Advanced Lubricants for Modern PM Applications

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Abstract

Most mechanical properties of powder metallurgical (PM) components significantly depend on the part's density. Considering the higher complexity of modern PM parts and the demand for higher strength with less weight, increased green and sintered densities are required. The development of new advanced lubricants is one key factor for this, providing additives with superior lubricity, clean burn-off and unsophisticated usability. This contribution documents recent developments in lubricant technology with experimental results from lab scale to serial production. The presented lubricant solutions allow powder compaction to higher density levels using lower lubricant additions without the need for heated tooling into a tight temperature range. Especially for complex shaped parts, the broader temperature range helps to keep the lubrication sufficient for tool sections with higher friction, resulting in ejection pressures less than 50% of the values seen for amide waxes.

Main text

Introduction

At first glance, lubricants in PM powders seem to be only one minor additive, which are completely removed in the final PM component. In reality, increasing density levels in combination with more complex part geometries require a very well-considered choice of the optimal amount and type of lubricant. In this context, the requirements for an optimal lubricant might differ depending on the process step the user is concentrating on. While a powder manufacturer might consider the blending behavior and the required powder processing most important, the parts producer will focus more on lubricity and burn-off. Figure 1 gives an overview of lubricant properties that must be considered during the material design process and might be of different importance depending on the chosen production process.

Figure 1: *Key properties of modern PM lubricants.*

It is obvious that the optimization of all listed key properties is not always possible and so the effective lubrication during the compaction process remains one of the most important requirements. With improved lubrication behavior, it is possible to reduce the amount of lubricant significantly. Considering a given material composition, the reduction of the lubricant is often the only possible way to achieve higher compaction densities and, by this, improve part properties like hardness or strength [1-5]. The theoretical (pore free) density of a blended material for this diagram can be calculated using the equation:

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$$\rho = \left(\sum_i \frac{c_i}{\rho_i} \right)^{-1}$$

In this equation, c_i are the weight concentrations of the ingredients and ρ_i are their respective densities. 100% density can be only achieved in the tool, whereas the density after ejection of the part cannot be more than 98-98.5% due to spring back [6].
This contribution will present new developments in the PM lubricant technology and will introduce a new additive designed for good lubricity over a wider compaction temperature range. This new lubricant, named AncorLube LV, was tested in lab and serial production environment for several key properties.

Lubricant Characterization

Before a new lubricant can be used in serial production, comprehensive lab testing is an essential part of the development process. As mentioned above, the test program has to cover a multitude of different key properties to ensure a smooth integration in all related serial production processes. Nevertheless, a good lubricity remains one of the key properties to be optimized.
A well-established method to quantify the lubricity of PM powders is to equip a compaction press with load cells on each tool component and detect the resulting pressures on each tool part during the compaction cycle. The press used for the initial design process in this investigation was an internally built six-ton one-way press which is shown in figure 2 on the left. The compacts used for the tests were bushings with 14.3 mm outer and 9.0 mm inner diameter. The heights of the compacts were adjusted to achieve different M/Q-ratios (lateral area divided by compacted area), which is measured for the friction in relation to the applied pressure. Typical resulting pressure curves for one-sided compaction are given in figure 2 on the right. The blue curve shows the resulting pressures on the lower punch of the tool. The values should be as high as possible during compaction (indicating effective lubrication) and as low as possible during the ejection of the part.

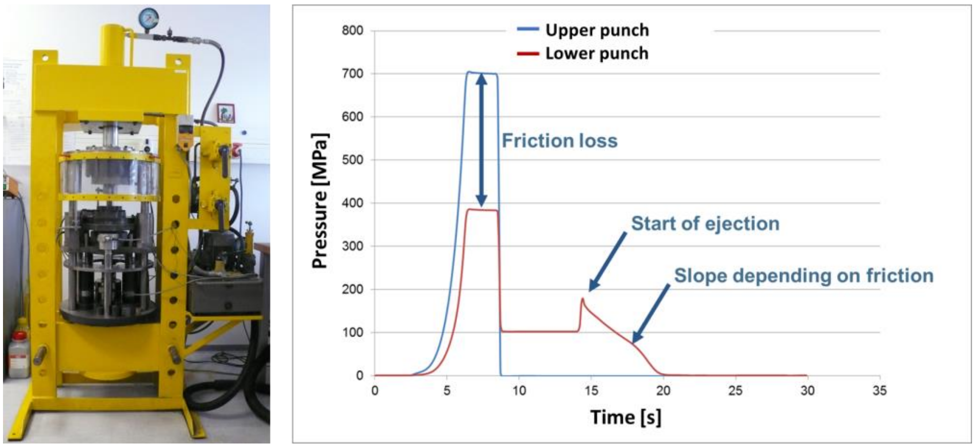

Figure 2: *Instrumented press used for measuring compaction pressures (left) and typical compaction curve for a bushing (OD=14.3 mm, ID=9.0 mm, Height=15 mm) (right).*

The described method was used to compare established lubricants like Acrawax C, Kenolube and AncorLube HDL to the newly developed lubricant, AncorLube LV. The measurements were done with warm die compaction using three different tool temperatures (25°C, 60°C and 80°C), a compaction pressure of 700 MPa and an M/Q ratio of 10. The powder blend used for the tests consisted of Ancorsteel 1000 BMn with 1.5% Cu, 0.55% C and 0.5% lubricant. Figure 3 gives an overview of the resulting pressures at the lower punch during compaction and compares the compressibility of the four premixes at the given temperature.
The measured values for compaction pressure at the lower punch confirm an excellent lubrication for the newly developed AncorLube LV compared to the other lubricant materials. Elevated tool temperatures lead to continuously improved lubricity of the AncorLube LV even up to 80°C, while the other lubricants show inferior performance at these rather high temperature levels. This is potentially caused by collapsing lubrication films in the tool due to lower viscosity of the lubricant at these temperature levels. The AncorLube LV was designed to work efficiently over a wider range of compaction temperatures. This ensures uniform lubrication even for complex shaped parts which have areas of higher friction causing locally increased heat. While former lubricants could not prevent local

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scoring in these overheated tool sections, AncorLube LV should give enough reserve to ensure stable lubrication.
The compressibility of the four premixes at different compaction temperatures and 700 MPa showed comparable results for the three advanced lubricants, Kenolube, AncorLube HDL and AncorLube LV. While the AncorLube LV was a little bit lower than the established AncorLube HDL at 60°C, it reached a higher density at temperatures of 80°C. This is underlining the wider application range in terms of tool temperature for the new lubricant.

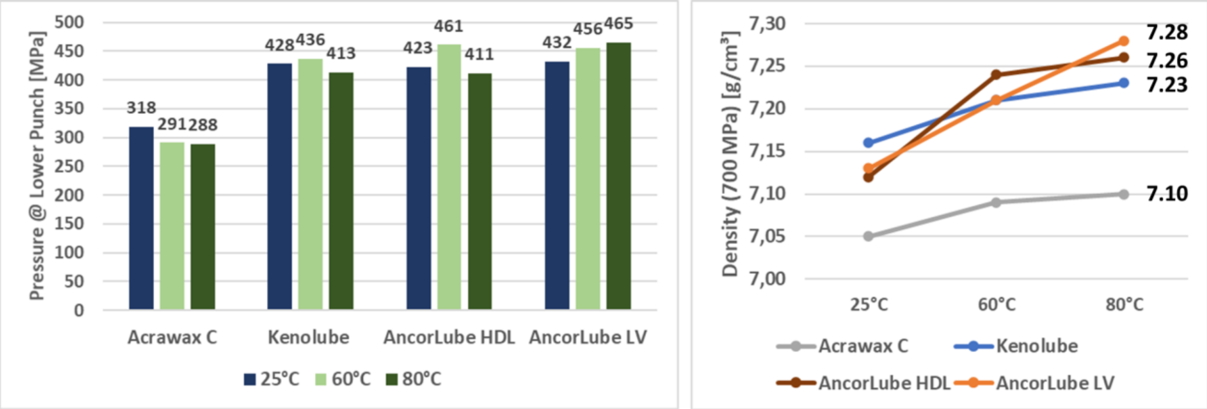

Figure 3: *Lubricity measurements for 700 MPa of different lubricants (left) and compressibility at three different tool temperatures (right) for premix material Ancorsteel 1000 BMn + 1.5% Cu + 0.55% C + 0.5% lubricant.*

Due to a higher need for good flowing powders with high apparent densities the demand of bonded powders increased significantly over recent years. Adding binders to these powder compositions will ensure an effective adhesion of fine powder fractions to the bigger base powder particles – but will not necessarily have lubricating capabilities. Therefore, the addition of highly effective lubricants that show a good performance even for low additions is recommended in order to keep the total organic additives low and ensure good achievable densities. On the other side, flow and apparent density of premix powders often suffer from the usage of lubricants with good lubricity since the ingredients of these lubricants are soft and greasy, which could deteriorate the flow. Therefore, bonded powders could be a good counterpart for advanced lubricants [7-8].

In order to investigate the potential use of the newly developed lubricant in Ancorbond powders, three different powder samples were manufactured. The Ancorbond baseline powder consisted of Ancorsteel 1000BMn base powder with 1.5% Cu and 0.55% C. Three different lubricants (Acrawax C, Kenolube and AncorLube LV) were added to this base composition with concentrations of 0.35%, 0.45% and 0.55%. The so created lab-scale powder blends were investigated in terms of apparent density, flow and lubrication behavior. Figure 4 shows the results of these measurements.
Bonded powders are often used to increase the speed of compaction tool filling by fast flow and high apparent densities resulting in less tool movement and lower filling height. The results of the powder trials document that all tested lubricants work well together with the Ancorbond system, resulting in high apparent densities and good flow. The AncorLube LV in this study was able to outperform the other compositions, showing the best performance for the lowest lubricant addition of 0.35%.
Strip&Slide measurements were performed for all compositions on the instrumented press described earlier. The tool temperatures for these trials were chosen in the range between 25°C and 90°C in order to confirm the good temperature tolerance of the AncorLube LV for Ancorbond powders as well. The right graph in figure 4 shows the ejection pressures measured for the powders with 0.35% lubricant additions. Lower values for these measurements are preferred since these mean an easier ejection of the compacted part after the densification process. It can be seen that the AncorLube LV shows the best performance of all lubricants over a wide temperature range and maintains a good performance even at temperature levels above 80°C. The preferred compaction temperature for the new lubricant should be chosen in the range of 60°C to 80°C depending on the complexity of the compacted parts and the amount of tool friction during the compaction process, potentially causing a local overheating in the tool. The fact that the lubrication film of the AncorLube LV in these hotter sections of the part should stay intact could, therefore, offer significant benefits for serial production processes.

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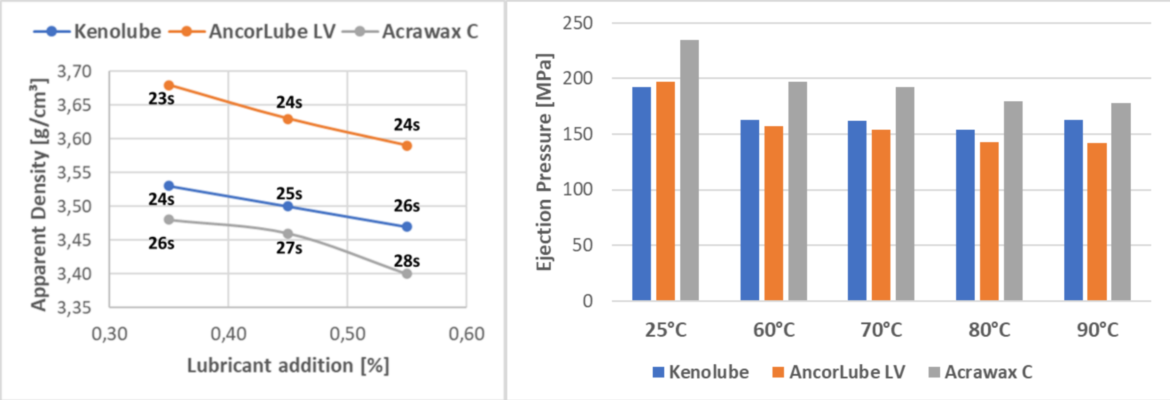

Figure 4: *Apparent densities and Hall flows for different lubricant concentrations (left) as well as ejection pressures at five different tool temperatures after 700 MPa compaction (right) for material Ancorsteel 1000BMn + 1.5% Cu + 0.55% C as Ancorbond plus 0.35% lubricant added.*

Although lubricity remains a key property of advanced lubricants, there are a multitude of aspects that need to be considered additionally. One property of lubricants that is moving more and more into focus over the recent years is their burn-off behavior. The additive is supposed to evaporate or decompose completely during the sintering process and leave the part with a residue-free and shiny metallic surface. The need for this is often driven by customer requirements or the usage of optical positioning systems during the parts manufacturing which may malfunction with stained parts. The tendency to form soot or other stains on the part surface is also dependent on the specific furnace delubrication technology, the powder composition (e.g. MnS content) and is more pronounced for higher part densities due to hindered transport of the lubricant from the core structure. In order to facilitate the burn-off process, burn-off-additives like CleanBurn have been introduced in the past. These additives mainly consist of oxidizing agents that decompose completely during the delubrication process. The degradation products of these additives are able to oxidize the residues of the lubricant and so facilitate the burn-off efficiency [2].
For the lubricant composition, metallic stearate free additives are highly preferred over those containing zinc because of their more complete burn-off resulting in cleaner parts and furnaces. As all other AncorLube variants, AncorLube LV was designed as a zinc-free lubricant offering advantages in parts surface finish compared to zinc-containing materials like zinc stearate or Kenolube.
Thermal gravimetric analysis (TGA) offers a good way to quantify lubricant burn-off and indecomposable residues like ashes. The left side of figure 5 shows a TGA graph displaying the relative weight loss for different lubricants for a temperature range between 100° and 800°C. The measurements have been done using an STA 449 C (Netzsch) under pure nitrogen atmosphere. The sample size for these investigations was 50 mg of pure lubricant without any additives or base powders. As expected, lubricants containing metal soaps like zinc stearate show a significantly higher amount of residue which will remain in the compact or on the compact's surfaces. For pure zinc stearate, the amount of ash stays clearly over 12%, while the amount of residue for Kenolube, which contains zinc stearate, is lower but still obvious. Acrawax C or other EBS waxes (N, N'-Ethylene Bis Stearamide) show a very clean and complete burn-off in this investigation. AncorLube LV was measured with the same final values for residues but with a start of the decomposition process shifted to lower temperature (start of curve decline). This earlier start of the burn-off process will be beneficial when the lubricant is entrapped inside the porosity of powder compacts providing more time in the sintering furnace for a complete burn-off.
Additional investigations have been done by compacting cylinders out of Ancorsteel 1000 B + 2% Cu + 0.8% C + 0.6% lubricant and sintering them at 1120°C in 90% N_2 / 10% H_2 atmosphere. The cylinders had a diameter of 38 mm with a height of approximately 25 mm and were compacted to a green density of 7.0 g/cm³. The photographs of the sintered parts in figure 5 show the best surface finish for AncorLube LV and Acrawax C additions, while the addition of Kenolube left significant surface stains.

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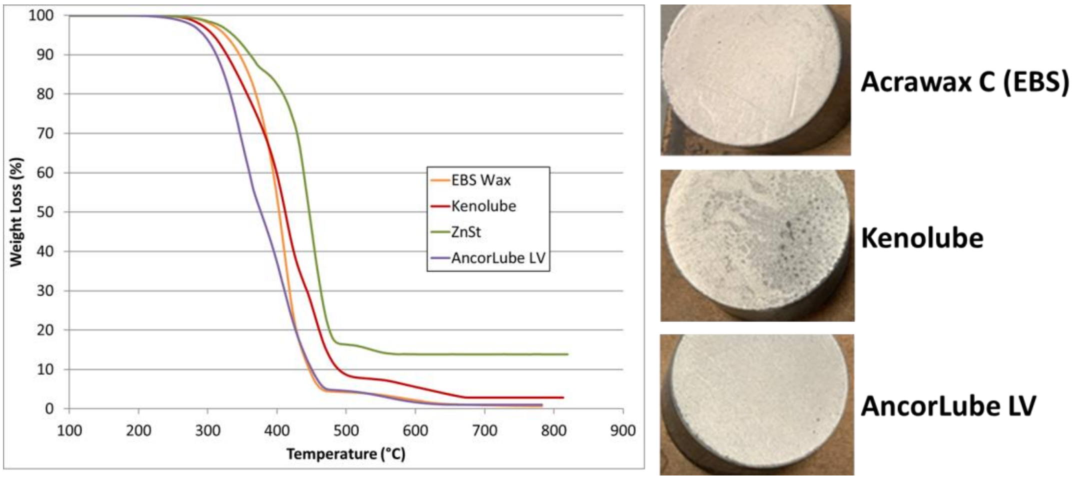

Figure 5: *TGA-measurement of pure lubricant samples (left) and surface finish of cylinders made of Ancorsteel 1000 B + 2% Cu + 0.8% C + 0.6% lubricant sintered at 1120 °C in an atmosphere of 90%N_2/10%H_2*

Serial production trials

After a comprehensive characterization of new lubricants with laboratory techniques, it is inevitable to collect results out of the first serial production trials with the same accurateness. Introducing new lubricants into a serial production environment can lead to changed performance caused by higher sample sizes and increased production rates for compaction and sintering. While the flow can look promising in a Hall flowmeter, the performance might change in a feeding hose of a continuously running production press. A higher number of different part geometries and tool temperatures help to understand the lubrication behavior during compaction. The surface finish after sintering might also change in a fully loaded production-sized furnace compared to the samples sintered in the lab.
After completion of the lab characterization, AncorLube LV was used in several serial production campaigns. The following paragraph of our paper will briefly describe the selected results of these trials.

As mentioned earlier, advanced lubricants can be critical for powder flow and apparent density due to their rather soft ingredients required for good lubricity. Therefore, the first production trial is mainly focused on powder flow and weight consistency.
A powder premix made of Ancorsteel 1000BMn + 17% FD10Cu + 0.65% C + 0.6% AncorLube LV was compacted on a 150-ton serial production press producing VVT stators. The stators were compacted to a green density of 6.9 g/cm³ according to the customer specifications. The die temperature during compaction was 65°C and the productivity of the press was chosen to be 10 parts/min. The automatic weight adjustment of the press was switched off during the compaction run in order to get an undisturbed analysis of the consistency of the powder flow. For a series of approximately 1500 parts, every fifth compact was weighed on an analytical balance. Figure 6 documents the weight scatter of the parts produced during this compaction run. It can be seen that the powder mix containing AncorLube LV showed a very consistent powder flow resulting in a low weight scatter of less than 0.2% over all analyzed parts. Considering that a VVT stator has a rather complex shaped geometry for powder filling, this trial can be clearly considered as a success.

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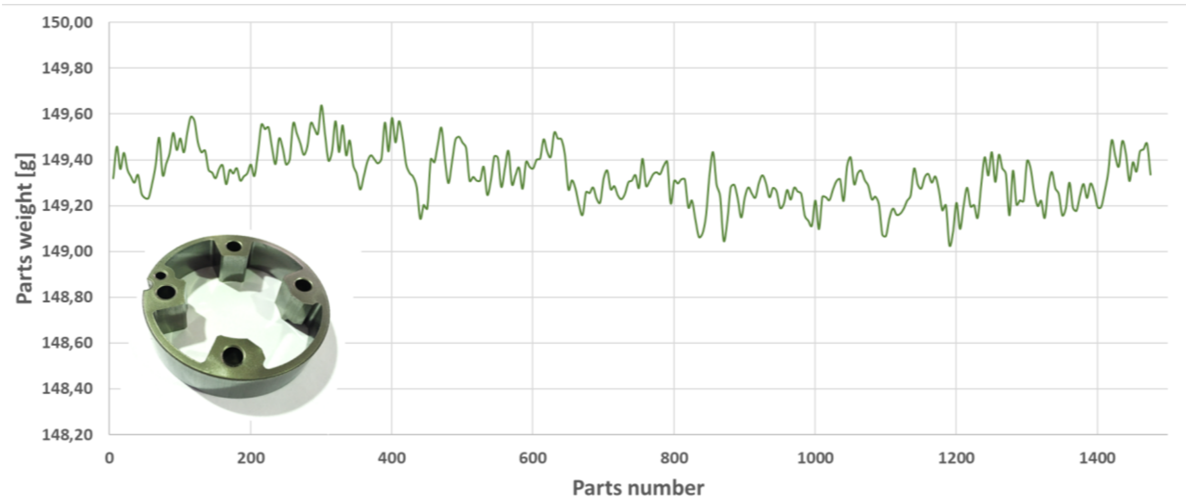

Figure 6: *Compaction study of VVT stator components with Ancorsteel 1000BMn + 17% FD10Cu + 0.65% C + 0.6% AncorLube LV, press rate of 10 strokes per minute*

Meanwhile, several other production trials were completed together with various parts manufacturers. Figure 7 shows details of two different parts used for these investigations. The bi-level gear on the left side of the figure was compacted using a premix powder of Ancorsteel FLD 49DH with 0.3% graphite and 0.45% lubricant. Initial trials using Kenolube or AncorLube HDL as a lubricant were not successful in reaching the required green density of 7.35 g/cm³ for these parts. Additionally, several regions of the part's outer surface showed scoring after a low number of compacted parts. Substituting the lubricant with AncorLube LV in this powder mix resulted in a stable serial production, producing parts of the required density level with a good surface finish. The tool temperature was controlled at 70°C while the compacted parts were measured at 80-85°C due to frictional heating.
Parts out of another production trial completed with AncorLube LV are shown on the right side of figure 7. The gears compacted in this investigation had a weight of approximately 1000 g and were compacted out of a premix with Ancorsteel 85HP, 0.25% graphite and 0.6% AncorLube LV. The new lubricant was introduced into this powder blend because the parts became extremely hot during ejection, causing surface scoring with the formerly-used lubricant due to failing lubrication at these high temperatures. The way to overcome this in the past was a reduction of compaction speed required to keep the part temperature at a moderate level. By introducing the AncorLube LV into this blend, the ejection speed could be increased significantly, resulting in a productivity increase of more than 40%. Although heated up by friction to temperatures of above 80°C, the parts' surface finish and tool lifetimes improved significantly. The improvement of the surface finish is shown on the right side of figure 7 with the former serial powder at the top and the AncorLube LV containing powder at the bottom.

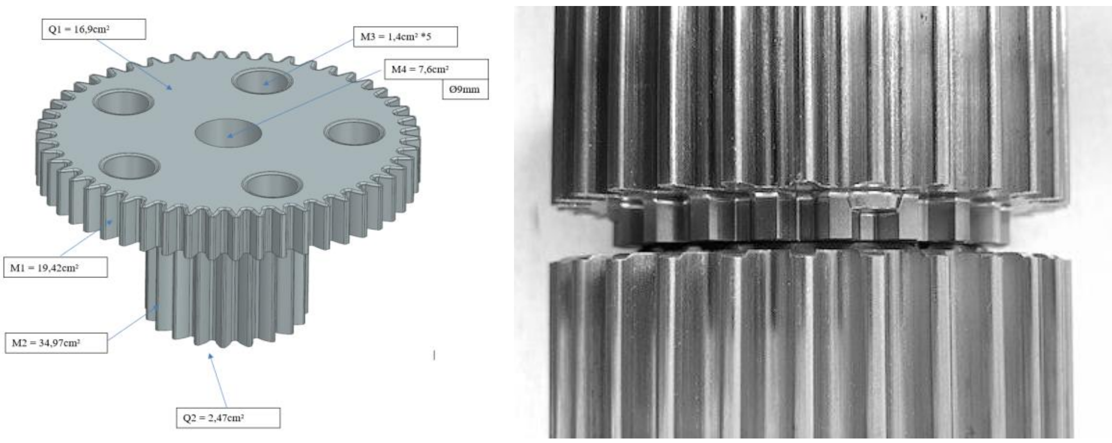

Figure 7: *Parts from different compaction studies*

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Conclusion

Advanced lubricants for modern PM applications require more than only good lubricity. The successful development of a new lubricant needs to cover a long list of additional aspects including powder flow, apparent density, burn-off behavior and safety aspects. Considering the multitude of potential key properties, a one-for-all lubricant might not be realistic, but a more diversified approach must be adopted. AncorLube LV provides a valuable addition to the lubricant toolbox offering superior lubricity in the first step. A wider range of usable tool temperatures for this new lubricant allows more process flexibility in terms of production speeds or lubricant contents. Especially the serial production examples in this contribution proved that this leads to increased productivities or more stable processes.
Powder flow and apparent density are well addressed by the advanced lubricant developments but can be further improved by the usage of bonded powders. Metallic-stearate-free lubricants like AncorLube LV are able to improve the delubrication inside the sintering furnace and can be even more improved by the addition of burn-off additives when it is required for high part density and high wall thicknesses in green compacts.
Advanced lubricant systems can offer solutions for any powder-metallurgical compact requirement, but a close collaboration between powder and parts manufacturer will remain key for a successful technical solution.

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