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Milling and Drilling Evaluation
of Stainless Steel Powder Metallurgy Alloys

Federal Manufacturing & Technologies

L. J. Lazarus

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L. J. Lazarus

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L. J. Lazarus, Project Leader

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Abstract

Near-net-shape components can be made with powder metallurgy (PM) processes. Only secondary operations such as milling and drilling are required to complete these components. In the past and currently production components are made from powder metallurgy (PM) stainless steel alloys. Process engineers are unfamiliar with the difference in machining properties of wrought versus PM alloys and have had to make parts to develop the machining parameters. Design engineers are not generally aware that some PM alloy variations can be furnished with machining additives that greatly increase tool life. Specimens from a MANTEC PM alloy property study were made available. This study was undertaken to determine the machining properties of a number of stainless steel wrought and PM alloys under the same conditions so that comparisons of their machining properties could be made and relative tool life determined.

Summary

Fabrication of components with powder metallurgy (PM) material and process produce near-net-shape (NNS) parts. Only secondary operations such as milling and drilling are required to complete these components. In the past and currently production components are made from PM stainless steel alloys.

In order to perform this study, near-net-shape machining parameters were used. NNS practices are in conflict with ISO machinability test procedures that require substantially larger depths of cut. Methods and procedures are presented for the machining evaluations and data reduction techniques. Machining data was prepared in a form to be included into machinability PM database.

Specimens became available for a MANTEC PM material study. These specimens are well documented. The processing and material properties were known. This allowed a machining study to be conducted without having to document the specimen materials.

A study was undertaken to evaluate the machining properties of fourteen PM-stainless steel alloys. Three 303, five 304, and six 316 stainless steel PM alloys were made and a comparison index to wrought 304 generated. Wrought 316L was also evaluated for comparison. These alloys were evaluated in milling and drilling under the same machining conditions. In this way comparison of forces and tool life could be made.

Discussion

Scope and Purpose

Production components have been made from powder metallurgy (PM) alloys. Near-net-shape (NNS) components can be made with PM processes. Only secondary operations such as milling and drilling are required to complete these components. Process engineers are unfamiliar with the difference in machining properties of wrought versus PM alloys and have had to make sample parts to develop the machining parameters. The objective of this project was to compare a number of PM alloys under the same test conditions so that comparisons of their machining properties could be made.

We used the testing format and data presentation developed for the USCAR CRADA (Cooperative Research and Development Agreement). Samples of all the PM SS alloys were obtained by the USCAR partners from MANTEC study. These stainless steel samples were part of a large MANTEC study that was never completed. Complete chemical and metallurgical properties were obtained on these samples.

Activity

Many production products are made from PM-SS blanks. A number of the features of the PM part are in their final form and only secondary machining operations are performed, typically milling and drilling. This is very similar to how the automotive companies use PM parts in their production systems. PM part features can be controlled to within ± 0.002 inch. It was felt that a similar project related to PM – stainless steel alloys – would be valid for Federal Manufacturing & Technologies (FM&T) application using the methods, equipment, testing procedures of the USCAR methods.

The USCAR partnership had obtained all the samples from a MANTEC PM alloy study. The USCAR partners were only interested in some of the alloys. The partners had no interest in the stainless steel PM samples. The MANTEC PM-SS samples were obtained for this study. Tables 1, 2, and 3 list the

manufacturing, chemical, and physical properties of the SS-PM materials used in this study.

A number of decisions were made in the USCAR CRADA project that impacted the test procedures, equipment used, and data reduction method. The CRADA partners [Chrysler, Ford, General Motors, Lockheed Martin Energy Systems Y-12, AlliedSignal FM&T (now Honeywell FM&T)] made these initial decisions to facilitate the project planning and determine the number of test specimens to order. We had to make a number of decisions so that a testing plan could be formulated based on the number of specimens available. We used the same guidance for this study to maintain consistency.

They were:

- Carbide cutting tools made from grade C-6 would be used for the milling machinability tests. Testing results would then be applicable to cutting tools having a longer tool life.
- High-speed steel 9-mm, 118-degree point drills would be used for the drilling tests.
- Use the ISO machinability procedures as the approved methods because of their worldwide acceptance. This decision led to a number of problems that had to be resolved by the CRADA partners and are reiterated here for reference.
- Since the powder metal alloys are to replace steel alloys, speeds and feeds similar to those used with 1045 steel were selected.
- It was assumed that drilled pucks could then be used for milling tests.
- All machinability testing would be performed without the use of metal removal fluids (MRFs).

Based on these decisions, a test specification was generated for milling and drilling tests (Appendix A). In order to be compatible with this testing, the same machining procedures, data reduction techniques, and data presentation were used unless specified. Table 1 lists the processes used to fabricate the specimen and the resultant density of the alloys. Table 2 lists the primary alloying elements. Table 3 is a listing of the physical properties. All alloys are defined in the 1997 edition of the Materials Standards for P/M Structural Parts (Standard 35). This is a publication of Metal Powder Industries Federation.

Table 1. Stainless Steel PM Specimen Manufacturing Matrix

Material Code	Base Alloy	Density g/cm ³	Sinter Cycle	Resin Impregnation
303N1	303	6.40	2050 F, D.A.	
303N2	303	6.49	2400 F, D.A.	
303N29	303	6.88	2400 F, D.A.	
304N1	304	6.43	2050 F, D.A.	
304N2	304	6.42	2400 F, D.A.	
304N29	304	6.88	2400 F, D.A.	
304L	304	6.51	2350 F, Vacuum	
304L9	304	6.90	2350 F, Vacuum	
316N1	316	6.43	2050 F, D.A.	
316N12	316	6.43	2050 F, D.A.	Yes
316N2	316	6.54	2400 F, D.A.	
316N22	316	6.54	2400 F, D.A.	Yes
316L	316	6.54	2350 F, Vacuum	
316L2	316	6.54	2350 F, Vacuum	Yes

D. A. cycle (dissociated ammonia atmosphere) causes nitrogen to dissolve into microstructure producing a material with higher hardness, strength, and lower ductility.

Vacuum cycle produces a material with more ductility and less strength and hardness than the D.A. cycle.

Table 2. Stainless Steel PM Specimen Composition Matrix

Material Code	Base Alloy	Density g/cm ³	Nickel %	Chromium %	Molybdenum %	Nitrogen %
303N1	303	6.40	12.65	18.3		0.38
303N2	303	6.49	12.65	18.3		0.35
303N29	303	6.88	12.65	18.3		0.23
304N1	304	6.43	11.4	18.95		0.41
304N2	304	6.42	11.4	18.95		0.3
304N29	304	6.88	11.4	18.95		0.25
304L	304	6.51	11.4	18.95		0.09
304L9	304	6.90	11.4	18.95		0.05
316N1	316	6.43	13.15	16.8	2.31	0.36
316N12	316	6.43	13.15	16.8	2.31	0.36
316N2	316	6.54	13.15	16.8	2.31	0.34
316N22	316	6.54	13.15	16.8	2.31	0.29
316L	316	6.54	13.15	16.8	2.31	0.07
316L2	316	6.54	13.15	16.8	2.31	0.04

Table 3. Stainless Steel PM Specimen Physical Properties Matrix

Material Code	Density g/cm ³	Tensile Strength psi	Yield Strength psi	Percent Elongation	Apparent Hardness HRB	Impact Energy
303N1	6.40	42,800	36,600	1.5	59	5.6
303N2	6.49	54,600	39,000	8.1	60	25
303N29	6.88	68,100	45,200	12.6	72	38.9
304N1	6.43	50,100	40,700	2.8	60	7.2
304N2	6.42	63,200	43,100	10.7	60	30.1
304N29	6.88	76,200	49,100	15.8	72	59.2
304L	6.51	44,900	23,300	19.8	30	51.3
304L9	6.90	57,000	26,800	26.9	52	95.1
316N1	6.43	47,500	39,300	2	61	6.9
316N12	6.43	47,500	39,300	2	61	6.9
316N2	6.54	61,900	43,200	9.9	58	27.1
316N22	6.54	61,900	43,200	9.9	58	27.1
316L	6.54	40,800	22,500	17.3	26	39.4
316L2	6.54	40,800	22,500	17.3	26	39.4

Machinability Tests - Machining Force Measurement System and Data Reduction

Cutting Force Instrumentation

In the Process and Machining Evaluation Lab (PMEL) at FM&T/KC an existing data logger was utilized to measure cutting forces during milling and drilling tests (Figures 1 and 3). The system used a piezoelectric cutting force milling table (referred to in the literature as a dynamometer) and a data logger board installed in a PC with auxiliary charge amplifiers. The Labview operating software was used to control the system, scale the data, and load Microsoft Excel spreadsheet (block diagram, Figure 2). The Excel statistical and plotting packages were used to reduce and plot the test data.

Figure 1. Monarch Cortland Machining Center With Test Instrumentation and Data Logger System

Force Measuring Setup for Machining Tests - Powder Metal Project

Figure 2. Block Diagram of Data Logger System

The data logger system (Figure 2) also had the capability to use stain-gaged sensors. Previous testing showed that results using the strain gage dynamometer were compared to runs using the piezoelectric dynamometer and similar results were obtained. The operating software allows the choice of either type of dynamometer by channel selection. The first four channels use the stain gage signal conditioning.

Figure 3. Force Table With PM Specimen Puck Installed in Holding Fixture for Milling Test.
(Round puck is installed. A similar set of jaws is bolted in when using square specimen.)

A Monarch Cortland quick-change tool holder was modified and strain gaged to convert it into a torque transducer using a slip ring assembly to connect the strain gages to the signal conditioning equipment. This transducer was used and proved unsatisfactory for drill testing for the following reasons. In order to increase sensitivity of the transducer to torque loads, the tool holder cross section was reduced to increase the shear stress on the outer fiber. The axial loads encountered in drilling were sufficiently high to deform the smaller section in buckling. This deformation was not repeatable and caused the calibration to change. Life problems were also encountered with the life of the bearings of the slip ring assemblies.

Torsional load measurements were determined using the tangential force recorded on the force table in the X and Y planes. When the cutting edges are parallel to the Y-axis of the dynamometer, the force is at a maximum and the force in the X-direction is at a zero. This is the indirect method of measuring the cutting torque. Torque was determined by multiplying the measured forces by the radius of the drilled hole. When power consumed in drilling was calculated using these values, it was artificially low and matched no previously reported data.

Because of these problems a piezoelectric torque dynamometer was purchased. This dynamometer (Figure 4) used the same charge amplifiers as the force table and signals were compatible with the existing software. Test drills were used to drill one additional hole and final torque load determined. A new drill was used to determine the initial torque load. Drilling torque for the intermediate points (50 and 75% wear) could not be determined without completely rerunning the tests.

Figure 4. Kistler Torque Dynamometer

Some problems were encountered with the torque generated with the torque dynamometer. Multiple tooling setups (a new and used drill for each sample), lack of specimens, and test fixturing that did not allow us to drill holes equidistant from the center of the dynamometer had an influence in the spread of the values. The average torque data for a specific alloy is much more consistent and is recommended for use by the author.

Data Reduction

All machining runs were sampled at a rate of 100 Hz per channel. This rate was selected because it allowed at least 4 points per tool rotation in drilling and 35-point/revolution/channel in milling. This sampling rate was high enough to ensure we could differentiate any aliasing of the data and recreate the data trace. Drilling runs were short so that no special methods were needed to load the test files into the Microsoft Excel software for analysis. In all cases possible we used Excel to calculate the averages, standard deviations, maximums, and minimums of the data sets. The person doing the data reduction was responsible for selecting the interval where the software would calculate the data. The graphic ability of Excel was utilized heavily to make these decisions. Machining data is usually constant because the depth

of cut, feed rate and rotation are constant during a run. The main variables are wear, heat, application of lubricant, and effects of chips. In the case of milling, a procedure was developed to handle the extremely large files generated during a run that was almost eleven-plus minutes in length.

Labview force data files were uploaded into Excel. Excel has a canned program that converts the Labview text (txt) file data structure into a spreadsheet structure. Each scanned text record becomes a row in the Excel spreadsheet. Excel allows the data to be reformatted and plotted. By using Excel's function libraries average, maximum, minimum, standard deviation could be obtained for set data range. Excel automatically determined these values after the period of analysis was selected. Data runs started before the tool engaged the workpiece so that the zero loads could be established. Data was analyzed after the cutting forces were established and consistent, usually after the cutter engaged the material. Runs were averaged until the load started to drop off as the insert exited the cut.

Drilling

Maximum axial force was recorded for every hole drilled. Initial runs using a strain gaged tool holder proved unsuccessful. A second attempt was made using the force table to obtain the tangential force because a torque calculation was not sensitive enough to yield reliable results. After a torsional dynamometer was obtained first-hole torque was obtained with new drills. Final torque runs were obtained using worn-out drills from this study to drill one more hole in the material that were originally tested. Torque runs were not obtained for the 50% and 75% points. Runs were under 10 seconds in length. The torsion files were loaded into Excel where the average, standard deviation, starting and ending torque were determined. A horsepower calculation then could be made.

Milling

A procedure was developed to reduce the milling data that would allow flexibility in reducing data without affecting the accuracy of the results. Milling files were extremely long, usually over 5 megabytes, making them very difficult to handle and examine with the same techniques used in turning and drilling. The text files generated by Labview could not be directly loaded into the Excel software because of size limitation. Since our test specimens were round, the longest cut was when milling the center of the puck. When the Y-axis cut would be at its longest length and the Y-axis loads would be at their maximum, the cutter path would be directly over the center of the dynamometer.

The Labview test files were first loaded into Microsoft Word because this software would not limit the size of the file loaded. A milling data file was typically 2100 to 2800 pages in length with a mean length of 2300 pages. Excel limits the file size it can load to 65,536 rows. Its plotting software limits a plot to 4000 rows. A data file of 135 pages was equivalent to an Excel file with 4000 rows of data. All channels sampled per sampling cycle were in one row.

Approximately 100 - 150 pages were copied around the midpoint of the file. This was a file of 2500 to

4000 data points that would be copied into a temporary file and then loaded into Excel and plotted easily. A file of 6000 rows represented milling a width of approximately one inch in the middle of the specimen. The whole data file would be plotted to determine if it was constant, repeatable, and consistent.

A section in the middle of the file of approximately 8 to 10 cycles would then be plotted. This would allow a closer look at the milling forces for each rotation of the cutter. Again we would examine data for any irregularities. If data looked good (high signal to noise ratio, low drift, a repeatable and consistent shape), the X, Y, and Z data was copied into a second set of columns. This data was then ordered by either descending or ascending order, depending whether the data was negative (X and Y-axis) or positive (Z-axis). By doing this we could average the top 2% of the data in the file. We could then obtain an average of the maximums and minimums for the data set. A copy of this worksheet is shown in Figure 5.

This ordered data was examined for consistency, and usually the first or second point would be 10 to 20% larger than the rest of the data. We believe this point was caused when a chip was double cut. We didn't want this data included in the force data. The next 50 points were then averaged together to determine the cutting force. Because of the geometry of the cut and the test setup the forces in the Y-axis were along the tangential axis of the milling cutter. The cutting torque was obtained by multiplying the tangential force by the tool radius (2.5 inch). The axial cutting force was also determined in a similar way.

Figure 5. In-process Screen Print of Typical Milling Data in Excel During Data Reduction

Because of the length of a milling pass (approximately 12 minutes) a zero shift was encountered, caused by the charge amplifiers. Since only one cutting edge was used and was not cutting for at least 60% of the tool rotation, the traces could be expanded and the zero point obtained during the portion of the rotation the cutting edge was not engaged into the workpiece. This value was then subtracted from the average and the corrected force was obtained. The reported forces were for the middle of the test pass while the material removed values are for the end of the pass. This was done because the specimens were round and the forces were at their maximum only during the middle of the pass. Wear measurements were only taken at the end of the test pass.

Other Measurements

Insert wear measurements were made on the PMEL's ROI measuring microscope (Figure 6) using the methods developed in the USCAR CRADA. Drill wear was measured using the procedure in Appendix C. This method was also developed during the USCAR CRADA. The failure criteria for both the milling

inserts and drills are listed in the test specifications included in Appendix A.

Heat is the destroyer of cutting tools. In this testing program coolants were not used to remove one of the variables so we could not depend on a secondary medium to control cutting edge temperatures. Because of these differences the effect of temperature difference of the cutting edge is magnified in these results. In the actual production environment this effect would not be noticeable because of the use of coolant.

Milling

In both milling and drilling the cutting tool rotates and the workpiece is stationary. In drilling, the cutting edges of the tool stay in continuous contact with the workpiece material and can produce continuous chips. In milling, the cutting tool rotates and the workpiece is stationary. In this process the cutting edge does not stay in continuous contact with the workpiece material. The process is discontinuous and the cut is considered interrupted. In turning, the chip thickness and cutting forces are constant for a revolution. Conversely, in milling the chip thickness and cutting forces vary because of the dual motion of the cutting tool and table travel. Another difference between milling and turning is the temperature cycling of the cutting edge. Because of the interrupted cut the cutting edge temperature is cycled each revolution. Tremendous tool heat develops when the tool is engaged in the workpiece with temperatures up to 2000°F.

Figure 6. Insert Wear Being Measured on the ROI Microscope. (Note wear scar on screen.)

For heavy metal removal, cutters offering a combination of negative-radial and positive-axial-rake geometry are the best choice. Such cutters are most commonly used in face milling because the chip flow will be away from the center of the cutter and upward away from the work. Chips are thereby prevented from clogging the cutter, damaging the carbide edge, or marring the surface finish.

A problem was encountered using the ISO procedure. During the USCAR CRADA the partners dealt with

this problem. This problem also affected this testing. The decisions made in the USCAR CRADA are presented here and were also used for this project.

"Tests were started using the ISO 8688 procedure (Tool Life Testing in Milling - Part 1: Face Milling). In order to accommodate near net shape machining the depth of cut was reduced from 0.100 to 0.030 in. Problems with our modified depth of cut were encountered. This procedure required a 0.100-inch DOC and measurement of the flank wear in area A2, Figure 5 (see figure 2 below) of the standard. Using a 0.030 DOC, the wear scar did not extend onto the flank face to allow a flank wear measurement. At the quarterly meeting, pictures were shown of the wear patterns and the problems associated with measuring wear per the ISO procedure. The wear in area A3 (Fig. 2) was well defined, and the wear scar extended into area A_f and A2. The partners agreed that wear measurements should be made in area A3 and we should use 0.040 in DOC for the milling tests. A milling test specification is included in Appendix 1."

Because of the cycling of forces and temperature due to the interrupted cut associated with every revolution of the cutter, the modes of tool failure can be different in milling. A milling insert is prone to chipping when higher production rates are attempted. Insert manufacturers put a small land or hone on the top face at the cutting edge to prevent chipping very early in the life of the insert and to promote normal insert wear.

The automotive partners recommended the speeds and feeds used in the USCAR study based on their experience with the PM alloys tested. The speed and feed combination selected yielded normal wear pattern with some chipping when used with wrought 304 samples. In most cases the chipping did not exceed the failure criteria defined by the ISO 8688-1 Standard. When testing some of the PM-SS alloys, this speed and feed combination proved too aggressive. In these materials it was not uncommon for the prominent insert failure mode to be chipping with some normal wear shown. Other SS-PM alloys were easily milled and testing had to be stopped because of lack of specimen needed to reach the wear failure criteria.

The same response was not obtained in drilling, and different speeds and feeds had to be used to obtain some tool life. The drilling speed and feed was modified and the test specification updated (see drilling section).

In some cases the insert didn't live for a single pass. The chip occurred at the P3 location (Figure 7) at the junction of the flank and prime flank face. The A2 face is considered the wipe face. This edge will remove the high spot generated by each rotation of the cutting edge. This accounts for the saw tooth wear pattern scene on this face. As the face was grooved it would not be effective in removing the high spot. The pitch between the grooves is equal to the feed per revolution (Figure 7).

This coding system includes

- code A, which refers to areas;
- code P, which refers to points;
- indexes, which refer to positions.

These codes and indexes shall be used in the data sheet, see the example in annex C.

Figure 5 – Deterioration position coding system

Figure 7. Deterioration Position Coding System ISO Std 8688 Part 1 (The terms and definitions taken from ISO 8688-1, Fig. 3, 4, 5 are reproduced with the permission of the International Organization for Standardization, ISO. This standard can be obtained from any ISO member and from the Web site of the ISO Central Secretariat at the following address: <http://www.iso.org>. Copyright remains with ISO.)

Figure 8 shows how the inserts mounted in the tool holder for use. Figure 9 shows the inserts in the machining position. It is easier to orient the wear pattern seen on the insert with this figure. Figure 10 shows how the inserts are pictured in ISO 8688-1, *First Editions, Tool life testing in milling - Part 1: Face Milling*. Figure 11 shows the relationship of the wear lands with the 0.030- and 0.040-inch depth of cut (DOC). For this study the partners agreed that for near-net-shape machining it was more important to measure the wear on the prime face than the flank face. By increasing the depth of cut from 0.030 to 0.040 inch we were able to get the whole prime face cutting the workpiece material. There is a short length on the flank face that is also worn. With the increased depth of cut we were able to generate some normal flank wear data that was hoped to compare with other studies. In addition, we prevented the entry scar from falling on the insert corner. This corner is prone to chipping. If the entry scar fell on top of this feature, the life of insert would be severely reduced and would have biased the test results.

Milling tests were run in accordance with *ISO 8688-1, First Editions, Tool life testing in milling - Part 1: Face Milling*, with the following exceptions:

Depth of Cut- 0.040 in., (1.02 mm); Width of Cut: Full width of puck (puck diameter 4 in. (101.6 mm); therefore the cut width varied from 0.1 to 4.0 inches. All runs were made with a Valenite 5 in. (127.0 mm) Face Mill Body B(5)10R-15P and SPKN 1203 EDR inserts grade 35M (Grade C5-6). New Valenite designations for holder and insert defined in ISO 8688-1. Geometry was not changed during testing.

Figure 8. Milling Insert Installed in Tool Holder Body (The terms and definitions taken from ISO 8688-1, Fig. 3, 4, 5 are reproduced with the permission of the International Organization for Standardization, ISO. This standard can be obtained from any ISO member and from the Web site of the ISO Central Secretariat at the following address: <http://www.iso.org>. Copyright remains with ISO.)

Figure 9. Insert Dimensions as Loaded in Figure 10. Insert Dimensions as They Appear in

Tool Holder Body ISO 8688 Standard (SPAN 1203 EDR)

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Figure 11. Wear Scar Generated by a 0.040-in. DOC as It Relates to the Different Insert Faces

Wear was measured on the A3 insert face as defined in Figure 5 of the ISO 8688-1. Failure criteria were 0.015-in. wear, chipping, or other sorts of wear as defined by Table 2, normal criteria category of ISO 8688-1. This 3-page long figure that defines test termination conditions is not included in this report for brevity.

A summary of the milling insert life (tool life) for the various PM alloys tested in the summary is presented below in Figures 12 and 13. When the insert wear land was 0.015-inch wide on the prime flank face or when the chipping of the cutting edge of the insert exceeded the requirements of ISO Standard 8688-1, Table 2, Figures 14 and 15 compare the amount of material removed by milling at the failure point. This value is an average of all inserts tested in a particular alloy under similar conditions. A summary of test results for each material tested is included in Appendix C of this report.

The tool life of the PM-SS alloys was then compared to the tool life of similar inserts tested in wrought 304L stainless steel. Wrought 304L stainless steel had a milling index of 1 by definition (Figures 14 and 15).

Figure 12. Summary of Tool Life in Various PM Alloys (A)

Insert life for 316L2, N12 was estimated because we ran out of specimen pucks. In these cases we estimated the life using a straight-line approximation based on a tool wear of 0.015. We then reduced this estimate by approximately 10% because the mortality curve for a cutting tool based on wear becomes exponential near the end of its life. The performance ratio was calculated using this estimated value.

Figure 13. Summary of Tool Life in Various PM Alloys (B)

Figure 14. Milling Performance Ratio of Various PM-SS Alloys (A)

Figure 15. Milling Performance Ratio of Various PM-SS Alloys (B)

Drilling

There is no ISO drill test procedure. Research by PMEL personnel came up with a number of drill test procedures found in machinability and cutting fluid evaluation testing. The CRADA partners agreed to use a variation of the Precision Twist Drill Co. (PTD) procedure distributed at the June meeting at FM&T/KC.

Drilling is one of the most common machining operations used in the metal fabrication industry. It is a quick and economical method of producing holes in a workpiece in a production environment. Many things are taken for granted and the complexities of the process and cutting tools involved in the process are not generally well understood. None of the standards organizations have ever published a drill test procedure because of the complications that surface when this processes is looked at carefully. In the bibliography a number of test procedures are listed. We utilized the procedure used by Precision Twist Drill Company (PTD) as the basis for the PMEL test procedure. Unlike the USCAR study, holes produced in testing were 1-inch deep blind holes. This was done because the specimen thickness was only 1.040 inches thick. This would also allow comparisons to other published studies on PM alloys. The drilling test specification is included in Appendix A.

One of the most difficult jobs in machinability testing is determining the failure criteria for a test. Criteria for test termination are defined in the ISO Standards for Milling and Turning testing. We used a similar criterion in drilling. The criteria we finally agreed on were:

- 0.015 wear of the lips at the corner of the lips and the margin.
- 0.015 wear of the margin.
- Two excursions to 1000-lbs axial load during drilling.

After achieving these test-ending criteria the drill can still continue to produce holes. Out of curiosity we have continued drilling and produced many holes. We have found that when the lips are worn more than 0.015, drill breakage is imminent. We have never seen a drill with lips worn to 0.020 cutting steel. This is not the case with margin wear. Drills continue to produce holes. It is more a function of desired consistency of the diameter of the hole. Sometimes margin wear resulted in catastrophic failure of the corner of the drill. Axial load of over 1000 lbs is an indication something is wrong. Drill squealing usually accompanies high axial loads and is warning of possible drill breakage.

The prime destroyer of perishable cutting tools in machining operations is heat. Cutting fluids, now called metal removal fluids (MRFs), have been developed over the years to remove heat, supply lubrication, and

control the reactivity of the freshly cut surfaces. The application of MRFs can be very variable during the machining process. This variability can have significant effect on the life of the cutting tool. For this reason it was decided to eliminate this variable from the testing and run them dry. This is also consistent with other PM drilling studies.

This decision to eliminate MRFs presented another problem and that was the buildup of heat in the tooling and the workpiece. The effects of breaks, tool measurement, and test duration had to be considered in the design of the testing program.

- In milling, over 60% of each revolution of the cutter is in air. Milling passes were much longer, on the order of 12 minutes. Actual cutting time was much less. A carbide insert was used. Carbide can maintain its hot hardness to a much higher temperature than high speed steel, and the overall effects were not significant.
- In drilling, the effect of heat buildup in the tool and workpiece were significant. The drills were made from high speed steel (HSS, M7 alloy) and the effects from heat occur at a much lower temperature.

The setup of a drill for wear measurement took much longer than setting up an insert for wear measurement. An additional setup was used to check for margin wear. In addition, in drilling the cutting tool conveys the chips from the cutting edge to the top of the workpiece where they are expelled. The deeper the hole, the longer the hot chips are in contact with the drill and the workpiece. The writer noticed that the chips are not as long as those generated by a wrought material (a chip is generated in less than a revolution). The chips are further broken up as they are conveyed up the flute, especially as the hole gets deeper. This increases the heat generated by the friction of conveying the chips. Samples of the very small chips (almost a powder) were taken.

In order to limit the effect of heat generated in drilling we added a 55-second cool-down dwell between holes. This allowed the drill and the workpiece to cool down slightly between holes. This reduced the impact of wear measuring and breaks on the overall results.

Initially we planned to turn the tool holder into a torque transducer. Extended length solid tool holders were purchased to allow installation of strain gages. A collet tool holder could not be used because the larger tool holder shank and because of the installation of an assembly nut. In order to obtain adequate sensitivity, a reduced section was machined into the extended part of the holder. The diameter of the extended section was reduced from 1.25-inch diameter to 0.875. Before being strain gaged the holders were checked for concentricity. The holders were found to be within 0.0006 TIR when a maximum sized gage pin was used instead of a drill. The tool holders were then instrumented and the assemblies were statically calibrated for a maximum load of 200 inch-lbs. Mounting of the slip ring assembly on the tool holder proved difficult because of the set-screw used to install the drill. The strain gages had to be installed between the tool holder taper and the set-screw. In use, this device proved accurate at higher torque loads but affected the dynamic zero, and the response at lower torque levels was non-linear. We found that this

device was more of a hindrance to obtaining accurate data than what was being generated. Because of this, the instrumented tool holder was abandoned.

Instead we planned to measure the applied torque by measuring the X-Y-Z force table. A series of three drills was run in wrought material. The X-Y response was digitized. A method similar to one used in milling was used to evaluate the last quarter-inch of drilling before the point broke through the bottom of the workpiece. This method proved somewhat successful. All dynamometer runs were recorded this way. The sensitivity was marginal in drilling when compared to the much higher forces recorded in milling. When sensitivity was increased, noise problems (both electrical and mechanical) were encountered. New charge amplifiers were obtained which only improved the noise problem slightly. When data reduction was started, we found significant problems with some of the data. Calculated theoretical torque and horsepower varied greatly from the measured values.

Because of this a piezoelectric torque dynamometer compatible with our charge amplifiers and recording equipment was obtained. Additional new drills were used in order to obtain the initial drilling torque for each material. All drills used in this study had been retained and were used again to generate one more hole to obtain the final cutting torque at drill failure (dynamometer run D).

Drills selected for this study had a black oxide finish all over, including the point. Some believe the oxide coating improves the life of a drill when used on ferrous materials. The coating resists the tendency of soft material to adhere to the cutting edges (built-up edge – BUE) and margins of the drill. Others feel this coating acts like a lubricant. Testing showed that when a bright pointed drill was tested it eventually formed an oxide coating because of heat buildup. We did not find a significant variation in drill life between coated and bright pointed drills. Enough drills of both kinds were not run to quantify the variation. Today, drills with titanium nitride are commonly used when drilling PM alloys. It was not felt worthwhile to evaluate oxide vs. bright points.

The measurement of the wear land on the cutting edge of a drill is very difficult because the cutting edge is always wearing away. At FM&T we usually use the backside of the margin as our reference point because this point is usually not subjected to any wear (Figure 17). In some cases where we had catastrophic failure of the corner of the cutting edge, the junction of the margin and point was damaged and this reference point was lost. From a number of observations of the point under the microscope we found that areas on the secondary clearance of the cutting edges almost never experienced any wear. Scribe marks were made on this surface and observed. We found we could scribe reference points on the secondary clearance surface. From this point on, all wear measurements in this study were made using these scribed references. After the scribed drill was assembled in the tool holder, the assembly was installed in the microscope measuring fixture and coordinates recorded as well as the location of the corner of the cutting edge. This location became the reference for corner wear measurements. Since the assembly was never disassembled during the test run, the references were never lost. When successive measurements were made, the assembly was oriented at its original coordinates and the references re-established.

Figure 16. Drill Point Attribute Definition

Figure 17. Drill Point With Measurement References Defined

On a new drill the coordinates of the cutting edge were recorded and any initial damage noted. Drill measurements were made with a microscope at approximately 400 power. Therefore, we can see even the slightest amount of damage. We contacted Precision Twist Drill after receiving our first lot of 200 drills. We noted a significant amount of damage to the drill corners (where the margin meets the cutting edge). FM&T Cutting Tool Engineering Specification will cause rejection of any drill with over 0.003 damage to the cutting edge. We met with PTD and showed them the damaged drills. They accepted the drills for credit and explained that they were changing the automated material handling equipment in their manufacturing cells to prevent as much damage as possible. Their rapid plant expansion has caused

problems that were now being corrected. Their engineer admitted to us that they would accept up to 0.005 damage to the corners of a drill.

When reviewing the drilling summaries, please note that the wear curves are offset on the wear axis. This is because of this damage. We tried to use drills that had less than 0.002 in damage. Also note that this damage affects the overall life of the drill. Part of the variation in drill life is caused by the amount of initial damage to the cutting edge at the corner. Since this damage is not easily seen without high magnification, the user is not aware of this problem. That is also why most cutting tool manufacturers limit the user to 10 power when inspecting new tools. Damage of 0.002 is significant when total wear to failure of the tool is 0.015 inch. We realize that significant wear occurs after drilling the first hole, but let the process control the wear and tool life and not the damage to the tool. If a tool with 0.005 wear were tested, it would have significantly less life than a drill without any damage.

All testing was performed without the use of metal working fluid. This presented a problem with the buildup of heat. As stated previously, heat is the destroyer of cutting tools. In the literature one finds comments concerning the buildup of heat in the drill causing the wear rate to accelerate. As the drill dulls, the cutting temperature increases. This is the common explanation on why a drill can be wearing linearly and near the end of the drill life it will wear exponentially. A dull drill generates a higher temperature at the cutting edge.

During the USCAR testing much effort was put into being consistent in how the tests were run. Short duration tests were run to determine the effect of heat in drilling. Holes were drilled as fast as possible, one right after the other. A second test was run in which a one-minute waiting period was inserted between holes. Life could be increased by 50% just by adding the wait. In production a metal working fluid is introduced into cut in order to wash away chips and lower the operating temperature of the drill. This flow of fluid also removes heat from the workpiece. Even with the one-minute delay between holes, it was noticed that the workpiece heated up over 75°F from the time the test was started until 25 holes were produced.

During initial testing in the USCAR project, heating problems associated with drilling without coolants, chip and powder formation in deep drilled holes, specimen thickness variation, and surface condition were discussed. From these discussions the drill test procedure was modified. A one-minute cool-down period was implemented between holes to reduce drill temperature buildup and to more closely model the temperatures in the actual production environment.

Initial testing started using the speed (116.5 SFM) and feed (11.4 IPM) as the USCAR study. Drill life was very short. Sets of tests were run to determine a more realistic set of speed and feed combination. The final speed selected for the test was 37.8 SFM (407 RPM) and feed of 1.9 IPM (0.0047 IPR). These values yielded longer, more consistent results.

We observed that small chips and powder were formed as holes were drilled. Because of the feed rate,

0.0047 in./rev, the chips were various shades of blue. As the drill wore, the chips would reach a straw color. This caused the chips to be brittle. As the drill progresses through the pucks, the small chips typical of PM alloys, investigated in this study, were being broken up as they were conveyed to the top of the hole. This added to heat generated in the drilling process.

A number of PM alloys have been developed with machining alloys. The imperfections also cause smaller chips to be produced. These small chips are not conveyed out of the holes as quickly as a larger chip with a standard flute spiral. The small chips break up as they are packed against each other in the flutes. As these chips get smaller, they try to get between the drill margin and the hole wall, causing excessive wear of the margin. This undermines the corner of the drill point and can lead to its collapse (Figure 18). The predominant failure mechanism for these PM alloys was margin wear. Drill manufacturers intentionally grind a taper down the length of the drill from the point. This is called back taper and is provided to reduce friction between the drill and the hole wall in the workpiece material. In a number of cases the cutting lips were undermined by wear on the margins. Eventually this will result in catastrophic failure of the cutting edge when it is undermined at the corner. The junction of the cutting lips and the margins at the corner of the point act similarly to the cutting edge of a reamer and control the size of the hole at the bottom. As the corner wears, this cutting rounds, but is still effective. If the wear moves up the margin, the effective cutting edge moves up into the back tapered area of the drill and hole size cannot be controlled. The result will be holes that are smaller in diameter at the bottom of the hole than if the margins were not as severely worn. Tests were stopped when the wear of the margin exceeded 0.015 inch.

We tried temperature sticks to determine the temperature of the cutting edges of the drill under test. The drill was cooling rapidly, and by the time the spindle was stopped the temperature had dropped significantly. In addition, the amount of contact affected how the wax compound melted. The sticks wouldn't respond quickly enough.

Figure 18. Detail of Worn Corner of a Test Drill

We did use an infrared thermometer to make this measurement. We had to keep the thermometer back from the drill to avoid hitting the optics with chips. As you move away from the drill, the measuring spot increases significantly. We had to wait until the drill point had retracted from the specimen and the Z-axis movement stopped. Measurements were made while the drill was still rotating, averaging the reading. When trying to sight the cutting edge, you also get a significant amount of background at room temperature and the other parts of the drill point which are not as hot. Therefore the temperatures recorded are significantly below actual cutting edge temperatures. We found an increase in drill temperature of at least 75°F from the first hole in a group of 10 to the last hole in the group. Temperatures of approximately 200°F were recorded on the first hole in a group and 275°F on the last hole in a group. Temperatures above 300°F were not encountered during the limited observations with the IR thermometer. The accuracy of the measurement was suspect and we stopped taking measurements.

Figure 19 is a comparison of the PM-SS alloys and wrought SS alloys tested. The life is calculated based on cubic inches removed. Again the results for the PM alloys were compared to results of drilling tests run on wrought 304L stainless steel. A performance ratio of drill life in PM alloys to wrought 304L is presented in Figure 20. Again by definition the performance ratio of wrought 304L is 1. Also note that that wrought 316L SS had a higher performance ratio of 1.2 when compared to 304L.

Figure 19. Drill Life in Various PM-SS Alloys

Figure 20. Drill Performance Ratio in Various PM Alloys

Accomplishments

When PM-SS parts are fabricated into production components, it is possible to incorporate machining additives and specify density of the finished part. This study shows how minor changes in an alloy's composition and density can affect the tool life. By changing the PM alloy selected from 304L9 to 316L, the drill life is increased by 500%. Even larger improvement in tool can be achieved in milling by selecting the correct PM-SS alloy. Product and process engineers now have a basis for discussion with the design agencies which can aid them in material selection.

In addition, the data tables provide the necessary information so that process planning can be accomplished prior to part fabrication.

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Appendix A

Test Specifications

Milling Test Specification

Specimen: Disk 4 inch diameter x 1.125 thick

Square 4.25 inch x 1.072 thick

Cutting Tool:

Face Mill: Valenite Model No.: B(5)10R15P

Axial Rake: 5 Deg Positive

Radial Rake: 0 Deg

Lead: 15 Deg

Insert: Valenite, SPKN 1203 EDER 35M, with 11 Deg Relief

Grade 35M (Grade C5-6)

Machine Type:

Monarch Cortland Machining Center

HP Available: 15 HP

Max Spindle Thrust: 2000 lbs

Max Speed: > 3,500 RPM

Max Feed: > 40 IPM

Tooling Setup:

Tool Holder: Monarch Cortland 2.00 inch Dia Face Mill Holder (Cat No. MMSA-45-24) .

Milling Pattern:

Feed cutter centerline down the centerline of the test specimen.

Machining Parameters:

Speed: 169 RPM (225 SFM)

Feed: 0.5 in/min (0.005 in/rev)

Depth of Cut:0.040 in

Equipment Used:

KIAG SWISS (Kistler) Force Table

KIAG SWISS (Kistler), Charge Amplifiers, Model 5001, (A, B, C)

Kistler Type 9275 Torque Dynamometer

Kistler Model 5841B1 3-Channel Charge Amplifier (Model 5010)

Kistler Model 5350 Transducer Simulator WITH Model 5371A Calibration Capacitors

ROI Measuring Microscope, with rotary mounting stage with attached 3 jaw chuck.

Mast extensions (4 inch extension when using solid tool holder

Equipment specified by Fig.1 attached.

Measurement Interval:

Measure wear of the insert after the first milling pass. Then measure the insert wear after every pass until failure. If it is obvious that the insert is wearing at a slow rate, measurement interval can be increased to every other pass. This may be further increased to 4 passes if the insert is not wearing. During this program this has happened infrequently with only a few materials. Take breaks only after a completed pass. Make sure to obtain wear measurements after the first pass and again at 0.0075, 0.0110 and 0.015 in flank wear. Make every attempt to determine any other reason for failure other than fatigue. D designates a failed insert computer run in the last digit of the file name. Designate wear patterns per the ISO procedure. Failure criteria are also defined by the ISO procedure.

Milling Loads

Record the X, Y, and Z force for each milling pass. Save the digital data for the initial pass and the last pass before a wear measurement is made. Retain data files until the 50%, 75% and failure points are determined. The initial file will be designated as the A run. Runs at the 50% (B), 75% (C) additional runs will be designated alphabetically starting with E and noted on the data sheet.

Controlling Document:

ISO Procedure 8688-2; Tool life testing in milling – Part 1: Face Milling

Drilling Test Specification

Specimen: Disk 4 inch diameter x 1.125 thick and 1.67 thick

Square 4.25 inch x 1.072 thick

Cutting Tool:

Drill Size: 9mm

Material: HSS (M7)

Length: Jobber Length

Type: General Purpose

Coating: Surface Treated (Oxide)

Point: 118 Degree

Drill selected for the test: Precision Twist Drill; Type 2AB; Stock No. 29090

Inspection : Drills to be measured by FM&T cutting tool inspection and met FM&T Specification.

Machine Type:

Monarch Cortland Machining Center

HP Available: 15 HP

Max Spindle Thrust: 2000 lbs

Max Speed: > 3,500 RPM

Max Feed: > 40 IPM

Tooling Setup:

Tool Holder: 9 mm end mill holder or

9 mm collet holder

Concentricity: Drill concentricity in machine spindle will be 0.0015 TIR max.

Drilling Pattern:

Pattern: Random

Spacing: A 4-inch diameter puck will yield 37 holes when the 9mm holes are on 13.5mm centers. The outside edges of four holes are within 1.5 mm of the specimen side. The 4.25 Squares will yield 52 holes with the same spacing. No hole closer than 4 mm from the edge.

Machining Parameters:

Speed: 1265 RPM (116.5 SFM)

Feed: 11.4 in/min (0.009 in/rev)

Stainless Steel

Speed: 407 RPM (37.8 SFM)

Feed: 1.9 in/min (0.0047 in/rev)

Equipment Used:

KIAG SWISS (Kistler) Force Table

KIAG SWISS (Kistler), Charge Amplifiers, Model 5001, (A, B, C)

Kistler Type 9275 Torque Dynamometer

Kistler Model 5841B1 3-Channel Charge Amplifier (Model 5010)

Kistler Model 5350 Transducer Simulator WITH Model 5371A Calibration Capacitors

ROI Measuring Microscope, with rotary mounting stage with attached 3-jaw chuck.

Mast extensions (4 inch extension when using solid tool holder. 9 inch extension when using

collet holder. When using collect holder a Monarch Cortland Tooling Fixture is mounted on the 3 Jaw chuck on the rotary stage.

Equipment specified by Fig.1 attached.

Measurement Interval and Dwell Time:

Measure wear of the drill point after the first hole is drilled. Then measure the drill wear every 10th hole until failure. If it is obvious that the drill is wearing at a slow rate, measurement interval can be increased to 20 holes. This may be further increased to 30 holes if the drills are not wearing. This has only happened a few times. Allow the drill to cool for 55 seconds between holes (We have found this waiting period to influence the life of the drill greatly). Care must be given to getting this interval correct because we are not drilling with coolant that would remove the heat from the tool.

Controlling Document:

No formal standard exists for drill testing. FM&T procedure is based on test procedure supplied by Precision Twist Drill.

Appendix B

PM Alloy Summaries

Milling

Drilling

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Appendix C

Drill Wear Measurement Procedures

INITIAL EXAMINATION OF DRILL - Using a collet tool holder

- Obtain drill, ensure no obvious damage.
- Obtain 3 x 5 ziplock bag.
- Obtain a 3 x 5 "Post-It-Note" and slice in half (3 x 2 ½) to make inserts for two bags.
- Obtain number from drill - puck log to identify tool. Mount drill in tool holder and check and adjust until run-out is below 0.001 on the tool setter. Unlike the procedure used for the solid holders, **the drill will not be removed from the tool holder until the test is completed.**
- Install 45 taper mounting cup in 3-jaw chuck on scope stage.
- Install assembled tool holder in measuring mounting cup
- Align the markings on the tool holder and the cup so that they are timed.
- Rotate the chuck until the cutting edges of the drill is approximately in-line with the X axis of the scope.

ADJUST THE SCOPE FOR MAGNIFICATION AND FOCUS

- Assure that the 2X lens is mounted on the scope.
- Locate the magnification power wheel approximately half way in its adjustment range for all measurements.
- Turn light source dial to the four o'clock position.
- Focal distance is approximately 1 3/8 inch with 2 X lens

"ZERO" THE DRILL IN THE SCOPE

- Measurements for this test are almost exclusively taken in the Y axis. Therefore the monitor need only have a clear horizontal line for a reference. Other markers on the screen cause no harm if they are not confusing.
- New drills will have some degree of corner-rounding on one or both cutting edges. These corners undergo changes after drilling the first few holes. These changes in the cutting edges render them useless as a reference point so a linkage must be made to a more durable location for use in measuring wear. The point where the drill margin intersects the secondary clearance is the point we use for this purpose. Although this point is readily seen, the true location is sometimes vague. A scribe line is put on the point face at this location. This mark is now our reference where the microscope zeros are set.
- Locate one cutting edge corner on the horizontal monitor line and move the stage to the other corner. Rotate the drill ½ the difference. Continue until the drill cutting edges are aligned with the axis of the scope.
- When the cutting edges are aligned with the scope stage, tighten the clamp to prevent further rotation. Note the angular setting on the post-it-note sliced in half earlier. This setting, along with the manufacturer's I.D. and the identified area of the chuck will serve to locate the tool at any time in the future.
- Again, check the alignment of the drill by comparing side to side. Set the Y axis display to zero when you are certain that the tool is, indeed, aligned correctly. Loosen the clamp and rotate slightly if necessary. Errors at this point will affect the outcome of the test. Be very sure before proceeding.

MEASURE THE MARGIN REFERENCE POINTS

- Due to variations in manufacturing, the two flutes are not equal in every respect.
- Measure and record the Y axis distance (taken perpendicular to a line drawn between the two corners of the cutting edges) to the secondary clearance intersection point. A negative and a positive number will be found which will be near to .035" and within .010 of each other in absolute value. Recall the "Reflect light on the side" technique from earlier for the most accurate reading.
- Record the two numbers on the post-it-note and attach it near the scope for reference.

This procedure assumes a drill has been prepared according to the steps earlier.

Mount Tool Holder

- Rotate chuck to reading from post-it-note and tighten the clamp.
- Insert tool holder in mounting cup and align timing marks. (See earlier steps)

Check Scope

- Assure the magnification power is midway in its travel and that the 2 X lens is installed.
- Adjust the light source dial to the four o'clock position. Correct focus will be found with the scope approximately 1 3/8" from the end of the tool.
- If the scope and the digital display have not been disturbed from the last use, a remarkably large portion of the time, the tool will locate within .001" of the last measurement.

Verify Tool Location

- Find the reference points on the margins and the deviation from the numbers on the post-it recorded earlier. Change zero on the digital display, and angular location as required to bring these two points back to their earlier readings.
- Extra caution here will yield additional confidence in measurements taken.
- When the tool is assured to be located where the display indicates it to be as originally set, record the distance on Y axis where the worn corner intersects the periphery of the tool.
- Record the other flute in the same manner.

Failure Conditions

The tool is considered failed when 1/2 of the margin distance is worn. Approximately .015". Use the "reflecting paper" technique to give another dimension to your observations. A tool that appears to not be wearing on the end may have a "leader" at the periphery that can be the precursor to unexpected failure. The corners are the indicators that show the most wear and the soonest. The cutting edges and the point will not show a fraction of the wear at the corners.

- A tool that exhibits wear anywhere but the corner should be clearly noted on the data sheet, and brought to investigator's attention before proceeding further.
- The only other failure mode, to date, has been catastrophic breaking of the drill. Usually in the part, but some sections have been successfully recovered for evaluation.

Note the Failure Mode on the Data sheet.

Continue testing until a failure occurs

When testing of a drill is complete or if there will be a disruption of the test, place the drill, along with the post-it-note, that has the scope set-up information, in the 3 x 5 ziplock bag for storage.