Wear Resistance and Mechanical Properties of Selected PM Aluminum Alloys and Composites

Chaman Lall and Paul Williamson*

China Metal Powder Inc.

Building A, Haigang Industrial Zone, Shashi, Shajing, Baoan,

Shenzhen, China

ABSTRACT

Wear resistance is often important in structural applications that use light weight PM aluminum alloys. Several aluminum PM alloys were evaluated for wear resistance using the ASTM G65 test method. This consists of dry sand that is dropped into the interface between the test sample and a rotating rubber wheel. Test results indicate that the ACT1 2014 alloy, which is the most popular PM aluminum alloy for structural parts, has slightly better wear resistance than the cast A380 alloy. Significantly better wear resistance was achieved with an Al-14%Si alloy and a ceramic reinforced composite. Surprisingly, a high strength Al-Zn alloy showed poor wear resistance, while pure Al demonstrated excellent wear resistance when a liquid was present. The wear resistance of the softer PM aluminum alloys was attributed to the creation of hard and soft spots at the wear interface. In the presence of a liquid at the interface, "hydroplaning" over the fluid trapped in the worn pockets is expected to occur.

INTRODUCTION

The powder metallurgy (PM) process of component manufacturing offers considerable advantages in the on-going goal to reduce vehicular weight, and thereby reduce fuel consumption. This manufacturing methodology is a relatively efficient and inexpensive process, with demonstrated capability to produce high volumes of aluminum components with a reasonable degree of precision.[1-4] Low density materials, such as alloys of aluminum, magnesium and titanium, offer the promise of light weight structural components with reasonable mechanical strength and wear resistance, for mobility applications.[2, 4-7]

While mechanical properties are very important for structural applications, there is sometimes the additional requirement for wear resistance in situations where two contacting components are in relative motion to each other. The interface between such components is a potential cause of concern with regard to component and system failure by wear.[8]

In an initial study using a specially-constructed test rig[9], roller chains were used to drive sprockets for selected periods of time (up to 1650 hours) and the wear on the sprockets was documented. While not totally immersed in oil, the test sprockets had "splashes" of oil on them. The preliminary findings of that study were that the sprockets made from the PM Al-Si alloy had comparable wear (diametral change) to those made from FC-0205 (6.7 g/cc, sintered, and heat treated).

One of the most successful production applications for PM aluminum in the automotive marketplace has been the camshaft bearing cap launched in 1991.[4, 10] Such components are simply referred to as "cam caps" and have been successfully produced and employed successfully for more than two decades. This is an extraordinary case where a relatively low hardness PM aluminum material is interfacing against a hard wrought steel cam shaft rotating at high speeds, while supporting significant side loads. Figure 1 shows one of the more complicated and largest cam caps made in the PM aluminum industry[11]. This particular design "bridges" both of the dual overhead camshafts and incorporates oil grooves and thrust faces.

Figure 1. PM Aluminum Camshaft Bearing Cap - 2006 Grand Prize Award Winner in the Automotive Category[11] (courtesy: Metal Powder Products, GM, and MPIF).

One of the purposes of this study is to explain technically why the bearing cam cap application is so well suited for PM aluminum from a wear perspective. Both the bearing material and the manufacturing process present inherent advantages in this wear "system", which also comprises the shaft material plus the environment (including engine oil and heat). The material supplied for this application generally conforms to material spec ASTM B595[12], having a density about 92% of the theoretical value.

Newer materials have been developed by the PM industry and are available for implementation into the marketplace, but the wear data available in the literature is fairly limited. Perhaps part of the reason is that wear results are so dependent on the specific application. While it is understood that wear by its very nature is a "total system" issue and it is very difficult to simulate real-world applications in the laboratory, we believe it is informative to document the results of carefully controlled lab tests. These results can provide guidance on material selection for subsequent validation tests in the field. The ASTM G65 test method[13], which uses dry sand, was selected as the initial evaluation method of choice. Wear resistance tests were conducted on several selected PM materials as well as the commonly used die cast material, A380. In addition, wear tests were conducted at the MPP Technology Center on a different test rig, where the additional variable of water was introduced to the test system.

EXPERIMENTAL

Test samples were compacted on laboratory equipment and sintered in production furnaces for the various blends shown in Table 1. Acrawax C at the 1.5 weight % level was used as the lubricant in all blends. Sintering was conducted in a protective atmosphere of 100% nitrogen and the temperature was set based on the blend, but generally above 600 ^{0}C (1112 ^{0}F).

Table I. PM Aluminum Blend Compositions (1.5% Acrawax Lube, Balance Aluminum)

Material		%Cu	%Si	%Mg	%Zn	% Others	MISC.
Al-Cu		4	0.7	0.5	-	< 1.5	
Al-Mg		4	0.5	2	-	< 1.5	
Al-Ceramic		4	0.7	0.5	-	< 1.5	5% Alumina
Pure Al		-	-	-	-	< 0.5	
Al-Si		2.5	14	0.7	-	< 1.5	
Al-Zn		1.5	-	2.5	5.5	< 1.5	

Mechanical property testing was conducted at the MPP Technology Center, while the majority of the wear tests were performed at Pennsylvania State University (Penn State) per ASTM G65. In this test, a rotating rubber wheel is rubbed against the sample being tested while dry sand is fed into the interface. The speed and number of revolutions of the wheel are recorded, as well as the mass of the test sample before and after the test to determine mass loss.

Additional wear testing was conducted at the MPP Technology Center. Disc samples were rubbed against a wheel imbedded with fine grit (600 SiC, nominally 15 microns in diameter), while a flow of water was maintained on the wheel. This added variable of liquid to the wear test method is significant and should be noted. Each material had nominally the same diameter and, therefore, the same surface area presented to the abrading wheel. Similarly, the same contact pressure was applied on each disc sample. A group or set of samples were tested at one time and the mass loss recorded at various intervals; the logic was that since all samples were experiencing identical test conditions, variations in test results should be purely material-related. Hence, these were strictly A-B comparisons of wear between materials being tested simultaneously. It was determined in preliminary work (during test method development), that the pores would pick up water and give a mass gain compared to the mass of the dry sample, leading to erratic test results. Our immediate solution to the problem was to vacuum oil impregnate the test samples with a heavy-weight oil, prior to running the wear test. As an alternative method, resin impregnation of the test samples should be equally effective.

RESULTS AND DISCUSSION

Table II shows the mechanical properties of the PM materials prepared for this study and the nominal densities of the samples being tested. (Note that no data is shown for the pure aluminum TRS bars because the ductility is too high for this test method). These properties are in general agreement with published literature for materials sintered in a nitrogen atmosphere[14-17]. While it is not the focus of this paper, it should be noted that compaction pressure, time at temperature, hold temperature, heat up and cooling rates are especially important in the sintering of aluminum alloys. Growth may occur first as the additives are dissolved into the aluminum powder, oxide reduction, followed by particle re-arrangement, liquifaction, densification, etc.[14, 16, 17] Nitrogen is an added factor in the sintering process; Schaffer and Hall[14] believe that at low compact densities, the gas can be play a greater role in the reduction of Al_2O_3 than Mg by the formation of AlN. Post-sinter processing can further increase yield and UTS values above 300 MPa.

Table II Measured Mechanical Properties of Selected PM Aluminum alloys.

Material	UTS (MPa)	Yield (MPa)	Elong. (%)	App. Hardn. (HRE)	TRS MPa)	Density (g/cc)
Al-Cu	**193**	**152**	**2**	**60**	**324**	**2.50**
Al-Mg	**241**	**193**	**3**	**80**	**448**	**2.55**
Al-Ceramic	**193**	**152**	**3**	**65**	**331**	**2.50**
Pure Al	**172**	**83**	**20**	**HRH 32**	**-**	**2.55**
Al-Si	**207**	**152**	**1**	**75**	**290**	**2.60**
Al-Zn	**276**	**172**	**1**	**70**	**586**	**2.70**

Penn State Dry Wear Data

Figure 1 show the mass loss for several PM aluminum alloys based on 5 separate test runs conducted at Penn State. The materials have been plotted on the horizontal axis in order of wear resistance – the best being on the left.

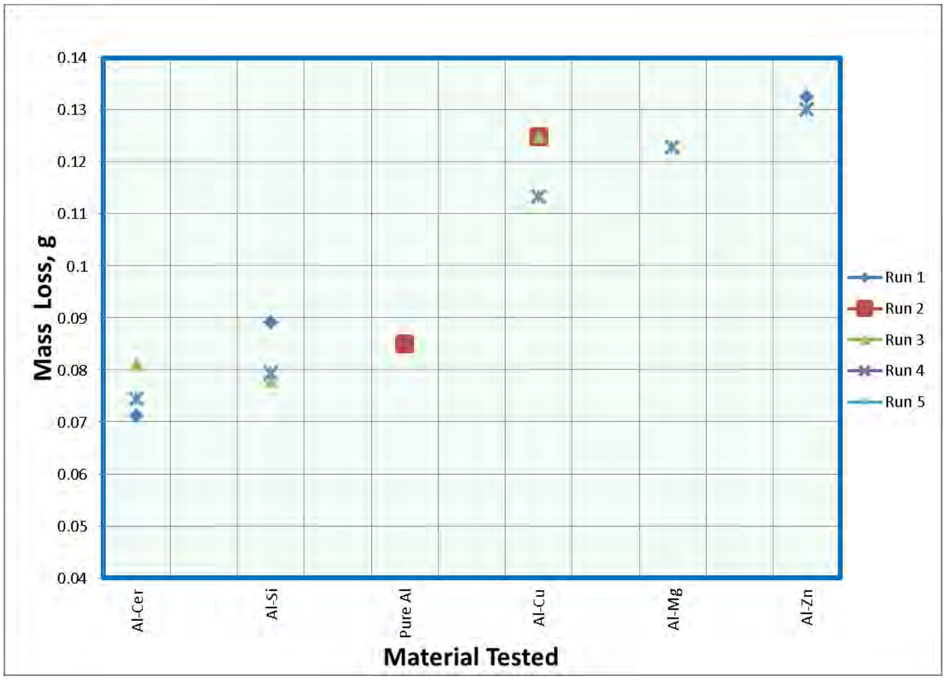


Figure 2. Mass loss observed for selected PM Al alloys subjected to test method ASTM G-65. Test data from five separate test runs; each test sample subjected to 100 wheel revolutions.

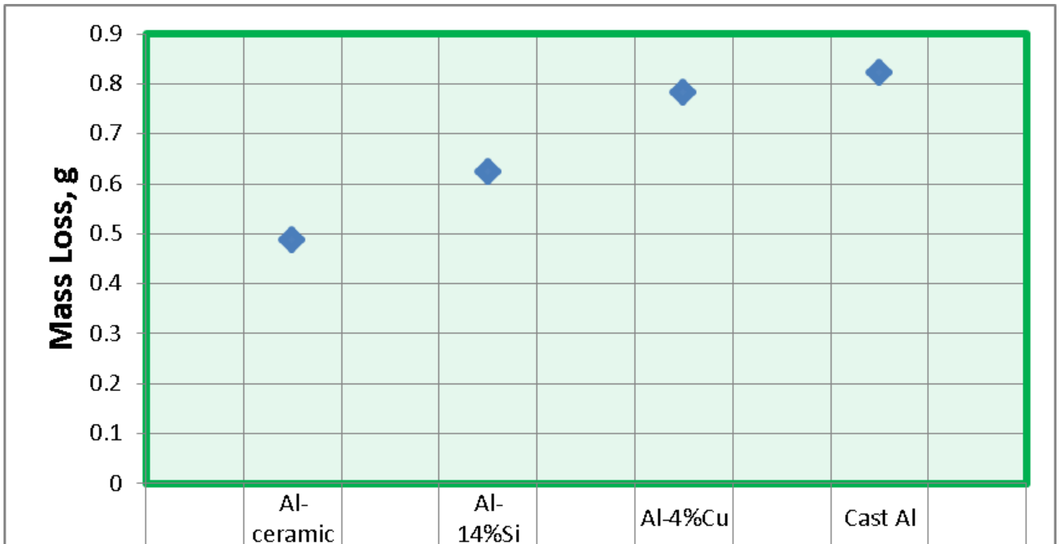
Leaving the pure aluminum PM sample aside for discussion a little later, the best wear resistance is exhibited by the aluminum-ceramic composite and the Al-14%Si samples. In both cases, hard particles/phases are the source of this desired property; discrete Al_2O_3 particles in the former and silicon[16] in the latter. Surprisingly, the harder and stronger alloys, Al-Mg and Al-Zn (Table II), displayed poorer wear properties than the softer materials, even the Al-Cu alloy (ACT1 2014) control sample.

In a follow-up study, several PM alloys and a die cast alloy commonly used in the automobile industry (Alloy 380; Al-8.5%Si-3.5%Cu), were tested in the same wear test fixture at Penn State, but the number of wheel rotations were increased from 100 to 1000. The test results are shown in Figure 4, where the mass loss is shown for each of the materials tested. While the absolute values for mass loss are higher (because of the larger number of revolutions and longer test time), the trends regarding wear resistance are identical to the data reported above.

A review of these test results suggests that the PM alloys offer improved wear resistance over the cast aluminum alloy. Even the Al-Cu alloy system that has become the material of choice for camshaft bearing applications is marginally better. The data appears to support the practical experience in the field; in over

2 decades of such components being produced and supplied by MPP, the automotive community has had very positive application results with the PM aluminum cam caps.

In preliminary wear tests conducted on dry samples with varying levels of Si, Bishop [16] reported that the wear resistance of the cast A380 material was similar to that of the Al-Si PM alloy system within the range of 6 to 15%Si. The current study shows a significant improvement in wear resistance with both the Al-14%Si alloy and the ceramic reinforced composite.



	Al-ceramic	Al-14%Si	Al-4%Cu	Cast Al
Al	0.4884	0.6247	0.7815	0.8211

Figure 3. Mass loss observed for selected PM Al alloys subjected to test method ASTM G-65. Each test sample subjected to wheel 1,000 revolutions.

<u>MPP Wet Wear Data</u>

In the wear tests conducted at MPP, selected PM samples were subjected to abrasion against a wheel embedded with 600 grit (nominally, 15 micron) SiC grit, using flowing water as the coolant/lubricant. Test samples were removed and weighed at selected intervals. The resulting mass loss is plotted in Figure 4. Again, the general trends regarding wear resistance are similar to the trends reported from the data collected by the Penn State test rig; the high strength Al-Zn has the poorest wear resistance, while the Al-ceramic composite has the best wear resistance. The gap in the middle of the graph is simply a reflection of the fact that data was collected on two separate occasions and other changes made (samples under test were not changed). The horizontal axis is not linear with respect to time. Furthermore, the pressure between the samples and the abrasive wheel, plus wheel rotation speeds were being altered from one test run to the next. Therefore, it is more informative to compare the mass loss between materials for a given run, and generally observe the overall trends.

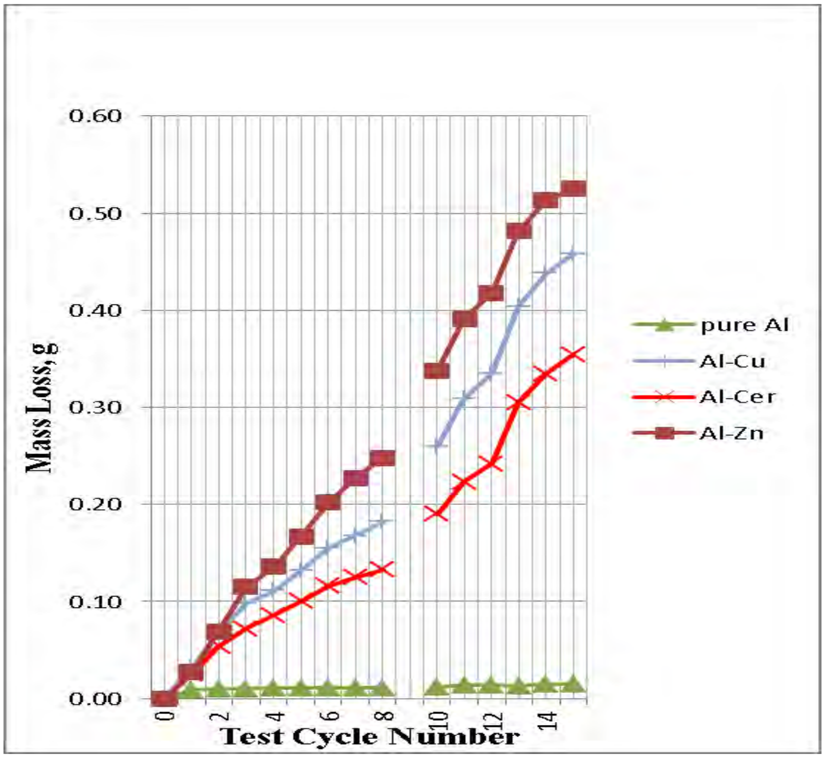


Figure 4. Mass loss exhibited by selected PM materials subjected to wear by a wheel bonded with 600 grit (nominally, 15 micron) SiC particles. Note the extraordinary lack of wear exhibited by the pure PM aluminum specimen.

The test data for the PM pure aluminum is, at first glance, quite perplexing, in view of the fact that the material is very soft (HRH 32; too soft for the HRE Rockwell scale). What is remarkable is the observation that mass changes in the pure aluminum were negligible (<0.02g) compared to the 0.3-0.5g loss in the other test samples, even after a couple of hours of running time. The answer to this puzzling test result lies in the micrograph shown in Figure 5. The wear tested surface is covered with embedded particles (SiC), presumably transferred from the abrasive wheel. It appears that the embedded SiC particles have created a new interface with "islands" of hard particles in a "sea" of soft aluminum. This is a perfect example for the conceptual model in which the soft background wears down to create "pockets" to hold the lubricating liquid (water), while the hard particles become the load-bearing phase. During the wear test, the pockets of water create a hydroplaning effect that separates the two faces - the test sample and the abrasive wheel.

Wear Concept

In order to explain the laboratory wear test results and field data, it is instructive to gather information about the surface of the wear test samples. Table III shows the surface finish measurements made on three of the materials after the wear testing at MPP. For those unfamiliar with this specific surface finish terminology, Figure 6 may assist in providing a visual illustration of the terms, Rk, Rpk and Rvk.

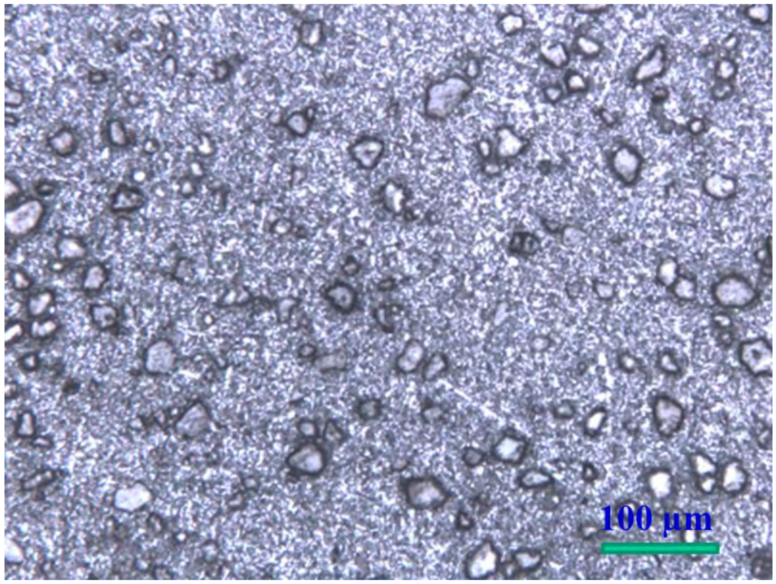


Figure 5. Surface of PM pure aluminum after the wear testing. Note degree and distribution of SiC particles embedded into the soft aluminum matrix. Original magnification 200x.

Table III. Surface Finish Data for 3 Selected PM Materials after Wear Testing at MPP (Numerical Values in microns)

	Rpk	Rvk	Rk
Pure Al	2	1.07	3.14
	2.03	0.82	1.65
Al-4%Cu	0.2	0.33	0.51
	0.16	1.44	0.55
Al-ceramic	1.07	2.45	2.99
	1.06	1.03	2.03

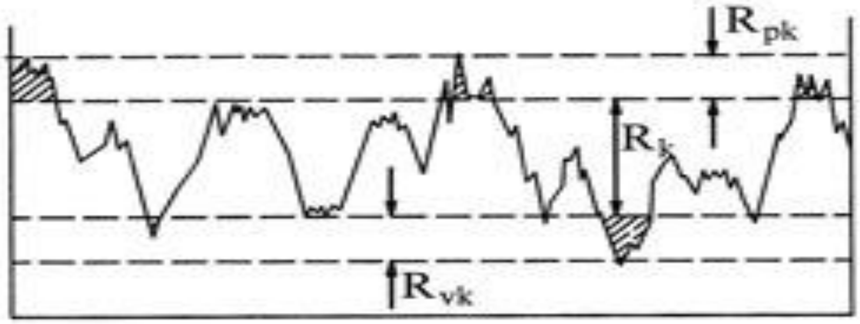


Figure 6. Schematic illustrating the terms Rk, Rpk and Rvk.

The surface finish data for pure aluminum indicates a fairly rough surface finish (high Rk, average), reflecting the effect of the SiC particles embedded in the wear interface. The Al-ceramic sample also shows a rough surface finish because of the Al_2O_3 particles that were mixed throughout the original blend.

A closer inspection shows a difference in the two samples, in that the pure Al has raised particles (higher Rpk, peak) compared to the Al-ceramic specimen. Yet the depressions in the pure Al are shallower (smaller Rvk, valley) than the Al-ceramic surface. The Al-ceramic matrix or background was apparently worn away during testing, below the original surface and thereby exposed the alumina that was added to the original blend. Perhaps some of the alumina particles were pulled out, leaving a void - which would give higher Rvk values.

The Al-4%Cu alloy sample exhibits a relatively smooth surface finish (low Rk) in comparison to the other two materials. There is no evidence of raised peaks (low Rpk values) or deep valleys (low Rvk, values). (The significance of the single large Rvk value needs to be determined with a larger sample size – was this due to a soft worn spot or an unusually large pore? Note that a chisel stylus, recommended for PM materials, was used in these surface measurements). The most important conclusion to be made is that a high level of SiC particle pick-up from the abrasive wheel was not evident for the Al-4%Cu alloy, indicating that the hardness of the nominal HRE 60 value is effective in preventing gross levels of particle transfer to the test specimen. That is not to suggest that absolutely no SiC particle transfer took place; further study of a statistically larger set of samples is required.

If this concept holds true, a new class of materials can be created in the manufacturing process by the intentional introduction of preselected (material, size, morphology) particles into the wear interface. This process of mechanically embedding of such particles can be done in a matter of seconds, and, therefore, should be fairly efficient and cost-effective in that the ceramic re-enforcement is not distributed throughout the body of the part. Perhaps a separate soft aluminum layer can be co-produced onto a much stronger substrate for more highly loaded applications. The end-product would not be the same as that produced by, for example, spray forming since the whole surface would have the same high hardness of the sprayed material. The ‘sea” of soft material as a backdrop is a necessary feature for this concept to work correctly.

To some degree, this hydroplaning effect can occur whenever PM components are used in the presence of a liquid. The wear interface can conceptually have seepage of liquid from the pores which would have trapped some of the liquid. This is, of course, the inherent feature and basis of low density “self-lubricating” PM bearings[18]; as the component heats up a little during use, the impregnated oil in the pores expands to the surface and creates a lubricated interface. The lubricating film reduces frictional heat and serves to regulate the bearing, and system, temperature.

Addition of hard particles to improve wear is not new as this is the basis of metal matrix composites[19], for example. In this case, ceramic oxides are often mixed into the metal matrix and the processing protocol is to maximize the metallurgical bonding of the particles to the matrix. Such is the case of the alumina particles in the Al-5% ceramic material which was included in the current study. An earlier study on the fatigue behavior of this composite system[20], evaluated the effect of alumina content from 0% to 15%. The study concluded that the 5% ceramic content gave the best fatigue properties; higher levels resulted in poorer mechanical properties. Scanning electron microcopy and fracture analysis work showed that the alumina particles were well-bonded to the aluminum metal matrix (Figure 7). A review of several SEM micrographs indicated that some ceramic particles were broken, yet the interface between the aluminum matrix and the ceramic was still intact.

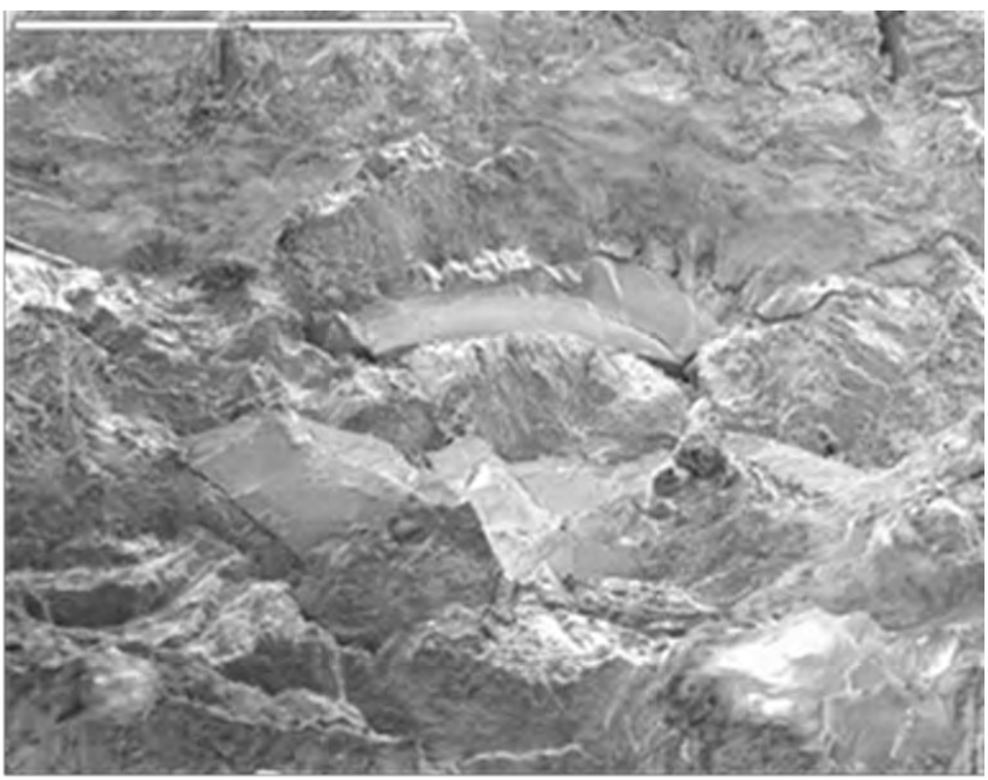


Figure 7. Al-5%ceramic composite, fatigue tested to over 500k cycles, showing good bonding between the ceramic and aluminum matrix [20].

Another thought to consider is that the soft materials can also “trap”/embed extraneous particles in the soft matrix and, possibly, in the pores that are open to the surface. In this way, the particles are prevented from continuing the damage/wear that they would otherwise do. An analysis of wear particle sizes [21-23] indicated that high concentrations of 15 micron particles freely floating in lubricating oil can promote the generation of still larger, and more damaging, particles. However, wear debris in which particles are near 3 microns or smaller may be beneficial in that they can polish the surfaces, resulting in the prevention of coarse particle generation. [24] This type of wear by very fine particles is fairly benign, resulting in nothing more than polished, smooth surfaces[24]. The intent clearly is to find a way to prevent coarse debris from being permitted to continue to the stage of catastrophic damage at the wear interface. In the specific test rig and test methodology used at the MPP Tech Center, the debris was being removed both by the continuous flow of water as well as the softer test materials.

Slattery et al [25], described a similar wear model in an unrelated application; liner-less aluminum-silicon cylinders. The cylinders bores were mechanically stripped to remove the softer aluminum matrix and expose the harder Si particles in preparation for testing. Their work showed that the worn surfaces had 5 times the roughness of the untested surfaces. Furthermore, they showed that very fine Si fragments break off from the larger particles and serve to polish the aluminum matrix, as well as enhancing wear resistance by embedding into the Al, creating a new interface. These observations are entirely consistent with the concepts described above in which the effect of very fine debris particles is considered to be benign. [24]

In the example given above of the hard camshaft and the soft aluminum PM cam caps, we believe that at least some of these phenomena are responsible for the remarkable performance of the PM material in this specific application, where the lubrication oil is present. During the initial engine start, the hard, ground camshaft will tend to wear the aluminum cam cap bearing, specifically the softer aluminum grains. The initial degree of wear at the “break-in” stage will depend on the surface finish of that camshaft; the finer the finish, the smaller the surface asperities and the less the wear of the aluminum cam cap. At the same time the hard phase(s) in the aluminum cam cap will tend to wear away/“polish” the surface asperities of the steel camshaft. Logically, the finer the surface asperities or “peaks” the smaller the size of the debris. If the debris size is 3 micron or less, the result is not much more than polishing of the two components, as discussed above. It is therefore important for the camshaft to be lapped so that the surface asperities are minimal in height.[26]

Once an engine is started, the engine oil will quickly soak all the components above the cylinder head, including the camshafts and cam caps. The oil grooves designed for the purposes of lubricating the camshafts will enhance this process and rapidly deliver the fluid where it is needed. The interface between the steel camshafts and the PM aluminum cam caps now has this lubricating film to reduce friction and wear. Referring to the (Rvk) surface finish data in Table II for the Al-4%Cu alloy, the gap is, on average, a micron or less so that the amount of oil retained in the worn aluminum pockets is very small. Assuming a shaft diameter of 2 cm and a linear contact length of 1 cm, the interface will have a surface area of about 6.3 cm^2. A film thickness of one micron calculates to a volume of the order of 0.006 cc. That is all that is needed to create and maintain the hydroplaning phenomenon that will protect both the camshaft and cam caps from wear.

We believe that the pores that are an inherent feature of powder metallurgy components become reservoirs for the engine oil, whether applied intentionally or caught in the spray from other close-proximity components above the cylinder head. Even when the engine is shut down, the oil is still retained in the pores, in addition to the interface between the steel camshaft and PM aluminum cam caps. Capillary action as a result of the narrow interconnected pores (cam cap densities are typically >92% of theoretical) plus the narrow gap between the camshaft and cam caps will minimize oil drainage.

This "lapped", smooth, surface of the PM cam cap combined with the slick oil creates a complementary system that is highly effective in resisting wear from a hard cam shaft rotating at high speeds. In the absence of coolant/lubricant (oil), the soft aluminum will tend to wear more, but there is also the likelihood that the material will smear over and again create a smooth surface that will have less of a tendency to wear than a rough surface. We believe that this is why the pure aluminum exhibited reasonable wear resistance in the tests conducted at Penn State under dry conditions. Some degree of embedding of particles is also likely.

One final thought to consider is that some degree of ductility is needed to "mold" or "seat" the two interfaces into each other, like a ball and socket for example. Rather than only certain raised sections at a microscopic level taking the load, the act of seating the two components results in any side load being taken up by a much larger interfacial surface area. If insufficient ductility is available (meaning some reasonable degree of difference between the yield point and UTS fracture point) the possibility of excessive component wear may become an issue. Empirical evidence suggests that 2% elongation or more is desirable for the types of applications discussed; much depends on the specifics of the application under consideration.

Optical Metallography

The following series of micrographs (Figures 8-12), show representative microstructures of the PM aluminum alloys discussed in this study. The Al-Cu alloy microstructure is well sintered with a small amount of an intergranular phase; presumably Si-Mg rich. The Guinier-Preston (GP) zones, which are the cause of strengthening in the Al-Cu system, are too fine to be resolved by optical metallography. $CuAl_2$ precipitates which can be formed by over-aging are clearly not present. This material was naturally aged and, specifically, not subjected to a long artificial aging cycle.

The Al-ceramic material has essentially the same microstructure, distinguished only by the added 5% Al_2O_3 particles that comprise the aluminum-ceramic composite. The macro apparent hardness of both materials is similar, with the re-enforced composite being slightly higher because of the added ceramic.

The microstructures of both the Al-Mg and the Al-Zn alloys are noteworthy for their lack of significant secondary hard phases. Both show microstructures that indicate that the additives have dissolved into the aluminum. Evidence of solid solution strengthening is provided by the high mechanical strength and high apparent hardness values, compared to the Al-Cu material.

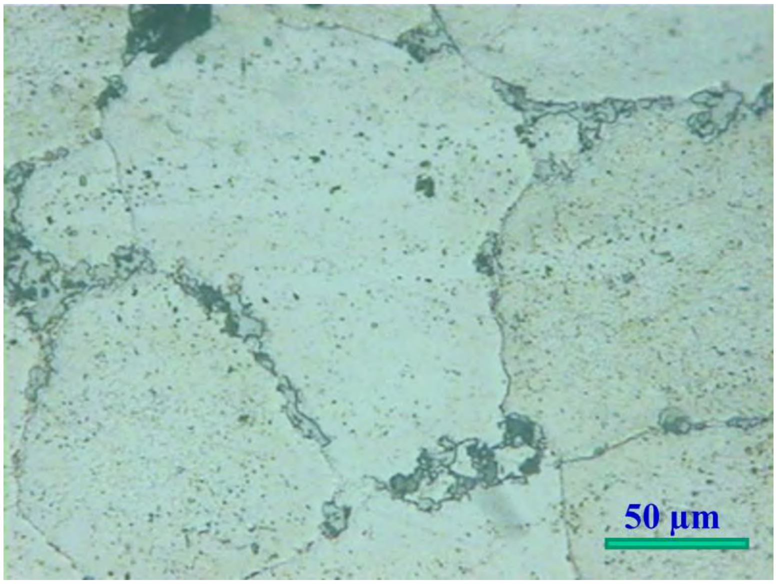


Figure 8. Al-4%Cu. Alpha aluminum with small amount of an intergranular phase – likely, Si-Mg rich. Original magnification 500x

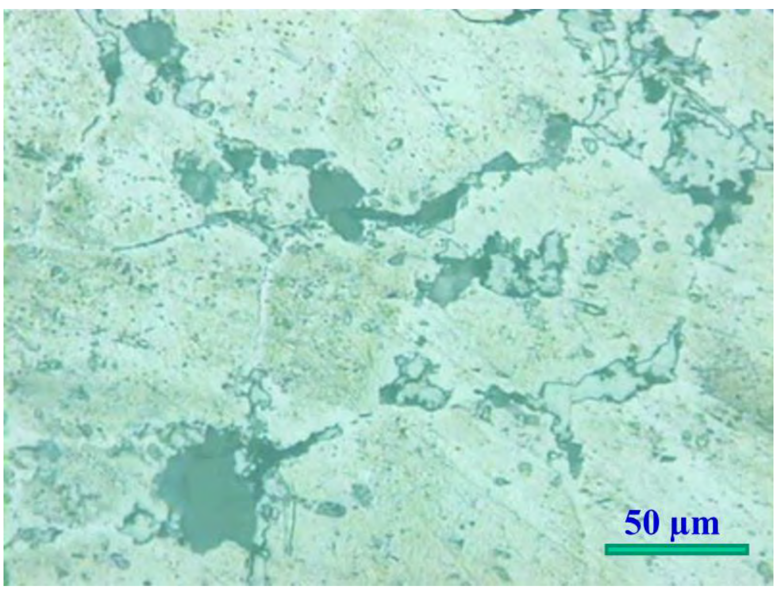


Figure 9. Al-5% ceramic. Primarily alpha aluminum. The coarse dark particles are alumina, while the light grey areas are a Si-Mg rich phase. Original magnification 500x

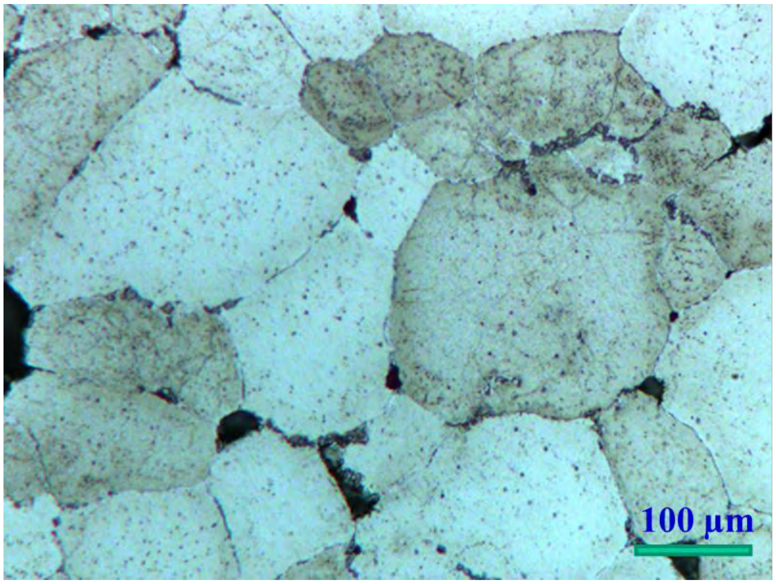


Figure 10. Al-2%Mg; Predominantly alpha aluminum grains, with Mg-rich phase at the grain boundaries. Original magnification 200x.

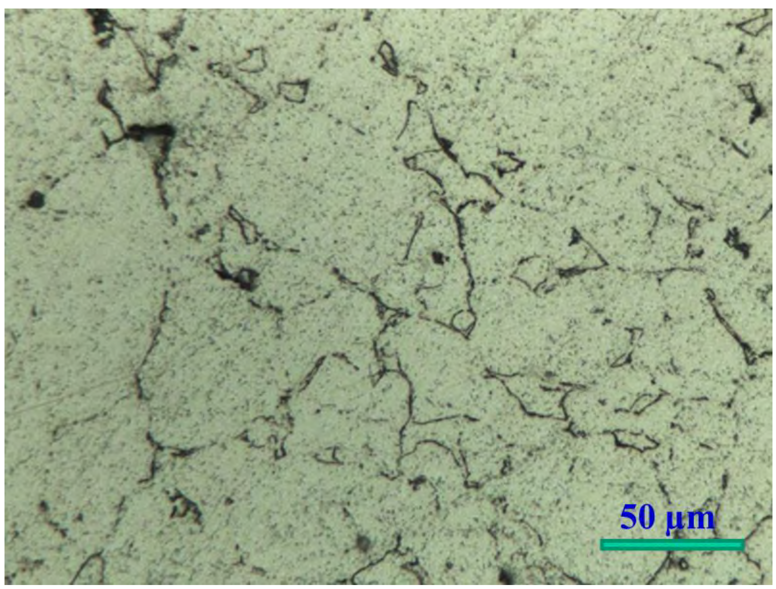


Figure 11. Al-5.5%Zn. Predominantly alpha aluminum grains. Original magnification 500x

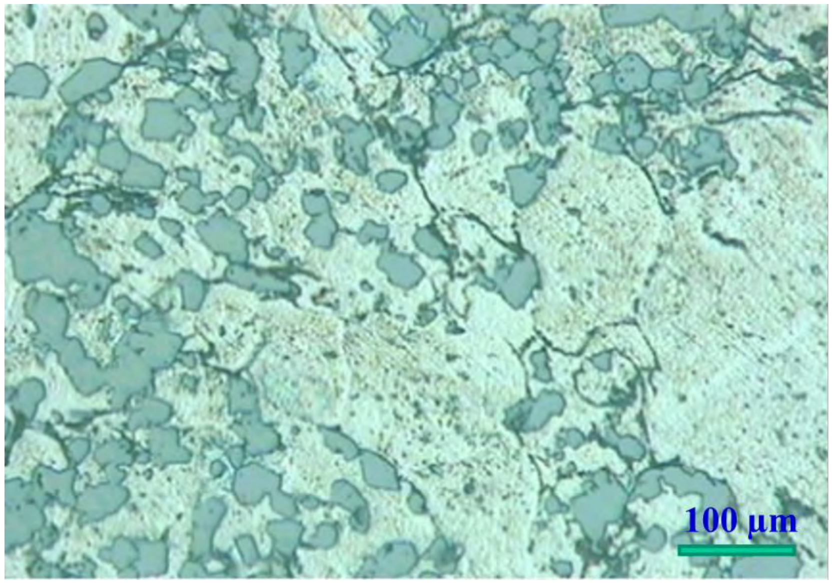


Figure 12. Al-14%Si. Alpha aluminum grains plus light grey Si-rich phase. Original magnification 200x.

As expected, the microstructure of the Al-Si alloy shows a Si-rich phase with a backdrop of alpha aluminum grains. The second phase is coarser and much more prominent than the level of Al_2O_3 particles that were intentionally added to make the aluminum-ceramic composite. Adding much higher levels than 5% of alumina tended to cause embrittlement[20] and was, therefore, avoided. That singular observation suggests that lowering the Si level might be helpful to improve ductility of the Al-Si alloy, without compromising wear resistance. A good balance of wear resistance and reasonable mechanical properties might require less than 10% Si system. A higher level of Si might be needed for the casting process to lower melting point and enhance liquid flow, but neither of those goals is desired or needed for the powder metallurgy method of component manufacturing. The precipitate was too fine in the Fe-14%Si alloy to be measured by use of a Knoop micro-hardness indenter.

CONCLUSIONS

The primary highlights of this study are:

1. The ASTM G-65 method of wear testing indicates that the PM Al-4 %Cu alloy used by MPP in making cam caps for more than 2 decades exhibits slightly better wear resistance than the cast aluminum A380 material.
2. Furthermore, introduction of a hard phase into the matrix (e.g. Al-14%Si) or hard particles (e.g. Al_2O_3 mixed into the Al-4%Cu alloy) enhances wear resistance. The aluminum - 5 % ceramic composite demonstrated the best wear resistance under dry conditions.
3. Pure aluminum exhibited a high degree of resistance to this type of abrasive wear, especially under lubricated conditions. Indications are that the soft aluminum matrix absorbed abrasive particles and, in effect, created a new composite wear interface comprising a soft matrix embedded with hard particles.

4. Further investigation is needed for verification, but the concept of a new class of materials that can be produced in a simple manufacturing process appears to be viable; hard particles are mechanically embedded into the wear surface. The design intent would be to create hydroplaning between the component interfaces in applications where a lubricating fluid is present; pockets of fluid in between the hard particles would serve that purpose.
5. Further R&D into the size and distribution of the hard particle additive and the effect on component wear is suggested. That data also needs to be correlated to the effect of the matrix hardness and composition.
6. The mechanical properties of the PM aluminum alloys sintered in a 100% nitrogen atmosphere are similar to the values reported in the published literature.

REFERENCES

1. C. Lall and W. Heath. "P/M Aluminum Structural Parts – Manufacturing and Metallurgical Fundamentals," *Intern. J. of Powder Metallurgy*, 2000, Vol. 6, No 6, pp. 45-50.
2. R. A. Chernenkoff and W. F. Jandeska, Jr. eds. *Proc. of the 200 International Conference on PM Aluminum and Light Alloys Automotive Applications,* MPIF, NJ, USA.
3. MPR Special Feature, "PM aluminum Drives Forward in New BMW Breakthrough", 2006, *Metal Powder Report*, No. 2, Feb., pp. 13-15.
4. S. Huo, W. Heath and D. Ryan. "Applications of Powder Metallurgy Aluminum for Automotive Valve Trains," 2008, *SAE International,* Paper No 08M-323.
5. R. Tandon, J. McConaghie, D. Madan, J. Paras, D. Kapoor, and K. Cho. "Magnesium Powder Technology for Ultralight Weight Applications," *Advances in Powder Metallurgy and Particulate Materials* -2000, MPIF, NJ, USA, Part 7, pp. 157-163.
6. D. Eylon and F.H. (Sam) Froes. "Titanium Powder Metallurgy Alloys and Composites," *ASM Handbook*, 1998, ASM International, Materials Park, OH, USA, Vol. 7, pp. 874-886.
7. F.H. (Sam) Froes. "Lightweight Heavyweight," *Metal Powder Report*, April 2002, Vol. 57, No. 4, p14.
8. R, Pike and J.M. Conway-Jones. "Friction and Wear of Sliding Bearings," *ASM Handbook*, 1992, ASM International, Materials Park, OH, USA, Vol. 7, pp. 515-521.
9. S, Huo and W. Heath. "Wear and Fatigue of Sintered Aluminum Materials," *Advances in Powder Metallurgy and Particulate Materials* – 2008, MPIF, NJ, USA, Part 10, pp. 97-103.
10. T. B. Gurganus. "Aluminum Powder Applications," *Advanced Materials and Processes,* Vol. 148, No. 2, pp. 57-59.
11. P.K. Johnson. "2006 PM Design Excellence Awards Competition Winners," *Intern. J. of Powder Metallurgy*, 2006, Vol. 42, No. 4, pp. 17-21.
12. ASTM B595. "Standard Specification for Sintered Aluminum Structural Parts" *2011 Annual Book of ASTM Standards,* ASTM, West Conshohocken, PA. USA.
13. ASTM G65. "Standard Test Method for Abrasion Using the Dry Sand/Rubber Wheel Apparatus," *2010 Annual Book of ASTM Standards,* ASTM, West Conshohocken, PA. USA.
14. G.B. Schaffer and B.J. Hall. "Sintering of Aluminum in Argon and Nitrogen," *Advances in Powder Metallurgy and Particulate Materials* – 2000, MPIF, NJ, USA, Part 13, pp. 139149.
15. C.D. Boland, D.P. Bishop, R.L. Hexemer and I.W. Donaldson. "On the Development of an Aluminum PM alloy for "Press-Sinter-Size" Technology," *Advances in Powder Metallurgy and Particulate Materials* – 2010, MPIF, NJ, USA, Part 7, pp. 64-77.
16. D.P. Bishop. "Recent Advances in the Development of "Press-and-Sinter" Aluminum PM Alloys for the Production of Light Weight Automotive Components," *Advances in Powder Metallurgy and Particulate Materials* – 2010, MPIF, NJ, USA, Part 7, pp. 92-110
17. S. Huo, B. Mais and J. Gradl. "Pressing Characteristics for PM Aluminum Alloys," *Advances in Powder Metallurgy and Particulate Materials* – 2012, MPIF, NJ, USA, Part 7, pp. 143-154.

18. N.A. Arnold and M. Schloder. “Powder Metallurgy Bearings,” *ASM Handbook*, 1992, ASM International, Materials Park, OH, USA, Vol. 7, pp. 1051-1064.
19. P.K. Rohatgi, Y. Liu and S. Ray. “Friction and Wear of Metal Matrix Composites,” *ASM Handbook*, 1992, ASM International, Materials Park, OH, USA, Vol. 18, pp. 801-811.
20. R.A. Chernenkoff, C. Lall and S. Huo. “Strain-Life Fatigue Characteristics of Powder Metallurgy Aluminum Composites,” *Advances in Powder Metallurgy and Particulate Materials* – 2006, MPIF, NJ, USA, Vol. 2, Part 9, pp.123-138.
21. R.E. Kaufmann. “Particle Size and Compositional Analysis of Wear Debris Using Atomic Emission Spectroscopy.” *Lubrication Engineering* – 1988, pp. 147-153.
22. P.G. Harrington. “Wear Particle Analysis: Maturing Tool for Predictive -Maintenance.” *Power,* July, 1987.
23. M.A. Maniscalco. “Wear Particle Analysis Indicates Machinery Condition” *Power Transmission Design,* June, 1987.
24. W.J. Maciag and M.A Mushenski. “New Bearing Design Concept – An Innovative U.S. Army Design Concept for Tactical Vehicle Bearings and Universal Joints.” *International Truck & Bus Meeting and Exposition* – November 17-19, 1997, SAE paper No. 973178, PA, USA.
25. B.E. Slattery, T. Perry, and A. Edrisy. “Microstructural Evolution of a Eutectic Al-Si Engine Subjected to Severe Running Conditions.” *Material Science and Engineering A* – 2009, Vol. 512, pp. 76-81.
26. R. Pike and J.M. Conway-Jones. “Friction and Wear of Sliding Bearings,” *ASM Handbook*, 1992, ASM International, Materials Park, OH, USA, Vol. 18, pp. 515-521.