

A PERFORMANCE COMPARISON OF CURRENT P/M LUBRICANTS AND ROUTES TO IMPROVEMENT

**Ann I. Lawrence, Sydney H. Luk and Jack A. Hamill
Hoeganaes Corporation,
Riverton, NJ 08077**

**Presented at PM² I'EC '97
International Conference on Powder Metallurgy & Particulate Materials
June 29 - July 2, 1997 Chicago, IL USA**

ABSTRACT

Greater demands are being placed on lubricant performance because of general industry trends toward more intricate part shapes with related tooling complexity and the incorporation of abrasive additives in mixes. To illustrate the significance of these performance demands, it is necessary to identify the role lubricants play in mixing and the P/M part manufacturing process. This work examines the effects of lubricants on material flow, apparent density, compaction, ejection characteristics and sintered properties. The findings identify key performance elements, which provide a model for developing an improved P/M lubricant. A performance comparison with a commercial lubricant highlights the advantages of a composite lubricant that was evaluated.

INTRODUCTION

Lubricants play an important role in P/M compaction and ejection pressing cycles. Specific additions of admixed lubricant reduce interparticle stresses and extend the working life of costly tooling. However, this is generally achieved as a trade-off with other important mix characteristics. Erratic flow, apparent density variability, lower compactability and burn-off issues are major concerns associated with lubricant selection, which impact the P/M manufacturing process.

Attempts to accommodate the various performance issues using existing lubricant technology have not proven to be adequate for more demanding applications. This is particularly true when introducing fine, abrasive particles such as ferrophosphorus (Fe_3P) additions. Overcoming these limitations will enhance P/M compact integrity, improve quality levels and broaden the overall number of P/M applications.

Previous studies have evaluated the performance characteristics of commercial lubricants by identifying the respective attributes of each type. [1 - 6] The study of lubricant particle size and shape has been somewhat more limited. [1, 6, 7] This investigation focuses on the chemical composition, along with particle size and shape, in an attempt to gain a clearer understanding of how each of these elements affects performance. With this information, plans have been developed for a new composite lubricant capable of meeting the ever increasing demands associated with more challenging applications.

EXPERIMENTAL PROCEDURE

The material system selected for this study was ANCORBOND~ 45P. It is composed of Ancorsteel® 1000B atomized iron powder with 0.45 w/o phosphorous introduced through the addition of 2.9 w/o ferrophosphorus (Fe3P). Ferrophosphorus was bonded to the base iron during premixing. Bonding serves to reduce the segregation of components of differing specific gravity and particle size in a mix along with dusting of fine particles during handling. A series of laboratory bottle mixes was prepared with this base material and various lubricants. Unless otherwise specified, 0.75 w/o lubricant was incorporated in the mixes. The lubricants were either commercial materials or were prepared in the laboratory.

The flow and apparent density of the mixes were measured according to MPIF Standards 03 and 04 [8]. The mixes were compacted into transverse rupture (TRS) bar test pieces for the determination of physical properties at 30, 40 and 50 tsi (415, 550, and 690 MPa). The actual compaction temperature was elevated to 145°F (63°C) to simulate the frictional heat generated during typical production operations. Green properties were obtained from bars of 0.5 inches (12.7 mm) nominal height. The results presented are an average of five determinations for each material at each test condition. Green density and green strength were evaluated according to MPIF Standards 45 and 15, respectively. The force required to eject a compact from the die cavity was measured in terms of stripping and sliding pressure. Stripping pressure is the force required to overcome static friction when the initial ejection process begins divided by the area of the test piece in contact with the die wall. Sliding pressure is the force required to overcome dynamic friction while the compact is moving during ejection divided by the same area. Sintered properties were determined from TRS bars nominally 0.25 inches (6.35 mm) in height. The test pieces were sintered at 2050°F (1120°C) in an atmosphere of 75 v/o hydrogen and 25 v/o nitrogen. Dimensional change from the die and transverse rupture strength were measured according to MPIF Standards 44 and 41.

RESULTS AND DISCUSSION

Commercial Lubricants

The properties of ANCORBOND 45P mixes prepared with eight commercially available P/M lubricants were determined and compared to elucidate the performance areas in which each of the lubricants excelled. The lubricants evaluated included two grades of ethylene bisstearamide (EBS 1 and EBS 2), stearic acid (HSt), zinc and lithium stearates (ZnSt and LiSt, respectively) and three composite lubricants (Comp 1, Comp 2, and Comp 3). The composite lubricants were EBS-based with additions of metal stearates and other lubricating substances. Comp 1 and Comp 2 contain zinc stearate. Lithium stearate is present in Comp 3.

SEM photomicrographs of ethylene bisstearamide, zinc stearate and composite lubricants are reproduced in Figure 1. The photographs illustrate the various particle shapes of the commercial materials. The shapes range from globular to flat with rounded, angular and planar features. The different magnifications at which the photomicrographs were taken should also be noted. The particle sizes of the lubricants varied considerably.

Tables I and II identify the powder, green and sintered properties for the mixes with the eight different commercial lubricants. Figure 2 presents the flow and apparent density that is

achieved with each of the lubricants. Stearic acid and the first composite lubricant yield the fastest flow times. The slowest flow is obtained with the ethylene bisstearamides. The commonly accepted inverse relationship between flow and apparent density holds true for ethylene bisstearamide lubricants as they also exhibit the lowest apparent densities. However, the relationship fails in that the fastest flowing mixes do not also have the highest apparent densities. The highest apparent densities are obtained with zinc and lithium stearate lubricants.

The effect of the type of lubricant and the compaction pressure on green density is shown in Figure 3. As anticipated, density increases with compaction pressure until a maximum is reached. The increase between 40 and 50 tsi (550 and 690 MPa) is less than that between 30 and 40 tsi (415 and 550 MPa). Ethylene bisstearamide provides the lowest green density. The highest green density at all compaction pressures is found for the mix containing stearic acid. With these two exceptions, there is not a significant difference in the values. It should be noted that green expansion of the stearic acid mixes increases rapidly with compaction pressure. At 50 tsi (690 MPa) it is almost 50% greater than the green expansion generated by the remaining commercial lubricants.

A similar presentation of green strength is shown in Figure 4. Stearic acid yields the greatest green strength values due in part to the high green density achieved. The Low green strength of the lithium stearate mixes explains its limited use in most ferrous P/M applications. Despite Low green density, ethylene bisstearamide lubricants provide good green strength.

Ejection pressures for the commercial lubricants at the highest compaction pressure of 50 tsi are illustrated in Figure 5. The first composite lubricant requires the lowest stripping and sliding pressures. For the lubricant series stearic acid, zinc stearate and ethylene bisstearamide, ejection pressure increases with lubricant melting point. However, melting temperature is not the sole determinant of ejection performance. The stripping pressure of the mix containing lithium stearate is between that of the zinc stearate and ethylene bisstearamide mixes although the melting point of lithium stearate is higher than that of ethylene bisstearamide.

Sintered property results reveal that the green density advantage of the stearic acid lubricant is lost upon sintering, especially at a compaction pressure of 30 tsi (415 MPa). The density differences observed for the two ethylene bisstearamides in the green state continue to exist after sintering. Although the second lubricant provides a higher green strength value at 50 tsi (690 MPa), the sintered strength drops significantly below that of the first ethylene bisstearamide. The sintered strength obtained with lithium stearate at 50 tsi (690 MPa) is also relatively poor.

Overall, composite lubricants perform as well as or better than the P/M industry standard lubricant, ethylene bisstearamide. The first and second composite lubricants provide better apparent density with faster flow. The green and sintered properties obtained are essentially equivalent to those with ethylene bisstearamide, yet the ejection pressures are lower with the composite lubricants.

Effect Of Lubricant Particle Size

To examine the effect of lubricant particle size on the properties of an ANCORBOND 45P mix,

eight lubricant fractions of narrow particle size distribution were prepared in the laboratory. EBS lubricant was milled to produce particles with a broad distribution of sizes. The resulting milled lubricant was then fractionated using an ultrasonic sieve. The mean size of the lubricant recovered from the screen cuts was determined independently using a laser light scattering technique.

The test results for the mixes containing different sizes of lubricant particles are summarized in Tables III and IV. With the exception of the mix containing the finest lubricant, apparent density increased slightly with increasing particle size. Flow was independent of particle size.

Figure 6 presents the effect of lubricant particle size on green density. Green density clearly increases with decreasing particle size. The difference between the mixes containing the coarsest and finest lubricants is a significant 0.20 g/cm^3 at a compaction pressure of 50 tsi (690 MPa). Green expansion does not exhibit a clear trend with particle size. Green strength, like green density, is inversely related to particle size. Thus as the large particles inhibit densification, they prevent formation of the interparticle iron contacts which contribute to green strength. However, Figure 7 shows that when the strength values are normalized by density, the results are generally linear across all compaction pressures and are independent of particle size. Green density, green expansion and green strength all increase with compaction pressure as expected.

The ejection pressure, measured as the required stripping and sliding pressures, provides an interesting result. As seen in Figure 8, stripping pressure in general increases slightly with compaction pressure. The sliding pressure for each mix also increases with compaction pressure from 30 to 40 tsi (415 to 550 MPa). However, the sliding pressure decreases at 50 tsi (690 MPa). Thus at least two opposing mechanisms contribute to sliding pressure, dominating at different compaction pressures. Over the lubricant particle size range studied, the ejection pressure is generally independent of size. However, the beginning of an upward trend in sliding pressure with decreasing lubricant particle size is observed at the smallest sizes.

The results for sintered density and dimensional change mimic those of the corresponding green properties. Transverse rupture strength, like green strength, is inversely related to lubricant particle size. However, when the sintered strength is normalized by the sintered density, as shown in Figure 9, a different phenomenon is observed. Unlike the illustration of the green properties in Figure 7, the sintered data is not linear. At each compaction pressure, a sharp increase in sintered strength occurs with small particle sizes. Thus sintered strength is not solely a function of the iron particle surface contact area. Rather, the size of the voids remaining in the compact following lubricant burn-off are a determining factor.

Obviously no single best lubricant particle size exists and compromises are necessary to achieve optimal properties. Higher densities and strengths are obtained with smaller lubricant particle sizes. Larger particles provide better lubricity as determined by lower ejection pressures. However, a functional upper limit on lubricant particle size exists to prevent segregation of the components in the iron powder mix.

Composite Lubricant Development

The data regarding the effects of lubricant chemical composition, particle shape and size

suggest the development of a new composite lubricant for the ANCORBOND 45P application.

Chemical Composition

To exploit the desirable characteristics of several commercial lubricants, four different chemical families of lubricants were identified for inclusion in the new composite lubricant (Comp N). The lubricant was prepared by fusing the constituents together and processing the product to achieve an acceptable particle size. One of the four constituents served as the base material and comprised the majority of the lubricant. The remaining three components were present in lesser amounts and were considered to be additives to the base.

Different species within each chemical family were considered as additives for the new lubricant. Melting point, solubility in the composite lubricant, and affinity for the iron powder surface are but a few of the properties that vary by species within a chemical family. Due to the excellent lubricating qualities of the new lubricant, only 0.35 w/o was incorporated in the test mixes. The results in Table V show the effect of different additives, keeping all other parameters constant. Overall, the new composite lubricants do not achieve the die fill, as measured by the apparent density and flow rate, that the current commercial composite lubricant provides. On the other hand, the ejection pressures required by the new lubricants are significantly lower than for the commercial lubricant. Of the three candidates, Additive 2A provides the highest apparent density. Slightly higher green strength and lower ejection pressures are realized with Additive 2C.

Once the additives had been selected, the relative ratios were adjusted to optimize the chemical composition of the new lubricant. Table VI contains the results illustrating the relationship between green properties and the amount of Additive 2A in the composite lubricant. Additive 2A was selected for inclusion because it aids compaction and decreases the required ejection forces. The experimental results confirm these attributes. However, the additive is detrimental to the flow of the mix. Deterioration in the sliding pressure also occurred at the highest addition level as the relatively soft and Low melting point additive caused sticking to occur at the die wall.

Particle Shape

The particle shape of the new composite lubricant was varied through the processing method employed to reduce the lubricant to an appropriate size distribution. SEM photomicrographs of the particles obtained from the three processes used are presented in Figure 10. Particle shape 1 is round and smooth while shapes 2 is flat and shape 3 is asymmetric with sharp surfaces. For the studies of the particle shape and size of the new lubricant, 0.5 w/o lubricant was added to the ANCORBOND 45P mix.

The results obtained from the mixes with lubricants of different shape are given in Table VII. The higher surface area of particle shape 3 provides a larger lubricating surface to reduce the required ejection pressures. Surprisingly, it did not also improve interparticle lubricity during compaction to increase green density.

Particle Size

Finally, different particle sizes and distributions of the new composite lubricant were evaluated.

Four distributions of particle sizes were prepared by fractionating a sample of lubricant having a broad distribution of shape 3 particles. Two types of coarse distributions were examined. Fine particles were removed from the coarse lubricant of narrow distribution. Fines were included to produce the broad distribution.

Tables VIII and IX contain the powder, green and sintered results. The fine lubricant yields higher green density and strength, but also greater ejection pressures, than the medium and coarse particle sizes. Comparing the two coarse distributions, the inclusion of some fines serves to enhance the green and sintered densities to the level of the fine lubricant. While the ejection pressures were also raised with the addition of fine particles, strip and slide were moderated by the coarse particles and did not reach the level required with fines alone.

The composite lubricant provides a 15% and 25% reduction in the stripping and sliding pressures, respectively in comparison with the best commercial composite lubricant. It should be emphasized that the level of lubricity achieved with 0.5 w/o of the new composite lubricant is similar to that of the commercial reference at a 0.75 w/o addition level. However, the effect of the lubricant in the complex motion of compacting and ejecting a green compact under production conditions is still under investigation.

These results indicate that the selection of a lubricant is not a simple process. At this point, compromises still must be made with regard to properties to optimize part production. Key lubricant performance elements need to be identified early in the development of new P/M applications. Only then will the parts producer and the powder supplier be able to combine their expertise to specify the appropriate lubricant. In the near future, it may become both necessary and possible to tailor the lubricant for each specific application.

CONCLUSIONS

A review of the properties of commercial lubricants and a study of the effect of particle size in ANCORBOND 45P mixes has been made. A new composite lubricant has been investigated for this material system.

The following can be concluded from the results:

1. Composite lubricants provide superior or equivalent powder, green and sintered properties in the mix as compared with the industry standard ethylene bisstearamide lubricant. Most notably, composite lubricants are capable of reducing the force required to eject the compact from the die.
2. No one lubricant particle size satisfies all of the desired requirements. Fine lubricants provide higher density and strength. Coarse lubricants reduce the ejection force required.
3. Progress has been made toward the development of a new composite lubricant. Stripping and sliding pressures have been reduced over those of commercial composite lubricants.

ACKNOWLEDGMENTS

The authors wish to acknowledge the support of Hoeganaes Corporation. They would also like

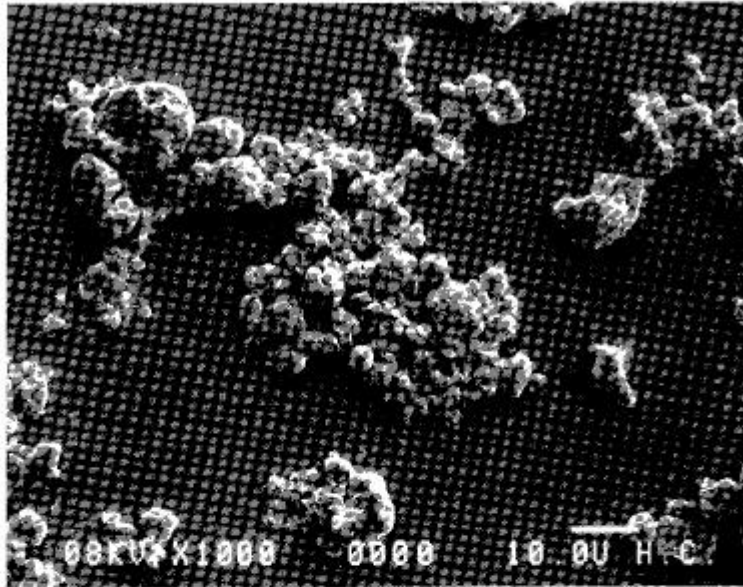
to thank Thomas Murphy, William Bentcliff and Maria Stromgren for their contributions to this paper.

REFERENCES

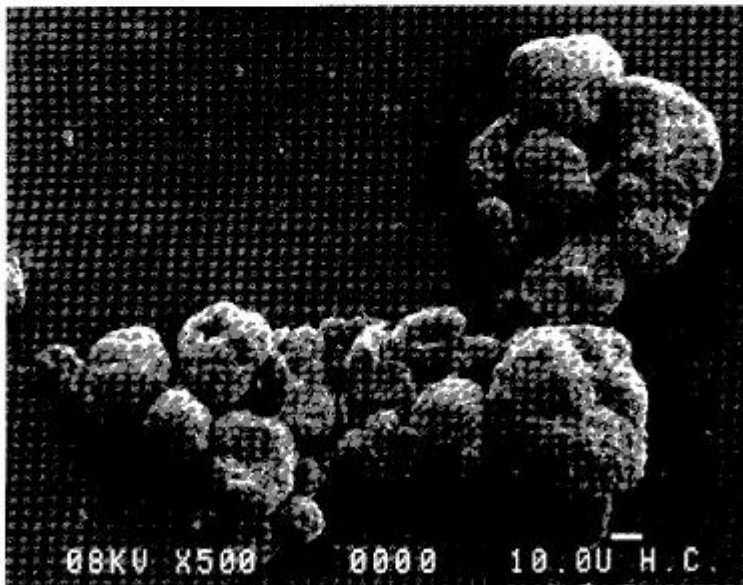
1. Ward, M., "Influence of Lubricants on Dimensional Changes and Mechanical Properties of Sintered Ferrous Compacts", *Powder Metallurgy*, 4, 1979, pp 193-200.
2. Kao, A. and Koczak, M.J., "Mixing and Compacting Behavior of Ferrous Powders", *International Journal of Powder Metallurgy and Powder Technology*, 16 (2), 1980, pp 105-121.
3. German, R.A., Christian, K.D.J., Sacher, R.S., Hall, L. and Reinert, J., "A Comparative Evaluation of Lubricants for Ferrous Structural Alloys", *Progress in Powder Metallurgy*, 42, 1986, pp 405-418.
4. Siddiqui, M.A. and Hamiuddin, M., "Effect of Lubricants and Compaction Pressure on Green Properties of Iron Powder Premixes", *Powder Metallurgy International*, 24 (2), 1992, pp 79-83.
5. Knopp, W.V., "Effect of the Type of Lubricant on Green Strength", *Advances in Powder Metallurgy and Particulate Materials* - 1993, Vol. 2, pp 27-33, Metal Powder Industries Federation, Princeton, NJ.
6. Klemm, U., Sobek, D. and Forster, E., "Evaluation of New Types of Lubricants by an Instrumented Compacting Tool", *Advances in Powder Metallurgy and Particulate Materials* - 1993, Vol. 2, pp 51-61, Metal Powder Industries Federation, Princeton, NJ.
7. Metz, P.A., Wolfe, J., German, R.M., Griffo, A. and Steranko, R.T., "Improved Control of Lubricant Particle Size Distribution and the Effects of Particle Size on P/M Processing", *Advances in Powder Metallurgy and Particulate Materials*- 1996, Vol. 2, pp 59-71, Metal Powder Industries Federation, Princeton, NJ.
8. "Standard Test Methods for Metal Powders and Powder Metallurgy Products", Metal Powder Industries Federation, Princeton, NJ, 1996.

Table III: Green Properties

Admixed Ni (w/o)	Compaction Pressure (tsi/MPa)	Green Density (g/cm ³)	Pore Free Density (g/cm ³)	Green Expansion (%)	Green Strength (psi/MPa)
0	30/415	6.97	7.45	0.19	3755/26
	40/550	7.20		0.23	3924/27
	45/620	7.26		0.24	4201/29
	50/690	7.29		0.29	4128/28
2	30/415	7.02	7.47	0.20	3239/22
	40/550	7.22		0.28	3757/26
	45/620	7.27		0.32	3487/24
	50/690	7.30		0.34	3756/26
4	30/415	7.03	7.48	0.21	3127/22
	40/550	7.25		0.28	3868/27
	45/620	7.29		0.30	4724/33
	50/690	7.32		0.34	4012/28
6	30/415	7.03	7.50	0.21	3258/22
	40/550	7.23		0.27	3741/26
	45/620	7.30		0.28	3578/25
	50/690	7.34		0.32	4299/30

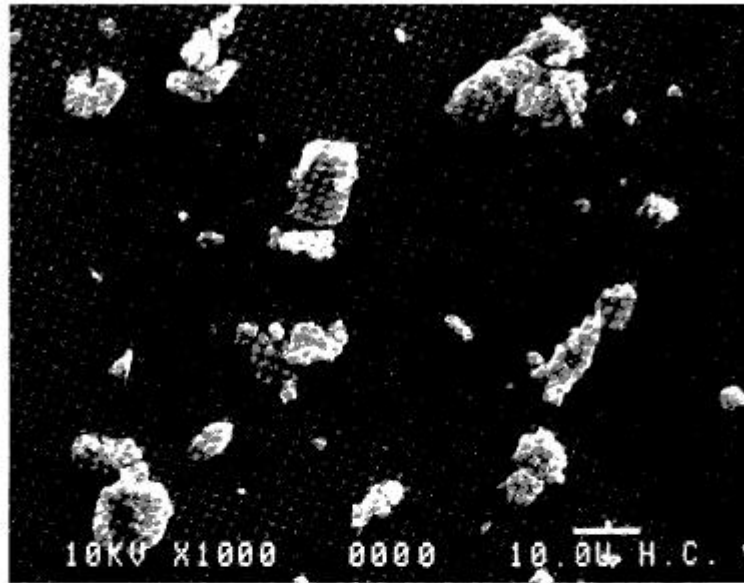


a - Ethylene bisstearamide

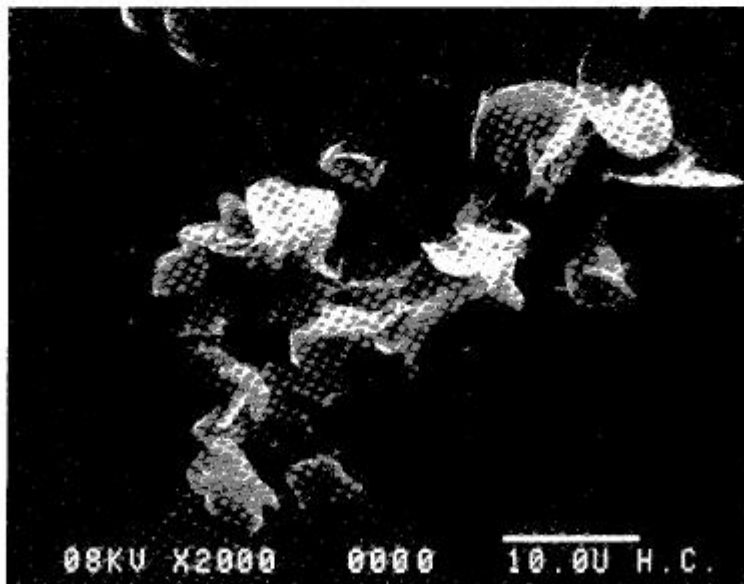


b - Ethylene bisstearamide

Figure 1: SEM Photomicrographs of Commercial Lubricants



c - Zinc Stearate



d - Composite Lubricant

Figure 1: SEM Photomicrographs of Commercial Lubricants

Table I: Powder and Green Properties with Commercial Lubricants
 ANCORBOND 45P with 0.75 w/o Lubricant

Lubricant	Apparent Density (g/cm ³)	Flow (s/50g)	Compaction Pressure (tsi / MPa)	Green Density (g/cm ³)	Green Expansion (%)	Green Strength (psi / MPa)	Stripping Pressure (psi / MPa)	Sliding Pressure (psi / MPa)
EBS 1	3.20	29	30 / 415	6.81	0.11	1990 / 13.7	3020 / 20.8	1760 / 12.1
			40 / 550	7.07	0.13	3050 / 21.0	3120 / 21.5	1390 / 9.6
			50 / 690	7.21	0.16	3430 / 23.6	4080 / 28.1	1590 / 11.0
EBS 2	3.27	31	30 / 415	6.79	0.10	2180 / 15.0	2820 / 19.4	1070 / 7.4
			40 / 550	7.01	0.14	2980 / 20.5	3470 / 23.9	1030 / 7.1
			50 / 690	7.14	0.16	3520 / 24.2	3680 / 25.4	960 / 6.6
HSt	3.28	24	30 / 415	6.87	0.12	2410 / 16.6	2150 / 14.8	830 / 5.7
			40 / 550	7.13	0.18	3490 / 24.1	2750 / 19.0	1040 / 7.2
			50 / 690	7.28	0.26	3870 / 26.7	3060 / 21.1	1080 / 7.4
ZnSt	3.42	27	30 / 415	6.81	0.12	1810 / 12.5	3310 / 22.8	1800 / 12.4
			40 / 550	7.09	0.13	2990 / 20.6	3350 / 23.1	1420 / 9.8
			50 / 690	7.22	0.18	3260 / 22.5	3470 / 23.9	1570 / 10.8
LiSt	3.43	28	30 / 415	6.81	0.12	1690 / 11.6	3190 / 22.0	1640 / 11.3
			40 / 550	7.07	0.15	2670 / 18.4	3480 / 24.0	1630 / 11.2
			50 / 690	7.20	0.18	2910 / 20.1	3720 / 25.6	1620 / 11.2
Comp 1	3.28	24	30 / 415	6.81	0.12	1930 / 13.3	2730 / 18.8	1070 / 7.4
			40 / 550	7.09	0.13	3030 / 20.9	2960 / 20.4	890 / 6.1
			50 / 690	7.21	0.19	3430 / 23.6	2940 / 20.3	970 / 6.7
Comp 2	3.39	27	30 / 415	6.81	0.09	2130 / 14.7	3010 / 20.8	1520 / 10.5
			40 / 550	7.07	0.13	2960 / 20.4	3110 / 21.4	1320 / 9.1
			50 / 690	7.21	0.16	3660 / 25.2	3290 / 22.7	1290 / 8.9
Comp 3	3.32	28	30 / 415	6.79	0.12	1780 / 12.3	3180 / 21.9	1820 / 12.5
			40 / 550	7.06	0.14	3020 / 20.8	3500 / 24.1	1920 / 13.2
			50 / 690	7.19	0.18	3190 / 22.0	3740 / 25.8	1660 / 11.4

**Table II: Sintered Properties with Commercial Lubricants
ANCORBOND 45P with 0.75 w/o Lubricant**

Lubricant	Compaction Pressure (tsi / MPa)	Sintered Density (g/cm ³)	Dimensional Change (%)	Transverse Rupture Strength (10 ³ psi / MPa)	Apparent Hardness (HRB)
EBS 1	30 / 415	6.95	-0.04	109.0 / 751.5	53
	50 / 690	7.26	0.00	148.5 / 1024.0	66
EBS 2	30 / 415	6.89	-0.05	110.5 / 762.0	52
	50 / 690	7.19	-0.01	132.5 / 913.5	63
HSt	30 / 415	6.92	-0.02	110.0 / 758.5	53
	50 / 690	7.30	+0.02	146.0 / 1006.5	69
ZnSt	30 / 415	6.94	-0.02	110.5 / 762.0	54
	50 / 690	7.27	0.00	144.0 / 993.0	68
LiSt	30 / 415	6.94	-0.03	109.0 / 751.5	55
	50 / 690	7.25	+0.02	133.5 / 920.5	68
Comp 1	30 / 415	6.91	-0.01	114.0 / 786.0	54
	50 / 690	7.26	+0.04	144.0 / 993.0	68
Comp 2	30 / 415	6.95	-0.05	115.0 / 793.0	53
	50 / 690	7.26	0.00	143.5 / 989.5	65
Comp 3	30 / 415	6.92	-0.02	106.5 / 734.5	55
	50 / 690	7.24	+0.03	144.5 / 996.5	67

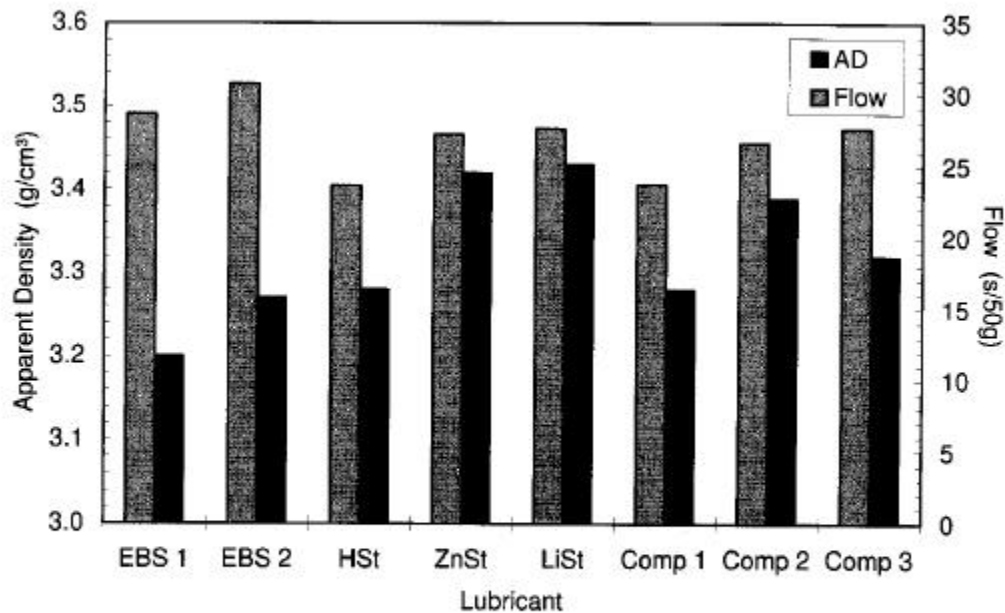


Figure 2: Powder Properties with Commercial Lubricants

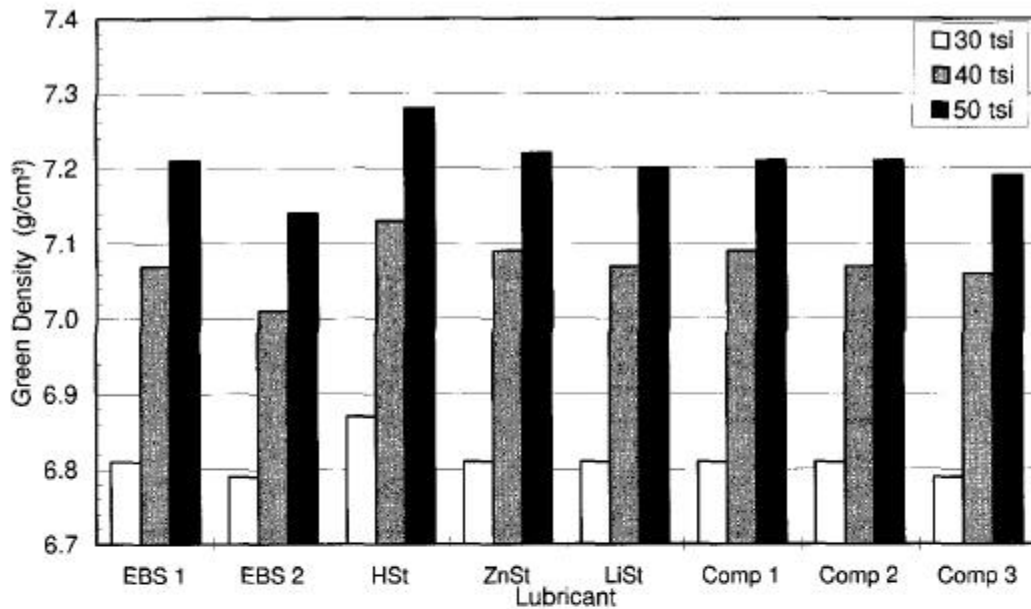


Figure 3: Green Density with Commercial Lubricants for Compaction Pressures of 30, 40 and 50 tsi (415, 550 and 690 MPa)

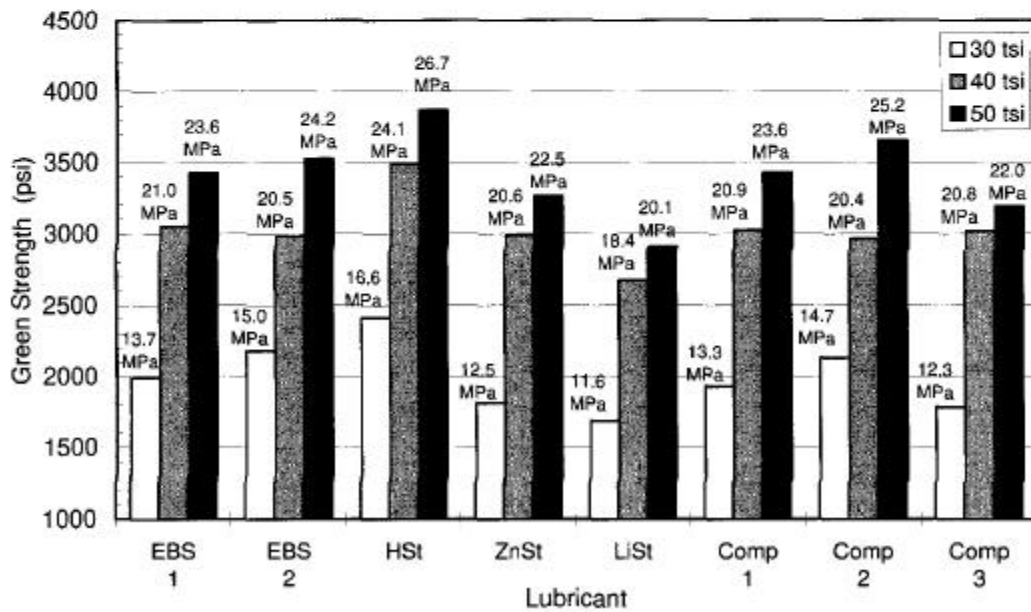


Figure 4: Green Strength with Commercial Lubricants for Compaction Pressures of 30, 40 and 50 tsi (415, 550 and 690 MPa)

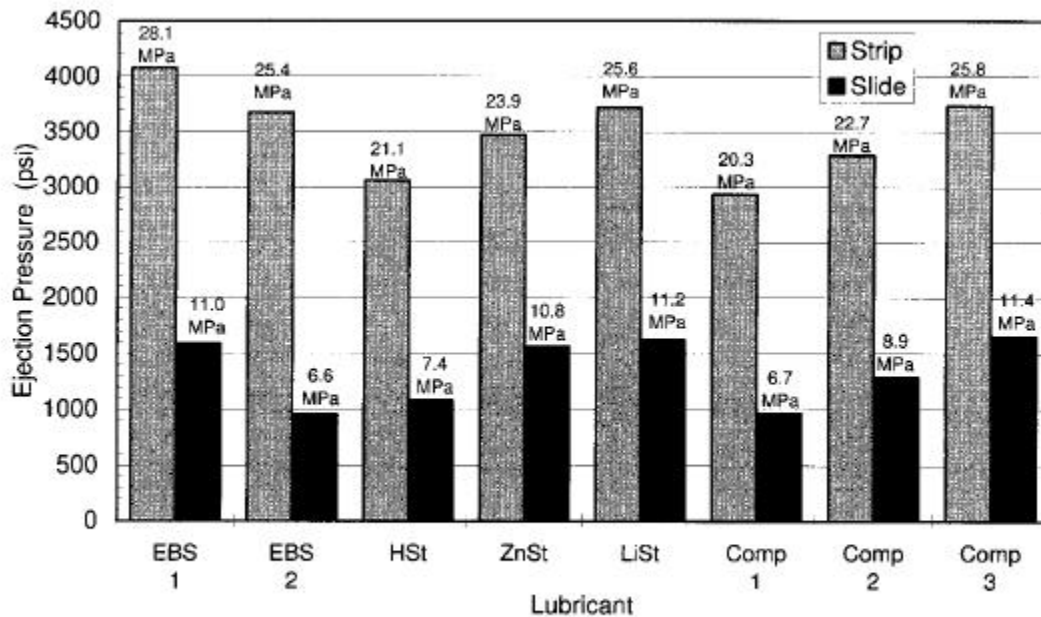


Figure 5: Ejection Pressure with Commercial Lubricants for a Compaction Pressure of 50 tsi (690 MPa)

Table III: Powder and Green Properties with EBS of Various Sizes ANCORBOND 45P with 0.75 w/o Lubricant

Mean Particle Size (µm)	Apparent Density (g/cm ³)	Flow (s/50g)	Compaction Pressure (tsi / MPa)	Green Density (g/cm ³)	Green Expansion (%)	Green Strength (psi / MPa)	Stripping Pressure (psi / MPa)	Sliding Pressure (psi / MPa)
196	3.21	32	30 / 415	6.62	0.10	1690 / 11.6	2960 / 20.4	980 / 6.8
			40 / 550	6.89	0.15	2120 / 14.6	3010 / 20.8	1510 / 10.4
			50 / 690	7.00	0.19	2640 / 18.2	3300 / 22.8	910 / 6.3
144	3.19	33	30 / 415	6.65	0.10	1750 / 12.1	2620 / 18.1	850 / 5.9
			40 / 550	6.87	0.14	2060 / 14.2	3010 / 20.8	1520 / 10.5
			50 / 690	7.03	0.19	2700 / 18.6	3580 / 24.7	1020 / 7.0
98	3.19	32	30 / 415	6.69	0.11	1910 / 13.2	3110 / 21.4	990 / 6.8
			40 / 550	6.91	0.14	2210 / 15.2	3200 / 22.1	1240 / 8.5
			50 / 690	7.05	0.17	2520 / 17.4	3240 / 22.3	820 / 5.6
57	3.18	32	30 / 415	6.74	0.14	2050 / 14.1	3060 / 21.1	1040 / 7.2
			40 / 550	6.98	0.12	2390 / 16.5	3260 / 22.5	1410 / 9.7
			50 / 690	7.11	0.16	2800 / 19.3	3450 / 23.8	850 / 5.9
36	3.15	31	30 / 415	6.78	0.14	2130 / 14.7	2930 / 20.2	1050 / 7.2
			40 / 550	7.03	0.12	2640 / 18.2	3220 / 22.2	1540 / 10.6
			50 / 690	7.15	0.16	2920 / 20.1	3170 / 21.8	930 / 6.4
24	3.15	32	30 / 415	6.79	0.12	2180 / 15.0	3110 / 21.4	1320 / 9.1
			40 / 550	7.06	0.12	2740 / 18.9	3400 / 23.4	1780 / 12.3
			50 / 690	7.19	0.15	3150 / 21.7	3050 / 21.0	1000 / 6.9
20	3.16	32	30 / 415	6.80	0.12	2170 / 15.0	3080 / 21.2	1380 / 9.5
			40 / 550	7.06	0.13	2840 / 19.6	3250 / 22.4	1740 / 12.0
			50 / 690	7.20	0.15	2870 / 19.8	3360 / 23.2	1040 / 7.2
14	3.21	32	50 / 690	7.22	0.16	2900 / 20.0	3330 / 23.0	1240 / 8.5

**Table IV: Sintered Properties with EBS of Various Sizes
ANCORBOND 45P with 0.75 w/o Lubricant**

Mean Particle Size (μm)	Compaction Pressure (tsi / MPa)	Sintered Density (g/cm^3)	Dimensional Change (%)	Transverse Rupture Strength (10^3 psi / MPa)	Apparent Hardness (HRB)
196	30 / 415	6.68	-0.08	81.5 / 562.0	37
	40 / 550	6.92	-0.03	93.0 / 641.0	46
	50 / 690	7.09	-0.10	106.0 / 731.0	52
144	30 / 415	6.70	-0.08	81.5 / 562.0	38
	40 / 550	6.95	-0.06	97.0 / 669.0	48
	50 / 690	7.09	-0.13	99.0 / 682.5	52
98	30 / 415	6.74	-0.12	88.5 / 610.0	41
	40 / 550	6.97	-0.08	101.0 / 696.5	50
	50 / 690	7.13	-0.17	103.0 / 710.0	55
57	30 / 415	6.78	-0.11	99.0 / 682.5	43
	40 / 550	7.02	-0.09	112.5 / 775.5	53
	50 / 690	7.19	-0.15	117.5 / 810.0	58
36	30 / 415	6.82	-0.09	104.0 / 717.0	44
	40 / 550	7.07	-0.12	120.5 / 831.0	54
	50 / 690	7.23	-0.12	127.5 / 879.0	60
24	30 / 415	6.84	-0.11	104.5 / 720.5	44
	40 / 550	7.09	-0.11	125.0 / 862.0	55
	50 / 690	7.25	-0.11	131.5 / 906.5	61
20	30 / 415	6.84	-0.12	107.5 / 741.0	45
	40 / 550	7.10	-0.09	120.0 / 827.5	56
	50 / 690	7.26	-0.11	138.0 / 951.5	61
14	50 / 690	7.28	-0.10	140.0 / 965.5	63

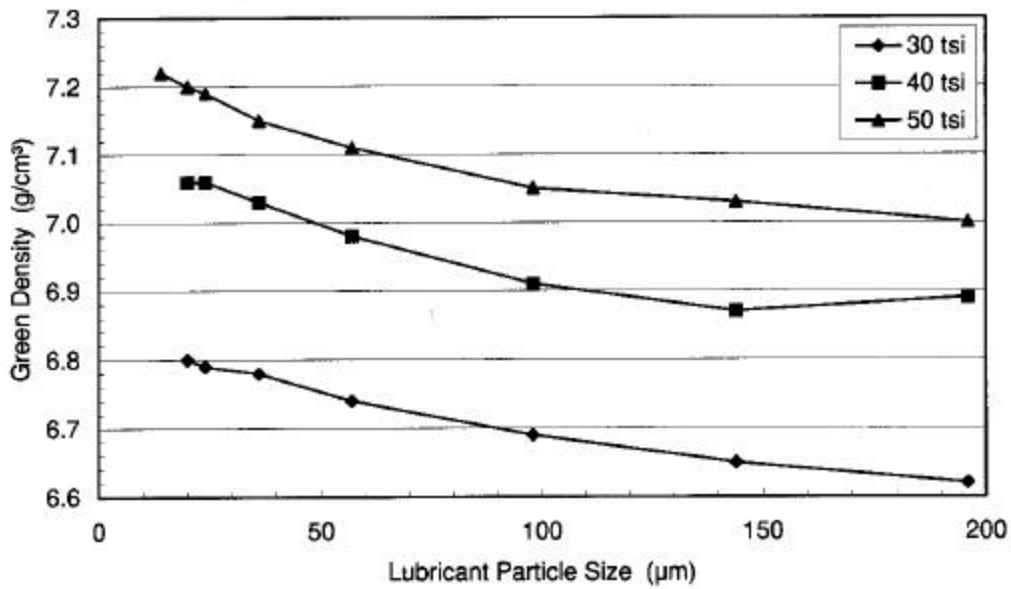


Figure 6: Green Density as a Function of Lubricant Particle Size for Compaction Pressures of 30, 40 and 50 tsi (415, 550 and 690 MPa)

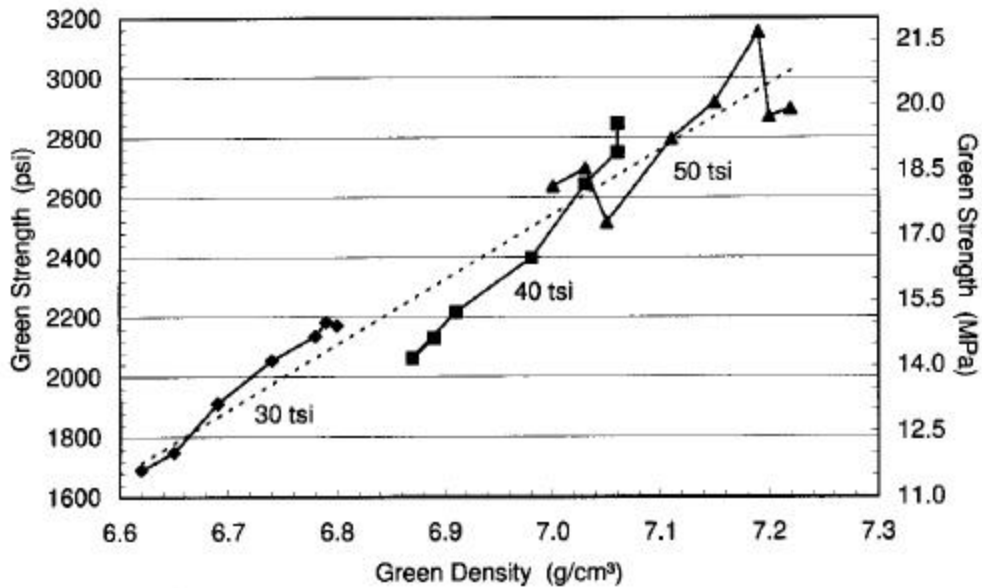


Figure 7: Green Strength as a Function of Green Density for Compaction Pressures of 30, 40 and 50 tsi (415, 550 and 690 MPa)

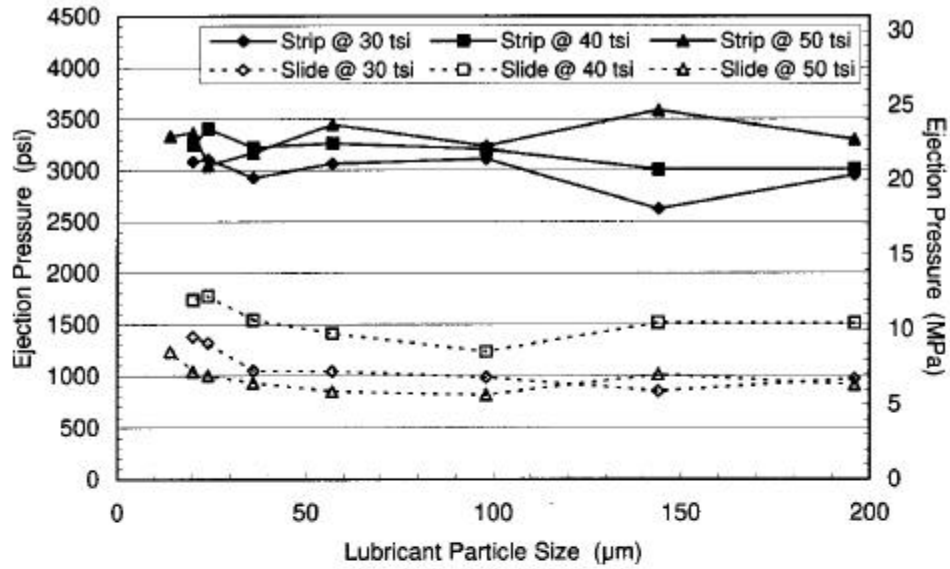


Figure 8: Ejection Pressure as a Function of Lubricant Particle Size for Compaction Pressures of 30, 40 and 50 tsi (415, 550 and 690 MPa)

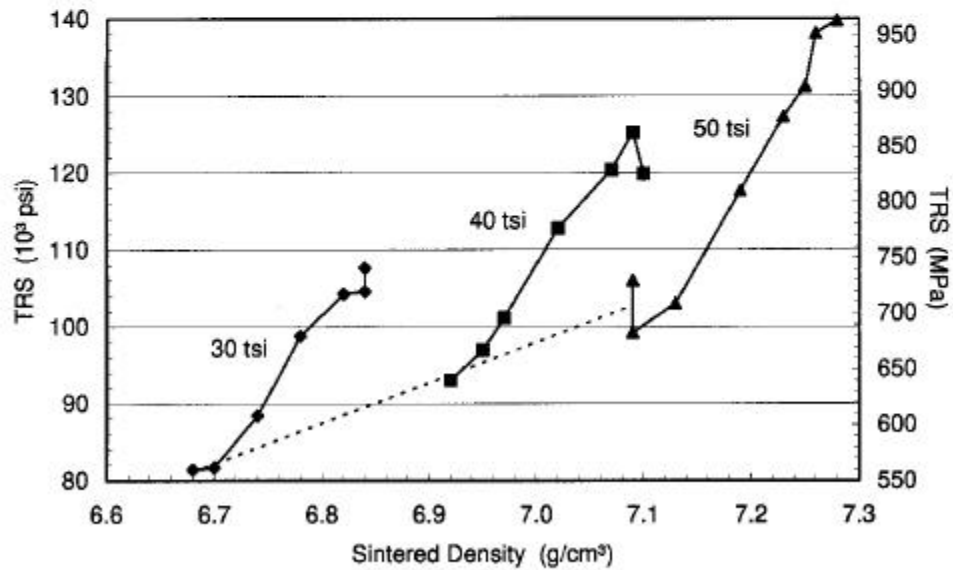


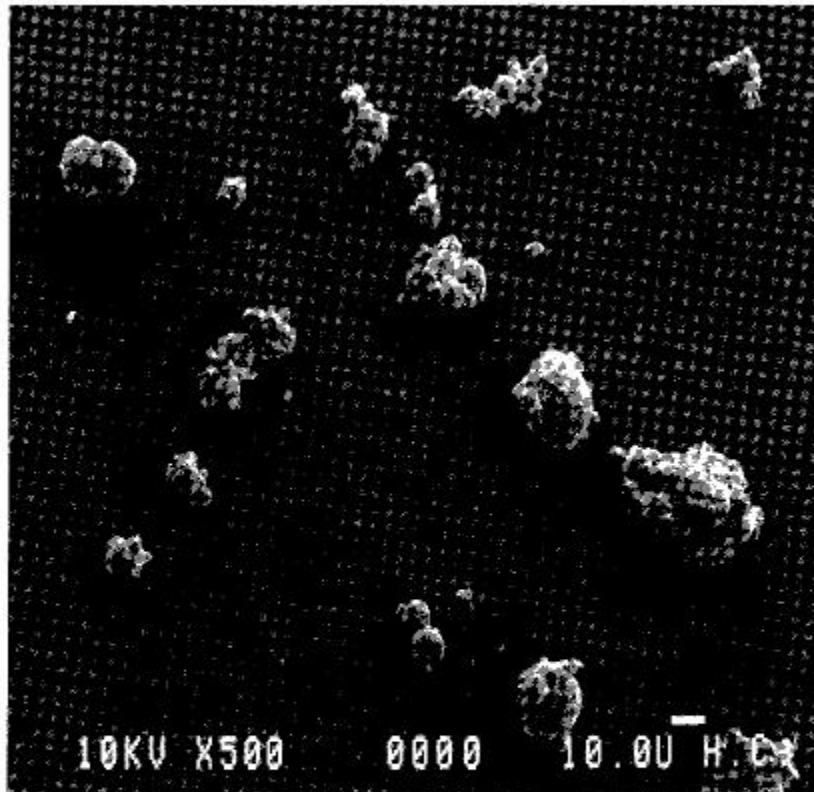
Figure 9: Sintered Strength as a Function of Sintered Density for Compaction Pressures of 30, 40 and 50 tsi (415, 550 and 690 MPa)

Table V: Powder and Green Properties with Composite Lubricants with Various Additives - ANCORBOND 45P with 0.35 w/o Lubricant Compacted to 50 tsi (690 MPa)

Lubricant	Apparent Density (g/cm ³)	Flow (s/50g)	Green Density (g/cm ³)	Green Expansion (%)	Green Strength (psi / MPa)	Stripping Pressure (psi / MPa)	Sliding Pressure (psi / MPa)
Comp1	2.95	26	7.22	0.15	4150 / 28.6	5710 / 39.4	3080 / 21.2
Comp N Additive 2A	2.88	28	7.24	0.16	3880 / 26.8	4080 / 28.1	1640 / 11.3
Comp N Additive 2B	2.83	29	7.23	0.17	3860 / 26.6	4310 / 29.7	1630 / 11.2
Comp N Additive 2C	2.82	29	7.22	0.16	3930 / 27.1	4190 / 28.9	1480 / 10.2

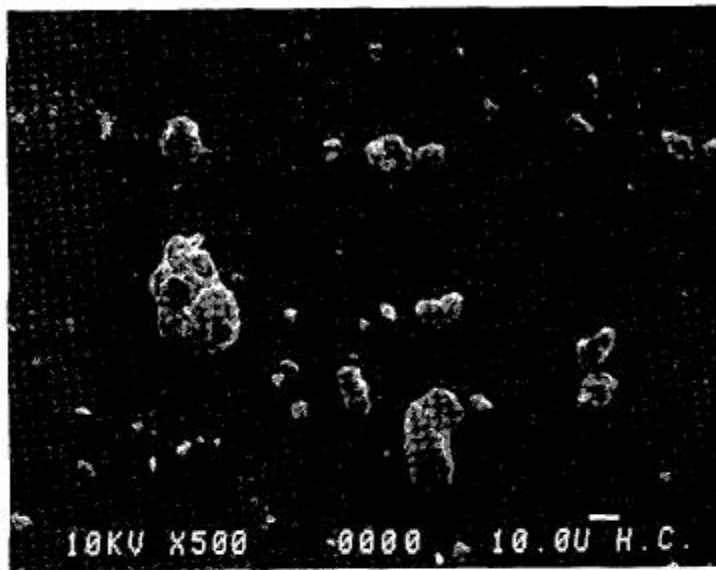
Table VI: Powder and Green Properties with Composite Lubricants with Various Ratios of Additives - ANCORBOND 45P with 0.35 w/o Lubricant Compacted to 50 tsi (690 MPa)

Lubricant	Apparent Density (g/cm ³)	Flow (s/50g)	Green Density (g/cm ³)	Green Expansion (%)	Green Strength (psi / MPa)	Stripping Pressure (psi / MPa)	Sliding Pressure (psi / MPa)
Comp1	3.03	26	7.23	0.14	3720 / 25.6	5260 / 36.3	2670 / 18.4
Comp N 5 w/o Additive	2.98	27	7.23	0.16	3350 / 23.1	3760 / 25.9	1380 / 9.5
Comp N 15 w/o Additive	3.00	27	7.25	0.17	3470 / 23.9	3720 / 25.6	134 / 9.2
Comp N 30 w/o Additive	2.94	29	7.26	0.18	3450 / 23.8	3490 / 24.1	150 / 10.3

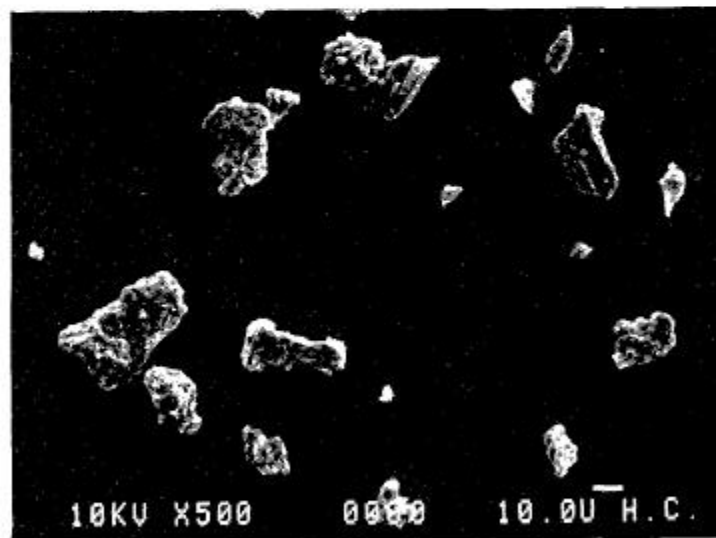


a - Shape 1

Figure 10: SEM Photomicrographs of Comp N Lubricant



b - Shape 2



c - Shape 3

Figure 10: SEM Photomicrographs of Comp N Lubricant

**Table VII: Powder and Green Properties with Composite Lubricants of Various Shapes -
ANCORBOND 45P with 0.5 w/o Lubricant Compacted to 50 tsi (690 MPa)**

Lubricant	Apparent Density (g/cm ³)	Flow (s/50g)	Green Density (g/cm ³)	Green Expansion (%)	Green Strength (psi / MPa)	Stripping Pressure (psi / MPa)	Sliding Pressure (psi / MPa)
Comp1	3.26	25	7.24	0.18	3210 / 22.1	3350 / 23.1	1530 / 10.5
Comp N Shape 1	3.14	30	7.25	0.21	3040 / 21.0	3300 / 22.8	1480 / 10.2
Comp N Shape 2	3.16	30	7.26	0.20	3040 / 21.0	3220 / 22.2	1710 / 11.8
Comp N Shape 3	3.11	32	7.23	0.20	2940 / 20.3	2980 / 20.5	1140 / 7.9

Table VIII: Powder and Green Properties with Composite Lubricants of Various Particle Sizes and Distributions - ANCORBOND 45P with 0.5 w/o Lubricant Compacted to 50 tsi (690 MPa)

Lubricant	Apparent Density (g/cm ³)	Flow (s/50g)	Green Density (g/cm ³)	Green Exp. (%)	Green Strength (psi / MPa)	Stripping Pressure (psi / MPa)	Sliding Pressure (psi / MPa)
Comp1	3.23	24	7.26	0.17	3560 / 24.5	3790 / 26.1	1560 / 10.8
Comp N Fine Size	3.05	33	7.25	0.18	3110 / 21.4	3360 / 23.2	1460 / 10.1
Comp N Medium Size	3.06	33	7.24	0.19	3070 / 21.2	2860 / 19.7	1120 / 7.7
Comp N Coarse Size Broad Distribution	3.09	33	7.25	0.17	3050 / 21.0	2980 / 20.5	1120 / 7.7
Comp N Coarse Size Narrow Distribution	3.10	31	7.22	0.19	2980 / 20.5	2590 / 17.8	860 / 5.9

Table IX: Sintered Properties with Composite Lubricants of Various Particle Sizes and Distributions ANCORBOND 45P with 0.5 w/o Lubricant Compacted to 50 tsi (690 MPa)

Lubricant	Sintered Density (g/cm ³)	Dimensional Change (%)	Transverse Rupture Strength (10 ³ psi / MPa)	Apparent Hardness (HRB)
Comp1	7.29	-0.06	145.0 / 1000.0	66
Comp N Fine Size	7.29	-0.06	153.0 / 1055.0	66
Comp N Medium Size	7.28	-0.06	148.0 / 1020.5	65
Comp N Coarse Size Broad Distribution	7.28	-0.07	144.5 / 996.5	65
Comp N Coarse Size Narrow Distribution	7.26	-0.06	144.5 / 996.5	65