

WARM DIE COMPACTION PROCESS TO ACHIEVE HIGHER GREEN DENSITY AND GREEN STRENGTH

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ABSTRACT

Demands for better performance and cost competitiveness of powder metallurgy (PM) parts have required a new insight to conventional warm compaction processing without heating the powder prior to die filling. It will eliminate the cost and temperature issues related to a separate powder heater. This paper will describe a new powder system designed for warm-die compaction at temperature ranges from 45 to 95 °C (110 to 200 °F). The objective is to achieve an increase of 0.1 g/cm³ over conventional single press/single sinter process and a minimum green strength of 13.8 MPa (2000 psi). Fundamentals of the warm-die compaction process as well as effect of temperature on lubrication and green properties will be presented to aid the parts producer in making high density, high green strength PM parts.

INTRODUCTION

The ability to manufacture net shape components is one of powder metallurgy's (PM) largest advantages as a manufacturing process. The material utilization for PM is typically higher than competing manufacturing technologies such as casting, hot forging or machining.¹ While PM competes with many of these manufacturing technologies with great success, the higher performing applications are more of a challenge due to the requirement to achieve high density. The mechanical performance of powder metallurgy is strongly dependent on the density achieved in the PM component. Tensile strength and fatigue strength increase in a linear fashion while elongation and impact resistance increase exponentially with density.²

Since most PM components are between 85 – 91% of the theoretical density, the tensile properties, for instance, are only 60 – 80% of the theoretical maximum. Therefore, increasing the achievable density with PM becomes a challenge for the industry to grow into high performance applications.

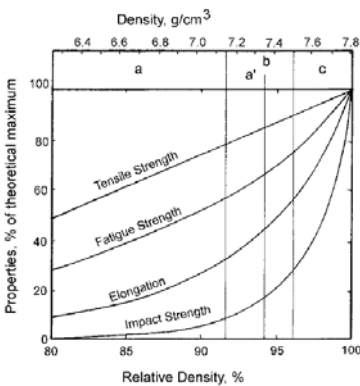


Figure 1. Relationship between density and mechanical properties²

While techniques for increasing density such as copper infiltration, high temperature sintering, double press / double sinter and powder forging have been in use for a number of years, it wasn't until the 1990's when a single compaction / single sinter option arose for high density which was comparable in cost to the conventional compaction technique.³ Warm compaction was introduced as a method for achieving densities between 7.20 - 7.40 g/cm³ utilizing a proprietary lubricant system allowing for the heating of the powder in combination with heated tooling.

Modeling of the compaction process by W.M. Long and G. Bockstiegel show that radial pressure is in inverse proportion to the yield point of the material.⁴ The models conclude that a powder material with a low yield point should exhibit a hydraulic behavior when compacted in a die. Therefore, if the yield point of the material can be lowered, the compressibility of the material will increase.⁴ In warm compaction, heat is utilized to lower the yield point of the iron powder which consequentially allows for deformation to occur with greater ease. An illustration of the effect of temperature on the yield point of PM materials is shown in Figure 2.

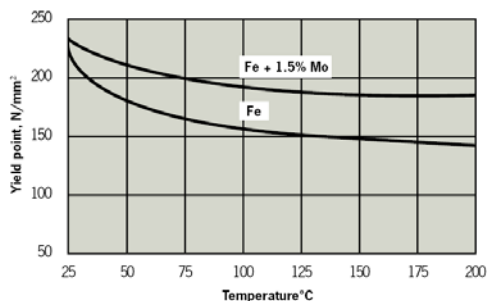


Figure 2. Influence of temperature on the yield point of iron and iron + molybdenum⁴

The heat is applied to both the powder and the tooling using equipment which provides uniform heat distribution. Heating of the powder is the most time consuming due to the relatively low thermal conductivity of the powder.⁴ Powder heating systems are designed in such a way where the powder is evenly heated to minimize variations in the powder temperature. The heat applied in the hopper hose, feed shoe and tooling is used to maintain the powder temperature of 120 °C (250 °F). It is important to control the heat as variations in temperature could result in poor powder flow, non-uniform tool expansion and inconsistent density in the components.

When the warm compaction process is properly implemented, green density improvements of up to 0.15 g/cm³ can be achieved compared to conventional compaction.⁵ This improvement leads to an increase in the mechanical performance. The heat applied also has another benefit in that the pore structure of the compacted component is improved compared to other compaction techniques. In a previous study, it was shown that at the same density level warm compaction will provide high dynamic performance due to the maximum pore length being decreased.⁶

Despite the increased properties, just a small portion of the components manufactured today utilize warm compaction. The input of temperature into the compaction process requires great care be taken to minimize variation in temperature. While the heating the tooling is generally considered the easiest aspect of warm compaction, controlling the temperature of the powder is often quoted as the largest issue limiting the proliferation of warm compaction. Variation in temperature can lead to poor powder properties. The robustness of the equipment, along with the low conductivity of powder, represents challenges in a manufacturing environment. The challenge of powder heating helped create another compaction technique where only the tooling requires heat. This method is named warm die compaction.

Warm die compaction utilizes temperature in a different way compared to warm compaction. Since the temperatures used with warm die compaction are much less than warm compaction, 60 °C vs. 120 °C (140 °F vs. 250 °F), only a slight decrease in the yield strength can be achieved. The temperature in warm die compaction is instead used to decrease the lubricant addition by softening the lubricant faster than in conventional compaction. This allows for a decrease in organic material added to the powder mixture resulting in higher density. Warm die compaction also suffers from restrictions due to temperature gradients, part size and shape, and lubrication of long components. This paper will examine the fundamentals of warm die compaction and evaluate a new lubricant system designed for warm die compaction.

FUNDAMENTALS OF WARM DIE COMPACTION

Warm die compaction utilizes heat to permit decreased levels of lubricant. The lubricant is able to be decreased due to the heat softening the lubricant and allowing it to migrate to the die surface faster to increase the amount of lubricant available at the tool surface. In Figure 3, a schematic of the compaction process shows how particles and lubricant move in the compaction process. After the powder is delivered to the die cavity, the particles of iron powder and lubricant are loosely packed. Once pressure is applied, the particles rearrange and air space is reduced. As different particle shape, size and density can affect the flow characteristics of a material system, they also affect the compressibility. In conventional compaction, solid lubricants are used which provide for particle to particle lubrication. The goal is to move the lubricant to the die wall during compaction and provide lubrication for ejection of the component. However, solid lubricants typically do not show much deformation during compaction.

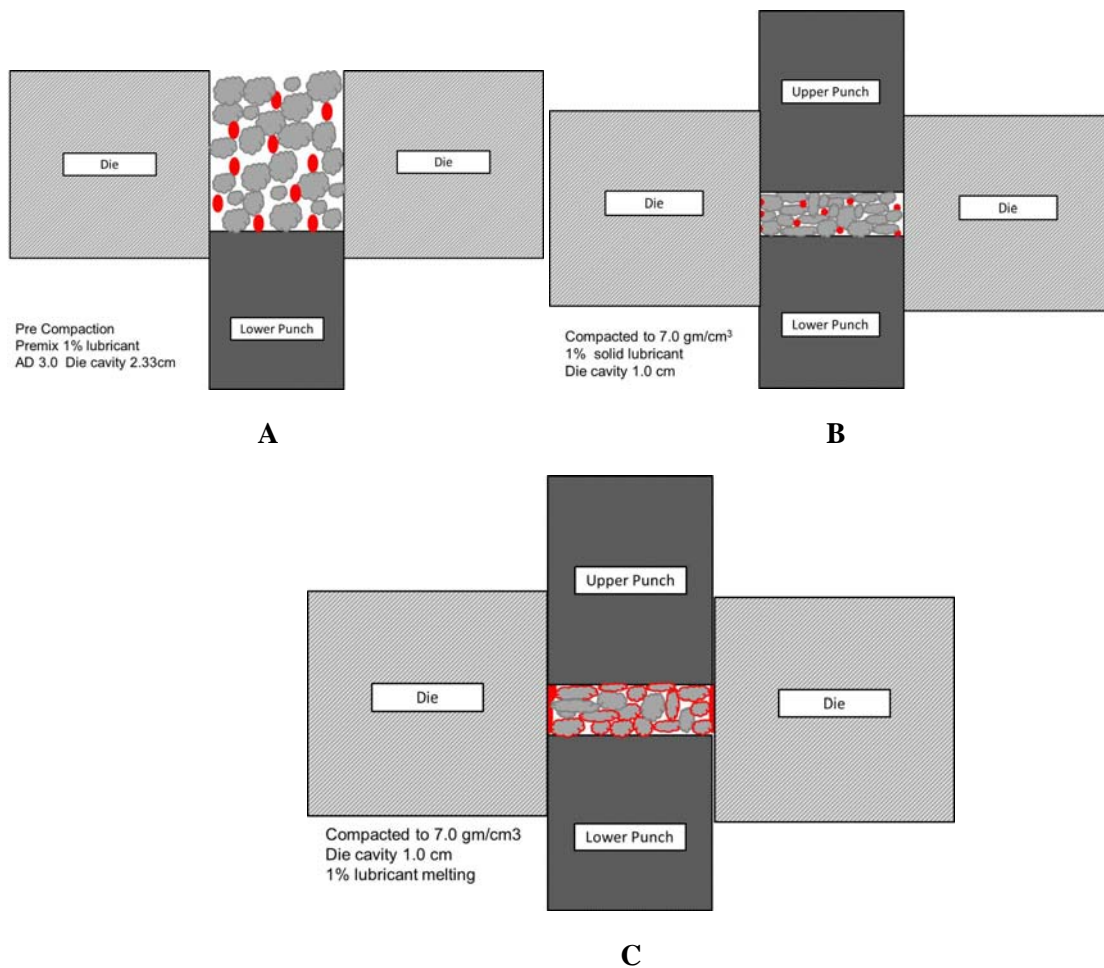


Figure 3. Schematic of compaction process and effect on lubricant, (A) die filling, (B) solid lubricant, (C) lubricant melting

Advanced lubrication systems, such as those used in warm compaction and warm die compaction, deform more during compaction compared to standard lubricants. The heat used during compaction softens the lubricant which aids in moving the lubricant to the die surface. In Figure 3C, a scenario is shown where the lubricant melts during compaction. This is typically to be avoided since a component rinsing step would be needed to remove the lubricant from the part surface. However, if the lubricant could completely coat the die surface, lower ejection forces would be observed.

To illustrate this concept, FC-0205 mixes were manufactured using two lubricants which have entirely different properties. The mixes manufactured are shown in Table 1.

Table 1: FC-0205 Composition of Mixes Manufactured for Fundamental Analysis (w/o)

Mix ID	Base Iron	Copper (%Cu)	Graphite (%C)	Lubricant (% Lube)
Stearic	ASC100.29	2	0.55	0.75 Stearic Acid
PolyEth	ASC100.29	2	0.55	0.75 Polyethylene

The main difference between the two lubricants is the melting point. Stearic acid has a relatively low melting point of 60 °C (140 °F) compared to the 104 °C (220 °F) melting point of polyethylene. To illustrate the effect melting point has on compaction, transverse rupture strength bars were compacted to a thickness of 13 mm (0.5 inch) at compaction pressures of 415, 550, and 690 MPa (30, 40, 50 tsi).⁷ Specimens were compacted using standard compaction and warm die compaction at a die temperature of 25 °C (75 °C) and 60 °C (140 °F) respectively. After compaction the specimens were measured for green density, green strength, and spring back.^{8,9,10} A standard thickness of 6.5 mm (0.25 in) was used for the determination of green strength.

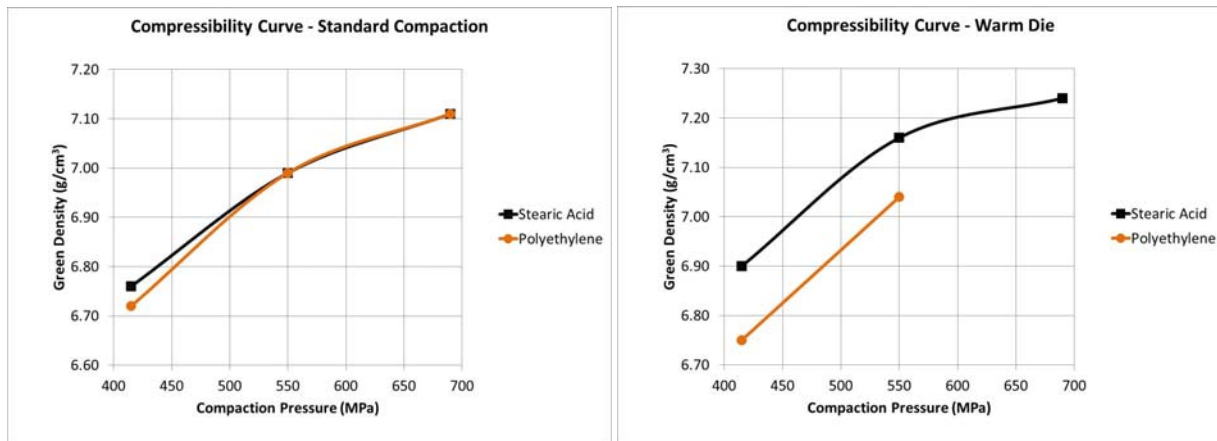


Figure 4. Compressibility curve for standard and warm die compaction of fundamental materials

At standard compaction temperature, there is no difference between the two materials. However, once the die is heated a large difference is observed. The stearic acid mix showed a large increase in green density compared to conventional compaction. This is due to the melting which the lubricant undertakes. Since the lubricant is squeezed toward the surface, more densification can take place due to the free space which the lubricant was occupying. Also, once the lubricant is liquid, compressibility increases compared to when it is in the solid state as liquids are more compressible than solids. The downside of the increased compressibility due to melting of the lubricant is that it pools at the surface. Photographs of the TRS bars after warm die compaction at 550 MPa (40 tsi) are shown in Figure 5.

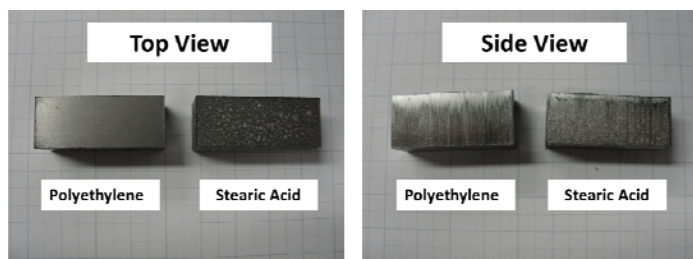


Figure 5. Photographs of fundamental materials at 550 MPa (40 tsi) compaction pressure

The polyethylene material showed no signs of melting. However, at the 550 MPa compaction pressure, a large amount of scoring was found on the side of the part. Noises associated with poor ejection were also observed. With these two phenomena occurring, compaction at the highest compaction pressure was not completed. The difference between standard compaction and warm die compaction is illustrated in the ejection performance of the lubricants. SEM images were taken on the sliding surface of the two materials. The images are shown in Figure 6.

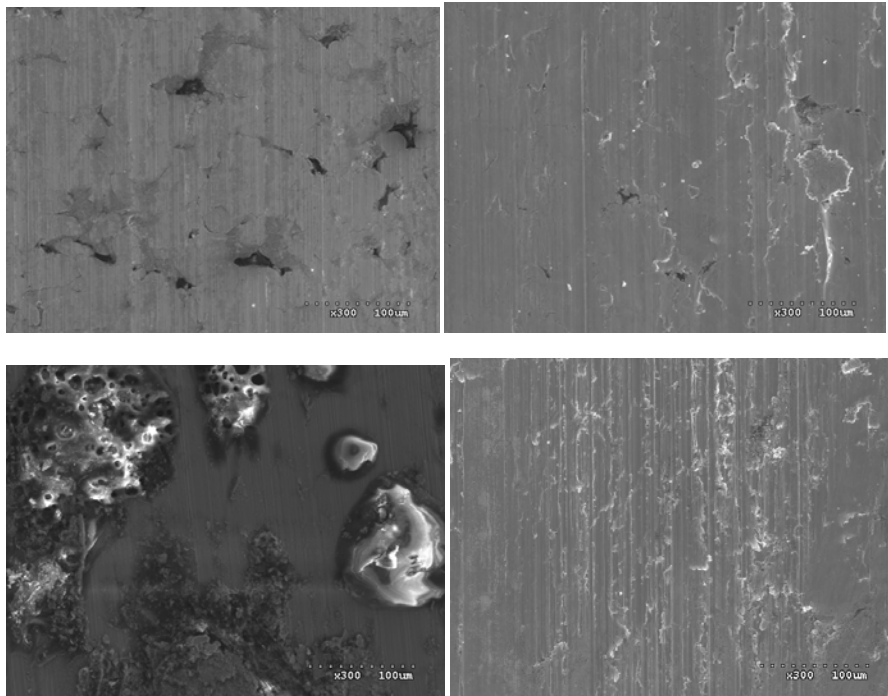


Figure 6. SEM images of TRS bars: top left – stearic acid standard compaction, top right – polyethylene standard compaction, bottom left – stearic acid warm die compaction, bottom Right – polyethylene warm die compaction

The polyethylene at both compaction temperatures exhibits similar behavior. Scoring on the surface is observed and the lubricant is found “smeared” on the surface. The stearic acid during standard compaction shows less scoring and is observed covering most of the surface. Once heated, the lubricant melts and pools on the surface as shown in Figure 6..

Standard thickness transverse rupture strength specimens were compacted using the same pressures and die temperatures for both lubricants. The green strength of the fundamental materials was evaluated and the results are shown in Figure 7.

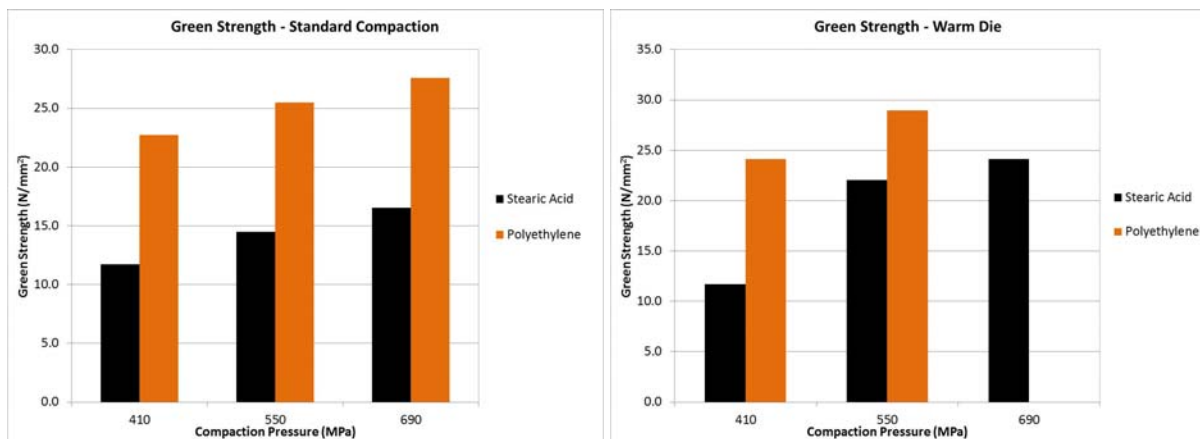


Figure 7. Green strength - fundamental materials

Both fundamental materials achieved increasing green strength as the density increased. The polyethylene material had significantly higher green strength than the stearic acid. Green strengths over 20 MPa (2900 psi) were achieved at every compaction pressure. At the highest compaction pressure tested for polyethylene, 550 MPa (40 tsi), a green strength of 29 MPa (4200 psi) was achieved.

The green expansion of the transverse rupture strength bars was measured for each compaction condition. The results are observed in Figure 8.

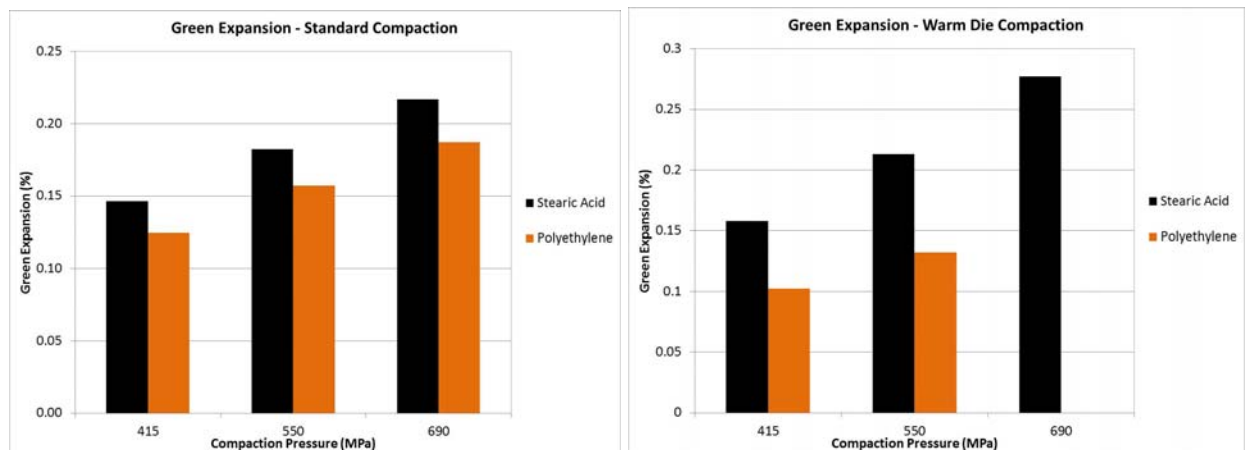


Figure 8. Green expansion – fundamental materials

Green expansion is a measure of the energy stored in a component. Once removed from the solid die, the energy is released and the component expands. For the two lubricants investigated, green expansion increases as compaction pressure increases. This is expected as more energy is transferred to the component as the compaction pressure increases. However, increasing the die temperature resulted in a different response from the two lubricants. For stearic acid, the amount of green expansion increases dramatically as die temperature increases. This is a function of lubricant melting. More energy is able to be stored in the component because of the space voided by the melting lubricant which is squeezed to the surface. Also due to the liquid nature of the stearic acid at the elevated die temperature, a hydraulic effect occurs in the component. Once the stearic acid becomes liquid, it acts as a hydraulic fluid which transmits energy more efficiently. Since the energy is transmitted more efficiently, more energy is inputted into the component.

For polyethylene, the green expansion decreases slightly once heat is applied to the die. Since the melting point of polyethylene is higher than the die temperature, the lubricant does not melt and the energy transmission from compaction to the component is not efficient.

In summary, the design of a lubricant is extremely critical for warm die compaction. A melting point too high or too low will result in decreased compressibility or liquification of the lubricant during compaction. This characteristic also plays a role in the ejection performance of the lubricant. Optimizing the lubricant to work with warm die compaction is extremely important in order to have a robust material solution. A new lubricant system has been developed and designed to be used in the warm die compaction process. This new lubricant system will be evaluated against an industry standard lubricant using different compaction pressures and die temperatures.

EXPERIMENTAL PROCEDURE

The new lubricant system (Intralube[®] E, Höganäs AB) was evaluated for suitability in warm die compaction against a common PM lubricant (Acrawax C, Lonza) at different lubricant addition levels. The lubricants were evaluated in a FC-0205 material system. The material composition of the mixes evaluated is shown in Table 2.

Table 2: FC-0205 Composition of Mixes Manufactured for Warm Die Compaction (w/o)

Mix ID	Base Iron	Copper (%Cu)	Graphite (%C)	Lubricant (% Lube)
Mix A	ASC100.29	2	0.55	0.75 Acrawax
Mix E1	ASC100.29	2	0.55	0.30 Intralube E
Mix E2	ASC100.29	2	0.55	0.50 Intralube E
Mix E3	ASC100.29	2	0.55	0.75 Intralube E

Premixes were manufactured in the NAH pilot mixing center. From each mix 40 mm (1.6 in) OD slugs were compacted to a thickness of 25 mm (1 inch) at compaction pressures of 415, 550, and 690 MPa (30, 40, 50 tsi).⁷ Specimens were compacted using standard compaction, warm die compaction with a die temperature of 60 °C (140 °F), and hot compaction at a die temperature of 95 °C (200 °F). After compaction the specimens were measured for green density and green expansion.^{8,9} Standard thickness TRS bars were compacted for the determination of green strength.¹⁰ The ejection characteristics were measured using an instrumented 100 T mechanical compaction press.

RESULTS – COMPRESSIBILITY

The compressibility curves for standard compaction, warm die and hot compaction are shown in Figure 9. During standard compaction, the two mixes with 0.75% lubricant had similar compressibility over the range of compaction pressures. The Mix E1 achieved the highest green density at the 690 MPa (50 tsi) compaction pressure due to the low amount of organic material present. However, at the 410 MPa (30 tsi) compaction pressure, this mix had the lowest green density. This is due to interparticle friction. The low amount of lubricant cannot move effectively between the particles to aid in densification due to the low energy input from compaction. At the lower compaction pressure, more lubricant is needed to overcome this phenomenon.

Once the temperature of the die is increased to 60 °C (140 °F), an increase in compressibility is observed for all of the mixes. While the mixes with 0.75% lubricant had similar performance during standard compaction, the Intralube[®] E mix had higher green density than the Acrawax mix with warm die. An increase of 0.03 g/cm³ was observed. For the mix with the lowest lubricant addition, no difference in green density was observed between standard and warm die compaction at compaction pressure of 410 MPa and 550 MPa (30 and 40 tsi). However, at the 690 MPa pressure (50 tsi), a small density gain of 0.03 g/cm³ was observed. Again, interparticle friction and the low lubricant level limit the compressibility of this material. The material with the best performance was Mix E2 with 0.5% lubricant addition. At this lubricant level, a density gain of 0.06 – 0.07 g/cm³ was observed over the range of pressures. At the highest compaction pressure, a density of 7.27 g/cm³ was achieved.

At the highest die temperature of 95 °C (200 °F), a different trend was observed. At this temperature, the mixes with the Intralube[®] E lubricant achieved higher density at all compaction pressures compared to the mix with Acrawax. However, the mix with the best performance was the Mix E2. This material continued

to gain compressibility while Mix E3 flattened at the higher compaction pressures. At the highest compaction pressure, Mix E2 was achieved a green density of 7.31 g/cm^3 .

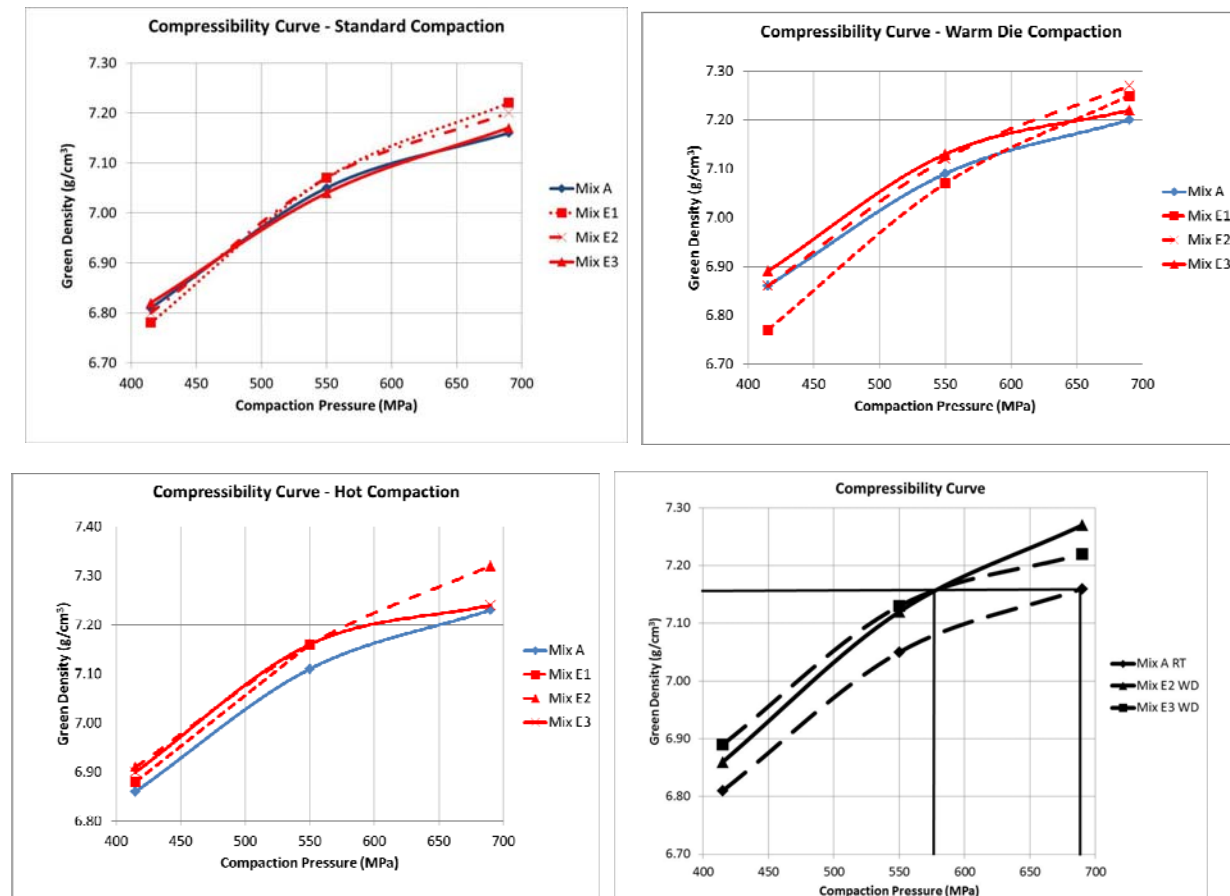


Figure 9. Compressibility curves – standard, warm die, hot compaction, & comparison

To evaluate the benefits of temperature addition to the compaction process, the industry standard material at room temperature was compared to Mix E2 and E3 under warm die compaction conditions. It was observed that compared to Mix A, the same density of 7.15 g/cm^3 could be achieved by Mixes E2 and E3 using 120 MPa less compaction pressure. This reduction in compaction force is similar to previously published data.¹¹ By using warm die compaction it would be possible to use the same compaction press to compact a larger part and still achieve density. It also allows the part fabricator to decrease the tonnage used allowing for a more consistent part over a compaction campaign.

The slope of the compaction curves between 550 MPa and 690 MPa (40 and 50 tsi) was calculated for Mix A using standard compaction, Mix E2 using warm die compaction and Mix E3 using hot compaction. The slopes are listed in Table 3.

Table 3. Slope of Selected Materials between 550 MPa and 690 MPa (40 and 50 tsi)

Property	Mix A Standard	Mix E2 Warm Die	Mix E3 Hot
Slope between 550 MPa & 690 MPa	0.000785	0.001071	0.000571

The slope of the compressibility curve is an indication on the amount of density which is still available to be gained and the lubricity remaining for the lubricant. As the slope decreases less density can be gained by increasing the compaction pressure. The slope of Mix A using standard compaction and mix E3 using hot compaction are similar and less than Mix E2 using warm die. This indicates there is little density to gain for Mix E2 by increasing the compaction pressure. The higher slope for Mix E2 is consistent with the optimum organic addition for this material system. A 0.5% lubricant addition leads to a higher pore free density compared to the 0.75% lubricant addition materials.

RESULTS – GREEN STRENGTH

Conventional transverse rupture strength bars with a 6.35 mm thickness (0.25 in) were compacted at each pressure and die temperature for the different mixes. The results of the green strength testing at 410 MPa (30 tsi) are shown in Figure 10.

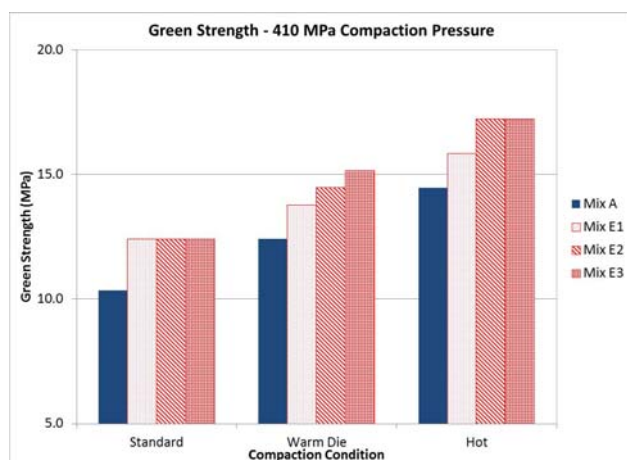


Figure 10. Green strength – standard, warm die, and hot compaction

Green cracks occur from three primary issues: poor surface finish on the tooling, improper motion of the tooling during compaction, and tensile stress during ejection.¹² If green cracks are present, the powder particles along the crack will not bond together during the sintering process leaving a weakened area in the component. The detection of green cracks can be difficult due to the inherent porosity of PM materials which creates noise during non – destructive testing techniques.^{13,14} To combat the threat of green cracks, sensitive parts often require the highest green strength possible.^{15, 16}

Since green strength is usually an issue at lower densities, the lowest compaction pressure tested was examined. The results show that the new lubricant system provides higher green strength regardless of compaction conditions. Once temperature is added to the compaction process, the new lubricant system provides an increased benefit. Green strengths of over 13 MPa (2000 psi) are achieved with warm die compaction. At this condition, Mix A achieves the same green strength as the new lubricant did using standard compaction. If the die temperature is increased, the new lubricant system attains a green strength of 17 MPa (2500 psi). The level of green strength achieved by the new lubricant system should be high enough to eliminate green cracks in most cases.

RESULTS – GREEN EXPANSION

Green expansion (spring back) measurements are presented in Figure 11. The measurement is critical as too much expansion can lead to green cracks and poor tolerances.¹²

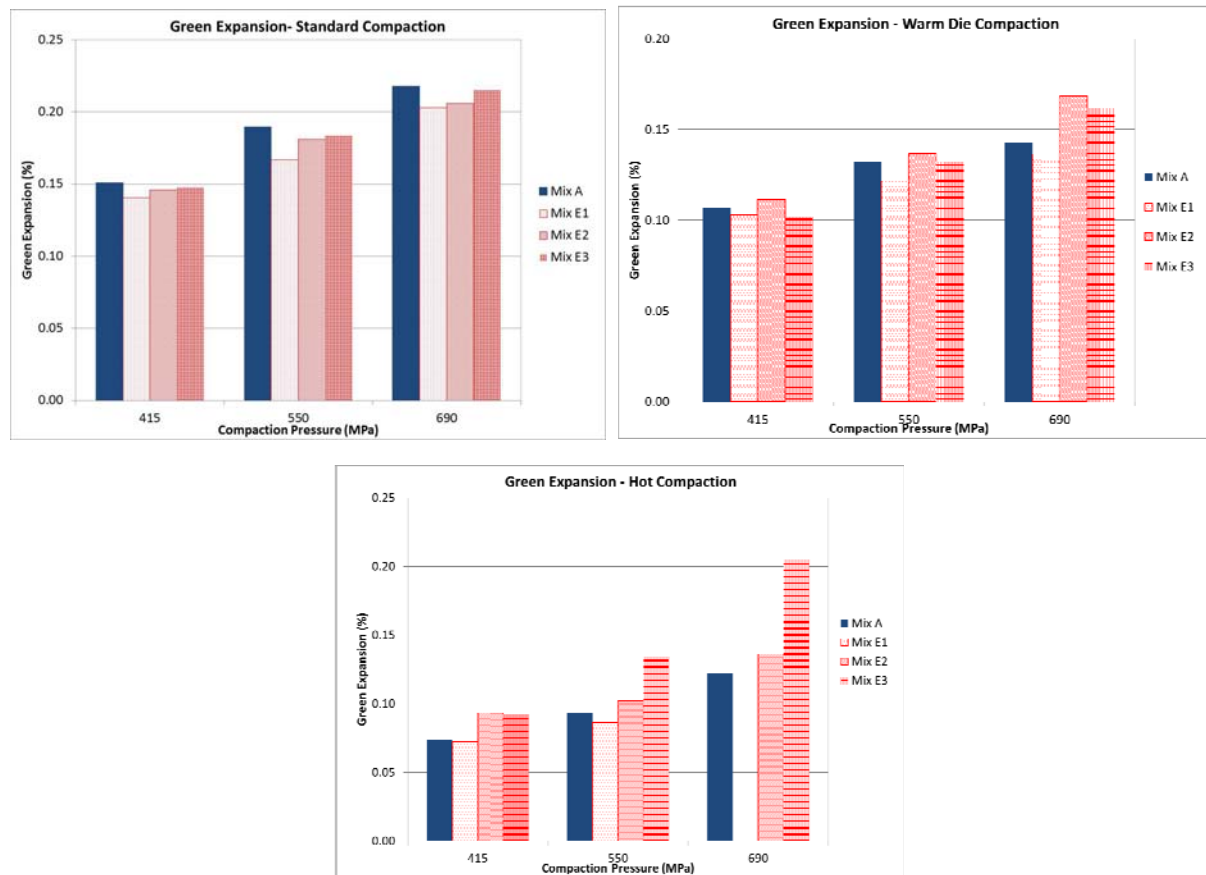


Figure 11. Green expansion – standard, warm die, and hot compaction

At standard compaction, Mix A had the largest amount of green expansion over the range of compaction pressure. Mix E3, which had the same amount of the new lubricant, had slightly lower green expansion than Mix A. Decreasing the amount of lubricant decreased the amount of green expansion.

When the die was heated to 60 °C (140 °F), a different trend was observed. In all cases, the green expansion was less than at standard compaction conditions. Using heat to reduce the amount of expansion could be beneficial for tight tolerance components. A decrease in green expansion was observed for all of the materials.

Under hot compaction conditions, Mixes E1 through E3 had the largest amount of green expansion. In the case of Mix E3, the green expansion was higher than at the 60 °C (140 °F) conditions. This is similar to the results observed in the analysis of the fundamental materials. At this die temperature, the new lubricant is close to its melting point which results in a hydraulic transfer of energy and more green expansion at the highest compaction pressure. Since the increase in green expansion is not larger than at standard conditions, we can surmise the lubricant did not completely melt.

RESULTS – EJECTION

The measurement of ejection performance is critical to understanding lubricant behavior. Two measurements are typically recorded. The stripping pressure or peak ejection force is a measure of the amount of pressure needed to start movement of a compact after compaction. This static force needs to be minimized to prevent green cracks.^{12,17} The amount of energy needed to keep the compact moving during ejection is called the sliding pressure or ejection energy. This property is related to the kinetic friction and should be stable until the component starts to exit the die.¹⁷ At this point, the ejection energy should decrease until the part is completely ejected. A schematic of a typical ejection curve is shown in Figure 12.

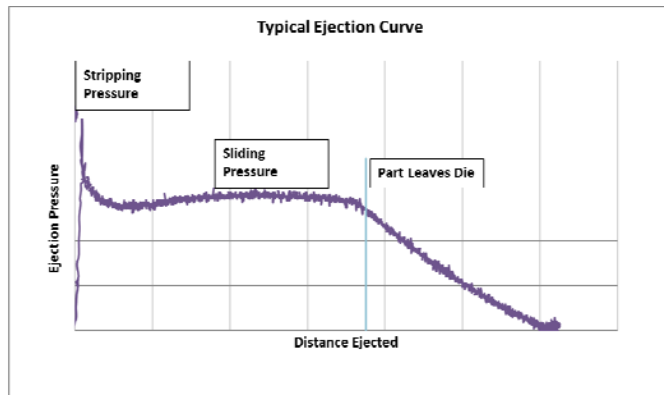


Figure 12. Typical ejection curve

An indication that the lubrication is not sufficient would be elevated stripping and sliding pressures. This indicates there is not enough lubrication to allow for easy movement of the part from the die after ejection. This could be related to insufficient level of lubricant, insufficient movement of lubricant during compaction or poor lubricity properties. Poor ejection characteristics can lead to increased risk for defects such as green cracks or premature wear of the compaction tooling.

Stripping and sliding pressures for the different materials under standard compaction conditions are shown in Figure 13.

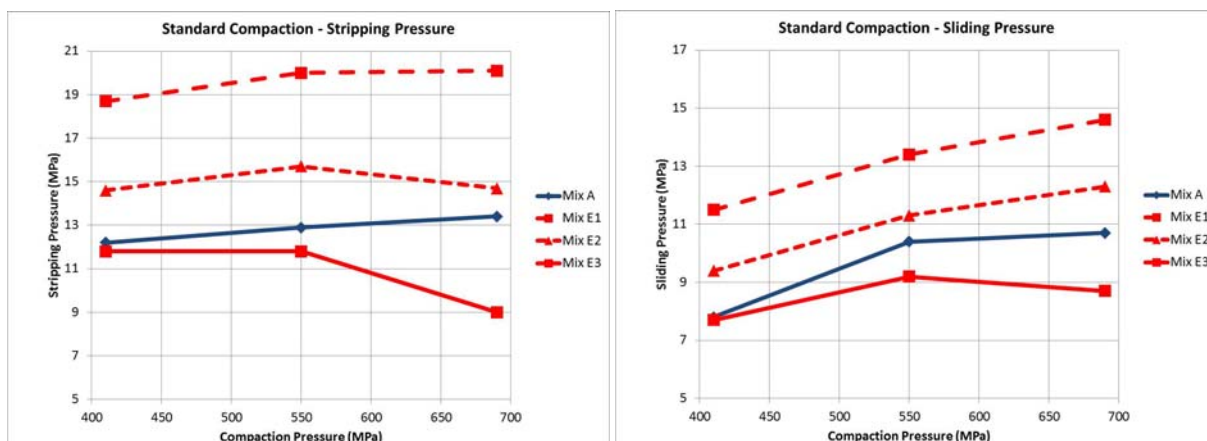


Figure 13. Stripping and sliding measurements – standard compaction conditions

Under these conditions, the mixes with the highest lubricant content had the lowest pressures as expected. The new lubricant system had lower pressures compared to the industry standard mix. At the highest

compaction pressure, Mix E3 reduced the ejection pressures by 30%. Mix E1 had the highest ejection pressures due to the low lubricant content. This indicates the lubricant is not able to move effectively to sufficiently coat the component for ejection.

The ejection characteristics for the new lubricant system under warm die conditions are compared to the industry standard lubricant under standard compaction conditions. This comparison is made due to the industry familiarity with these conditions. The results are shown in Figure 14.

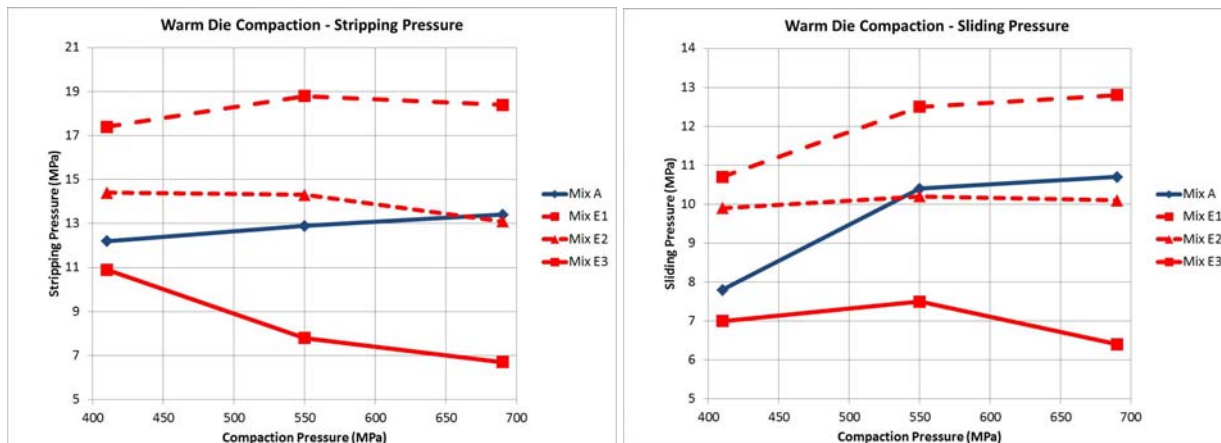


Figure 14. Stripping and sliding measurements – warm die compaction

Under these compaction conditions, all mixes had a decrease in the stripping and sliding pressure due to the heat introduced to the die. At this condition, Mix E2 has lower stripping and sliding pressures compared to the industry standard lubricant. Mix E3 provided a 50% improvement in lubricity compared to the industry standard lubricant. The slopes of the curves for E2 and E3 indicate stable lubrication between the tool surface and component surface. At the highest compaction pressure, a decrease in stripping and sliding pressure is found for these two mixes. The increased energy from compaction squeezes the lubricant out to provide a very good coating on the component surface.

DISCUSSION

The results of the testing showed that for both lubricant systems, the application of heat during the compaction process increased the green density achieved. For the industry standard lubricant, a gain of 0.05 g/cm^3 was achieved while the new lubricant system achieved an increase of 0.10 g/cm^3 at the highest compaction pressure of 690 MPa (50 tsi).

The heat used to increase the compressibility is a combination of frictional heat from compaction and the heat applied to the die. In this case, small specimens with a simple geometry were used to illustrate the potential gains in density. For larger components or components with a more complex geometry, more frictional heat will be generated. Controlling the total heat is critical to maintaining a robust process in a production environment. The heat must be controlled to limit the possibility of overheating and melting the lubricant. As was observed in the fundamental lubricant analysis, when the lubricant melts the possibility for liquid pooling on the surface of the parts becomes a concern. The green expansion also increases as the lubricant becomes more like a liquid. This would lead to a decrease in the tolerance capability of the process.

While controlling the frictional heat is important, controlling the heat applied to the die is just as critical. In the pictures below, two different methods were photographed using an infrared camera. One die is

heated using electrical cartridge heaters, while the other utilizes heated oil circulating through the die. The die with electrical cartridge heaters has much higher temperatures closer to the cartridge location. The die heated with hot oil provides a more even distribution of the heat with minimized hot spots.

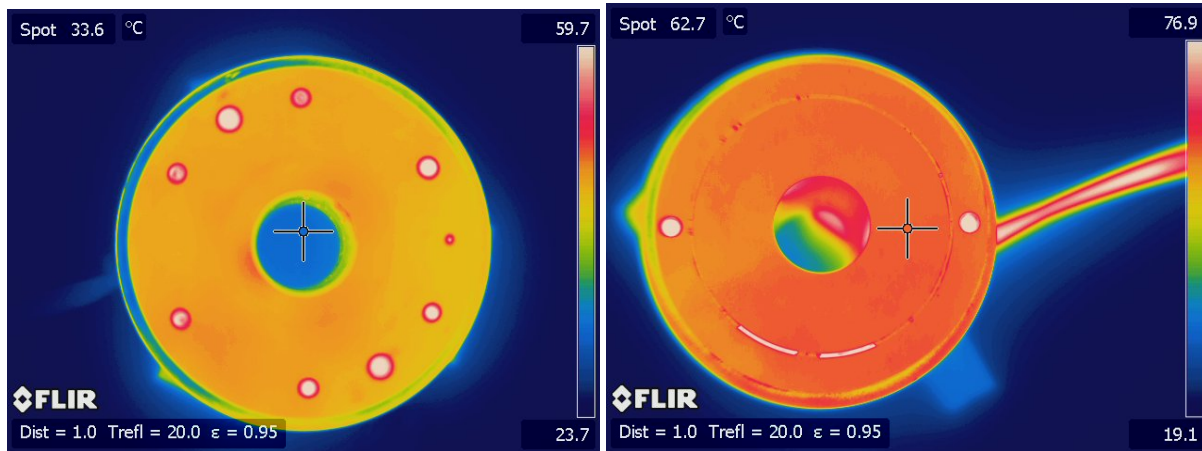


Figure 15. Infrared images of cartridge heated (left) and oil heated (right) die

Since the application of heat to the die produced an increase in green density, it is important to understand the reason behind the density gain. At similar lubricant levels, both lubricant systems provided an increase in density. This is due in part to better particle rearrangement in the die cavity because of the softened lubricant particles. Also the heat allows for easier deformation of the particles during compaction.¹¹ Both of these phenomena occur and are influenced by the amount of lubricant present and the pressure applied. It was shown that at low compaction pressure the mix with the lowest amount of lubricant also had the lowest green density. Conventional thought is that removing organic or low density materials from the mix composition is the key to achieving high green densities. This is true, but only at higher compaction pressures. The higher compaction pressures are needed to aid the lubricant in moving between the particles and assisting in overcoming particle to particle friction. At low compaction pressures, the energy input is not enough to overcome the interparticle friction.¹²

Examining these principles shows that an optimization is necessary to create a robust process. Understanding the geometry of the part, the compaction parameters and the lubricant performance characteristics is vital to maintaining a compaction process which will be robust enough for a production environment. Depending on the component geometry, the energy which the component will receive from compaction can vary creating density gradients through the part. These gradients can then result in differences in green strength and green expansion. By optimizing the lubricant and compaction parameters, green strengths high enough to eliminate the risk for green cracks can be achieved. At the lowest compaction pressure, the new lubricant system was observed to achieve green strengths of over 13 MPa (1900 psi) which is enough to reduce the risk of green cracks. Addition of heat to the compaction process only increased the green strengths which could be achieved.

Tolerances were also improved by addition of heat to the compaction process. Lower green expansion was observed for each lubricant at elevated compaction temperatures. Care needs to be taken to control the heat as green expansion can increase significantly if the lubricant liquefies or becomes too much like a hydraulic fluid.

In summary, a green density increase of 0.10 g/cm^3 can be achieved using warm die compaction. However, this is most likely the maximum that can be achieved in an ideal setting. The optimizations of

the compaction parameters and lubricant system which must occur to compensate for the geometry of the component limit the gain which can be practically achieved. Realistically, a green density increase of 0.05 – 0.07 g/cm³ should be expected for a complex shape in a production environment.

CONCLUSIONS

- Design of a lubricant system, especially with regards to melting point, is critical for functionality in a warm die compaction process. Melting points which are too high or too low can result in poor compressibility, liquification of the lubricant, and excessive green expansion.
- Using proper lubricant design, a green density improvement of 0.10 g/cm³ can be achieved under ideal conditions. Optimizing based on the component and processing lowers the realistic gain to 0.05 – 0.07 g/cm³.
- Addition of heat to the compaction process increase the green strength observed. Green strengths of 15 MPa (2200 psi) and higher were observed for the new lubricant system. These green strength levels are required to decrease the risk of green cracks in thin sections or low density regions.
- The new lubricant system was able to reduce the ejection pressures by 30 – 50% compared to the industry standard lubricant.

FURTHER WORK

This work focused on providing a fundamental analysis of warm die compaction in an ideal setting with a simple geometry. Future work will focus on evaluating this technology in a manufacturing environment. Variables such as method of heat application, part geometry and lubricant level will be evaluated.

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