Novel High Performance Lubricants for

Conventional and High-Density Compaction

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ABSTRACT

Lubricants play an important role in the manufacturing of powder metallurgy components. This is even truer nowadays as some parts manufactured using the PM route become more complex, taller or require higher densities to be achieved. Due to increased concerns about the environmental impacts of many industrial processes as well as other more practical considerations (parts appearance, compressibility, shelf-life of metal powders) there is a pressure to find alternatives to traditional lubricants. Such alternative lubricants must provide excellent lubrication, clean burn-off, good flow properties and should not extensively limit the compressibility.

Eight potential alternative lubricants were tested for their ejection properties, compressibility, flow behaviour and their impact on the mechanical properties. The novel formulations were tested against a Kenolube benchmark. It was found that one proprietary formulation, developed by RTMP, offers compressibility similar to Kenolube while maintaining better ejection performance. Furthermore, the flow of the powder mix and its die-fill performance are comparable to Kenolube when flowing agents are properly added to the mix. Although some impact has been measured on the sintered properties, it is believed that this impact is limited and could perhaps be mitigated with further research work. This formulation appears to answer many of the requirements that a high performance lubricant should be able to fulfill.

INTRODUCTION

In the compaction of powder metallurgy components, lubricants are required to reduce both the internal friction (particle to particle) and the external friction (particles to die wall). The usage of a lubricant in the press and sinter process is a double-edged sword as it is necessary to ease both the compaction and the ejection of the part. Yet, lubricants have little use once the part has been ejected out of the die. Excess lubricant on the surface of the green part can cause metal dust or leftover powder to stick to the surface.

Such particles could later sinter on the part, creating a surface defect that could potentially lead to the part being rejected. Improper lubricant or excess lubricant could negatively impact the sintered properties by creating larger than desirable porosities within the sintered part. This could contribute to lower sintered mechanical properties. [1] Furthermore, lubricants can cause stains to appear on the sintered parts if the lubricant burn-off was not carried out properly or if the lubricant, by its inherent composition, has the tendency to stain the parts.

Reflecting this important role is the amount of research conducted on finding innovative lubricants. RTMP has devoted much effort in this field, as demonstrated by several papers presented at international conferences.[2, 3, 4] Latest efforts have been concentrated on finding fatty-acid based lubricants which are free of zinc stearates. As a matter of fact, lubricants containing zinc stearates, albeit their excellent flow properties, are slowly being phased out mainly due to the deposition of zinc oxide in sintering furnaces and adverse environmental impacts through furnace exhaust fumes. [5, 6]

An ideal lubricant would consequently offer good die-wall lubrication at the lowest possible concentrations. It would furthermore be malleable enough at the targeted compaction temperature such that it does not extensively limit the compressibility of the powder mix. Other key characteristics should include: rapid and even flow, good die-filling performance, excellent surface finish, high green and sintered strength and easy admixing to a raw powder feedstock.

As research progresses on all these fronts, it appears very difficult to reach all of these goals through the usage of a single chemical compound. High performance lubricants are bound to become increasingly more complex and probably tailor-made to target a given application's key characteristics. Consequently, some formulations presented herein are derivatives of other lubricants developed by RTMP mainly to achieve higher green densities. [4] It has been suggested that some of these lubricants could perhaps be combined with other waxes, such as EBS wax, to obtain formulations which favours low ejection forces.

This paper presents some of the work that has been conducted on innovative lubricant formulations developed by RTMP. The lubricants were evaluated on a test rig which can reproduce industrial compaction conditions. Complementary to these tests, other key characteristics such as apparent density, sintered properties, flow and die-filling behaviour were evaluated.

EXPERIMENTAL PROCEDURE

ATOMET 1001HP, a water-atomised steel powder manufactured by Rio Tinto Metal Powders was used in all mixes presented in this study. The powder was admixed with 1.8%Cu, 0.7% natural graphite and 0.7% of the lubrication system to be characterised. A mix containing 0.7% by weight of Kenolube P11, a widely used lubricant in the PM industry, manufactured by Höganäs AB was used as a reference. Mixes tested are described in Table 1. All lubricant combinations are proprietary formulations designed by RTMP. PR-1 is a formulation aimed at providing low ejection forces while lubricant HD-C and the combination of HD-C and HD-A were designed as high-density lubricants.

The apparent density was measured using the Hall flow apparatus as described in MPIF Standard 4. [7] The flow rate was evaluated with the same apparatus following guidelines specified in MPIF Standard 3. [7] Compaction and ejection behaviour was evaluated on a 150 t Gasbarre mechanical press, which is equipped with strain gauges to constantly monitor the forces on the top and bottom punch. This equipment is available at the National Research Council, Boucherville (Canada). Rings were pressed in a tungsten carbide die, 25.4 mm (1.0 in) across with a core pin of 14.2 mm (0.6 in) in diameter. For this experiment, rings of 12.7 mm (0.5 in) high were compacted at a stroke rate of five parts per minute. The M/Q ratio of the test part, defined as the lateral area over compacted area [5], was 4.54. In comparison,

standard TRS bars have a M/Q ratio of about 1.4. This confirms that the test parts are much harder to eject than small compacts. Compaction was performed at four pressures, namely about 485, 620, 715 and 825 MPa (35, 45, 52 and 60 tsi) with the cold compaction and warm die compaction techniques. Cold compaction was performed in a non-heated, non-cooled die (room temperature) while the die was heated to 60°C for the warm compaction technique. [5] In all cases, the powder was not heated prior to compaction.

Table 1: Mixes tested in this study.

Mix	Group	Base Powder	Lubricant 1	Lubricant 2	Lubricant 3	Total Lubricants (%)
1			HD-A (0.25%)	HD-C (0.25%)	EBS (0.20%)	0.7
2	1		HD-A (0.21%)	HD-C (0.21%)	EBS (0.28%)	0.7
3			HD-A (0.14%)	HD-C (0.14%)	EBS (0.42%)	0.7
4		AT-1001HP Lot 361820	HD-A (0.10%)	HD-C (0.10%)	EBS (0.50%)	0.7
5			HD-A (0.35%)	HD-C (0.35%)	-	0.7
6	2		HD-A (0.49%)	HD-C (0.21%)	-	0.7
7			HD-C (0.17%)	EBS (0.53%)	-	0.7
8			PR-1 (0.7%)	-	-	0.7
KEN	Both		Kenolube P11	-	-	0.7

The characterisation of the different lubricant formulations was done with the intent to duplicate industrial conditions. Through different tests over time, it was determined that the shear rate (dependant on the compaction rate) at which parts are pressed has a great influence on the behaviour of the lubricants. Consequently, the parts that were compacted for this study have a high M/Q ratio and are also compacted at high stroke rates.   The die material, WC-Co, was also selected due to its wide use amongst parts manufacturers.
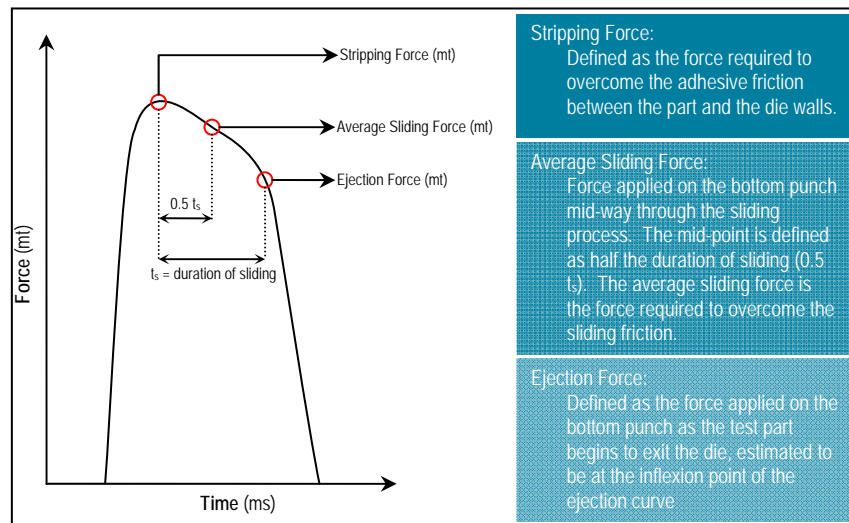

Figure 1. Typical ejection curve with associated key ejection data obtained from the curve.

The press monitoring software outputs a compaction curve and an ejection curve. The ejection curve shows the force applied on the bottom punch as the test part is ejected in function of the elapsed time. As the press is running a sequence of test parts, each ejection curve is recorded and later transferred to a second software which extracts key data from the curve. Figure 1 shows a typical ejection curve and details how each the different key ejection characteristics are derived from the ejection curve. Each test

part ejected provides as much as four key ejection characteristics: stripping force, average sliding force, ejection force and maximum force (more often than not equal to the stripping force). A more detailed explanation of the ejection process can be found in German (2005). [8]

The recorded forces were adjusted to take into account the variation in the parts height. Equation 1 was used to transform the recorded forces (stripping, average sliding and ejection forces) into shear stress.

$$\tau = \frac{F}{\pi h (d_o + d_i)}$$ (1)

In equation 1, d_o represents the outer diameter (in this case, 25.4 mm or 1 inch) and d_i the core pin diameter of 14.2 mm (0.56 in). This procedure ensures that the reported data accounts for small changes in the parts height, which would affect the required forces to complete the ejection of a part. For the sake of simplicity, in this article, the different shear stresses are referred to as forces.

The die-fill performance was measured using an in-house test rig which is composed of die cavities of varying volume. The apparatus is composed of a flat table on which a feed shoe slides at a speed of 8 cm s^{-1} (3.15 in s^{-1}). The shoe fills rectangular shaped cavities that become gradually narrower as the shoe proceeds toward the end of its course. The table has six cavities of 3, 4, 5, 6, 10 and 18 cm^3 (0.183, 0.244, 0.305, 0.366, 0.610 and 1.098 in^3). After each test, the powder in the cavities is taken out and weighed. The test is repeated 10 times for each powder mix.

Sintered properties were measured on standard TRS specimens according to MPIF Standard 41 [7]. The test bars were sintered in a furnace under a 90% N_2 / 10% H_2 atmosphere for 25 minutes at the temperature of 1120°C (2048°F). Green properties were also measured on TRS specimens.

RESULTS AND DISCUSSION

Group 1 – Physical Properties and Compaction/Ejection Behaviour

The lubricants in group 1 are derivatives of high density lubricants HD-A and HD-C combined with EBS wax as shown in Table 1. Table 2 shows the apparent density and flow rates for mixes containing these lubricants. As the concentration of HD-A and HD-C lubricants is decreased, the apparent density increases. The flow rate is not affected by the varying concentration of EBS wax, with values in the vicinity of 32 s $50g^{-1}$. Apparent density is much lower for all these lubricants when compared to the Kenolube reference. The reference has a much better flow than all the group 1 lubricants. This is most likely due to the presence of metallic stearates in the Kenolube reference. It is common knowledge that metallic stearates help to improve flow properties in steel powder mixes [8].

Table 2: Flow rate and apparent density data for group 1 lubricants.

	MIX 1	MIX 2	MIX 3	MIX 4	KEN
Apparent Density (g cm^{-3})	2.87	2.88	2.91	2.92	3.31
Flow Rate (s $50g^{-1}$)	32.5	32.0	31.7	32.4	28.7

There is a significant difference in the compressibility of some of the group 1 lubricants when compared to the Kenolube reference. Most group 1 lubricants, namely mixes 1, 2 and 3 show a lower

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compressibility at room temperature than the reference. At 60°C, all group 1 lubricants are either as compressible as Kenolube or slightly better than the reference.
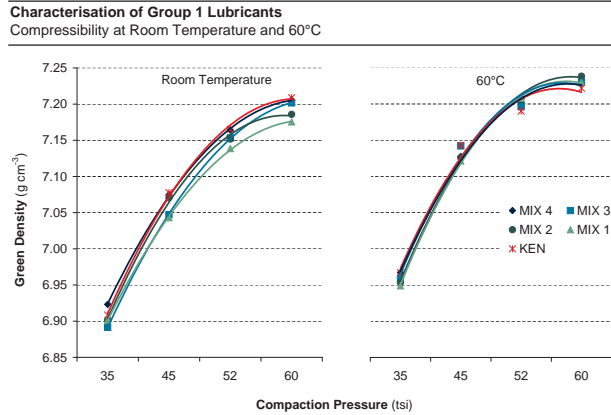
Characterisation of Group 1 Lubricants
Compressibility at Room Temperature and 60°C

Characterisation of Group 1 Lubricants
Stripping Forces at Room Temperature and 60°C

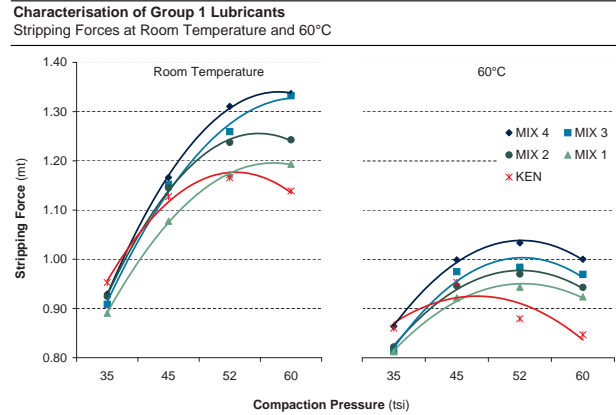**Figure 2.** Green density achieved at compaction pressures of 35, 45, 52 and 60 tsi, room temperature and 60°C.

Figure 3. Stripping forces measured at compaction pressures of 35, 45, 52 and 60 tsi, room temperature and 60°C.

In terms of ejection properties, group 1 lubricants are generally harder to eject than the Kenolube reference. This is shown in Figure 3 through Figure 5. Mix 1 is the lubricant that has the closest performance to Kenolube. Figure 3 shows the stripping forces required to initiate the ejection cycle at various compaction pressures. For both compaction temperatures, results are comparable to Kenolube at lower compaction pressures but higher stripping forces are required at compaction pressures of 52 and 60 tsi. The same conclusion can be drawn for sliding and ejection forces which are shown in Figure 4 and Figure 5. There is a strong dependency of the concentration of EBS wax on the ejection performance. Indeed, at both die temperatures, higher stripping, average sliding and ejection forces are required to eject the part when the EBS wax concentration is increased.
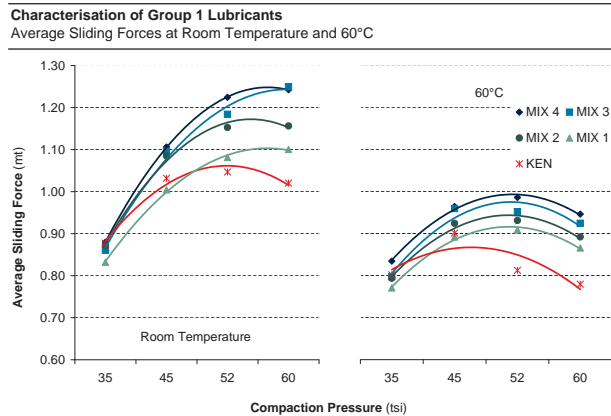
Characterisation of Group 1 Lubricants
Average Sliding Forces at Room Temperature and 60°C

Characterisation of Group 1 Lubricants
Ejection Forces at Room Temperature and 60°C

Figure 4. Average sliding forces measured at compaction pressures of 35, 45, 52 and 60 tsi, room temperature and 60°C.
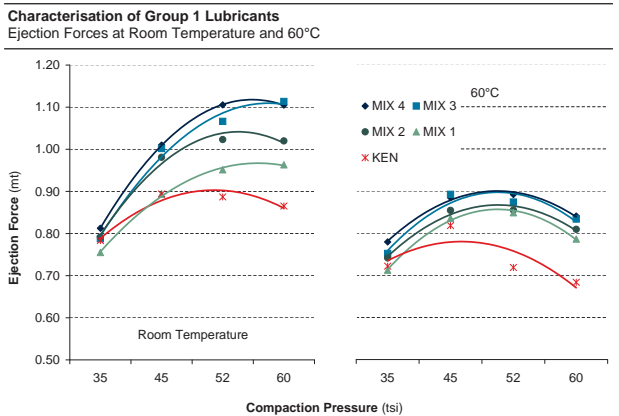
Figure 5. Ejection forces measured at compaction pressures of 35, 45, 52 and 60 tsi, room temperature and 60°C.

Group 2 – Physical Properties and Compaction / Ejection Behaviour

The group 2 lubricants are other formulations which either do not contain EBS wax or contain no HD-A lubricant. Mix 8 contains a proprietary lubricant developed by RTMP, which is a combination of different organic waxes. As for the mixes belonging to group 1, all mixes in group 2 have a relatively poor flow with values between 33.4 and 36.3 s 50 g^{-1}. Shown in Table 3 is the apparent density and flow

rate data. The Kenolube reference mix has a higher apparent density and a much better flow rate, again, most likely related to the presence of metallic stearates.

Table 3: Flow rate and apparent density data for group 2 lubricants.

	MIX 5	MIX 6	MIX 7	MIX 8	KEN
Apparent Density (g cm^{-3})	2.84	2.86	3.09	2.80	3.31
Flow Rate (s 50g^{-1})	34.0	34.7	36.3	33.4	28.7

The compressibility of the different formulations is shown in Figure 6. Contrary to group 1, which had different levels of high density lubricants, the final green densities obtained at the compaction pressures of 35, 45, 52 and 60 tsi are either lower or equal to the Kenolube reference. At room temperature, all group 2 lubricants but mix 7 perform as well as Kenolube. Using warm die compaction, mixes 7 and 8 have compressibility values slightly under the reference mix. However, the maximum green density reached at the compaction pressure of 60 tsi is nearly equal for all the lubricants.   Mix 5 is more compressible than the Kenolube mix over the entire compaction pressure range. This result was expected as mix 5 is composed in equal proportions of lubricants HD-A and HD-C. Lubricant HD-C was specifically developed for high density applications. Mix 6, which is also composed of the same lubricants – yet in different concentrations – is slightly less compressible than mix 5. This is an indication that the HD-C lubricant is capable of reaching higher densities than the HD-A lubricant.
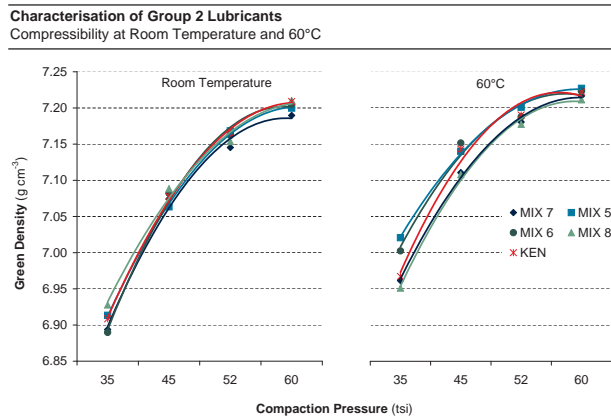

Figure 6. Green density achieved at compaction pressures of 35, 45, 52 and 60 tsi, room temperature and 60°C.
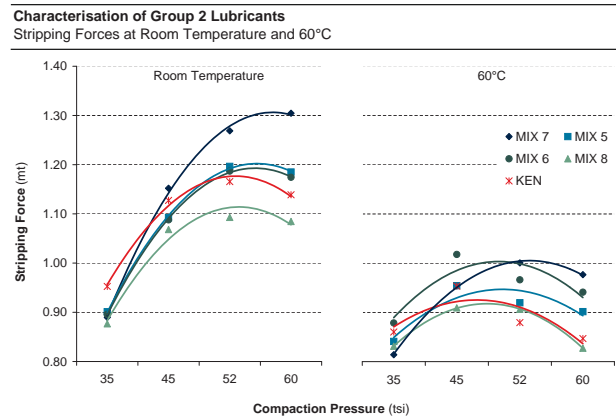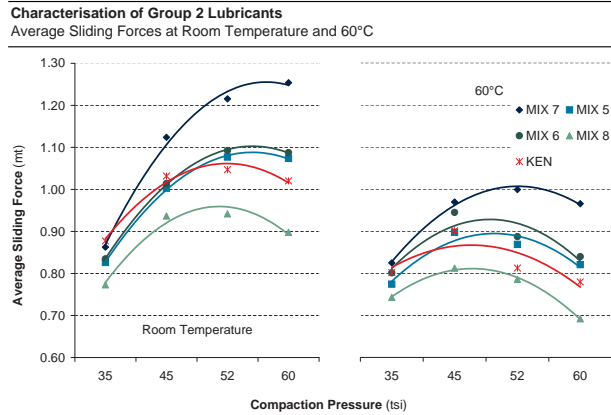

Figure 7. Stripping forces measured at compaction pressures of 35, 45, 52 and 60 tsi, room temperature and 60°C.

In terms of ejection performance, Figure 7 through Figure 9 clearly demonstrate that some lubricant formulations from group 2 have excellent behaviour. Figure 7 shows the stripping forces required to get the parts moving out of the die. Mix 7 offers the worst performance of group 2 with stripping forces above nearly all lubricants at compaction pressures of 52 and 60 tsi. This result is not surprising due to the high concentration of EBS wax and is in line with the results from the group 1 lubricants. Mix 6 has stripping forces about equal to Kenolube when the compaction is done at room temperature but requires more force with warm die compaction. Mix 5 has stripping forces very similar to those of Kenolube at both room temperature and 60°C. This shows that a higher amount of the lubricant HD-C is beneficial to the ejection process. It is only at compaction pressures of 52 and 60 tsi that Kenolube displays slightly lower stripping forces. However, the difference remains marginal. Mix 8 is easier to strip out of the die than the Kenolube reference at room temperature and is about equal to Kenolube at 60°C.

Roughly the same conclusions can be drawn based on Figure 8 and Figure 9 for the average sliding forces and ejection forces. Mix 7 – which contains a higher EBS wax concentration – showed the highest

ejection forces. Mixes 5 and 6 posted similar results, with mix 5 showing slightly lower ejection forces at both compaction temperature. The performance of both mixes is also similar to that of Kenolube at room temperature and 60°C. The best performance is provided by mix 8 which has lower ejection forces under all compaction conditions. Furthermore, at higher compaction pressures mix 8 shows a pronounced decline in the ejection forces. This behaviour clearly indicates the superior lubrication provided by this proprietary formulation. In effect, the performance of mix 8 increases when compaction conditions become more severe.

Figure 8. Average sliding forces measured at compaction pressures of 35, 45, 52 and 60 tsi, room temperature and 60°C.
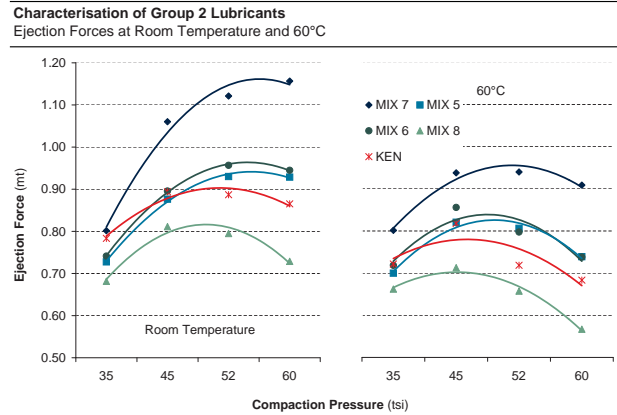

Figure 9. Ejection forces measured at compaction pressures of 35, 45, 52 and 60 tsi, room temperature and 60°C.

Die-Fill Performance

The flow rate is indeed an important characteristic of any powder mix and is evidently influenced by the lubricant contained in the said mix. Yet even more important is the actual die-fill performance which measures the packed density and the relative variance in weight in multiple cavities.
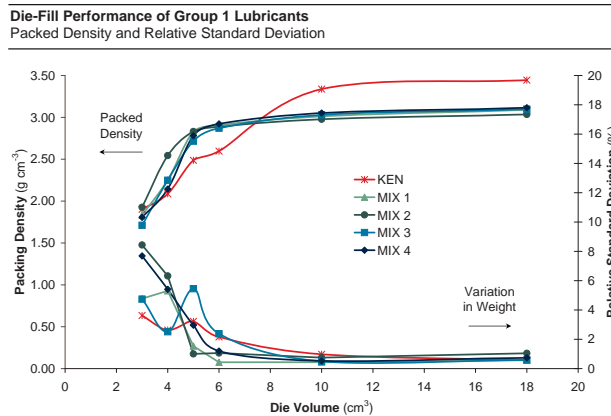

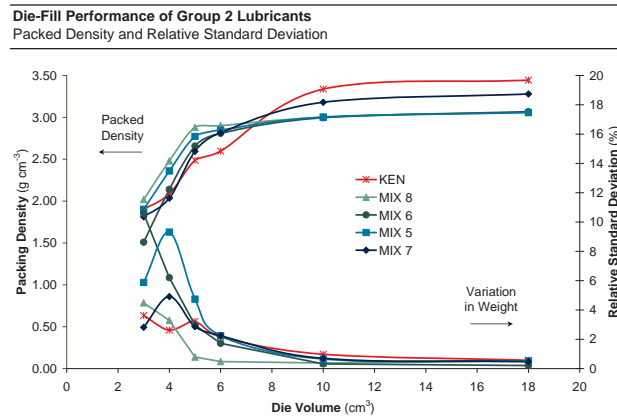**Figure 10.** Die-fill performance of group 1 lubricants.

Figure 11. Die-fill performance of group 2 lubricants.

Figure 10 shows the results obtained after completing 10 runs with each of group 1 lubricants on the die-fill test rig. The packed density obtained on the largest cavities, reported on the left-hand scale, is lower for all group 1 lubricants except Kenolube. This is due to the higher apparent density of the Kenolube reference mix, 3.31 g cm^{-3} against an average of 2.90 g cm^{-3} for the other group 1 lubricants. For all mixes, the packed density remains stable and later drops as the cavity volume decreases. However, it can be seen that the packed density begins to decrease at a much smaller die volume for mixes 1 through 4

compared to the Kenolube mix. In effect, the 5 cm^3 cavity has a packed density very close to the maximum packed density. For the Kenolube reference mix, the packed density of the 5 cm^3 cavity is about 25% lower. For all mixes, the variation between the different runs increases as the die volume decreases. However, the variation for smaller cavities is greater for the group 1 lubricants when compared to Kenolube. In effect, for Kenolube, the maximum relative standard deviation is 3.6% compared to about 5 to 8.5% for mixes 1 through 4. For mixes 1, 2 and 4, the relative standard deviation becomes equal or better than the reference mix for die volumes of 5 cm^3 and up.

Similar results are obtained for the lubricants of group 2. Again, the packed density reaches higher values for the Kenolube reference mix, due to the difference in the apparent density of the samples. Mixes 5, 6 and 8 have lower packed densities and mix 7 has a packed density between those of samples 5, 6 and 8 and Kenolube. This is in agreement with the apparent densities of the different mixes which average 2.83 g cm^{-3} for mixes 5, 6 and 8, 3.09 g cm^{-3} for mix 7 and 3.31 g cm^{-3} for Kenolube. The same phenomenon described for the group 1 lubricants is observed for mixes 5, 6 and 8, that is, the packed densities remained stable at all die cavities between 5 and 18 cm^3. In terms of relative standard deviation, mixes 5 and 6 offer the worst performance. The maximum relative standard deviation is around 10% for mix 6 (3 cm^3 die volume) compared to only 3.6% for the Kenolube reference and 4.5% for mix 8. At the 5 cm^3 cavity, all group 2 lubricants but mix 8, are on par with the Kenolube mix. Mix 8 has a better performance with its relative standard deviation reaching 0.8% at the 5 cm^3 opening compared to about 3.5% for the Kenolube mix.

Evaluation of Sintered Properties

The sintered properties were measured for all the lubricants of groups 1 and 2 as well as for the Kenolube reference mix. Presented in this section are the most relevant properties: transverse rupture strength (TRS), dimensional change from green size and apparent hardness. Figure 12 and Figure 13 show the various TRS values obtained from compacts pressed at room temperature and at different green densities. Kenolube offers the best TRS values across the entire density range and is only equalled by mix 7. The underlying causes for such results were not investigated. However, it is plausible to believe that the particle size distribution of the different lubricants might play a role in the different values recorded.
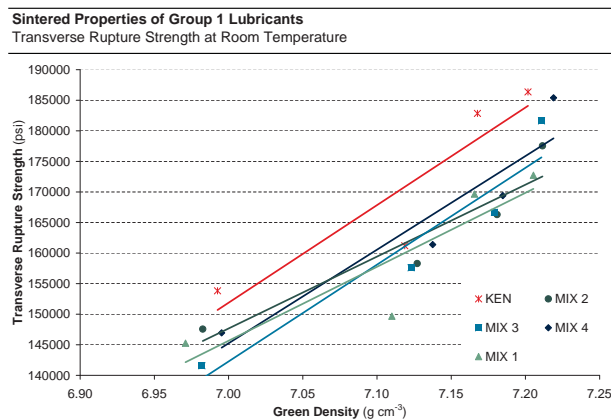

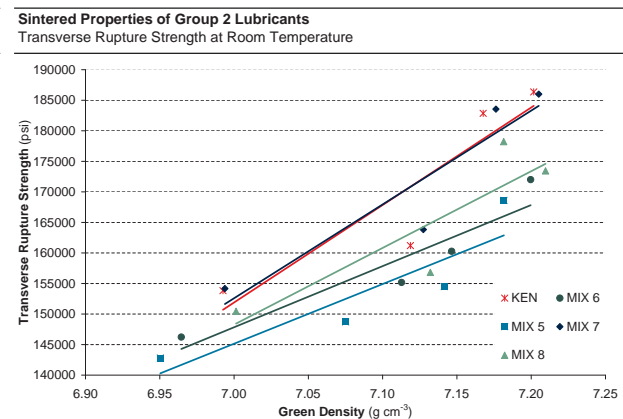**Figure 12.** TRS values for samples pressed at room temperature, group 1 lubricants.

Figure 13. TRS values for samples pressed at room temperature, group 2 lubricants.

Figure 14 and Figure 15 show the dimensional change from green size measured on compacts pressed at room temperature and at various green densities. The dimensional change response for all group 1 lubricants is very comparable, with values close to 0.20% at the low end of the density range to 0.25% for

higher densities. Kenolube limits the growth during sintering to 0.15% but this value remains almost constant at all densities investigated. Within group 2 lubricants, apart from Kenolube, only mix 7 has a stable response with a dimensional change of about 0.21% over the whole density range.
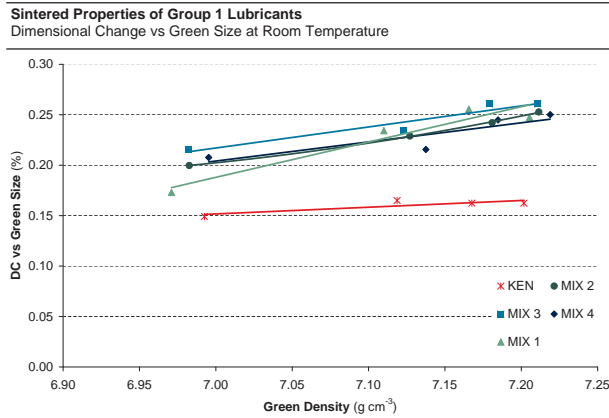
Sintered Properties of Group 1 Lubricants
Dimensional Change vs Green Size at Room Temperature

Sintered Properties of Group 2 Lubricants
Dimensional Change vs Green Size at Room Temperature

Figure 14. Dimensional change from green size for compacts pressed at room temperature, group 1 lubricants.
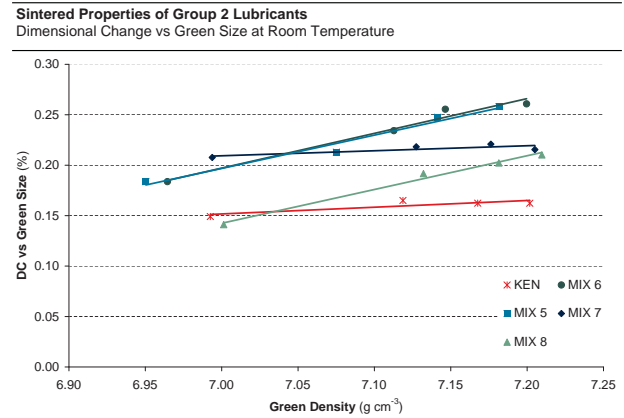
Figure 15. Dimensional change from green size for compacts pressed at room temperature, group 2 lubricants.

The other group 2 lubricants, mixes 5, 6 and 8 have seen an increase in dimensional change in function of the green density. Mix 8, however, shows a growth similar to Kenolube at the lower density tested but about 0.06% larger than Kenolube at the high end of the density range. Mixes 5 and 6 have a response very similar to the group 1 lubricants.
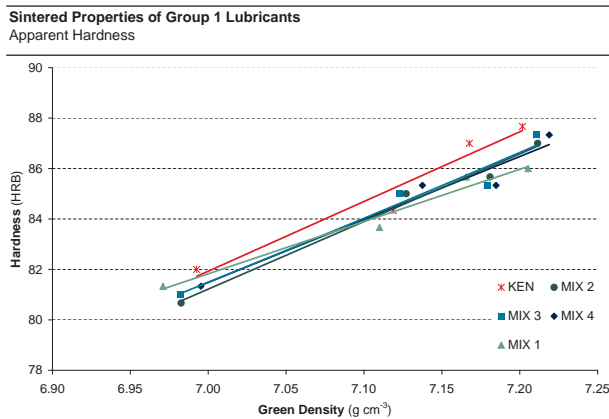
Sintered Properties of Group 1 Lubricants
Apparent Hardness

Sintered Properties of Group 2 Lubricants
Apparent Hardness

Figure 16. Apparent hardness data for samples pressed at room temperature, group 1 lubricants.
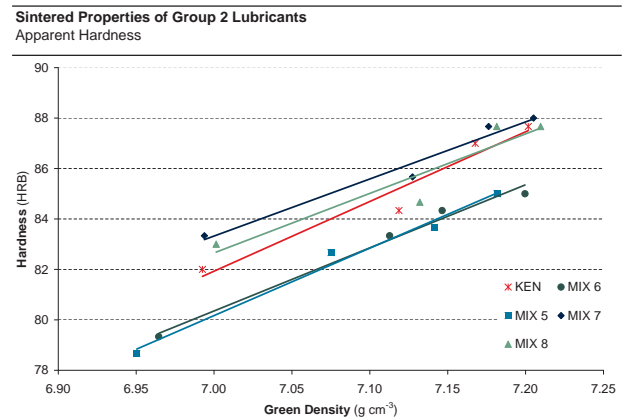
Figure 17. Apparent hardness data for samples pressed at room temperature, group 2 lubricants.

For all group 1 lubricants, the apparent hardness is similar to Kenolube at all the green densities tested. In effect, Figure 16 shows that the curves nearly overlap with perhaps a small difference of about 1 HRB in the high end of the density range. Figure 17 shows the same data for group 2 lubricants. In this case, mixes 7 and 8 are similar to Kenolube with a slightly higher apparent hardness at the low end of the density range but equal at green densities around 7.20 g cm^{-3}. Mixes 5 and 6 both have lower apparent hardness readings about 5 HRB below the other lubricants across the entire density range.

Enhancement of Flow Rate and Apparent Density of Mix 8

Throughout the different lubricant formulations tested, only the PR-1 lubricant has provided better ejection behaviour than the Kenolube reference. Indeed, this mix has a compressibility rating similar to the Kenolube reference mix both at room temperature and with warm die compaction. Furthermore, the ejection behaviour is excellent, with stripping, average sliding and ejection forces constantly lower than the forces obtained with Kenolube. However, as shown in Table 3, the apparent density and flow rate of mix 8 are far inferior to those of the reference mix. Even though the die-fill performance appears to be relatively good, there is a need to improve the flow behaviour so that it can approach the performance offered by the Kenolube.

In order to improve the flow properties and the apparent density, different sequences and methods of admixing a flow enhancer in the base powder were tested. Table 4 shows the data obtained after adding flow enhancer to the powder mix using four different methods. The results are compared to the initial method used for the preparation of mix 8.

Table 4: Flow rate and apparent density data obtained for mix 8 with different addition methods.

	MIX 8	METHOD A	METHOD B	METHOD C	METHOD D	KEN
Apparent Density ($g\ cm^{-3}$)	2.80	2.89	2.95	3.03	3.15	3.31
Flow Rate ($s\ 50g^{-1}$)	33.4	28.4	26.9	26.4	26.9	28.7

Each modification that was made to the addition technique has led to improvement in both the flow rate and the apparent density. The apparent density went from an initial 2.80 $g\ cm^{-3}$ to 3.15 $g\ cm^{-3}$, a 12.5% improvement. This increase in apparent density comes coupled with a significant improvement in the flow rate. With method A, the flow rate as improved to 28.4 $s\ 50g^{-1}$ from the base rate of 33.4 $s\ 50g^{-1}$. Other admixing techniques were also effective at improving the flow rate with the best performing method scoring 26.4 $s\ 50g^{-1}$. On a flow rate basis alone, the difference between methods B, C and D was not significant.

Figure 18 shows the die-fill performance of mix 8 and the other mixes in which flow enhancers were added following the four different methods. The maximum packed density obtained with the various admixing methods increases to reach the maximum value for method D. This is in direct relationship to the increased apparent densities obtained with the different methods, as demonstrated in Table 4. With all four methods tested, the flow rate is significantly improved which yields a much better filling performance. In effect, the packed density remains almost unchanged for the entire range of cavity volumes investigated.
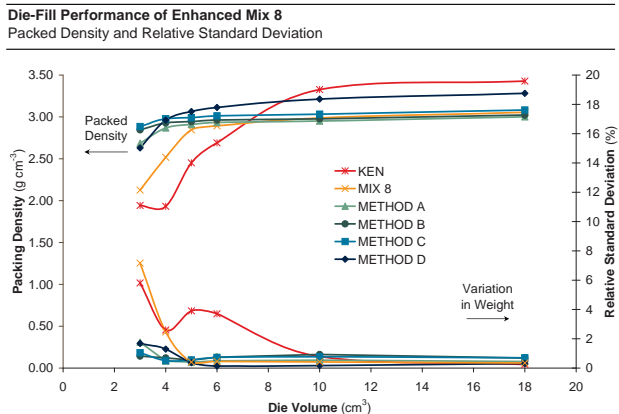
Figure 18. Improvement in die-fill performance of mix 8
compared to the Kenolube reference and to the original mix 8.

For methods A, B and C, the maximum packed density is obtained with the 4 cm^3 die cavity whereas with method D, this occurs with the 6 cm^3 die. On the other hand, the Kenolube mix can only reach its maximum packing factor with the 10 cm^3 die cavity. Furthermore, the relative standard deviation from the enhanced mixes is significantly lower. In effect, the largest relative standard deviation for all of these mixes is about 0.9% compared to 5.8% for the Kenolube mix and 7.2% for the original mix 8.

CONCLUSION

Novel lubricants are becoming more complex as the PM industry evolves. A good lubricant nowadays has to offer more than good ejection behaviour. It must also enable higher densities to be reached. Due to environmental constraints, the use of heavy metal stearates must be phased out, which creates additional limitations to overcome. Amid the race towards improved mechanical properties the PM industry is facing, the sintered strength must not be decreased through the use of an environmentally-friendly lubricant. The flowability must be maintained since it plays an important role in the part to part weight consistency as well as in the productivity of the press.

The challenge therefore lies in finding alternative lubricants which can perform as well – if not even better – than the traditional lubricants which have been used over the past decades. It has been demonstrated that some fatty-acid based lubricants can deliver such a performance. With the proper design characteristics in mind, some organic waxes can be used to deliver better ejection properties than Kenolube. This gain in the ejection performance is achievable with somewhat limited impact on the sintered properties. Combined with the adequate manufacturing technique for the lubricant or the metal powder mix, the flow properties can also be maintained.

The lubricant PR-1, used in mix 8, has demonstrated its superior ejection performance over Kenolube. Furthermore, this lubricant offers equal compressibility to Kenolube. Through the admixing of flowing agents, the lubricant also has superior die-filling behaviour. The flow rate of the powder mix is also superior to Kenolube which, in turn, can increase the part to part weight consistency and can help improve productivity. Such results are particularly significant due to the method through which they were obtained. In effect, the use of a large industrial press, which was equipped with strain gauges and capable to operate at shear rates not usually seen on laboratory equipment, is a definite advantage. Results obtained on such a large equipment can easily be reproduced under industrial conditions. Parts manufacturers should therefore expect to see similar improvements on their own production lines.

11

However, more research still has to be conducted on the potential effects of the lubricants presented in this study. It is required to gain a better understanding of the mechanisms that affect the transverse rupture strength and the dimensional change. It is also necessary to complete some development work in flow behaviour of these new lubricants to verify how the addition method of the flow enhancer will affect the ejection performance. Complementary to these tests, the part to part weight consistency will be evaluated. Furthermore, the hygroscopicity of these novel lubricants was not investigated and will require some more research in the upcoming future.

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