Improved Lubrication during Compaction by Highly Efficient Lubricants and Heated Tool Die

Mats Larsson

Höganäs AB, Höganäs, Sweden
mats.larsson@hoganas.com

Keywords: High density, Lubricant, Warm die compaction.

Abstract
A high density is a prerequisite for making high strength PM components. By increasing the density, both strength, and in particular fatigue strength and ductility are improved.

To achieve high density one of the key issues is to use as low amount of lubricant as possible in order to increase the theoretical density to which the mix can be compacted. However, the lubrication must be efficient enough to eject the pressed part from the tool without deteriorating the surface of the part due to friction. Insufficient lubrication may also lead to damage of the press tool.

Warm die compaction is a process route that is increasingly used for production of high density PM components. By heating the tool die the efficiency of the lubricant will be enhanced, thus allowing a lower amount of lubricant to be used. Efficient lubrication does not only influence the ejection of the part but also the overall density, as well as the density distribution inside the pressed component. Lower friction during the compaction results in less density gradients in the pressed part.

In this paper results are presented from measurements of the lubrication during the compaction. The results include different lubricants and how heated tool die influences the lubrication as well as density of the parts.

Introduction
High density is a crucial factor in achieving a high strength PM material. Both strength and ductility are improved by increasing the density. There are different routes available for production of high density PM components such as powder forging, high temperature sintering, copper infiltration, double pressing/double sintering and warm compaction [1].

A processing route for production of high density PM components which is gaining in popularity is warm die compaction. This is a technology where mixes with highly efficient lubricants using a relatively low content are compacted with a heated tool die, and at a relatively high compaction pressure [2]. A benefit of this process route is the relative simplicity. There are no additional processing steps and the only addition to the standard PM processing route is a heating device for the tool die.

Intralube® E mixes are well established on the market and contain a lubricant system suitable for warm die compaction. In the results section the lubricant of this mix type is referred to as Lube E.

To assess the performance of lubricants, the commonly used method is to measure the peak ejection force or the energy required to eject the part from the tool die. Friction also plays an important role during the compaction of a green body and as a result there will be density gradients in the green body. If the compaction is done single sided from the top, i.e. the lower punch does not move in relation to the die, the pressure and thus the density will decrease by increasing distance from the upper punch. This is illustrated in Figure 1. This shows the compaction principle used in the trials presented in this paper where the friction during compaction was measured. Measuring the force transmitted to the lower punch as a methodology, to assess the friction during compaction has previously been presented [3].

In Figure 1 the forces acting on the body during the densification are indicated. The upper punch is assumed to have entered the die and already compacted the powder to a certain degree so that the axial stress in the powder directly underneath the punch face is p_0. The variable vertical distance from the punch face is z.

Imagine the powder column in the die as being composed of thin discs stacked upon one another like coins. Consider one disc at distance z from the punch face with a height dz and cross-sectional area A.

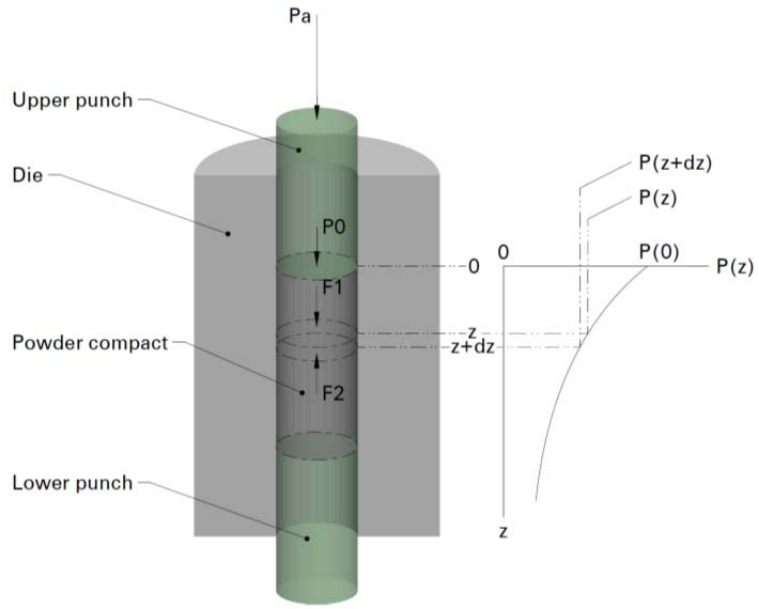


Figure 1. Axial stress P(z) in a powder mass as a function of distance z from the face of the upper compaction punch.

A force equilibrium equation for the disc is given in Equation 1.

$$\downarrow: F_1 - F_2 - f = 0 \qquad (1)$$

Where **f** is the frictional force between the powder compact and the die wall. The forces $\mathbf{F_1}$ and $\mathbf{F_2}$ can be expressed as:

$$F_1 = p \cdot A \qquad (2)$$

$$F_2 = (p + dp) \cdot A \qquad (3)$$

A is the cross-sectional area of the die (and punches) which are assumed to be constant and independent of z.

Assume that the pressure **p** is constant over the cross-sectional area **A,** and that the normal pressure on the powder compact $\mathbf{p_N}$ from the die wall is proportional to **p** (the conditions are idealized by assuming that **p** is constant over **A** and that $\mathbf{p_N}$ is linearly proportional to **p**).

The normal pressure $\mathbf{p_N}$, in the radial direction, can be expressed as:

$$p_N = k \cdot p \qquad (4)$$

Where **k** is a proportionality constant. The normal force **N**, in the radial direction acting on the disc, can be expressed as:

$$N = k \cdot p \cdot C \cdot dz \qquad (5)$$

Where **C** is the circumference of the disc. The frictional force **f** can be expressed as:

$$f = \mu \cdot N = \mu \cdot k \cdot p \cdot C \cdot dz \qquad (6)$$

Where **μ** is the coefficient of friction between the disc of compacted powder and the die wall. By inserting equation (2), (3) and (6) in the equilibrium equation (1) an expression can be derived for the pressure on the powder **p**, at a distance **z** below the upper punch:

$$p(z) = p_0 \cdot e^{-\frac{\mu \cdot k \cdot C}{A} \cdot z} \qquad (7)$$

Where $\mathbf{p_0}$ is the pressure acting on the powder and when z = 0, i.e. the pressure of the upper punch. By rearranging Equation 7 an expression for the factor $\mu \cdot k$ can be derived:

$$\mu \cdot k = \frac{A}{z \cdot C} \cdot [\ln(p_0) - \ln(p)] \qquad (8)$$

Thus, by measuring the pressure on both the upper and lower punch from a single sided compaction, the product of the friction coefficient (μ) and proportionality constant (k) can be determined. However, it is not possible to separate μ and k without measuring the radial force, which is experimentally challenging and not included in the scope of this investigation.

Experimental

Equipment

To investigate the compaction performance a Dorst EP70M electro-mechanical press was used. This can be seen in Figure 2. In addition to the load measuring system for the upper punch, this press was also equipped with an auxiliary load cell positioned under the lower punch. This enabled the measurement of forces acting on the upper punch, lower punch and core rod.



Figure 2. Dorst EP70 M press installed at Höganäs R&D department.

The pressed parts were of ring geometry with diameters 35/25 mm and heights of 5, 15 and 25 mm. These were compacted at compacting pressures of 500, 700 and 900 MPa. Compaction was made both with the die at room temperature as well as with the die heated to 60°C. 10 specimens were compacted for each test series. Forces and positions throughout the compaction cycles were logged from the compaction of the last five specimens. Peak ejection force, ejection energy and force transmitted to the lower punch were evaluated from the logged data. Green density was measured on two specimens from each series by weighing air and water.

The withdrawal force of the press was limited to 150 kN and for this reason not all combinations of lubricant, part height and compacting pressure were possible to eject. Some data points are therefore missing. The withdrawal force was exceeding the limit and ejection was not possible especially at the combination of high compacts and high compacting pressures.

In Figure 3 a typical compaction cycle is illustrated with forces and positions of the tool members plotted versus time. In this cycle the compaction is taking place between 5000 to 6000 ms on the x-axis. As can be seen the force on the lower punch is lower than the force on the upper punch due to friction between the part being compacted, and the tool die and core rod respectively.

After 6000 ms the ejection of the compacted part follows and during the ejection the counter pressure of the upper punch was set to 1 kN. From the logged ejection curves the static peak ejection force and ejection energy were evaluated. The ejection energy was calculated by integrating the area under the force-displacement curves from the ejection. The ejection energy and ejection force were divided by the envelope surface of the parts and expressed as J/cm² and N/mm² respectively.

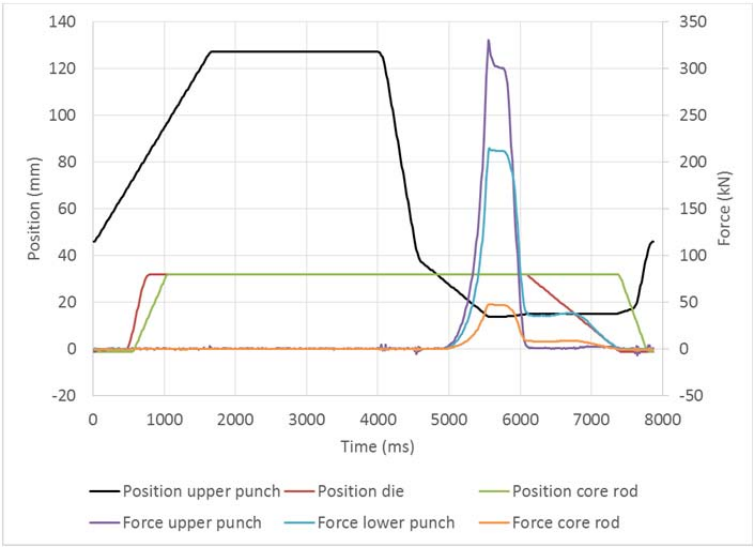


Figure 3. Press kinematics and forces of a typical cycle where a 15 mm high part was compacted to 700 MPa.

Mixes

All mixes included in the investigation had a nominal composition of Astaloy 85 Mo + 0.5% C-UF4 + Lubricant. Astaloy 85 Mo is a water atomized iron powder pre-alloyed with 0.85% molybdenum. The types and contents of the lubricants in the mixes are presented in Table 1. The pore free density of the mixes, calculated based on the density of the different mix constituents, is also included in Table 1.

Table 1. Analyses of mixes.

Mix number	Type of lubricant	Nominal lubricant content (%)	Analysis		Theoretical pore free density of mix (g/cm³)
			Graphite (%)	Lubricant (%)	
1	Lube E	0.50	0.50	0.50	7.49
2	Lube E	0.75	0.51	0.73	7.36
3	Lube E	1.00	0.48	0.95	7.25
4	Zn-st	0.75	0.48	0.73	7.40
5	Amidewax	0.75	0.48	0.73	7.37

Results and discussion

Influence of part height, compacting pressure and die temperature

Data is presented from 18 trials with mix 2 to assess the influence of the part height, compacting pressure and die temperature. In Figure 4 the lower punch pressure is plotted versus the compaction pressure. Without friction between the compact and press tool, the lower punch pressure would be the same as the pressure that the upper punch exerts on the green body. Ideal conditions such as these are indicated by the grey dashed line in the diagram. In practice there was a loss due to friction and the pressure on the lower punch was smaller. In Figure 5 the pressure loss, defined as the compaction pressure minus the lower punch pressure is presented. By far the strongest effect was the pressure loss increased by increasing the height of the compact. This is a direct consequence of the larger area that the friction is acting on. The pressure loss was also increasing slightly by increasing compacting pressure. This trend was more pronounced when increasing the height of the compact. Finally, it can be seen that the pressure loss was smaller when the tool die was heated to a temperature of 60°C.

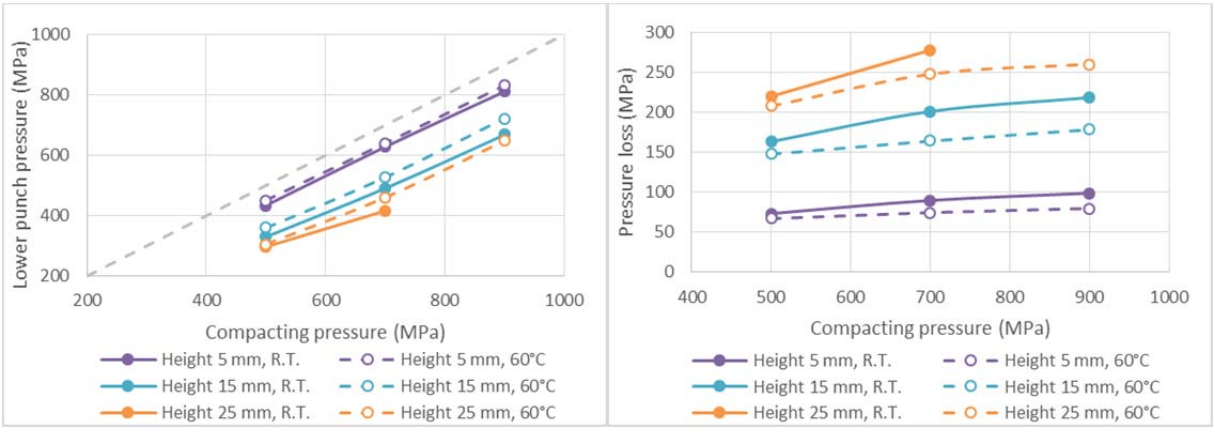


Figure 4 and 5. Pressure transmission to lower punch (left) and pressure loss (right) versus compaction pressure.

In Figure 6 and 7 the peak ejection force and ejection energy are presented. In absolute terms the peak ejection force was increasing more or less proportionally with the height (and the envelope surface) of the compacts. Thus the peak ejection force expressed as N/mm² was more or less independent of the height of the parts. With a heated tool die the peak ejection force decreased, most significantly at higher compacting pressures. With the tool die at room temperature the peak ejection force was increased by increasing the compacting pressure but with the tool die heated to 60°C. The influence of the compacting pressure was then smaller.

The ejection energy in Figure 7 differs from the peak ejection force in Figure 6. One of the fundamental differences is that the height of the part will influence not only the surface area on which the friction acts, but also the distance required to eject the part. As in the case of the pressure loss presented in Figure 5, the strongest effect was that the ejection energy increased by increasing height of the compact. The ejection energy increased as the compacting pressure was increased from 500 to 700 MPa, but did not further increase when the pressure was increased to 900 MPa. Finally it can be seen that the ejection energy was smaller when the tool die was heated to a temperature of 60°C.

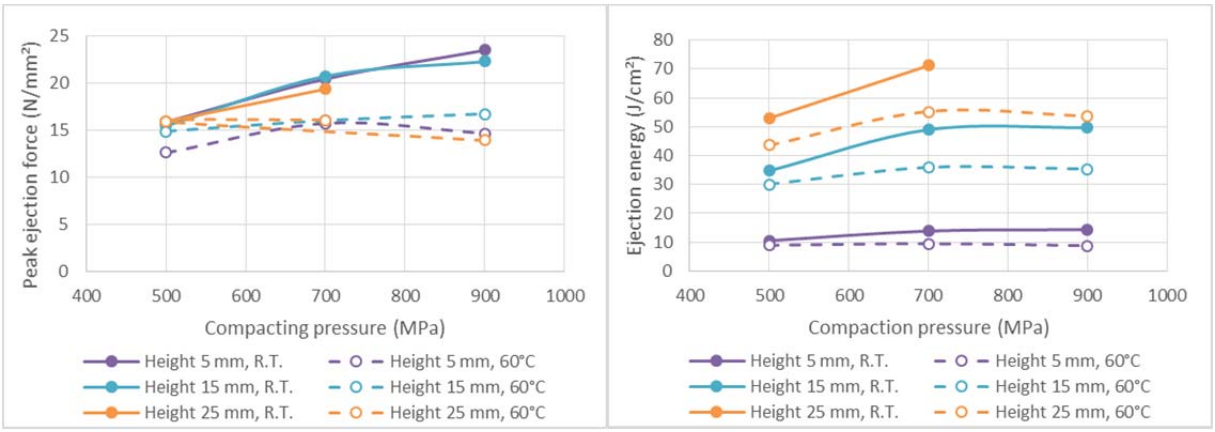


Figure 6 and 7. Peak ejection force (left) and ejection energy (right) versus compaction pressure.

From the pressure loss the product of the friction coefficient and proportionality constant (μ*k) was calculated, as can be seen in Figure 8. A general trend was that μ·k was decreasing with increased compacting pressure, as the efficiency of the lubricant was enhanced by higher pressure. The lubrication and thus μ*k was improved by increasing the tool die temperature.

In Figure 9 compressibility curves are presented. The influence of tool die temperature and height of the compact was more significant at the lower compacting pressures, and was less significant at the highest, as the density was approaching the theoretical density of the powder mix. A density of 7.30 g/cm³ corresponds to 99.1% of the theoretical density of the powder mix. By heating the tool die the pressure loss from the friction was decreased and as a consequence compressibility was increased. In Figure 9 the overall density is presented and the improvement in density from heating the tool die is even higher locally in the neutral zone.

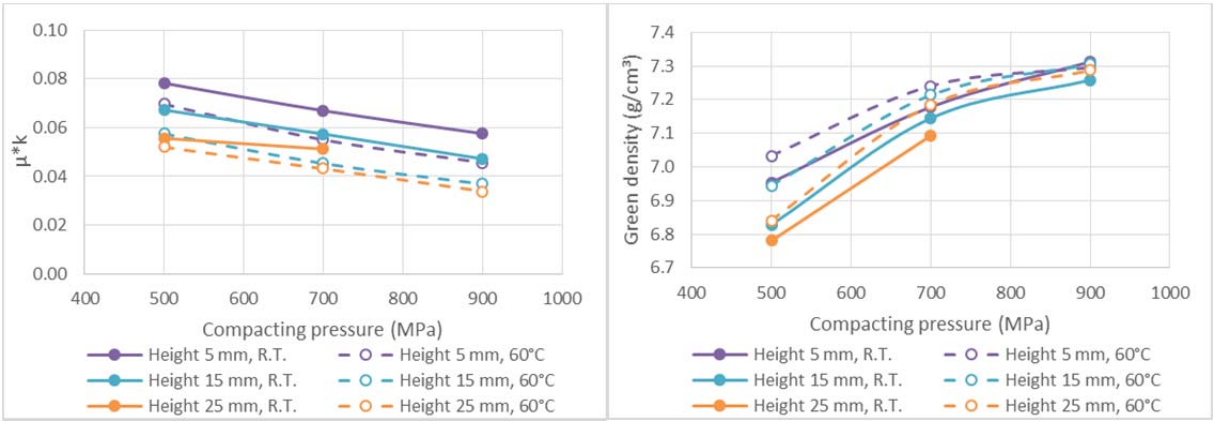


Figure 8 and 9. Friction (left) and green density (right) versus compaction pressure

Influence of lubricant type and content

In Figure 10 to 15 the performance of mix 2, 4 and 5 are presented. These three mixes have nominally 0.75% lubricant added as Lube E, Zn-st and Amidewax respectively. No data is available for the mixes with Zn-st and Amidewax. The lubricant compacted with the tool die heated to 60°C because the withdrawal force exceeded 150 kN and the parts were not possible to eject under this condition.

In Figure 10 and 11 the lower punch pressure and pressure loss are respectively plotted versus the lubricant content. Both these figures show the same effect. Compared at 0.75% lubricant content, the best lubrication was achieved by the mix with Lube E and the worst lubrication was achieved using the mix with Zn-st. By increasing the lubricant content and by heating the tool die the pressure loss decreases and the pressure transmitted to the lower punch increases.

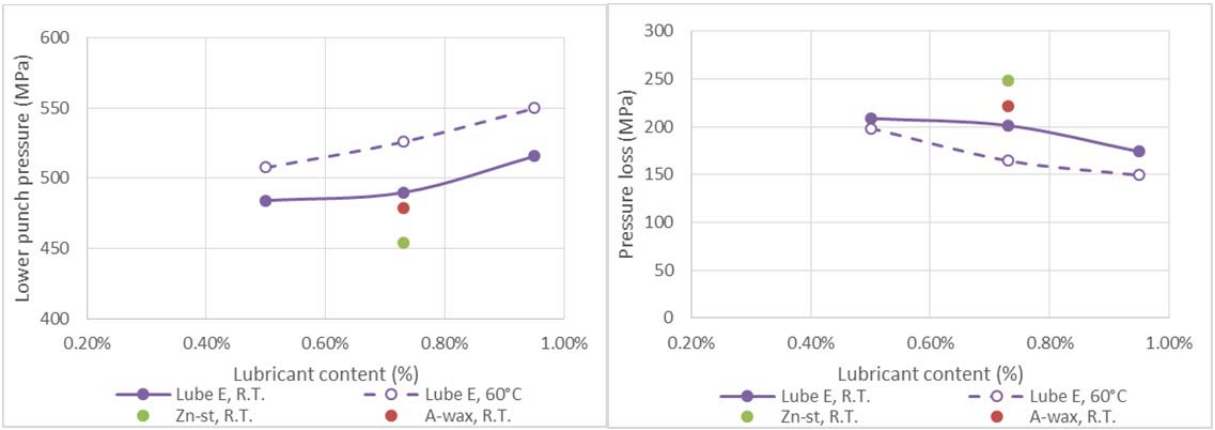


Figure 10 and 11. Pressure transmission to lower punch (left) and pressure loss (right) versus lubricant content.

Comparing ejection force, ejection energy and friction of the three lubricants show similar patterns as for the pressure loss to lower punch. This can be seen in Figure 12, 13 and 14. The improvement from increasing the lubricant content and by heating the tool die is even more significant for the ejection force and ejection energy.

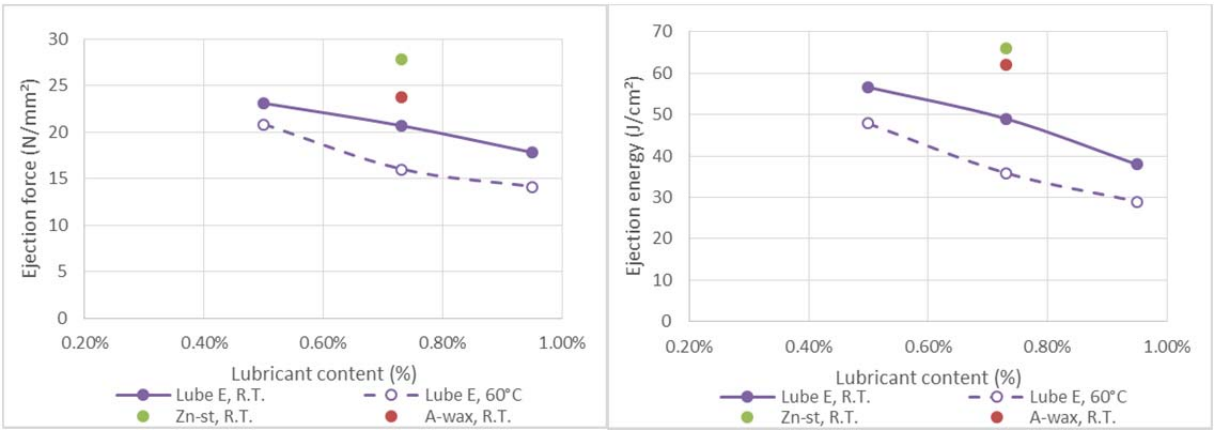


Figure 12 and 13: Peak ejection force (left) and ejection energy (right) versus lubricant content.

In Figure 15 green density is plotted versus lubricant content. With tool die at room temperature the mix with 0.75% Lube E was about 0.05 g/cm³ higher in density compared to the mixes with same amount of Zn-st or Amidewax lubricant. By heating the tool the mixes with varying amount of Lube E as lubricant all increased in green density. At the pressure used, 700 MPa, the green density was similar for the mixes with 0.5% Lube E and 0.75% Lube E. By further increasing the Lube E content to 1.0% the green density dropped due to the lower theoretical full density of the mix.

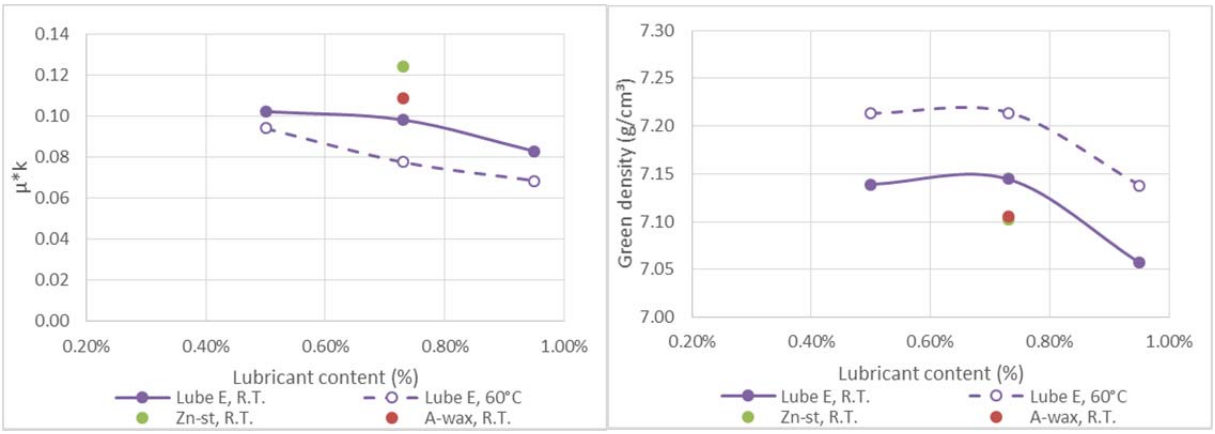


Figure 14 and 15. Friction (left) and green density (right) versus lubricant content.

Influence of lubricant content and pressure

Lubricant content and compacting pressure are dependent upon each other. At higher compacting pressures the lubricant content and resulting lower theoretical full density of the mix will be a limiting factor for the achievable density. To enable a lower lubricant content the improvement in lubrication from heating the tool die is of interest. High compacting pressure is also a prerequisite for high density. Against this background, the interaction between lubricant content, compacting pressure at room temperature, and the tool die heated

to 60°C, is of interest to study. The performance of mix 1, 2 and 3 with different amounts of Lube E are presented in Figure 16 – 21.

In Figure 16 and 17 the pressure transmission to lower punch and pressure loss to the lower punch are plotted versus the compaction pressure. As can be expected the pressure transmitted to the lower punch was higher, and the pressure loss was smaller with higher lubricant content. As seen previously, the pressure loss was smaller when the tool die was heated to a temperature of 60°C.

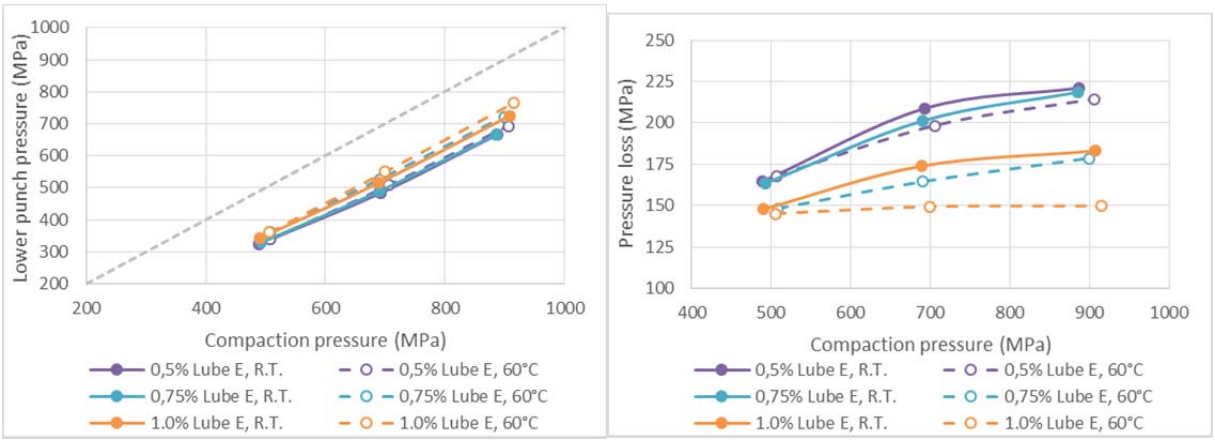


Figure 16 and 17. Pressure transmission to lower punch (left) and pressure loss (right) versus compacting pressure.

As also seen previously, the peak ejection force and ejection energy were more influenced by the lubricant content and tool die temperature at the higher compacting pressure, as can be seen in Figure 18 and 19. By heating the tool die to 60°C the mix with 0.50% Lube E performs as well as the mix with 0.75% Lube E compacted at room temperature in terms of pressure loss to the lower punch, peak ejection force (except at 500 MPa) and ejection energy. Similarly, the mix with 0.75% Lube E compacted at 60°C performs as well as the mix with 1.0% Lube E compacted at room temperature.

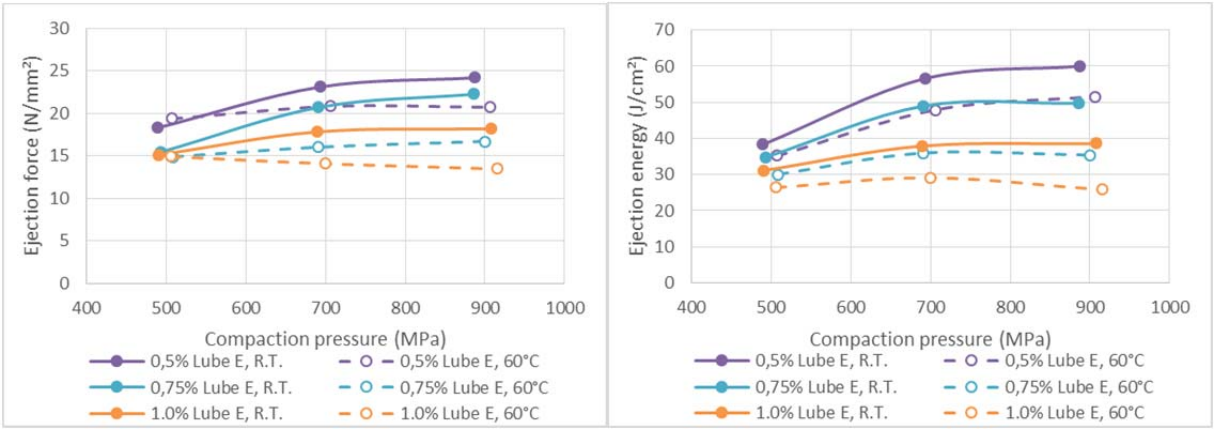


Figure 18 and 19. Peak ejection force (left) and ejection energy (right) versus compacting pressure.

In Figure 20 and 21 compressibility curves are presented and expressed in absolute numbers and percent of pore free density. From these curves the drawback of increasing the lubricant content can be seen. As the pressure was increased, the density of all mixes approach 99% of the theoretical pore free density, as can be seen in Figure 21. Since a higher content of lubricant decreases the theoretical density of the mix, the achievable density at the highest compacting pressure was determined by the lubricant content. With lower lubricant content the compressibility at high pressure was increased, see Figure 20. At all compacting pressures

the compressibility increased by heating the tool die to 60°C. The fact that the lubrication also improves by heating the tool die enables a lower lubricant amount to be used. This also maintains ejection performance and thus enables a further increase in compressibility.

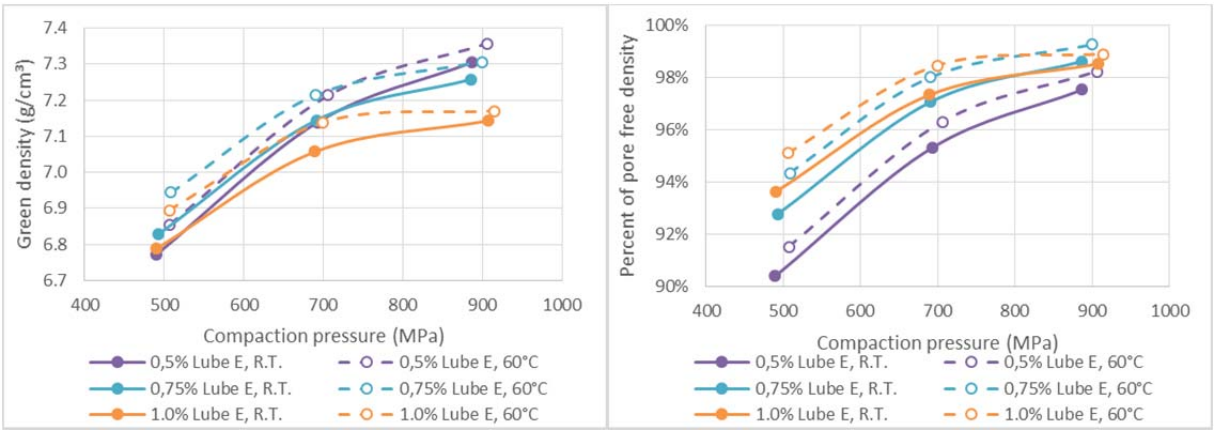


Figure 20 and 21. Green density (left) and percent of pore free density (right) versus lubricant content.

Conclusions

Warm die compaction is a cost-effective process route for making high density PM parts.

By using Intralube E mix, the better lubrication enables lower amounts to be used compared to mixes using Amidewax or Zn-st as a lubricant.

By heating the tool die in combination with the Intralube E mix, the friction is lowered.

The combination of Intralube E mix and heated tool die enable lower lubricant amounts to be used, and thus enable the compaction of PM components to a higher density.

With efficient lubrication and lower friction, the overall density of the compact is higher and the density gradients in the compact are smaller.

References

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