutting fluid showed no improvement in tapping torque or drill life compared to uncoated cutting tools evaluated with cutting fluid.

2. The use of cutting fluid dramatically reduces the tapping torque generated in most cases; the exception being found for the harder to lubricate workpieces such as L-605 and Ti-6Al-4V alloys.

3. A reduction in tapping torque as high as 37% was achieved for certain workpiece/coated tap/cutting fluid combinations compared to tests with cutting fluid only. Other combinations exhibited increased torque values as high as 31%.

4. Endurance tapping tests performed for either 60 or 120 holes on a limited number of selected workpiece/coated tap/cutting fluid

combinations exhibited similar average tapping torques compared to tests using cutting fluid only.

5. L-605 and Ti-6Al-4V alloys failed endurance tapping testing in less than 60 holes. In multiple pass testing on Ti-6Al-4V a significant improvement in the number of holes was obtained for coated tap with cutting fluid compared to test with cutting fluid only, however, the results could not be repeated. A similar result was achieved in drilling tests with Ti-6Al-4V.

CONCLUSIONS

The use of solid film lubricated taps and drills has not been shown to provide significantly improved tool life under the experimental conditions established in this program. Previous studies have shown ambiguous results wherein significant improvements have been achieved under certain laboratory or production types of environments while in other studies no improvement was observed. These results are probably due to lack of control of the many parameters associated with this technology, e.g., feed rate, cutting speed, tool metallurgy and design, cutting fluid, workpiece dimensions, etc. This suggests that fundamental studies are required wherein the aforementioned parameters are varied over a representative range of extremes in order to determine basic relationships.

RECOMMENDATIONS

Where production type testing of solid film lubricated cutting tools has proved favorable, studies to determine suitable Naval Air Rework Facility (NAVAIREWORKFAC) applications should be performed.

In order to better define those areas of application where solid film lubricated cutting tools would be expected to provide beneficial results, fundamental studies should be performed.

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BACKGROUND

The technology of solid film lubrication has been reviewed in several excellent publications (1,2,3) and will not be further discussed here. Studies on the application of solid film lubricants to cutting tools have shown ambiguous results. Sentyurikhina and Nikolaeva (4) reported that the wear resistance of taps and screwing dies used on Mn-C-Ni-Cr steel 45 was increased 100%, the life of milling cutters working on aluminum alloy AL-4 increased 100 to 150%, the life of form tools cutting Cr-Mn-Ti steels (18 KHBT and 25 KHGT) increased 50 to 100% and the life of reamers working on steel 40R increased 50%. Additional studies showed that the life of 3.2 to 12 mm (0.126 to 0.472 in.) drills used on Cr-Mn-Si (30 KHGSA) was increased 300%. The life of milling cutters used on titanium was increased 100%. The life of taps was five times greater and the life of timber saws was increased 200%. All of the above results used a solid film lubricant containing molydenum disulfide (MoS_2) lubricating pigment.

A study coordinated by the Aeronautical Analytical Rework Program at NAVAIRDEVCEN (5) reported on the findings of various military facilities using solid film lubricant coated tools in a productive environment. The following paragraphs summarize the results reported in reference (5).

NAVAIREWORKFAC, Alameda has done considerable work using Microseal 100-1 on ten types of cutters used in tape machines. These cutters include: staggered tool side mill, cobalt steel end mill, helical end mill, side cutter (staggered tooth), double margin PMJ mill, and carbide end mill. Microseal 100-1 is graphite, impinged permanently by a patented air tool into the surface of the metal. It was reported that the tool life was extended by eight times when these coated tools were used on aluminum.

At the NAVAIRDEVCEN, one evaluation studied the effect of solid film lubricant coatings when drilling a titanium alloy. The three coatings were:

1. MIL-L-81329 - Lubricant, Solid Film Extreme Environment
2. MIL-L-23398 - Lubricant, Solid Film, Air Drying
3. NAVAIRDEVCEN B-9 Formulation with ATA and Graphite

A table drill press, using a No. 10 drill made of high-speed steel and rotating at 300 rpm was used to drill 100 holes into 0.32 cm (0.125 in.) Ti (6Al-6V-2Sn) alloy. A sulphurized oil was used as a coolant for the uncoated drill. Using a MIL-L-81329 coating, 100 holes were completed before the drill was considered dull. The MIL-L-23398 coating resulted in the last 30 holes out of a 100 having burrs, and the B-9 special formulations had burrs from the beginning with the last 25 holes extremely hard to drill. In comparison using the uncoated drill with coolant oil, only the first two holes had no burrs. Cobalt shell mills coated with a MIL-L-8937B material were also evaluated. The coated shell mill completed 15 sides of the specimens whereas the uncoated shell mill completed five sides and half-completed five more sides.

The Naval Air Engineering Center (NAVAIRENGCEN) evaluated some indexable inserts, twist drills and taps. The indexable inserts were used on AMS 5643 stainless steel. Inserts coated with MIL-L-8937 lubricant obtained a 50 percent deeper cut which decreased the manhours spent on the job. On twist drills, the MIL-L-8937 coating increased the number of finished workpieces only by one but there was less buildup of welded material on the drill tip. The tapping process normally requires the use of two taps (one undersize) to prevent tearing of the thread and produces two or three holes. The taps, coated with C 2502, tapped 12 holes to size in one pass through each hole.

NAVAIREWORKFAC, North Island, under the auspices of Engineering Proposal 4021, evaluated taper locks, drills and reamers coated by Bogg's File Sharpening Company. The extension of wear life on the ball mills was almost three-fold. The tap life was extended by seven times in addition to the savings resulting from not having to remove broken taps.

A study performed by the Northrop Corporation (6) on the effect of solid film coatings on tool life produced the following conclusions for milling operations:

1. Solid film coatings exhibited lower wear rate and resultant cutting forces under laboratory machining conditions.

2. Boggs A-2513 coating prepared to meet MIL-L-46010 specification, had the highest performance rating when milling AISI 4340, Ti-6Al-4V and L-605 under laboratory conditions.

3. Coated cutting tools had the same tool life as uncoated tools when machining 7075-T7351 aluminum, 4130, 4330M HSLA steels and Ti-6Al-4V airframe components under production conditions.

4. Solid film coatings had no beneficial effect on cutting tool life when used in a production environment.

5. Laboratory test methods of coated cutter evaluations cannot be correlated to production machining operations.

Mr. R. Hegler reported in reference (7) on the solid film lubricants being tested on some machining operations at the Naval Ordnance Station (NOS), Louisville, Kentucky. For some milling operations using mills sprayed with solid film lubricant favorable results were achieved. On other operations such as drilling, tapping, etc. there was no noticeable improvement.

Limited work performed at NAVAIREWORKFAC, Jacksonville (8) showed that a MIL-L-8937 film provided the best improvement in tool life of the coatings that were evaluated. With a 4340 workpiece 1.6 cm (0.625 in.) thickness, and a high speed tool steel drill coated with MIL-L-8937, 90 holes were drilled before the tool required sharpening. With the uncoated drill only 30 holes could be made. On H-11 steel using carbide drills capability increased from 2 holes to 6-8 holes. An astounding result was achieved on Al 2024-T4 0.95 cm (0.375 in.) plate where the uncoated drill lasted for 1200 holes while the coated drill produced 32,000 holes.

E X P E R I M E N T A L

TEST EQUIPMENT

The test apparatus used in this program has been previously described (9), (10); it consists of a small drill press with a floating table. A Research Appliance Company, Model No. 1155 cutting fluid tester was modified by replacing the standard dynamometer torque indicating scale with an electronic recorder which receives signals from a load cell attached to the torque arm on the floating table and a pneumatic system was installed which provided a constant feed mechanism. Figure 1 is an overall view of the experimental set-up. Figure 2 is a close-up view of the tapping head and vise for holding the workpiece.

TEST SPECIMENS

The nominal metallic composition of the workpieces used in this program is given in Table 1. The measured hardness in both Rockwell and BHN hardness numbers is shown in Table II. The workpieces for the tapping tests were prepared according to Figure 3. The drilling test workpieces are the same dimensions as the tapping test workpieces but without the holes. The taps were 0.64 cm (0.25 in.) 20 NC plug, HSS precision ground while the drills were 0.64 cm (0.25 in.) high speed twist drills conforming to National Standards Association, Inc. (NAS) specification 907.

COATINGS AND CUTTING FLUIDS

The various coatings evaluated in this program are listed in Table III. In some cases, the coatings were applied by the manufacturer and were used as received. Some of the coatings were prepared in-house using commercially available solid film lubricant formulations. No surface pretreatments were used with these coatings. One coating (ATA-2) was both formulated and applied in-house using a formulation consisting of 7.5 g ATA powder, 3 g graphite and 67 g phenolic resin conforming to MIL-R-3043.

A list of the cutting fluids used is found in Table IV.

TEST PROCEDURES

Tapping (Six-Hole Test)

Six holes are tapped and the maximum torque developed for each hole is used to obtain an average torque. A new tap is used for each six-hole test.

Tapping (Endurance Test)

Holes are continuously tapped until either 120 or 60 holes are achieved in one pass.* The maximum torque developed for each hole is used to obtain an average torque. In tests where 60 tapped holes could not be achieved in one pass, the number of tapped holes was recorded and average torques reported. In some tests multiple passes were attempted and the number of passes required to tap the hole was recorded. A new tap was used for each endurance test.

Drilling

The test apparatus required converting the tapping head to the drilling head. Once the drilling head was installed a modification was needed on the pneumatic system piston linkage in order to achieve proper cutting depth. On attempting to drill the first hole it was found that not enough force was present to penetrate the workpiece. Since deadlines had been established for reporting of data, it was decided to commence testing via the manual mode even though the feed rate would not be constant. The number of holes that could be produced, before failure, was reported. Failure was determined by noting drill breakage or chipping or the inability to produce the next hole. Torque readings were recorded for the initial tests. These appeared to be a function of the feed rate and pressure exerted by the operator and varied accordingly. All of the readings were rather low (230 g.m (20 in. lb.) or less) even when a significant force was required by the operator to complete the hole. Because of this subsequent readings were not obtained.

TEST CONDITIONS

All tests (tapping and drilling) were conducted at a tool speed of 7.62 surface meters per minute (25 surface feet per minute) which is equivalent to 385 revolutions per minute.

Cutting fluids were applied to the cutting tool just prior to entering the workpiece. The entire area was thoroughly wetted with the cutting fluid. If the cutting fluid was contained in an aerosol can it was directly sprayed onto the surfaces. Otherwise, a syringe was filled with the fluid and used to distribute the fluid on the cutting tool and workpiece.

RESULTS AND DISCUSSION

TAPPING

Six-Hole Tests

Appendix A contains the data generated under the six-hole test phase of this program. Table V summarizes the average torques obtained for the following conditions: dry, cutting fluid only, coated tap only. As is to be expected the torques for the dry condition are extremely

*A pass is defined as the cutting tool entering the workpiece and then being retracted.

high in the neighborhood of 690-920 g.m (60-80 in. lb.). The use of cutting fluid dramatically reduces the torque generated in most cases the exceptions being found with the harder to lubricate workpieces such as L-605 and Ti-6Al-4V. The use of a coated tap without cutting fluid, in general, exhibited higher torques when compared to the cutting fluid only tests.

Table VI summarizes the results obtained on the use of coated taps in the presence of cutting fluids. For comparison purposes Table VII was prepared showing the percent change in tapping torque for the combined cutting fluid - coated tap tests relative to the tests with cutting fluid only. As can be observed for certain workpiece/coated tap/cutting fluid combinations, a reduction in torque as high as 37% was achieved. Other combinations exhibited increased torque values as high as 31%.

At this point in the program, it was not certain how the degree of reduced torque observed in the six-hole tests for some of workpiece/coated tap/cutting fluid combinations would translate into prolonged tool life, therefore, a selected number of endurance tests were performed.

Endurance Tests

Appendix B contains the data generated under the endurance test phase of this program. Table VIII summarizes the average torque values obtained for bare tap-cutting fluid tests and coated tap-cutting fluid tests. For the first three combinations studied the average torque was approximately the same for both test conditions. The SS 17-4/RMF/5306 combination in the six-hole test exhibited a 31% increase in torque compared to the bare tap-cutting fluid test, while the 4130/MM27/C2502 combination exhibited a 25% decrease in torque compared to the bare tap-cutting fluid test. The first test where at least 60 holes could notbe achieved in one pass occurred in the L-605/RMF/C2502 combination. For the bare tap with cutting fluid 12 holes were tapped before the tap would not go through the 13th hole. With the coated tap and cutting fluid this occurred at the 17th hole. The average torque in both cases was approximately the same, 592 g.m (51.4 in. lb.) vs. 629 g.m (54.6 in. lb.).

The second test where 60 holes could not be achieved occurred with the Ti-6 Al-4V/RMF/C2502 combination. It was decided at this point to investigate the technique of multiple pass on those holes where the tap would not go through in one pass. As shown in Table B-5 of Appendix B for the first run on the bare tap with cutting fluid the first four holes were tapped in one pass, the next eight holes required two passes, the next two holes required three passes, the next two holes required four passes. The 17th hole required ten passes at which point the test was stopped. For the coated tap with cutting fluid, the first eight holes required only one pass, the next twelve required two passes, the next three required three passes, the next four only required two passes, the next eleven required three passes. The 39th hole required four passes, the 40th hole six passes and the 41st hole required eight passes at which point the test was stopped. This was the first significant improvement in tool life to be observed, however, a duplicate test (Run 2) failed to repeat the beneficial results achieved in Run 1.

Finally, Table IX shows a comparison of the average tapping torques from the six-hole tests and those obtained on the first six holes of the endurance test where such comparisons could be made. In some instances, the torques do not vary widely but for the majority of the cases, a significant difference in average torque values was obtained.

Drilling

Table X shows the results of drilling tests performed on a limited number of workpiece/coated tap/cutting fluid combinations. For SS-17-4 and Ti-6Al-4V workpieces, the coated drill (several coatings) without the use of cutting fluid lasted 2 to 14 holes. The 4130 workpiece being easier to machine showed substantially longer life (46,80+ holes) with only two of the coatings evaluated under the same conditions. Tests with cutting fluid for coated and uncoated drills were then conducted. For the SS-17-4 workpiece failure of the coated tool (five different coatings) ranged from 24 to 78 holes. With the uncoated drill three runs produced the following number of holes to failure: 122, 58 and 94 averaging 91 holes. With the Ti-6Al-4V workpiece only one coating was evaluated. For the first run the coated tool lasted 308 holes while the uncoated tool lasted 149 and 142 holes in duplicate tests. A repeat run with the coated tool resulted in only 143 holes to failure. Similar unrepeatable results were observed in the tapping test for the same workpiece and coating. Special drills (NAS 907 Type J) were procured for testing the L-605 cobalt base alloy. The wear life of this drill even for the base line studies was extremely poor. Coated drills exhibited no improvement. An attempt was made to determine failure based on the consistency of the dimensions of holes produced or burr formation at the exiting portion of the hole. No conclusive results were obtained.

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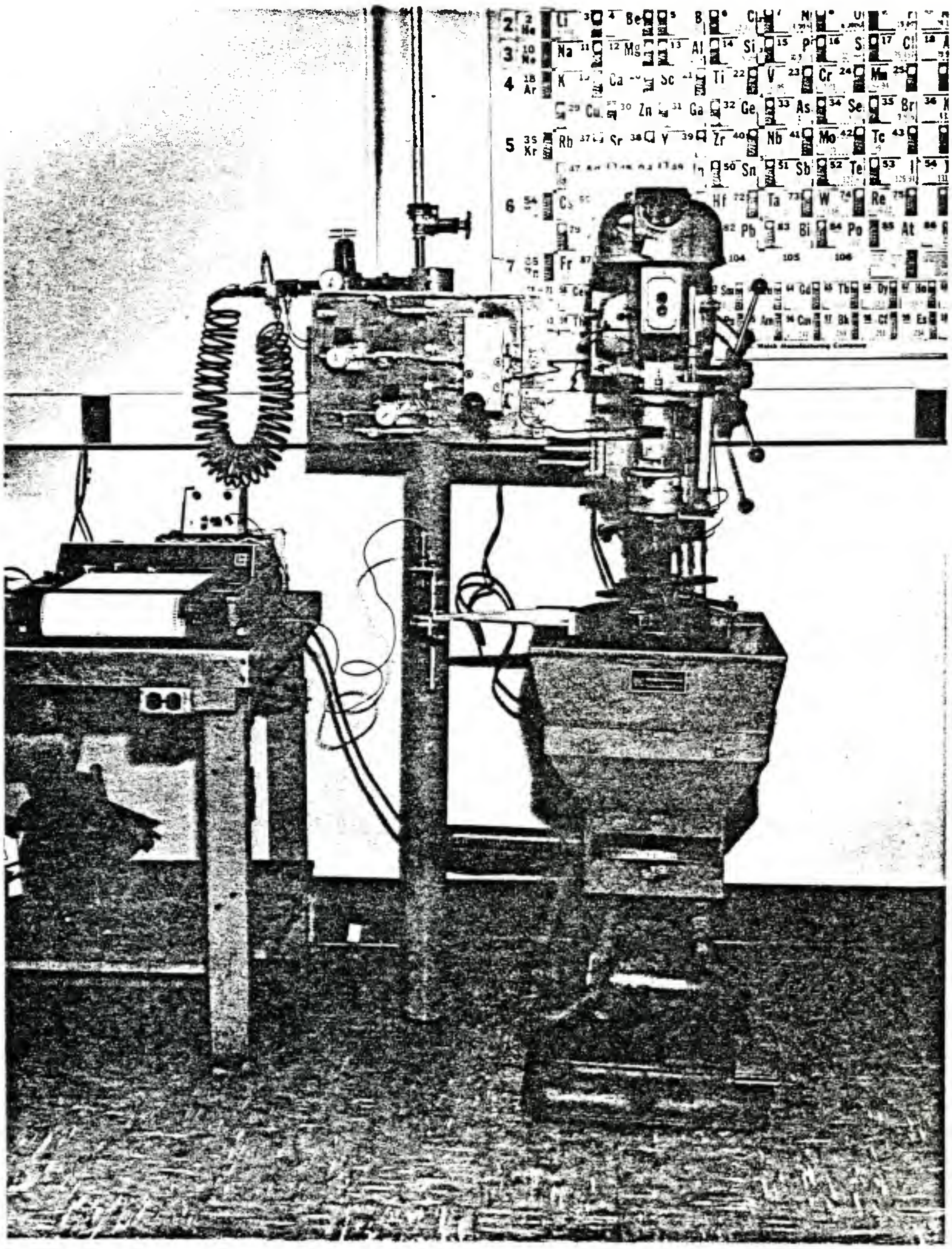

FIGURE 1. CUTTING FLUID TESTER WITH ELECTRONIC TORQUE RECORDER AND PNEUMATIC FEED SYSTEM

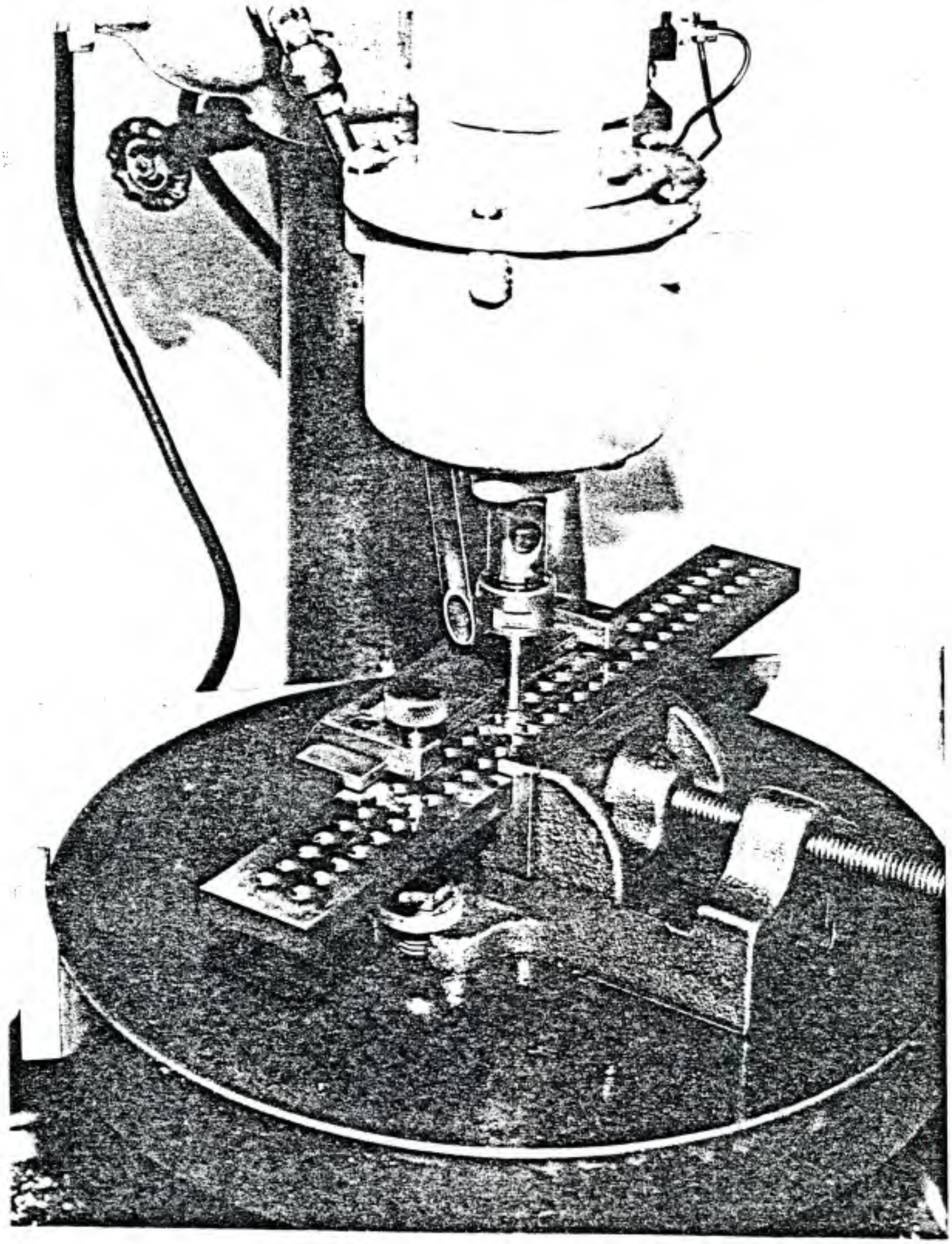

FIGURE 2. CLOSE-UP VIEW OF TAPPING HEAD AND VISE FOR HOLDING THE WORKPIECE

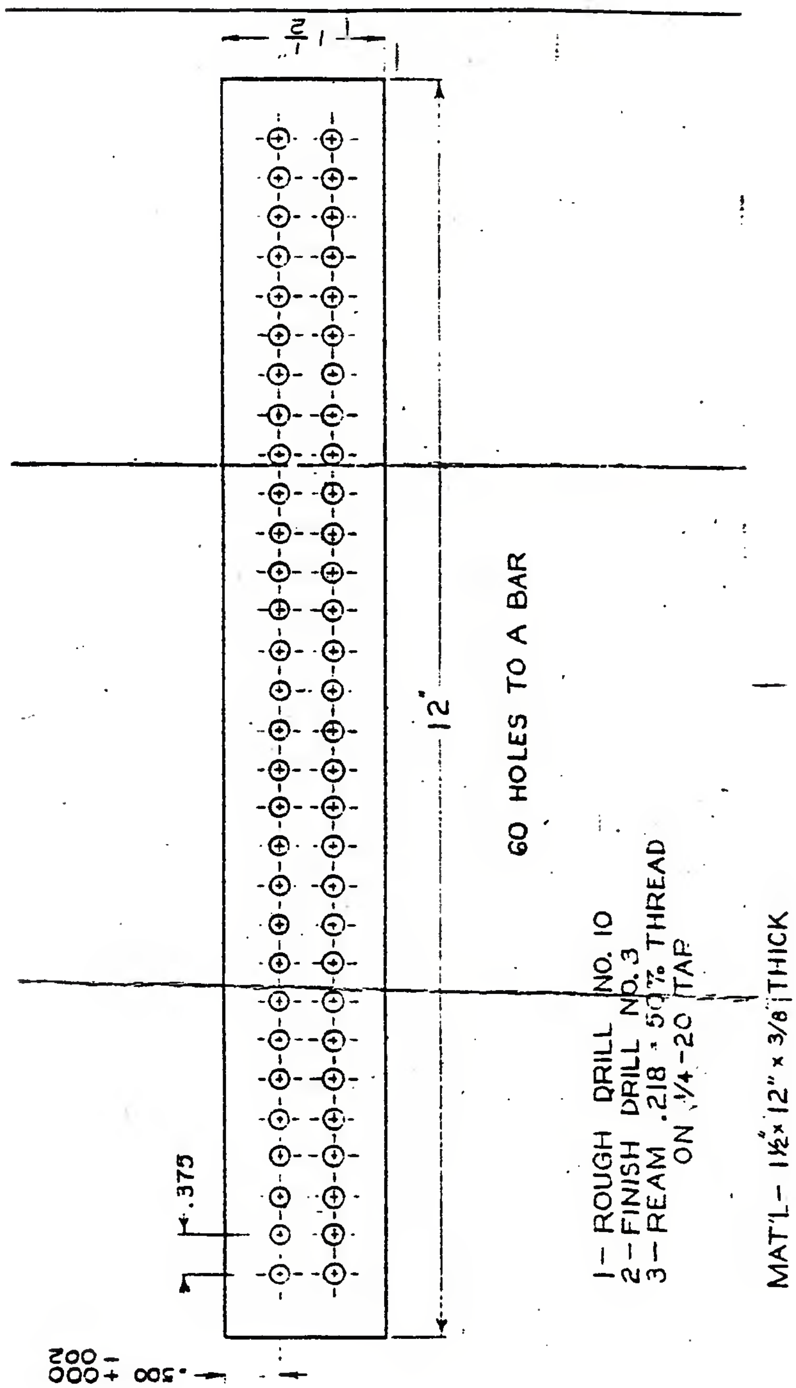

FIGURE 3. WORKPIECE DRAWING AND SPECIFICATION

TABLE I. NOMINAL METALLIC COMPOSITION OF WORKPIECES

Workpiece	C	Mn	Cr	Mo	W	Ni	Si	Fe	Co	Al	Ti	V	P	S	Cu	Cb	Ta	Zn
AISI 1020	0.2	0.45	--	--	--	--	0.6	Bal.	--	--	--	--	.04	.04	--	--	--	--
AISI 4130	0.3	0.5	0.95	0.2	--	--	0.5	Bal.	--	--	--	--	.04	.04	--	--	--	--
7075-T6	--	0.1	--	--	--	--	0.7	--	--	Bal.	--	--	--	--	0.1	--	--	1.3
17-4 PH (Stainless Steel)	0.7	1.0	16.5	--	--	4.0	1.0	Bal.	--	--	--	--	.04	.03	4.0	0.35	0.35	--
L-605	0.1	1.5	20.0	--	15.0	10.0	1.0	3.0	Bal.	--	--	--	--	--	--	--	--	--
Ti-6Al-4V	0.1	--	--	--	--	--	--	0.3	--	6.0	Bal.	4.0	--	--	--	--	--	--

TABLE II. MEASURED HARDNESS OF WORKPIECES

Workpiece	Rockwell	BHN
AISI 1020	B79	146
AISI 4130	B92	194
7075-T6 Al	B92	194
Stainless Steel 17-4 PH	C36	329
L-605 Cobalt	C25	258
Ti-6Al-4V	C35	320

TABLE III. COATINGS EVALUATED UNDER PROGRAM

Code	Coating Designation	Manufacturer	MIL-SPEC	Composition	Coating Applied By
C2502	Boggs C2502	Boggs Tool Processing and File Sharpening Company Paramount, CA	--	MoS_2 + Phenolic Resin Binder	Manufacturer
200-1	Microseal 200-1	E/M Lubricants West Layfayette, IN	--	MoS_2 + Inorganic Binder	Manufacturer
220	Lubri-Bond 220	Electrofilm, Inc. North Hollywood, CA	MIL-L-23398	MoS_2 + Epoxy Resin	NAVAIRDEVCEN
2396	Lube-Lok 2396	Electrofilm, Inc. North Hollywood, CA	MIL-L-81329	MoS_2 + Graphite + Sodium Silicate Binder	NAVAIRDEVCEN
5306	Lube-Lok 5306	Electrofilm, Inc. North Hollywood, CA	MIL-L-8937	MoS_2 + Phenolic Resin Binder	NAVAIRDEVCEN
Ni-W	Nickel-Tungsten	---	--	Ni-W Brush Plating	NAVAIREWORKFAC North Island
ATA-1	Arsenic Thioantimonate Powder	Pennwalt King of Prussia, PA	--	Arsenic Thioantimonate + Inorganic Binder	E/M Lubricants
ATA-2	ATA in B-9 Formulation	Formulated in-house	--	ATA + Graphite + Phenolic Resin	NAVAIRDEVCEN
OSM	Boggs Oil Saturation Method	Boggs Tool Processing and File Sharpening Company Paramount, CA	--	Proprietary Surface Treatment	Manufacturer

TABLE IV. LIST OF CUTTING FLUIDS

MM27:	Mobilmet 27 Mobil Oil Corporation New York, NY
RMF:	Ralmike's Microfinish Tool-A-Rama South Plainfield, NJ
CCD:	CCD Solvent Barrett Chemical Company Philadelphia, PA
BDN:	Zurnagent BDN O. F. Zurn Company Philadelphia, PA

TABLE V. SUMMARY OF AVERAGE TAPPING TORQUES g.m (in. lb.) FOR BARE TAP, BARE TAP WITH CUTTING FLUID AND COATED TAP (SIX-HOLE TESTS)

	Workpiece					
	1020	4130	7075-T6	SS 17-4	L-605	Ti-6Al-4V
Bare Tap	942 (82)	942 (82)	668 (58)	783 (68)	876 (76)	899 (78)
Bare Tap + Cutting Fluid						
MM27	472 (41)	415 (36)	278 (24)	438 (38)	806 (70)	899 (78)
RMF	--	--	--	415 (36)	818 (71)	864 (75)
CCD	--	--	--	472 (41)	899 (78)	553 (48)
BDN	--	--	--	726 (63)	852 (74)	979 (85)
Coated Tap No Fluid						
C2502	634 (55)	760 (66)	611 (53)	668 (58)	956 (83)	933 (81)
200-1	622 (54)	--	726 (63)	--	--	--
220	645 (56)	645 (56)	691 (60)	668 (58)	--	--
2396	541 (47)	530 (46)	726 (63)	461 (40)	518 (45)	--
5306	714 (62)	622 (54)	--	922 (80)	--	--
Ni-W	795 (69)	668 (58)	622 (54)	795 (69)	726 (63)	852 (74)
ATA-1	--	--	--	772 (67)	--	680 (59)
OSM	--	--	--	--	887 (77)	933 (81)

TABLE VI. SUMMARY OF AVERAGE TAPPING TORQUES g.m (in. lb.) FOR COATED TAPS WITH CUTTING FLUID TESTS

(SIX-HOLE TESTS)

Cutting Fluid	Coating	Workpiece 1020	4130	7075-T6	SS 17-4	L-605	Ti-6 Al-4V
MM 27	C2502	311 (27)	311 (27)	207 (18)	461 (40)	829 (72)	887 (77)
MM 27	200-1	300 (26)	--	253 (22)	--	--	--
MM 27	220	369 (32)	323 (28)	242 (21)	--	--	--
MM 27	2396	346 (30)	334 (29)	323 (28)	--	--	--
MM 27	5306	334 (29)	334 (29)	--	--	--	--
MM 27	Ni-W	472 (41)	415 (36)	323 (28)	--	--	--
RMF	C2502	--	--	--	380 (33)	760 (66)	968 (84)
RMF	200-1	--	--	--	--	--	--
RMF	220	--	--	--	449 (39)	--	--
RMF	2396	--	--	--	403 (35)	576 (50)	--
RMF	5306	--	--	--	541 (47)	--	--
RMF	Ni-W	--	--	--	449 (39)	737 (64)	--
RMF	ATA-1	--	--	--	380 (33)	--	622 (54)
RMF	OSM	--	--	--	--	783 (68)	841 (73)

TABLE VII. PERCENT CHANGE IN TAPPING TORQUE FOR COMBINED CUTTING FLUID - COATED TAP TESTS RELATIVE TO TESTS WITH CUTTING FLUID ONLY (SIX-HOLE TESTS)

Cutting Fluid	Coating	Workpiece 1020	4130	7075-T6	SS 17-4	L-605	Ti-6Al 4V
MM 27	C2502	-34	-25	-25	+5	+3	-1
	200-1	-37	---	-8	---	---	---
	220	-22	-22	-13	---	---	---
	2396	-27	-19	+17	---	---	---
	5306	-29	-19	---	---	---	---
	Ni-W	0	0	+17	---	---	---
RMF	C2502	---	---	---	-8	-7	+12
	200-1	---	---	---	---	---	---
	220	---	---	---	+8	---	---
	2396	---	---	---	-3	-30	---
	5306	---	---	---	+31	---	---
	Ni-W	---	---	---	+8	-10	---
	ATA-1	---	---	---	-8	---	-28
	OSM	---	---	---	---	-4	-3

TABLE VIII. SUMMARY OF AVERAGE TAPPING TORQUE (ENDURANCE TESTS)

				Torque, g.m (in. lb.)	
Workpiece	Cutting Fluid	Coating	# of Holes	Bare Tap - Cutting Fluid	Coated Tap Cutting Fluid
SS 17-4	RMF	5306	120	410 (35.6)	384 (33.3)
4130	MM27	C2502	60	317 (27.5)	324 (28.1)
SS 17-4	RMF	ATA-2	60	392 (34.0)	399 (34.6)
L-605	RMF	C2502	12	592 (51.4)	--
			17	--	629 (54.6)

TABLE IX. COMPARISON OF AVERAGE TAPPING TORQUES g.m (in. lb.) FROM THE SIX-HOLE TESTS AND THOSE OBTAINED ON THE FIRST SIX HOLES OF THE ENDURANCE TEST

			Cutting Fluid Only		Cutting Fluid and Coated Tap	
Workpiece	Cutting Fluid	Coating	From Six-Hole Tests	From Endurance Tests	From Six-Hole Tests	From Endurance Tests
SS 17-4	RMF	5306	415 (36)	369 (32)	541 (47)	380 (33)
				346 (30)		
4130	MM27	C2502	415 (36)	300 (26)	311 (27)	230 (20)
L605	RMF	C2502	818 (71)	611 (53)	760 (66)	634 (55)
				634 (55)		
Ti-6 Al-4V	RMF	C2502	864 (75)	634 (55)	968 (84)	634 (55)

TABLE X. DRILLING TEST RESULTS

Workpiece	Uncoated Tool Run 1	Uncoated Tool Run 2	Coated Tool Coating	Coated Tool Run 1	Coated Tool Run 2	Coated Tool + Cutting Fluid Coating	Coated Tool + Cutting Fluid Run 1	Coated Tool + Cutting Fluid Run 2	Uncoated Tool + Cutting Fluid Run 1	Uncoated Tool + Cutting Fluid Run 2	Uncoated Tool + Cutting Fluid Run 3
	No. of Holes										
SS-17-4	4 fail	5 fail	C2502	10 drill chipped	4 fail	C2502	78 fail	---	122 fail	58 fail	94 fail
			Ni-W	2 fail	3 fail		32 fail	---	---	---	---
			200-1	14 fail	5 fail	200-1	46 fail	---	---	---	---
			ATA-2	4 drill chipped	4 fail	ATA-2	24 drill broke	---	---	---	---
			5306	7 fail	6 fail	5306	70 fail	---	---	---	---
Ti-6Al-4V	---	---	C2502	12 fail	---	C2502	308 fail	143 fail	149 fail	142 fail	---
			Ni-W	2 tip broke	---		---	---	---	---	---
			200-1	5 fail	---		---	---	---	---	---
			ATA-2	10 fail	---		---	---	---	---	---
			5306	3 fail	---		---	---	---	---	---
4130	28+	---	C2502	46 drill broke	---		---	---	---	---	---
			Ni-W	80+	---	C2502	70+	---	70+	---	---
L-605	0 fail	---	ATA-2	0 fail	---	ATA-2	0 drill broke	---	1 fail	---	---
			5306	0 fail	---	5306	0 fail	---	---	---	---

APPENDIX A

TAPPING TORQUE TEST RESULTS (SIX-HOLE TESTS)

TABLE A1. TAPPING TORQUE g.m (in.lb.), AISI 1020 WORKPIECE

Cutting Fluid	Coating	Hole Number 1	2	3	4	5	6	Avg
None	None	728 (63.0)	1016 (88.2)	954 (82.8)	912 (79.2)	1026 (89.1)	1057 (91.8)	949 (82.4)
None	None	653 (56.7)	1068 (92.7)	1016 (88.2)	995 (86.4)	923 (80.1)	954 (82.8)	935 (81.2)
MM27	None	332 (28.8)	498 (43.2)	435 (37.8)	467 (40.5)	456 (39.6)	404 (35.1)	432 (37.5)
MM27	None	342 (29.7)	342 (29.7)	518 (45.0)	477 (41.4)	1016 (88.2)	404 (35.1)	517 (44.9)
None	C2502	415 (36.0)	207 (18.0)	622 (54.0)	975 (84.6)	674 (58.5)	933 (81.0)	638 (55.4)
MM27	C2502	228 (19.8)	332 (28.8)	332 (28.8)	342 (29.7)	332 (28.8)	321 (27.9)	314 (27.3)
None	200-1	684 (59.4)	684 (59.4)	664 (57.6)	684 (59.4)	467 (40.5)	581 (50.4)	627 (54.4)
MM27	200-1	270 (23.4)	270 (23.4)	311 (27.0)	332 (28.8)	332 (28.8)	- (-)	303 (26.3)
None	220	612 (53.1)	518 (45.0)	664 (57.6)	664 (57.6)	684 (59.4)	705 (61.2)	642 (55.7)
MM27	220	290 (25.2)	394 (34.2)	415 (36.0)	373 (32.4)	332 (28.8)	415 (36.0)	370 (32.1)
None	2396	363 (31.5)	498 (43.2)	788 (68.4)	581 (50.4)	570 (49.5)	456 (39.6)	543 (47.1)
MM27	2396	290 (25.2)	311 (27.0)	353 (30.6)	353 (30.6)	- (34.2)	353 (30.6)	394 (29.7)
None	Ni-W	664 (57.6)	985 (85.5)	643 (55.8)	695 (60.3)	881 (76.5)	902 (78.3)	795 (69.0)
MM27	Ni-W	456 (39.6)	498 (43.2)	456 (39.6)	539 (46.8)	456 (39.6)	456 (39.6)	473 (41.4)
None	5306	570 (49.5)	622 (54.0)	705 (61.2)	767 (66.6)	788 (68.4)	798 (69.3)	708 (61.5)
MM27	5306	353 (30.6)	270 (23.4)	311 (27.0)	387 (33.6)	353 (30.6)	353 (30.6)	338 (29.3)

TABLE A2. TAPPING TORQUE g.m (in.lb.), AISI 4130 WORKPIECE

Cutting Fluid	Coating	Hole Number 1	2	3	4	5	6	Avg
None	None	653 (56.7)	715 (62.1)	1109 (96.3)	995 (86.4)	995 (86.4)	995 (86.4)	911 (79.1)
None	None	684 (59.4)	933 (81.0)	1006 (87.3)	1161 (100.8)	1006 (87.3)	1026 (89.1)	970 (84.2)
None	None	622 (54.0)	1058 (91.8)	995 (86.4)	985 (85.5)	1026 (89.1)	1006 (87.3)	950 (82.5)
MM27	None	473 (41.4)	373 (32.4)	404 (35.1)	473 (41.4)	446 (38.7)	473 (41.4)	442 (38.4)
MM27	None	332 (28.8)	435 (37.8)	415 (36.0)	404 (35.1)	363 (31.5)	384 (33.3)	388 (33.7)
None	C2502	435 (37.8)	581 (50.4)	550 (47.7)	1026 (89.1)	1016 (88.2)	954 (82.8)	760 (66.0)
MM27	C2502	270 (23.4)	332 (28.8)	394 (34.2)	270 (23.4)	311 (27.0)	- (-)	316 (27.4)
None	220	404 (35.1)	456 (39.6)	467 (40.5)	778 (67.5)	850 (73.8)	892 (77.4)	642 (55.7)
MM27	220	301 (26.1)	259 (22.5)	259 (22.5)	301 (26.1)	373 (32.4)	415 (36.0)	318 (27.6)
None	2396	353 (30.6)	415 (36.0)	456 (39.6)	560 (48.6)	726 (63.0)	684 (59.4)	532 (46.2)
MM27	2396	435 (37.8)	363 (31.5)	259 (22.5)	353 (30.6)	321 (27.9)	- (-)	328 (28.5)
None	Ni-W	539 (46.8)	726 (63.0)	619 (56.7)	705 (61.2)	643 (55.8)	726 (63.0)	666 (57.8)
MM27	Ni-W	475 (41.2)	373 (32.4)	394 (34.2)	373 (32.4)	435 (37.8)	425 (36.9)	412 (35.8)
None	5306	435 (37.8)	518 (45.0)	622 (54.0)	622 (54.0)	674 (58.5)	829 (72.0)	617 (53.6)
MM27	5306	353 (30.6)	270 (23.4)	311 (27.0)	387 (33.6)	353 (30.6)	353 (30.6)	338 (29.3)

TABLE A3. TAPPING TORQUE g.m (in. lb.), 7075-T6 WORKPIECE

Cutting Fluid	Coating	Hole Number 1	2	3	4	5	6	Avg
None	None	560 (48.6)	726 (63.0)	760 (66.0)	778 (67.5)	747 (64.8)	780 (67.5)	725 (62.9)
None	None	415 (36.0)	601 (52.2)	643 (55.8)	767 (66.6)	778 (67.5)	767 (66.6)	662 (57.5)
None	None	601 (52.2	591 (51.3)	612 (53.1)	612 (53.1)	726 (63.0)	653 (56.7)	632 (54.9)
MM27	None	228 (19.8)	238 (20.7)	238 (20.7)	259 (22.5)	249 (21.6)	249 (21.6)	244 (21.2)
MM27	None	290 (25.2)	301 (26.1)	311 (27.0)	311 (27.0)	311 (27.0)	321 (27.9)	308 (26.7)
None	C2502	473 (41.4)	653 (56.7)	622 (54.0)	664 (57.6)	632 (54.9)	622 (54.0)	612 (53.1)
MM27	C2502	207 (18.0)	218 (18.9)	197 (17.1)	207 (18.0)	197 17.1)	207 (18.0)	206 (17.9)
None	200-1	550 (47.7)	788 (68.4)	778 (67.5)	736 (63.9)	757 (65.7)	- (-)	726 (63.0)
MM27	200-1	259 (22.5)	238 (20.7)	249 (21.6)	249 (21.6)	259 (22.5)	259 (22.5)	252 (21.9)
None	220	539 (46.8)	767 (66.6)	767 (66.6)	- (-)	- (-)	- (-)	691 (60.0)
MM27	220	238 (20.7)	238 (20.7)	238 (20.7)	238 (20.7)	238 (20.7)	259 (22.5)	242 (21.0)
None	2396	581 (50.4)	798 (69.3)	684 (59.4)	788 (68.4)	705 (61.2)	788 (68.4)	725 (62.9)
MM27	2396	311 (27.0)	311 (27.0)	318 (27.6)	332 (28.8)	332 (28.8)	332 (28.8)	323 (28.0)
None	Ni-W	684 (59.4)	675 (58.6)	456 (39.6)	643 (55.8)	622 (54.0)	622 (54.0)	617 (53.6)
MM27	Ni-W	478 (41.4)	270 (23.4)	290 (25.2)	280 (24.3)	280 (24.3)	301 (26.1)	317 (27.5)

TABLE A4. TAPPING TORQUE g.m (in.lb.) SS 17-4 WORKPIECE

Cutting Fluid	Coating	Hole Number 1	2	3	4	5	6	Avg
None	None	498 (43.2)	581 (50.4)	975 (84.6)	643 (55.8)	995 (86.4)	954 (82.8)	774 (67.2)
None	None	467 (40.5)	895 (77.4)	895 (77.4)	705 (61.2)	933 (81.0)	895 (77.4)	797 (69.2)
MM27	None	415 (36.0)	435 (37.8)	456 (39.6)	456 (39.6)	404 (35.1)	456 (39.6)	438 (38.0)
MM27	None	435 (37.8)	415 (36.0)	456 (39.6)	518 (45.0)	435 (37.8)	415 (36.0)	446 (38.7)
CCD	None	- (-)	456 (39.6)	435 (37.8)	435 (37.8)	560 (48.6)	456 (39.6)	468 (40.6)
CCD	None	456 (39.6)	435 (37.8)	497 (43.2)	435 (37.8)	467 (40.5)	560 (48.6)	475 (41.3)
BDN	None	612 (53.1)	550 (47.7)	736 (63.9)	655 (56.9)	757 (65.7)	695 (60.3)	667 (57.9)
BDN	None	809 (70.2)	954 (82.8)	729 (63.3)	591 (51.3)	923 (80.1)	570 (49.5)	774 (67.2)
RMF	None	415 (36.0)	394 (34.2)	477 (41.4)	415 (36.0)	384 (33.3)	415 (36.0)	417 (36.2)
RMF	None	550 (47.7)	378 (32.8)	353 (30.6)	332 (28.8)	363 (31.5)	415 (36.0)	422 (36.6)
None	C2502	435 (37.8)	487 (42.3)	518 (45.0)	581 (50.4)	995 (86.4)	1016 (88.2)	673 (58.4)
MM27	C2502	456 (39.6)	415 (36.0)	435 (37.8)	467 (40.5)	446 (38.7)	550 (47.7)	462 (40.1)
RMF	C2502	363 (31.5)	311 (27.0)	332 (28.8)	394 (34.2)	342 (29.7)	508 (44.1)	374 (32.5)
None	220	518 (45.0)	477 (41.4)	456 (39.6)	912 (79.2)	809 (70.2)	829 (72.0)	667 (57.9)
RMF	220	581 (50.4)	394 (34.2)	415 (36.0)	518 (45.0)	415 (36.0)	363 (31.5)	448 (38.9)
None	2396	477 (41.4)	456 (39.6)	435 (37.8)	435 (37.8)	477 (41.4)	- (-)	455 (39.5)
RMF	2396	435 (37.8)	415 (36.0)	353 (30.6)	435 (37.8)	353 (30.6)	415 (36.0)	401 (34.8)
None	Ni-W	809 (70.2)	757 (65.7)	819 (71.1)	- (-)	- (-)	- (-)	795 (69.0)
RMF	Ni-W	581 (50.4)	415 (36.0)	498 (43.2)	373 (32.4)	373 (32.4)	436 (37.8)	446 (38.7)

TABLE A4. TAPPING TORQUE g.m (in. lb.) SS 17-4 WORKPIECE
(Continued)

Cutting Fluid	Coating	Hole Number 1	2	3	4	5	6	Avg
None	5306	912 (79.2)	892 (77.4)	871 (75.6)	995 (86.4)	- (-)	- (-)	918 (79.7)
RMF	5306	643 (55.8)	529 (45.9)	560 (48.6)	550 (47.7)	487 (42.3)	498 (43.2)	545 (47.3)
None	ATA -1	477 (41.4)	498 (43.2)	1016 (88.2)	892 (77.4)	871 (75.6)	892 (77.4)	774 (67.2)
RMF	ATA-1	394 (34.2)	457 (39.7)	363 (31.5)	384 (33.3)	332 (28.8)	- (-)	374 (32.5)

TABLE A5. TAPPING TORQUE g.m (in. lb.), L605 WORKPIECE

Cutting Fluid	Coating	Hole Number 1	2	3	4	5	6	Avg
None	None	829 (72.0)	1058 (91.8)	844 (73.3)	902 (78.3)	881 (76.5)	892 (77.4)	901 (78.2)
None	None	871 (75.6)	892 (77.4)	881 (76.5)	902 (78.3)	912 (79.2)	871 (75.6)	888 (77.1)
None	None	871 (75.6)	871 (75.6)	861 (74.7)	829 (72.0)	788 (68.4)	829 (72.0)	842 (73.1)
MM27	None	912 (79.2)	902 (78.3)	923 (80.1)	684 (59.4)	933 (81.0)	964 (83.7)	887 (77.0)
MM27	None	850 (73.8)	726 (63.0)	757 (65.7)	757 (65.7)	664 (57.6)	653 (56.7)	735 (63.8)
CCD	None	726 (63.0)	1244 (108.0)	964 (83.7)	964 (83.7)	964 (83.7)	933 (81.0)	967 (83.9)
CCD	None	581 (50.4)	664 (57.6)	975 (84.6)	933 (81.0)	892 (77.4)	943 (81.9)	832 (72.2)
BDN	None	829 (72.0)	871 (75.6)	861 (74.7)	861 (74.7)	861 (74.7)	829 (72.0)	852 (74.0)
BDN	None	861 (74.7)	861 (74.7)	861 (74.7)	861 (74.7)	850 (73.8)	871 (75.6)	861 (74.7)
RMF	None	778 (67.5)	892 (77.4)	892 (77.4)	892 (77.4)	923 (80.1)	912 (79.2)	881 (76.5)
RMF	None	353 (30.6)	975 (84.6)	850 (73.8)	829 (72.0)	778 (67.5)	723 (63.0)	752 (65.3)
None	C2502	964 (83.7)	923 (80.1)	1037 (90.0)	933 (81.0)	912 (79.2)	933 (81.0)	950 (82.5)
MM27	C2502	798 (69.3)	829 (72.0)	829 (72.0)	829 (72.0)	850 (73.8)	850 (73.8)	832 (72.2)
RMF	C2502	767 (66.6)	723 (63.0)	- (-)	788 (68.4)	723 (63.0)	778 (67.5)	756 (65.6)
None	2396	684 (59.4)	539 (46.8)	508 (44.1)	477 (41.4)	435 (37.8)	435 (37.8)	513 (44.5)
RMF	2396	622 (54.0)	601 (52.2)	539 (46.8)	539 (46.8)	550 (47.7)	- (-)	570 (49.5)
None	Ni-W	664 (57.6)	695 (60.3)	695 (60.3)	829 (72.0)	- (-)	- (-)	721 (62.6)
RMF	Ni-W	601 (52.2)	581 (50.4)	581 (50.4)	560 (48.6)	705 (61.2)	684 (59.4)	738 (64.1)

TABLE A5. TAPPING TORQUE g.m (in.lb.) L605 WORKPIECE
(Continued)

Cutting Fluid	Coating	Hole Number 1	2	3	4	5	6	Avg
None	OSM	892 (77.4)	892 (77.4)	881 (76.5)	871 (75.6)	892 (77.4)	892 (77.4)	887 (77.0)
RMF	OSM	539 (46.8)	840 (72.9)	829 (72.0)	850 (73.8)	829 (72.0)	829 (72.0)	787 (68.3)

TABLE A6. TAPPING TORQUE g.m (in.lb.) Ti-6Al-4V WORKPIECE

Cutting Fluid	Coating	Hole Number 1	2	3	4	5	6	Avg
None	None	995 (86.4)	954 (82.8)	954 (82.8)	954 (82.8)	954 (82.8)	871 (75.6)	947 (82.2)
None	None	767 (66.6)	933 (81.0)	788 (68.4)	871 (75.6)	871 (75.6)	809 (70.2)	840 (72.9)
None	None	954 (82.8)	933 (81.0)	746 (64.8)	892 (77.4)	788 (68.4)	1120 (97.2)	905 (78.6)
MM27	None	933 (81.0)	954 (82.8)	871 (75.6)	954 (82.8)	933 (81.0)	954 (82.8)	933 (81.0)
MM27	None	788 (68.4)	788 (68.4)	912 (79.2)	912 (79.2)	892 (77.4)	892 (77.4)	864 (75.0)
CCD	None	581 (50.4)	674 (58.5)	539 (46.8)	518 (45.0)	560 (48.6)	560 (48.6)	573 (49.7)
CCD	None	- (-)	539 (46.8)	550 (47.7)	529 (45.9)	550 (47.7)	477 (41.4)	529 (45.9)
BDN	None	- (-)	923 (80.1)	933 (81.0)	892 (77.4)	954 (82.8)	933 (80.1)	925 (80.3)
BDN	None	1047 (90.9)	1068 (92.7)	1006 (87.3)	1037 (90.0)	1026 (89.1)	975 (84.6)	1026 (89.1)
RMF	None	- (-)	861 (74.7)	788 (68.4)	757 (65.7)	778 (67.5)	809 (70.2)	798 (69.3)
RMF	None	954 (82.8)	933 (81.0)	954 (82.8)	912 (79.2)	902 (78.3)	892 (77.4)	925 (80.3)
None	C2502	954 (82.8)	933 (81.0)	954 (82.8)	933 (81.0)	902 (78.3)	912 (79.2)	931 (80.8)
MM27	C2502	871 (75.6)	892 (77.4)	892 (77.4)	881 (76.5)	881 (76.5)	871 (75.6)	881 (76.5)
RMF	C2502	954 (82.8)	985 (85.5)	1026 (89.1)	975 (84.6)	933 (81.0)	923 (80.1)	967 (83.9)
None	OSM	964 (83.7)	964 (83.7)	933 (81.0)	923 (80.1)	923 (80.1)	902 (78.3)	935 (81.2)
RMF	OSM	829 (72.0)	861 (74.7)	861 (74.7)	809 (70.2)	829 (72.0)	829 (72.0)	836 (72.6)
None	ATA-1	746 (64.8)	819 (71.1)	695 (60.3)	581 (50.4)	539 (46.8)	684 (59.4)	677 (58.8)
RMF	ATA-1	601 (52.2)	581 (50.4)	684 (59.4)	581 (50.4)	622 (54.0)	643 (55.8)	619 (53.7)
None	Ni-W	892 (77.4)	871 (75.6)	850 (73.8)	850 (73.8)	850 (73.8)	829 (72.0)	857 (74.4)
RMF	Ni-W	850 (73.8)	871 (75.6)	829 (72.0)	829 (72.0)	829 (72.0)	850 (73.8)	843 (73.2)

APPENDIX B

TAPPING TORQUE TEST RESULTS (ENDURANCE TESTS)

TABLE B1. ENDURANCE TEST ON SS 17-4 WORKPIECE

Hole No.	Torque g.m (in. lb.) Bare Tap-RMF Cutting Fluid	5306 Coated Tap-RMF Cutting Fluid
1	363 (31.5)	456 (39.6)
2	301 (26.1)	332 (28.8)
3	487 (42.3)	342 (29.7)
4	384 (33.3)	415 (36.0)
5	342 (29.7)	342 (29.7)
6	342 (29.7)	373 (32.4)
7	394 (34.2)	373 (32.4)
8	373 (32.4)	373 (32.4)
9	342 (29.7)	435 (37.8)
10	290 (25.2)	384 (33.3)
11	311 (27.0)	363 (31.5)
12	332 (28.8)	342 (29.7)
13	311 (27.0)	363 (31.5)
14	353 (30.6)	404 (35.1)
15	373 (32.4)	384 (33.3)
16	394 (34.2)	394 (34.2)
17	384 (33.3)	373 (32.4)
18	384 (33.3)	394 (34.2)
19	311 (27.0)	394 (34.2)
20	373 (32.4)	415 (36.0)
21	394 (34.2)	404 (35.1)
22	394 (34.2)	394 (34.2)
23	363 (31.5)	394 (34.2)
24	342 (29.7)	394 (34.2)
25	373 (32.4)	394 (34.2)
26	342 (29.7)	353 (30.6)
27	311 (27.0)	321 (27.9)
28	290 (25.2)	394 (34.2)
29	332 (28.8)	415 (36.0)
30	342 (29.7)	342 (29.7)
31	446 (38.7)	301 (26.1)
32	435 (37.8)	394 (34.2)
33	456 (39.6)	353 (30.6)
34	435 (37.8)	342 (29.7)
35	404 (35.1)	311 (27.0)
36	477 (41.4)	363 (31.5)
37	477 (41.4)	498 (43.2)
38	435 (37.8)	446 (38.7)
39	415 (36.0)	394 (34.2)
40	404 (35.1)	508 (44.1)
41	435 (37.8)	280 (24.3)
42	456 (39.6)	353 (30.6)
43	384 (33.3)	478 (41.4)
44	373 (32.4)	332 (28.8)
45	518 (45.0)	384 (33.3)

TABLE B1. ENDURANCE TEST ON SS 17-4 WORKPIECE
(Continued)

Hole No.	Torque g.m (in. lb.) Bare Tap-RMF Cutting Fluid	Torque g.m (in. lb.) 5306 Coated Tap-RMF Cutting Fluid
46	353 (30.6)	290 (25.2)
47	435 (37.8)	311 (27.0)
48	478 (41.4)	290 (25.2)
49	415 (36.0)	353 (30.6)
50	373 (32.4)	332 (28.8)
51	456 (39.6)	353 (30.6)
52	446 (38.7)	342 (29.7)
53	435 (37.8)	280 (24.3)
54	518 (45.0)	373 (32.4)
55	435 (37.8)	373 (32.4)
56	394 (34.2)	373 (32.4)
57	404 (35.1)	311 (27.0)
58	384 (33.3)	311 (27.0)
59	415 (36.0)	363 (31.5)
60	342 (29.7)	373 (32.4)
61	311 (27.0)	539 (46.8)
62	404 (35.1)	384 (33.3)
63	446 (38.7)	435 (37.8)
64	394 (34.2)	373 (32.4)
65	394 (34.2)	311 (27.0)
66	446 (38.7)	384 (33.3)
67	487 (42.3)	539 (46.8)
68	384 (33.3)	373 (32.4)
69	415 (36.0)	373 (32.4)
70	415 (36.0)	384 (33.3)
71	353 (30.6)	374 (32.4)
72	321 (27.9)	404 (35.1)
73	415 (36.0)	384 (33.3)
74	321 (27.9)	342 (29.7)
75	342 (39.7)	363 (31.5)
76	404 (35.1)	290 (25.2)
77	415 (36.0)	415 (36.0)
78	415 (36.0)	353 (30.6)
79	311 (27.0)	550 (47.7)
80	446 (38.7)	467 (40.5)
81	384 (33.3)	415 (36.0)
82	415 (36.0)	415 (36.0)
83	248 (21.5)	415 (36.0)
84	467 (40.5)	353 (30.6)
85	477 (41.4)	404 (35.1)
86	467 (40.5)	363 (31.5)
87	550 (47.7)	353 (30.6)
88	539 (46.8)	377 (32.7)
89	456 (39.6)	353 (30.6)

TABLE B1. ENDURANCE TEST ON SS 17-4 WORKPIECE
(Continued)

Hole No.	Torque g.m (in. lb.) Bare Tap-RMF Cutting Fluid	5306 Coated Tap-RMF Cutting Fluid
90	508 (44.1)	276 (24.8)
91	539 (46.8)	435 (37.8)
92	477 (41.4)	342 (29.7)
93	415 (36.0)	301 (26.1)
94	498 (43.2)	342 (29.7)
95	415 (36.0)	332 (28.8)
96	498 (41.4)	373 (32.4)
97	456 (39.6)	467 (40.5)
98	456 (39.6)	415 (36.0)
99	518 (45.0)	332 (28.8)
100	478 (41.4)	415 (36.0)
101	404 (35.1)	446 (38.7)
102	467 (40.5)	417 (36.5)
103	508 (44.1)	417 (36.5)
104	498 (43.2)	384 (33.3)
105	384 (33.3)	415 (36.0)
106	404 (35.1)	363 (31.5)
107	446 (38.7)	363 (31.5)
108	456 (39.6)	539 (46.8)
109	373 (32.4)	435 (37.8)
110	467 (40.5)	435 (37.8)
111	487 (42.3)	332 (28.8)
112	354 (30.7)	290 (25.2)
113	435 (37.8)	384 (33.3)
114	394 (34.2)	290 (25.2)
115	518 (45.0)	332 (28.8)
116	456 (39.6)	363 (31.5)
117	539 (46.8)	321 (27.9)
118	508 (44.1)	426 (37.0)
119	- (-)	342 (29.7)
120	- (-)	311 (27.0)
AVG	410 (35.6)	384 (33.3)

TABLE B2. ENDURANCE TEST ON AISI 4130 WORKPIECE

Hole No.	Torque g.m (in. lb.) Bare Tap-MM27 Cutting Fluid	C2502 Coated Tap-MM27 Cutting Fluid
1	280 (24.3)	176 (15.3)
2	311 (27.0)	265 (23.0)
3	238 (20.7)	265 (23.0)
4	332 (28.8)	270 (23.4)
5	280 (24.3)	161 (14.0)
6	373 (32.4)	270 (23.4)
7	467 (40.5)	249 (21.6)
8	353 (30.6)	342 (29.7)
9	290 (25.2)	311 (27.0)
10	353 (30.6)	290 (25.2)
11	228 (19.8)	342 (29.7)
12	301 (26.1)	363 (31.5)
13	348 (30.2)	280 (24.3)
14	321 (27.9)	270 (23.4)
15	363 (31.5)	249 (21.6)
16	270 (23.4)	477 (41.4)
17	290 (25.2)	353 (30.6)
18	296 (25.7)	321 (27.9)
19	332 (28.8)	321 (27.9)
20	353 (30.6)	290 (25.2)
21	311 (27.0)	348 (30.2)
22	301 (26.1)	425 (36.9)
23	327 (28.4)	286 (24.8)
24	290 (25.2)	270 (23.4)
25	321 (27.9)	373 (32.4)
26	270 (23.4)	301 (26.1)
27	353 (30.6)	348 (30.2)
28	321 (27.9)	316 (27.4)
29	353 (30.6)	265 (23.0)
30	373 (32.4)	342 (29.7)
31	373 (32.4)	363 (31.5)
32	373 (32.4)	265 (23.0)
33	311 (27.0)	373 (32.4)
34	332 (28.8)	311 (27.0)
35	295 (25.6)	353 (30.6)
36	242 (29.7)	373 (32.4)
37	353 (30.6)	373 (32.4)
38	342 (29.7)	353 (30.6)
39	290 (25.2)	336 (29.2)
40	353 (30.6)	172 (14.9)
41	280 (24.3)	384 (33.3)
42	311 (27.0)	363 (31.5)
43	290 (25.2)	363 (31.5)
44	342 (29.7)	415 (36.0)
45	228 (19.8)	373 (32.4)

TABLE B2. ENDURANCE TEST ON AISI 4130 WORKPIECE
(Continued)

Hole No.	Bare Tap-MM27 Cutting Fluid	C2502 Coated Tap-MM27 Cutting Fluid
46	373 (32.4)	357 (31.0)
47	394 (34.2)	529 (45.9)
48	373 (32.4)	342 (29.7)
49	290 (25.2)	373 (32.4)
50	353 (30.6)	204 (17.1)
51	280 (24.3)	218 (18.9)
52	342 (29.7)	358 (31.1)
53	353 (30.6)	270 (23.4)
54	259 (22.5)	280 (24.3)
55	327 (28.4)	348 (30.2)
56	249 (21.6)	384 (33.3)
57	244 (21.2)	301 (26.1)
58	259 (22.5)	415 (36.9)
59	301 (26.1)	348 (30.2)
60	223 (19.4)	353 (30.6)
AVG	317 (27.5)	324 (28.1)

TABLE B3. ENDURANCE TEST ON SS 17-4 WORKPIECE

Hole No.	Torque, g.m (in. lb.) Bare Tap-RMF Cutting Fluid	ATA Coated Tap-RMF Cutting Fluid
1	353 (30.6)	415 (36.0)
2	353 (30.6)	612 (53.1)
3	353 (30.6)	332 (28.8)
4	373 (32.4)	467 (40.5)
5	321 (27.9)	207 (18.0)
6	321 (27.9)	477 (41.4)
7	332 (28.8)	373 (32.4)
8	384 (33.3)	435 (37.8)
9	373 (32.4)	415 (36.0)
10	373 (32.4)	384 (33.3)
11	363 (31.5)	415 (36.0)
12	321 (27.9)	373 (32.4)
13	425 (36.9)	431 (37.4)
14	384 (33.3)	332 (28.8)
15	425 (36.9)	332 (28.8)
16	415 (36.0)	394 (34.2)
17	373 (32.4)	342 (29.7)
18	311 (27.0)	394 (34.2)
19	394 (34.2)	477 (41.4)
20	404 (35.1)	332 (28.8)
21	353 (30.6)	394 (34.2)
22	394 (34.2)	332 (28.8)
23	435 (37.8)	394 (34.2)
24	415 (36.0)	311 (27.0)
25	332 (28.8)	431 (37.4)
26	431 (37.4)	358 (31.1)
27	420 (36.5)	378 (32.8)
28	435 (37.8)	415 (36.0)
29	356 (30.9)	384 (33.3)
30	348 (30.2)	301 (26.1)
31	425 (36.9)	357 (31.0)
32	456 (39.6)	270 (23.4)
33	456 (39.6)	342 (29.7)
34	404 (35.1)	384 (33.3)
35	394 (34.2)	373 (32.4)
36	353 (30.6)	373 (32.4)
37	498 (43.2)	415 (36.0)
38	285 (24.7)	373 (32.4)
39	415 (36.0)	435 (37.8)
40	321 (27.9)	353 (30.6)
41	394 (34.2)	684 (59.4)
42	336 (29.2)	332 (28.8)
43	290 (25.2)	379 (32.9)
44	404 (35.1)	446 (38.7)
45	435 (37.8)	415 (36.0)

TABLE B3. ENDURANCE TEST ON SS 17-4 WORKPIECE

Hole No.	Torque, g.m (in. lb.) Bare Tap-RMF Cutting Fluid	ATA Coated Tap-RMF Cutting Fluid
46	435 (37.8)	404 (35.1)
47	363 (31.5)	472 (41.0)
48	363 (31.5)	327 (28.4)
49	446 (38.7)	622 (54.0)
50	425 (36.9)	342 (29.7)
51	585 (50.8)	452 (39.2)
52	431 (37.4)	632 (54.9)
53	404 (35.1)	404 (35.1)
54	373 (32.4)	399 (34.6)
55	363 (31.5)	425 (36.9)
56	400 (34.7)	394 (34.2)
57	394 (34.2)	353 (30.6)
58	550 (47.7)	415 (36.0)
59	311 (27.0)	342 (29.7)
60	518 (45.0)	394 (34.2)
AVG	392 (34.0)	399 (34.6)

TABLE B4. ENDURANCE TEST ON L-605 WORKPIECE

Hole No.	Torque, g.m (in. lb.) Bare Tap-RMF Cutting Fluid	C2502 Coated Tap-RMF Cutting Fluid
1	560 (48.6)	570 (49.5)
2	622 (54.0)	581 (50.4)
3	581 (50.4)	688 (59.4)
4	622 (54.0)	688 (59.4)
5	643 (55.8)	668 (58.0)
6	622 (54.0)	591 (51.3)
7	601 (52.2)	612 (53.1)
8	601 (52.2)	661 (57.4)
9	612 (53.1)	632 (54.9)
10	570 (49.5)	643 (55.8)
11	529 (45.9)	632 (54.9)
12	539 (46.8)	622 (54.0)
13	Could not go through hole in one pass	622 (54.0)
14	-	622 (54.0)
15	-	622 (54.0)
16	-	622 (54.0)
17	-	622 (54.0)
18	-	Could not go through hole in one pass
AVG	592 (51.4)	629 (54.6)

TABLE B5. ENDURANCE TEST ON Ti-6Al-4V WORKPIECE

Hole Number	Bare Tap-RMF Cutting Fluid Run 1	Bare Tap-RMF Cutting Fluid Run 2	CR502 Coated Tap-RMF Cutting Fluid Run 1	CR502 Coated Tap-RMF Cutting Fluid Run 2
	No. of Passes			
1	1	2	1	1
2	1	1	1	1
3	1	1	1	1
4	1	2	1	1
5	2	1	1	1
6	2	1	1	1
7	2	1	1	1
8	2	1	1	2
9	2	1	2	2
10	2	1	2	2
11	2	2	2	2
12	2	2	2	2
13	3	2	2	2
14	3	2	2	2
15	4	2	2	1
16	4	2	2	2
17	10	2	2	2
18	-	3	2	2
19	-	3	2	3
20	-	3	2	3
21	-	2	3	4
22	-	5	3	4
23	-	5	3	4
24	-	4	2	4
25	-	4	2	-
26	-	6	2	-
27	-	6	2	-
28	-	-	3	-
29	-	-	3	-
30	-	-	3	-
31	-	-	3	-
32	-	-	3	-
33	-	-	3	-
34	-	-	3	-
35	-	-	3	-
36	-	-	3	-
37	-	-	3	-
38	-	-	3	-
39	-	-	4	-
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