Production Experience with Advanced Lubricants for Improved Compaction Performance

Rich Bon[1], Jeff Howie[2]

[1] Alpha Precision Group, Ridgway, PA 15853

[2] Alpha Precision Group, Wyandotte, MI 48192

Kylan McQuaig[3], Lars Wimbert[4], Bruce Lindsley[3], Jay Stoner[3]

[3] Hoeganaes Corporation, Cinnaminson, NJ 08077

[4] Hoeganaes Corporation Europe, Radevormwald, Germany

Abstract

Demands on powder metallurgy (PM) lubricants are intense and complicated due to the wide range of PM processes utilized. Necessary lubricant properties include ability to mix uniformly at scale, good powder flow and fill in powder premixes, excellent ejection of compacted parts, and clean burn-off behavior during sintering. Many of the advanced lubricants used in previous generations of PM parts have now been rendered obsolete due to the inclusion of metallic stearates and other unwanted raw materials in their formulation. Today's advanced lubricants, such as AncorLube LV, are far more clean-burning and environmentally friendly, resulting in parts with full lubricant removal and a desired surface finish. This lubricant has now been used in a production setting for an extended period with positive results. The benefits of this lubricant, the improvements observed, and potential opportunities of using advanced lubricants in varying part geometries throughout the PM process are explored.

Introduction

Although lubricants in powder metallurgy (PM) premix compositions may initially appear as minor additives that are eliminated in the final PM component, the reality is that as density levels increase and part geometries become more complex, selecting the optimal amount and type of lubricant becomes crucial. Typical PM lubricants consist of metallic stearates, amide waxes, or a combination thereof, and are commonly utilized to allow for proper compaction and ejection of parts in press-and-sinter applications [1-3]. These lubricants have historically been used at additions between 0.5-1.5 wt.% and while non-metallic additions to powder premixes are undesirable, admixed organic lubricants have proven to be necessary in the production of PM parts. Alternative solutions, such as die wall spray, have never proven to be a robust production alternative for most parts producers [4-5].

The requirements for an ideal lubricant may vary depending on the final part application, on the necessary processing steps, and on the point of view of the user. For instance, while a powder manufacturer may prioritize blending behavior and powder processing, a parts producer might emphasize lubricity and burn-off. Figure 1 provides an overview of lubricant properties that must be considered during the material design process. The figure tries to group key properties to the different process steps and additional fields like purchasing, health, safety, and environment.

Figure 1: Essential properties needed in modern PM lubricants (colors reflect different process steps)

Based on the figure above, the ideal PM lubricant must be well-rounded to meet a number of requirements including excellent lubricity over a range of compaction temperatures, homogeneous blending of the powder premix, clean burn-out in sintering of the compacted parts, and minimal impact on mechanical properties of the sintered parts. The desired lubricant properties also include high apparent density and good flow of the powder premix, elimination of scoring on parts and compaction tooling, high green strength and green density of compacted parts, low environmental or safety implications, and a long shelf life. While development of new lubricants can be a challenge, it has been shown in previous studies that this could be completed successfully with a thorough lubricant development plan [6].

This work focuses on the newly developed AncorLube LV lubricant and offers a comparison to established PM lubricants in large-scale powder premixes. The most utilized PM lubricants consist of amide waxes and metallic stearates (such as zinc and lithium stearate). These lubricants tend to blend well in premixes and offer many benefits, but do not have optimal lubricity and the metallic stearates, specifically, do not burn out as cleanly as other alternatives, as shown in Figure 2 [7-9]. This figure shows a comparison of sintered parts produced using a common metallic stearate and amide wax lubricant, sintered in various atmospheres. This type of staining, in addition to other cleanliness and environmental concerns, makes the use of a metallic stearate lubricants an unattractive choice for today's industry.

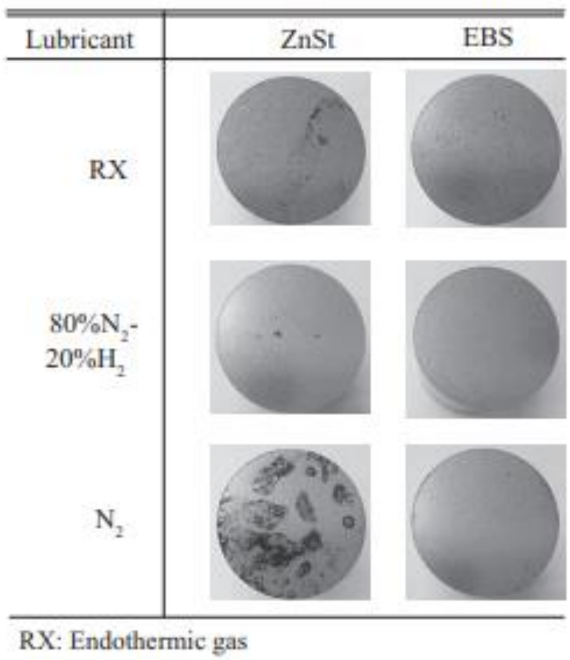

Figure 2: Comparison of sintered surface finish between common metallic stearate and amide wax in various sintering atmospheres [7]

Amide waxes, such as ethylene bis stearamide (EBS), shown in the figure above, offer a much cleaner-burning alternative, making them the most popular choice for conventional powder metallurgy parts. But recent cost pressures and limited lubricity, requiring higher lubricant addition, have begun to limit their effectiveness and attractiveness, especially in high density applications and in complicated part geometries. Most newer "advanced" PM lubricants have greater lubricity and are specifically designed to operate at elevated die temperatures in lower additions of 0.25-0.60 wt% [10-13]. By using lubricants at lower additions and with increased die temperatures, the pore free density of the powder premix can be increased, allowing for parts compacted to higher green and sintered density, resulting in drastic improvements in part performance both mechanically and magnetically [14-16].

Experimental Procedure

Previous work focused on the development and optimization of the AncorLube LV chemistry and particle size distribution for maximum lubricity, while further experiments were completed in several stages to ensure ideal performance in all areas of the standard PM production process. In the current study, ejection forces were measured using cylindrical specimens with a small radius and high overall length to test the lubricant in a more challenging compaction process. The nominal cylinder size was 1.4 cm (0.55 inch) diameter and 2.7 cm (1.05 inch) height.

For this portion of the study, ejection data was collected over a range of conditions using a lab-scale hydraulic press and carbide insert die, utilizing a compaction pressure of 40 tsi (550 MPa). All mixes produced were an MPIF standard FC-0208 composition with 2 wt% admixed copper and 0.9 wt% graphite. Lubricant addition was varied at 0.30, 0.45, 0.60, and 0.75 wt% and die temperatures of both 60 and 80 °C (140 and 175 °F) were used. The AncorLube LV lubricant was compared to industrial standard lubricants, EBS wax and Kenolube. Ejection data was taken on an average of five samples minimum after a break-in period of the die to allow values to stabilize. The die was cleaned between every set of samples when any condition was changed.

To understand AncorLube LV behavior on a production scale, full truckload premixes were produced. Production blends were produced at Hoeganaes Corporation in Gallatin, TN in quantities of approximately 20,000 kg (44,000 pounds). A standard FC-0208 premix was used as the baseline with 0.5% MnS added and a nominal addition of 0.75% "standard" PM lubricant (0.50% EBS Wax + 0.25% low ash zinc stearate), compared to identical premixes with 0.45% and 0.55% AncorLube LV additions. Using each premix, sprockets were compacted at Alpha Precision Group in Ridgway, PA to an overall green density of 7.0 g/cm^3. The parts were nominally 12.1 cm (4.8 inch) OD and 4.0 cm (1.6 inch) overall length (OAL) with a mass of 1,650 grams (3.6 pounds). The part geometry is shown in Figure 3.

Figure 3: Sprocket geometry shown in die face view (left) and punch face view (right)

Results and Discussion – Laboratory Ejection Testing

Building on the laboratory results of the previous year [6], the authors of this paper looked to further test the lubricant under more difficult compaction conditions, followed by an extended industrial trial. First, ejection studies were repeated in a laboratory setting using a more difficult cylindrical geometry with a calculated M/Q ratio, defined as the lateral area over the compacted area, of approximately 7.5. As M/Q ratio increases, a greater portion of the compacted part is in contact with the die, putting a greater stress on the lubricant within the green compact. Contrasting with the industry standard rectangular bars in previous work, with an M/Q ratio of approximately 3.0, the current work was a better test of the various lubricant options in a more challenging part geometry.

The first round of testing was completed using a die temperature of 60 °C, which is assumed to be a temperature occurring in typical production tooling and conditions due to frictional heating. In Figure 4 below, the sliding ejection pressures, observed at a die temperature of 60 °C, show a significant benefit using either of the alternatives to EBS wax, regardless of lubricant addition. At lower lubricant additions, specifically, the benefits of the alternative lubricants became apparent. EBS wax at 0.3% addition resulted in such poor ejection that the ejection pressure jumped dramatically, and samples could not be successfully ejected without significant scoring and cracking. AncorLube LV was found to be the best lubricant option, offering approximately 5-10% improvement over Kenolube depending on lubricant addition.

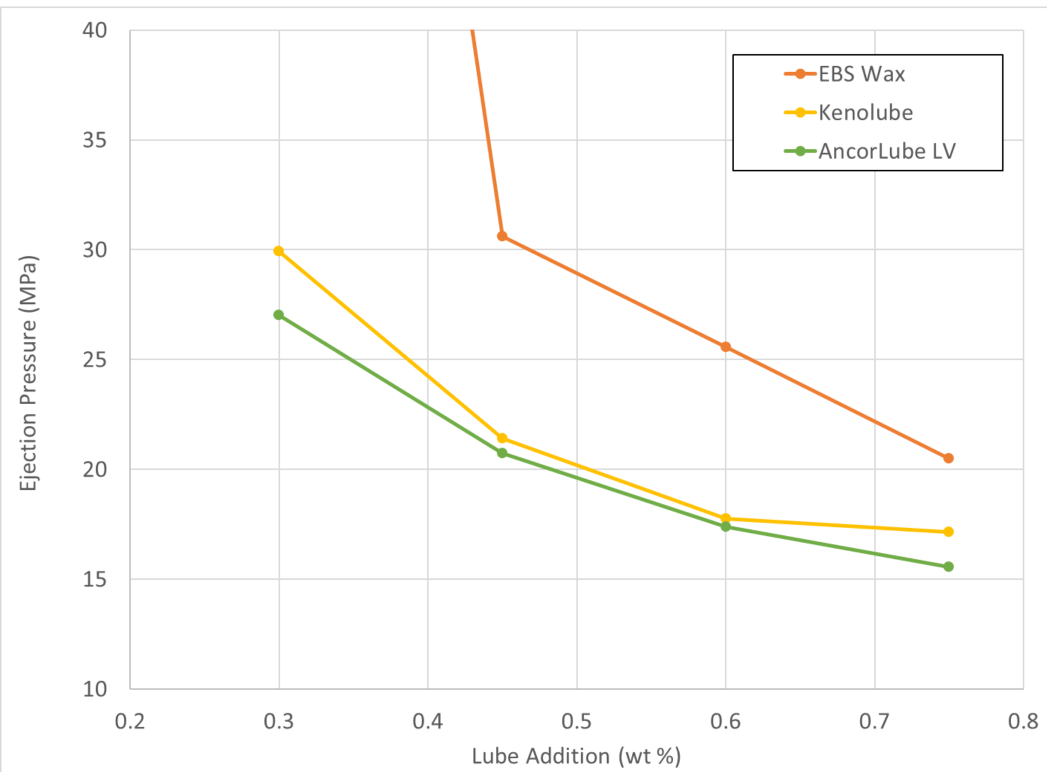

Figure 4: Ejection pressure vs. lubricant addition at a die temperature of 60 °C

Next, the die temperature was increased to 80 °C and the same study was repeated. Higher temperature is crucial because it is expected that advanced lubricants will most commonly be used with difficult-to-eject parts or with low lubricant additions to achieve high density. Both compaction scenarios are likely to take place with elevated die temperatures either through die heating or high frictional forces. The results of this portion of the study are shown in Figure 5 below. In this scenario, a much greater differentiation can be seen in lubricant performance. The EBS wax actually improved slightly with additional die heat, but was still the worst performing option and resulted in only one successfully ejected part at 0.3% addition. The Kenolube improved at 0.3% addition, but was found to degrade at every other addition level, while the AncorLube LV was found to improve in every tested premix addition. Because the AncorLube LV lubricant is specifically designed to perform across a wide range of die temperatures, especially higher die temperatures, an improvement of 15-25% over Kenolube was now observed depending on lubricant amount.

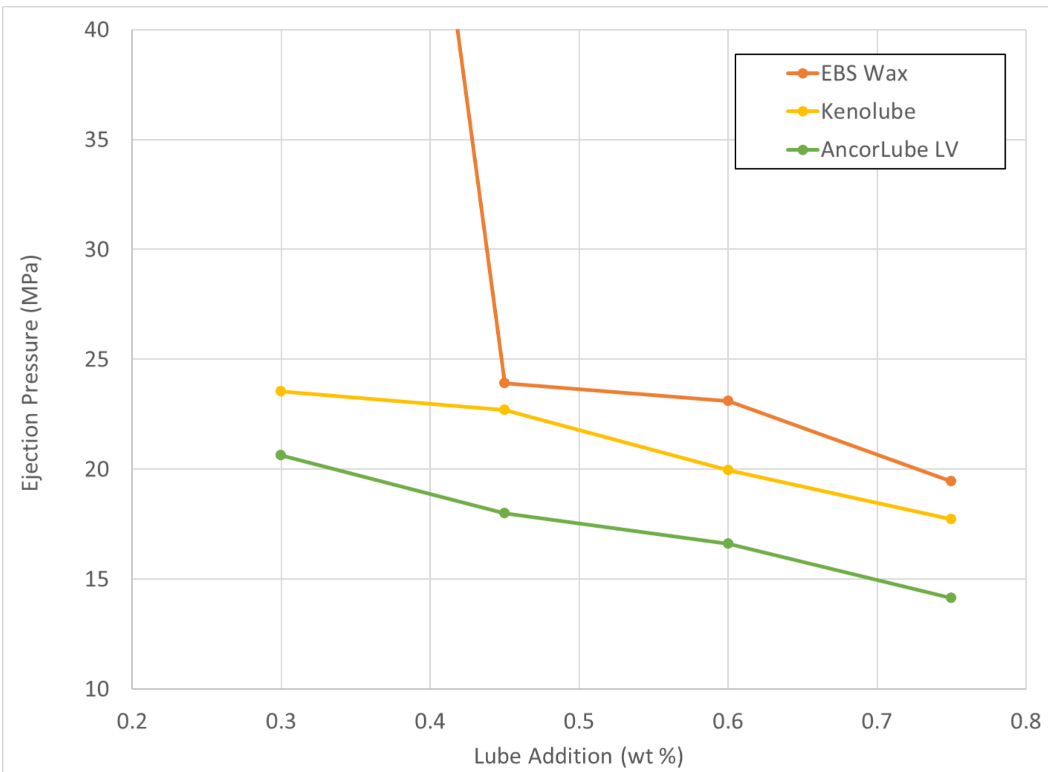

Figure 5: Ejection pressure vs. lubricant addition at a die temperature of 80 °C

Images of the compacted cylindrical specimens are shown in Figure 6, so that surface finish comparisons can be made across a range of lubricant types, lubricant additions, and die temperatures. As mentioned previously, EBS wax at a level of 0.3% addition was largely not feasible. At 60 °C, no samples were successfully ejected from the die and only a single sample was achieved at 80 °C. As seen in the figure, this was the worst case for surface finish as significant part scoring was observed. As expected, with increasing lubricant addition, surface finish improved and part scoring was reduced, though not eliminated completely simply due to the condition of the experimental die surface. This trend is observed regardless of lubricant type or compaction die temperature.

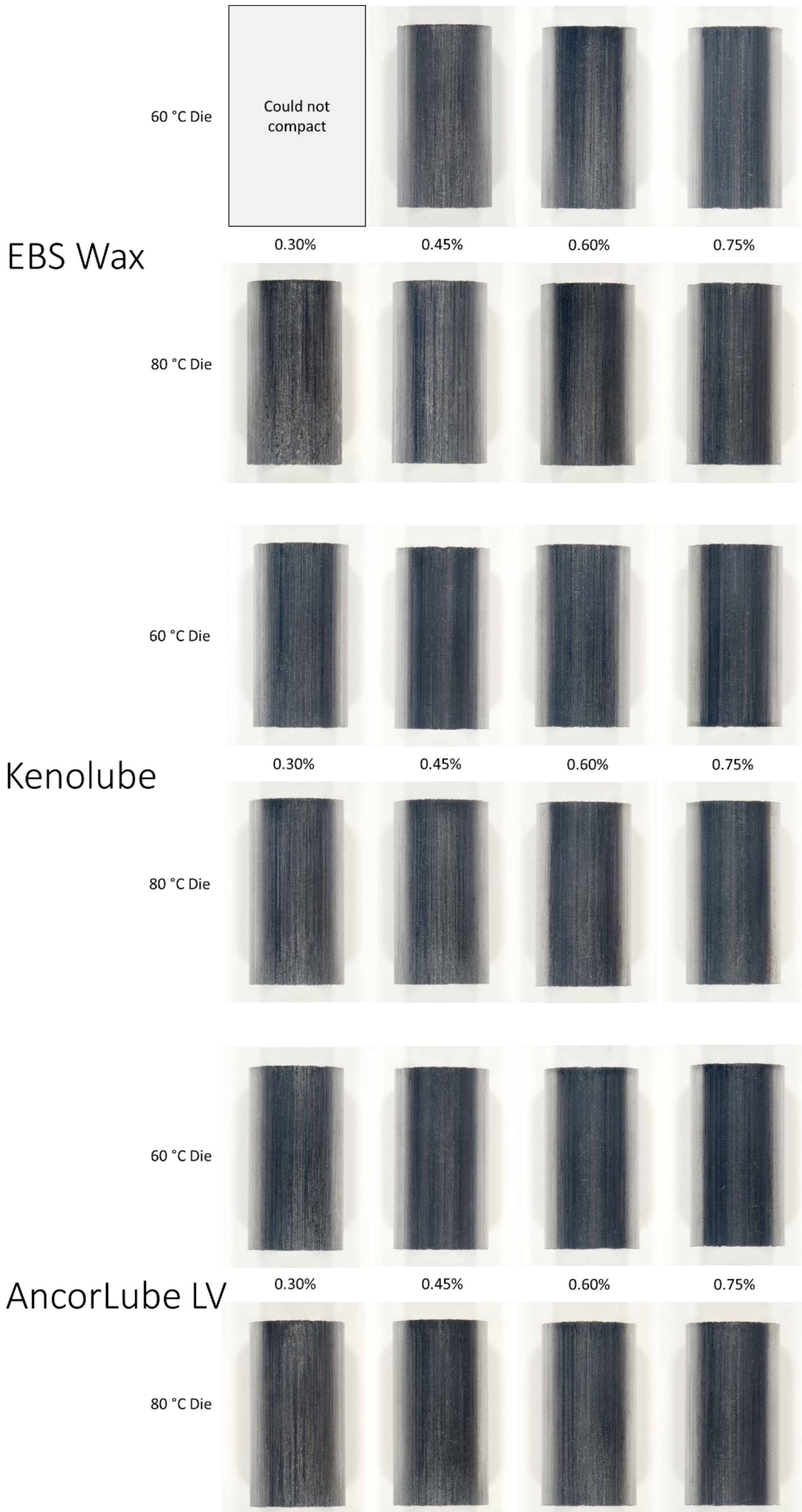

Figure 6: Surface finish of ejected green specimens for EBS wax, Kenolube, and AncorLube LV over a range of die temperatures and lubricant additions

All lubricant types showed some level of part surface scoring at 0.3% addition, as this is approaching the minimum suggested premix lubricant content, regardless of premix composition or lubricant type. In general, Kenolube showed a significant improvement over EBS wax in nearly all conditions, and AncorLube LV showed further improvement in surface finish, especially with a die heated to 80 °C. At 0.75% lubricant addition, all samples showed good surface finish, though this was the minimum lubricant addition necessary to achieve a clean surface finish when using EBS wax. With Kenolube and AncorLube LV, 0.6% addition seemed to be sufficient to allow for minimal scoring.

To compare the ejection data from the various lubricants in a different way, linear best fit lines were applied to the ejection data for each lubricant at the two die temperatures, as shown in Figures 7 and 8 below. Figure 7 shows the data with a die temperature of 60 °C, where EBS wax is far inferior to the other two lubricants tested. It was interesting that all three lubricants displayed a best fit line with a similar slope, though the Kenolube and AncorLube LV begin to slowly converge with increasing lubricant content. At a die temperature of 80 °C, again, all three lubricants show a very similar slope, though it is a much more shallow slope than was observed at 60 °C.

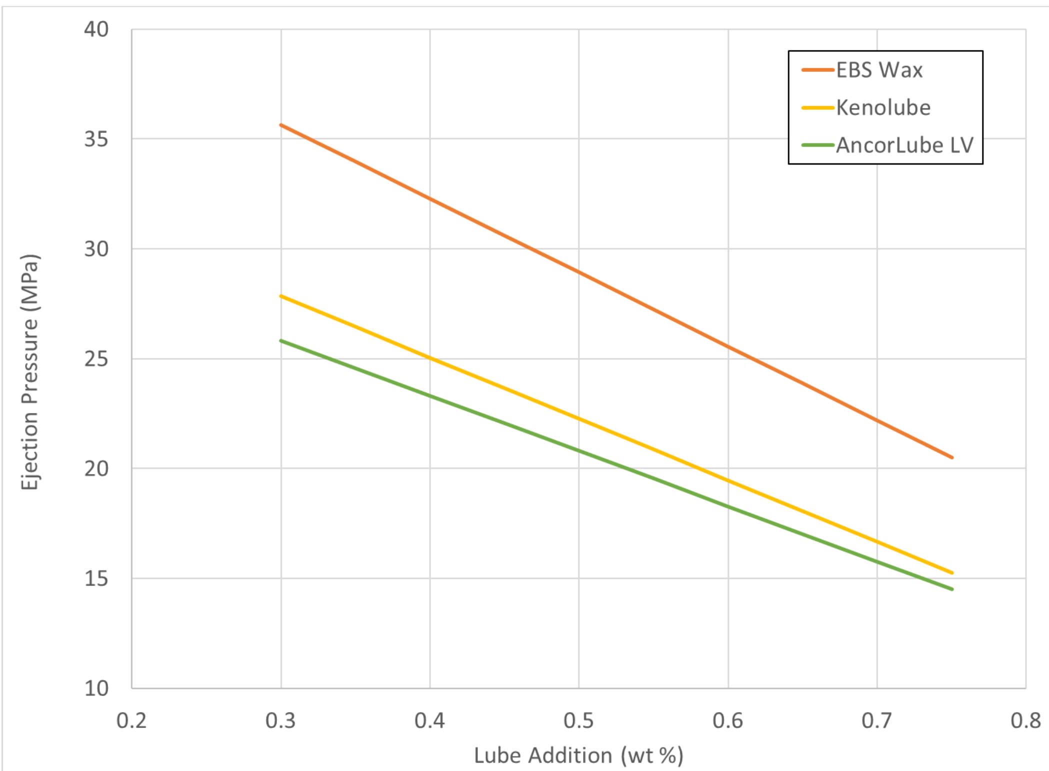

Figure 7: Best fit lines for ejection vs. lubricant addition at a die temperature of 60 °C

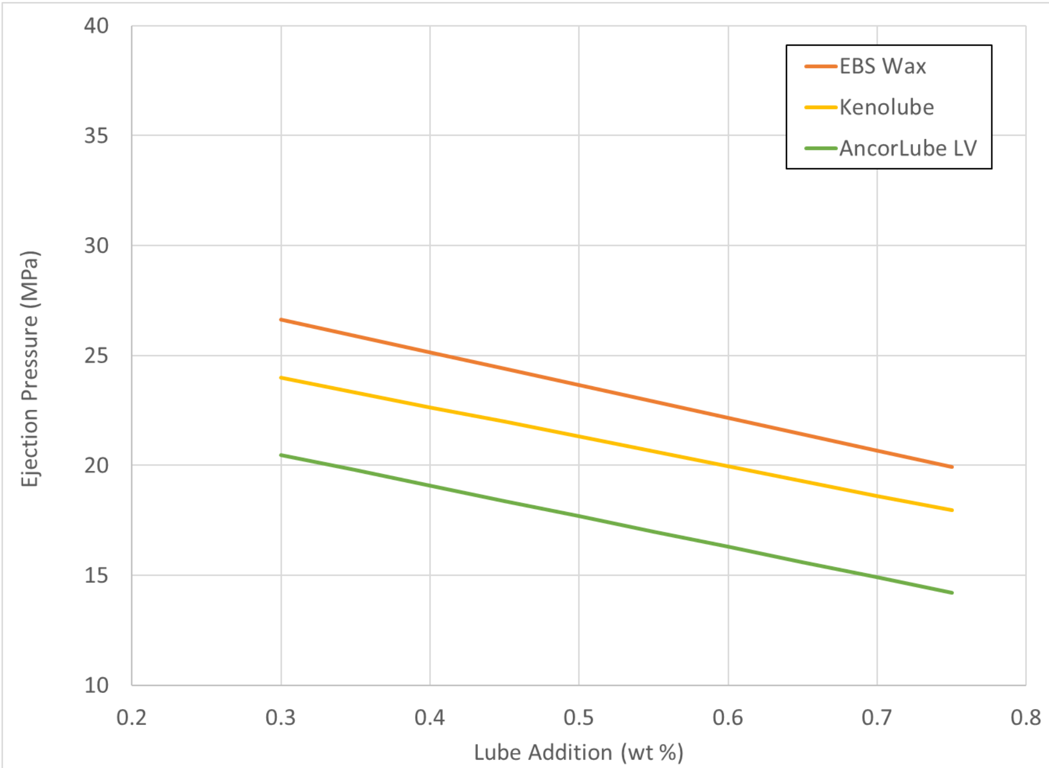

Figure 8: Best fit lines for ejection vs. lubricant addition at a die temperature of 80 °C

Table I: Comparison of estimated lubricant content needed to achieve ejection pressure of 20 MPa

Lubricant	Needed addition with 60 °C Die (wt %)	Needed addition with 80 °C Die (wt %)
EBS Wax	0.77	0.75
Kenolube	0.58	0.60
AncorLube LV	0.53	0.33

Using this methodology, it becomes easy to then compare the amount of lubricant need to achieve similar part ejection at each die temperature. A summary is presented in Table I, showing the amount of each lubricant needed to lower the ejection force to 20 MPa. At both die temperatures, this corresponded well to an EBS wax addition of approximately 0.75%, which is a typical premix addition in the PM industry for this lubricant. Qualitatively, it is widely believed that an addition of approximately 0.60% Kenolube can achieve similar lubricant performance, which is why this is also a very common premix addition in the PM industry. Good correlation was confirmed in a quantitative manner using this experimental method, as approximately 0.75% EBS wax and 0.60% Kenolube were found to be needed to lower the ejection force to 20 MPa at each die temperature. With a die temperature of 60 °C, the AncorLube LV is estimated to achieve similar ejection behavior with a lower addition of 0.53%. With a die heated slightly hotter to 80 °C into the “ideal” range for AncorLube LV, it was found that the lubricant addition can be reduced to approximately 0.33% for the AncorLube LV, while the EBS Wax and Kenolube additions required remained largely unchanged from 60 °C.

This finding is positive for several reasons. The AncorLube LV lubricant not only functions well at a "standard" die temperature, but also shows optimal performance at higher die temperatures that are commonly seen with more difficult-to-compact parts. Also, the fact that the lubricant can be used at lower additions allows for higher green density compaction, which is also commonly paired with die heating to lower the yield strength of the iron. Lower lubricant content can also lead to reduced premix cost, increased green strength, and improved burn-out upon sintering.

Results and Discussion – Production Data

Based on the completed laboratory ejection study, it was believed that 0.45% and 0.55% AncorLube LV additions were more than sufficient to provide equivalent lubrication to the incumbent lubricant system, containing 0.75% standard PM lubricant. Therefore, large-scale premixes using both AncorLube LV additions were produced to be compared to an existing commercial premix.

Initial trials utilized the sample premix containing 0.55% AncorLube LV and showed no difference in green springback on the outer diameter, hub outer diameter, minor inner diameter, or c-bore. The overall green density distribution was also similar when compared to parts produced with the premix containing the standard production lubricant. The density distribution in the parts produced with 0.75% production lubricant and 0.55% AncorLube LV is presented in Table II, with five different sections of the part compared with each lubricant type.

Table II: Green density distribution observed in production premix and 0.55% AncorLube LV premix

Green Density (g/cm^3)	Production (0.75% Lubricant)		Sample (0.55% AncorLube LV)	
	Front	Back	Front	Back
Section 1	6.754	6.842	6.799	6.846
Section 2	6.546	6.553	6.650	6.633
Section 3	7.052	7.043	7.097	7.097
Section 4	6.971	6.943	6.880	6.889
Section 5	7.018	7.022	6.975	6.982

Using the standard production premix and the sample with 0.55% AncorLube LV, good process capability control for weight and OAL were achieved. Capability analyses for weight and OAL are shown in Figures 9 and 10, respectively. For both weight and OAL, Cpk values between 1.35 and 1.50 were achieved with each premix using a sample size of ~200 parts taken randomly throughout the production run. The sample utilizing the 0.45% AncorLube LV was also run through production settings with good results, but the sample size was too small to be included in this analysis. With this sample, it was observed that necessary press compaction tonnage was reduced slightly, and the standard deviation part-to-part was improved by 10%. The weight and OAL were found to be within acceptable levels for the 0.45% AncorLube LV sample as well. The press was not capable of measuring ejection forces on these parts, but no significant part scoring or differences in surface finish were observed when comparing the three sets of compacted green parts.

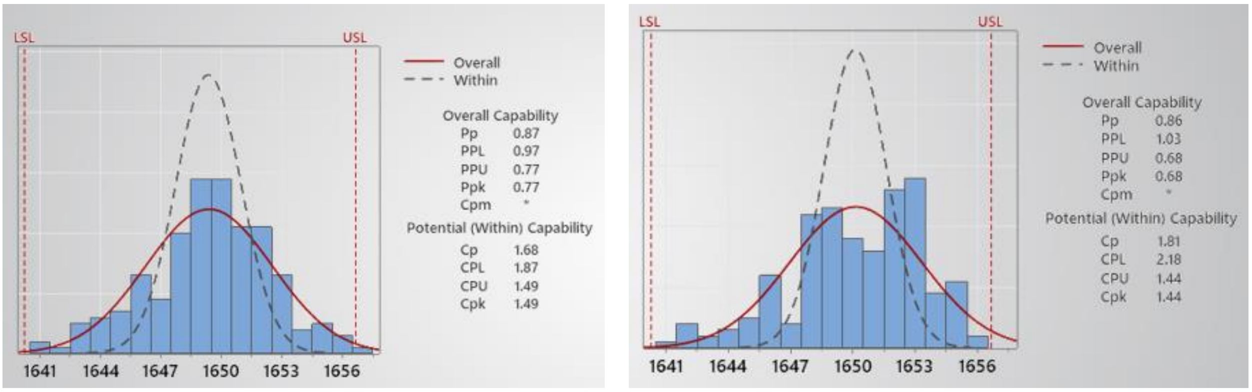

Figure 9: Process capability for weight on production (left) and 0.55% AncorLube LV sample (right)

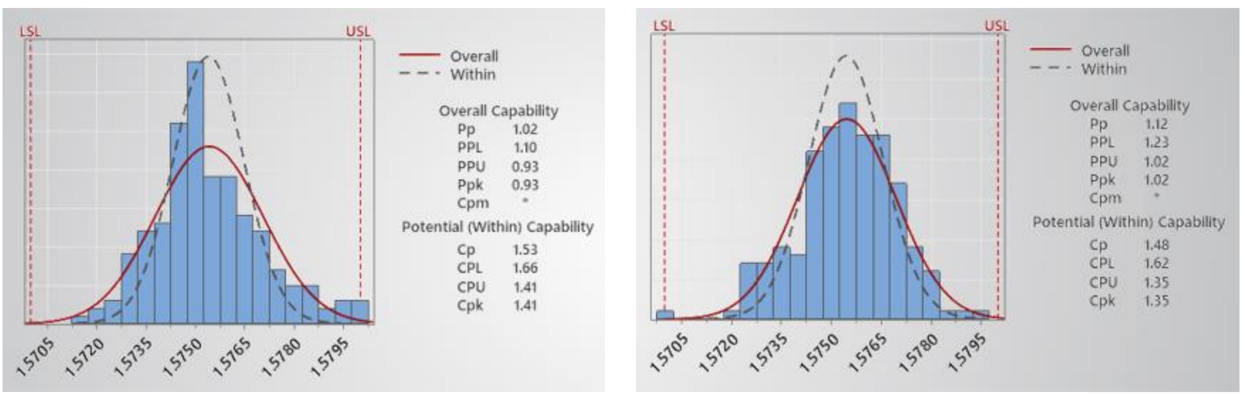

Figure 10: Process capability for OAL on production (left) and 0.55% AncorLube LV sample (right)

After completing successful compaction studies on each premix, parts were sintered in large runs in a continuous belt furnace to observe any sooting behavior, as well as the final sintered part surface finish. The production premix has a known history of sooting, leaving black residue on the furnace belt over time. Because the AncorLube LV premix is metallic stearate free and was shown in previous studies to exhibit excellent burn-out behavior in TGA, no sooting was expected with this lubricant. As expected, the parts compacted with the production lubricant exhibited typical heavy sooting and spotting, while the parts produced with both samples containing AncorLube LV had a clean surface finish, as shown in Figure 11.

Figure 11: Sintered surface finish on standard production (left) and 0.55% AncorLube LV sample (right)

In addition to those benefits outlined above, some further premix improvements were also realized through conversion to the AncorLube LV. Though the AncorLube LV is metallic stearate free and generally exhibits lower apparent density than alternatives such as zinc stearate or Kenolube, these samples displayed similar lubricity at a lower addition, allowing for a reasonable premix apparent density and powder flow with no significant shift from the production material. A general increase in green strength of 25% or more was observed, increasing further as the parts were compacted at higher temperature. This correlates well with laboratory observations, where green strength improvements of 50% or greater were measured when compacting AncorLube LV at a die temperature of 80 °C and comparing to an equivalent premix containing EBS wax.

The ability to reduce lubricant content offers several benefits including lower pore free density and the capacity to achieve higher green density parts. Lower lubricant content with no metallic stearate present leads to fewer issues with lubricant burn-off in the sintering furnace, lower emissions, and a substantially reduced environmental effect. Finally, utilizing a lower lubricant addition results in the potential for cost savings as the entire portfolio of standard PM lubricants continues to become more expensive.

Conclusions

As a result of the experimental work performed during this study, the following observations were made:

- The newly developed AncorLube LV lubricant is found to have superior lubricity and lower ejection forces when compared to industry standard lubricants, EBS wax and Kenolube. The difference becomes more drastic with a die temperature increase to 80 °C, where the AncorLube LV operates in its ideal range.
- Using estimates based on laboratory ejection data, it is estimated that 0.75% EBS wax is approximately equivalent to 0.60% Kenolube at both die temperatures tested. These typical PM lubricants can be replaced by approximately 0.53% AncorLube LV at a die temperature of 60 °C and by 0.33% AncorLube LV at a die temperature of 80 °C to achieve equivalent ejection behavior.
- Large PM sprockets were produced successfully using production-sized premix samples containing AncorLube LV with significantly reduced lubricant content compared to the commercial alternative. No significant difference in springback, green density, weight stability, overall length, or part surface finish was observed.
- The use of lower lubricant content and removal of metallic stearates resulted in a significant reduction in sooting and staining observed on the furnace belt and final sintered parts. Additional benefits over standard production material included increased green strength, improved de-lubrication, and potential for higher density compaction if needed.

Acknowledgements

The authors want to thank Edwin Schnaider, Jason Gotta, and Eric Alesczyk for all their contributions to this manuscript. Without their help, this degree and quality of analysis would not be possible.

References

1. H. Rodrigues, S. Madill, M. Folliard, T. Liu, “Optimizing Compacting Lubricant Selection – A Comparison Study of Various Commercially Available Lubricants”, *Proceedings of the 2008 World Congress on Powder Metallurgy & Particulate Materials*, Washington, D.C., June 8–12, 2008.
2. N. Solimanjad and M. Larsson, “Tribological Properties of Lubricants Used in PM Process”, Hoganas AB, pp. 1-10.
3. C. Schade, M. Marucci, F. Hanejko, “Improved Powder Performance Through Binder Treatment of Premixes”, *Proceedings of the 2011 International Conference on Powder Metallurgy & Particulate Materials*, San Francisco, California, May 18–21, 2011.
4. P. Lemieux, S. Pelletier, P.E. Mongeon, Y. Thomas, L.P. Lefebrvre, F. Chagnon, “A New Approach to Die Wall Lubrication for P/M Applications”, *Proceedings of the 2001 International Conference on Powder Metallurgy & Particulate Materials*, New Orleans, Louisiana, May 13–17, 2001.
5. D. Toledo dos Santos, M. Zadra, L. Girardini, P. Albonetti, S. Bordin, A. Molinari, “Influence of Die Wall Lubrication on Tensile Properties of High Temperature Sintered and Sinterhardened Low Alloy Steel”, *Powder Metallurgy,* Vol. 63, No. 4, pp. 268-276, 2020.
6. K. McQuaig, L. Wimbert, B. Lindsley, N. Kraus, “Development of Advanced Lubricants for New PM Applications”, *Proceedings of the PowderMet 2022 Conference*, Portland, Oregon, June, 2022.
7. T. Kawano, T. Ono, Y. Ozaki, “Analysis of Dewaxing Behavior of Iron Powder Compacts Based on a Direct Observation of Decomposing Lubricant During Sintering in a Furnace”, JFE Technical Report, No. 16, March 2011.
8. D. Saha and D. Apelian, “Control Strategy for the De-lubrication of P/M Compacts”, *International Journal of Powder Metallurgy,* Vol. 38, No. 3, pp. 71-79, 2002.
9. M. Larsson, M. Ramstedt, “Lubricants for Compaction of PM Components”, *Proceedings of the 2003 International Conference on Powder Metallurgy & Particulate Materials*, Sao Paulo, Brazil, 2003.
10. P. Sokolowski and C. Schade, “Engineered Lubricant System for Demanding Applications”, *Proceedings of the 2015 International Conference on Powder Metallurgy & Particulate Materials*, San Francisco, California, May 17–20, 2015.
11. K. McQuaig, C. Schade, P. Sokolowski, “Development of a Lubricant System for Improved Performance of Premixes”, *Proceedings of the 2013 International Conference on Powder Metallurgy & Particulate Materials*, Chicago, Illinois, June 24–27, 2013.
12. S. St-Laurent, Y. Thomas, L. Azzi, “High Performance Lubricants for Demanding PM Applications”, *Advances in Powder Metallurgy and Particulate Materials,* Vol. 1, Part 3, pp. 1-13, 2006.
13. A. Neilan, R. Warzel, P. Knutsson, A. Ahlin, “High Performance Lubricant for Warm Die Compaction”, *Proceedings of the PowderMet 2015 Conference,* San Diego, California, May 20, 2015.
14. F. Hanejko, “Single Press/Single Sinter Solutions to High Density”, *Powder Metallurgy,* Vol. 53, No. 2, pp. 100-103, 2010.

15. F. Hanejko, "Warm Die Compaction with Reduced Lubricant Levels Promoting Higher Green and Sintered Densities", *Proceedings of the APMA 2015 3rd International Conference on Powder Metallurgy,* Kyoto, Japan, November 8-10, 2015.
16. S. Turenne, C. Godere, Y. Thomas, "Effect of Temperature on the Behaviour of Lubricants During Powder Compaction", *Powder Metallurgy,* Vol. 43, pp. 139-142, 2000.