EJECTION PERFORMANCE OF AN IMPROVED DIE WALL LUBRICATION TECHNOLOGY USING COMPOSITE LUBRICANTS

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ABSTRACT

A new approach in the method of depositing an external lubricant on the die walls of a powder metallurgy press has been developed which allows the compaction of parts from mixes with no or minimal lubricant content. By heating the die to moderate temperatures (70°C - 100°C) and using new composite lubricants, optimum thickness lubricant layers can be deposited allowing the compaction-ejection of difficult parts.

Trials were carried out on an industrial press with measurement of the compaction and ejection forces for different parts and powder mixes. In particular, an iron-resin powder mix with no internal lubricant was pressed into rectangular shapes of different thicknesses and punch profiles. Mixes for high density applications were also pressed into rectangular shapes using die wall lubrication (DWL). The results are compared to those obtained with regular mixes containing 0.75% wax and special mixes intended for high density applications (low internal lubricant) pressed without the DWL.

INTRODUCTION

Much effort has been devoted in recent years to the development of new compaction techniques leading to ferrous PM part densities above 7.20 g/cm^3 by single pressing / single sintering processes. Compaction techniques such as warm compaction (WC) and warm die compaction (WDC) increase part density and can be cost-competitive compared to double pressing / double sintering and forging techniques. Typically, final densities in the range of 7.25 to 7.45 g/cm^3 can be achieved after a single press/single sinter step with WC and WDC.

While there were multiple studies done on the efficiency of lubrication for press-ready mixes during their compaction and ejection, only small number of studies covered the efficiency of lubrication of a dedicated die wall lubrication system.[1-3] This technology is presently only in limited use for simple, low aspect ratio parts partly because the methods used to apply the lubricant on the walls of the die (such as electrostatic and tribostatic charging) limit the choice of lubricants and the coating thickness. Tribostatic charging is a complex technology and only certain material combinations provide acceptable charging effect [4], which furthermore has limited duration due to the unavoidable charge decay. Additionally, the lubricant layer thickness is limited as the lubricant itself becomes a barrier to the deposition of additional layers of the same lubricant. Since the force of metal particles moving along the wall during die filling typically exceeds that of the electrostatic attraction of the lubricant to the wall, the lubricant can be carried to the bottom of the die, creates agglomerates and eventually surface defects. An additional problem is that the best charging lubricants are not necessarily optimal for their lubrication effect.

The key factor in die wall lubrication is the surface wetting effect of a liquid lubricant. The adhesion of liquid to a solid surface far exceeds that of electrostatic forces between surfaces and particles, and provides better resistance to the mechanical forces of moving powder particles during the die filling operation. A combination of a solid and liquid lubrication product which causes a liquid phase to appear on the die wall directly during application thus allows the mixture to adhere to the walls effectively, resisting the powder friction during die cavity filling. If the solid and liquid portions of the lubricant are chosen to resist the high shear stress of the die pressing and ejection cycle, such mixture becomes a highly efficient die wall lubricant even for high aspect ratio parts. The development of the die wall lubrication system used in this work is based on the importance of the lubricant preparation and application methods.

The following diagrams and photograph in Figure 1 outline the features of the recently developed lubrication system capable of applying composite lubricant layers with adjustable thickness and high adhesion to the die walls. Moreover, in operation, the excess lubricant (overspray) is collected and recycled in the system leaving a cleaner environment around the press.

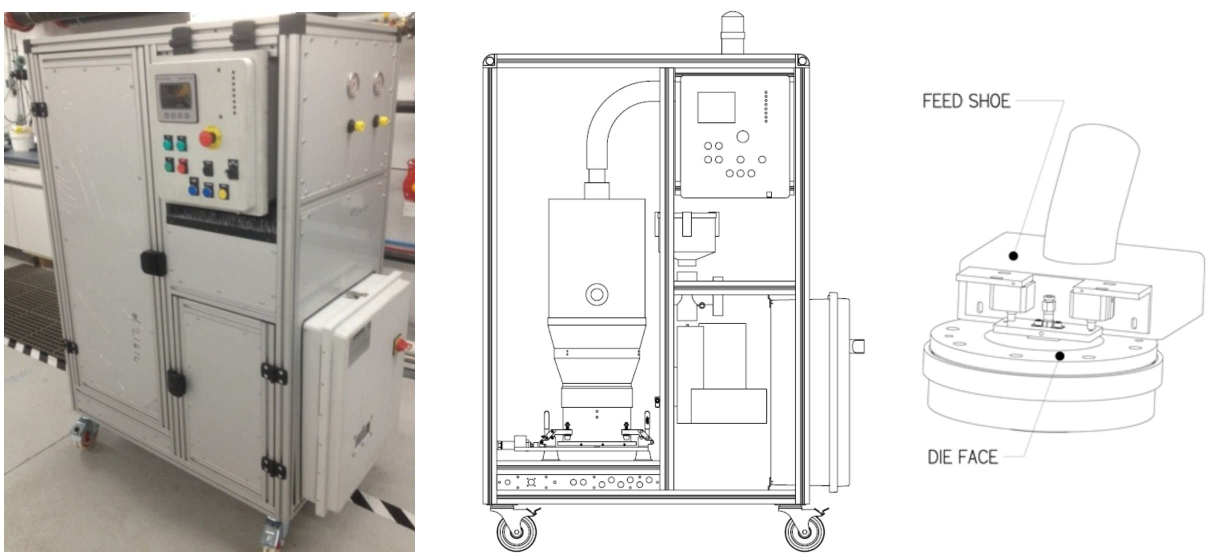

Figure 1. The IMFINE[*] die wall lubrication system: photograph and diagram of the dosing unit with the recycling system and control panel and a detail of the lubricant delivery nozzle attached to the feed shoe.

A unique application area for the use of a DWL system is the production of PM parts based on SMC (Soft Magnetic Composite) powders, specifically engineered for AC magnetic applications. Such parts compete against laminations in various electromagnetic devices including electric motors. The general principle of these materials is based on iron particles insulated by a thin organic or inorganic coating, or a combination of both. This thin coating acts primarily as an electrical barrier to suppress Eddy currents in AC fields while providing magnetic flux path in three dimensions. After consolidation into pressed parts, SMC parts are heat treated at low temperature in order to achieve moderate strength and some extent of stress relief.

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By minimizing or even eliminating the internal lubricant, higher densities and magnetic performance can be achieved.

Another interesting area for the use of the DWL technology is the production of high density parts targeted for improved static and dynamic properties. The possibility to reduce the amount of internal lubricant is a key factor in these cases. Using DWL, the level of internal lubricant in premixes can be kept very low, typically below 0.2%. The possibility to reduce the internal lubricant level in premixes is also desirable for environment reasons and cost reduction.

In this paper, two case studies are presented in which the new DWL system was used for the production of SMC parts and high density parts. The emphasis is placed on the compaction and ejection behaviour of these mixes under different conditions.

EXPERIMENTAL PROCEDURE

The compaction and ejection behaviour of the mixes was evaluated on a 150 T (1335 kN) mechanical press at the National Research Council Canada (NRCC in Boucherville, Quebec). The bottom punch was equipped with strain gauges in order to monitor the compaction and ejection forces applied on the parts. A tool steel die was used for the compaction of thick bars similar in shape to standard transverse rupture bars: 34.82 mm (1.371 in) long by 13.23 mm (0.521 in) wide and at least 25.4 mm (1 in) high. The warm die compaction technique was used with the die heated between 60°C (140°F) and 90°C (195°F) and the powder kept at room temperature. The DWL machine was synchronized with the feed shoe movement and the excess lubricant spray recirculated. Compressibility curves were generated for all mixes tested in this study by compacting thick bars in manual mode. The process variability or stability was assessed by pressing thick bars in automatic mode at a stroke rate of five parts per minute (speed selected for comparison purposes only – not a process limitation).

For each compacted bar, an ejection curve which records the ejection force as a function of the elapsed time was produced by the press software. The curves were analysed using a custom software and the maximum force corresponding to the stripping force was extracted for each bar and converted to a shear stress by calculating the maximum force divided by the lateral friction surface area (= 2 x (length + width) x height). The density of the specimens was measured using the Archimedes' method.

CASE STUDIES

Part I: Compaction of the iron-resin powder mix with no internal lubricant

The DWL system was used for the compaction of ATOMET EM-1, an iron-resin soft magnetic composite powder [5] manufactured by Rio Tinto Metal Powders. This material is produced from a high purity water-atomized iron powder, providing high compressibility achieving high densities and good magnetic properties, and organic compounds providing the electrical insulation and strength. The powder mix has little internal lubricity capability and thus requires lubrication of the die walls during compaction. The main merit of this SMC material is its high strength which is partly attributable to the absence of internal lubricant. After pressing, parts are usually cured at a low temperature (160°C to 325°C) in air to cross-link the resin and achieve the high strength.

In addition to the compaction and ejection behaviour of the powder, several different aspects of the DWL performance were evaluated, including the type of composite lubricant, the part shape or design with different die filling arrangements and finally the stability or part-to-part consistency.

Powder compressibility and ejection behaviour

By lubricating the die walls with composite lubricants, it was possible to press ATOMET EM-1 bars at the maximum achievable thickness allowed by the press, e.g., 100 mm in die cavity height corresponding to 36 mm high compacted bars weighing approximately 117 g. One of the green bars is shown in Figure 2 with a typical surface appearance due to a thin lubricant smear. Although the shape is simple, the ejection surface is rather large giving an M/Q ratio (friction surface /compacting surface) above 7. The compressibility of the mix was obtained by increasing the compaction force gradually and measuring the density of the green bars. The effect of increasing the compacting pressure on the stripping ejection pressure and density of the bars is illustrated in Figure 3 together with an ejection curve typical for a 7.25 g/cm³ density bar.

Figure 2. Surface appearance of a green bar with a typical lubricant smear.

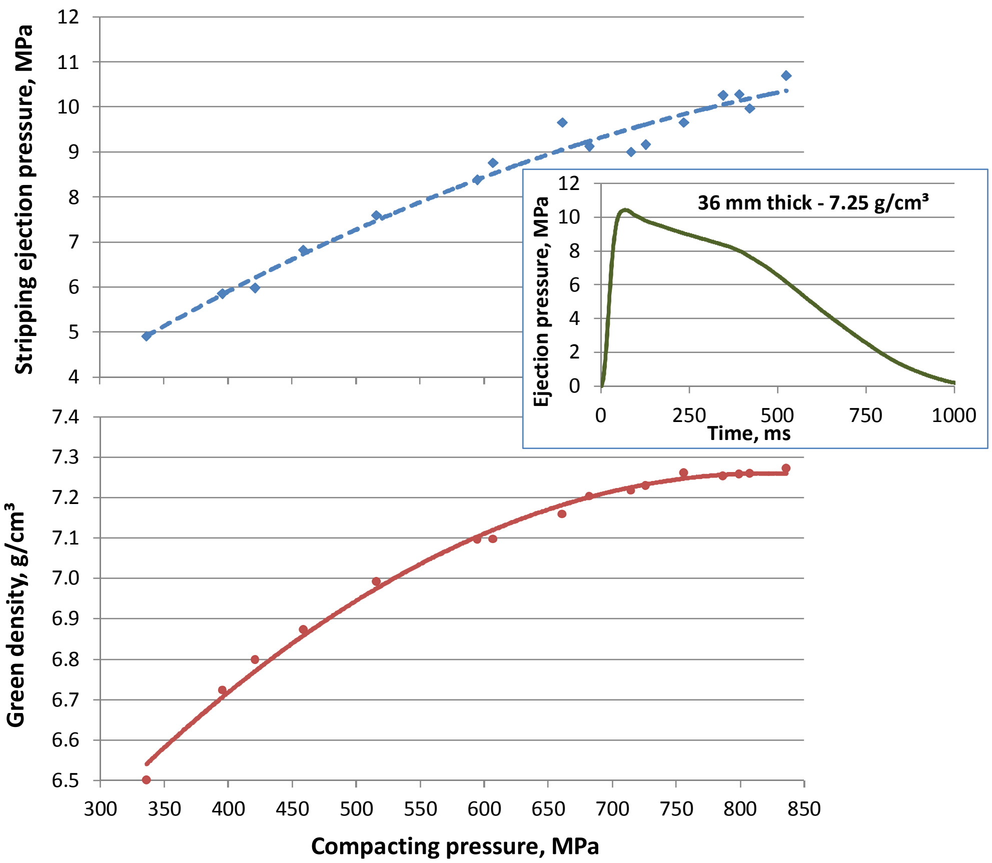


Figure 3. Stripping ejection pressure as a function of the compacting pressure (top) and compressibility curve (bottom) for the ATOMET EM-1 pressed in thick bars using DWL. Embedded graph shows a typical ejection curve for a 7.25 g/cm³ EM-1 thick bar.

The compaction and ejection of the bars were easy in all cases with a maximum stripping ejection pressure below 11 MPa (0.8 tsi) at densities around 7.25 g/cm³. By examining the embedded ejection curve, one can appreciate the ease of ejection with no high peak stripping pressure and rather smooth sliding of the bar out of the die (ejection pressure continuously decreases during ejection).

Effect of the type of external lubricant

Various external lubricant compositions were tested for the compaction of thick EM-1 bars and ejection curves are shown in Figure 4 for four composite lubricants sprayed on the die walls. What differentiates the curves is the height of the ejection peak and the sliding behaviour. For example, if Lub-A10P gives the lowest ejection peak at start, Lub-A5P gives the highest (50% higher). Lub-A10L gives a medium ejection peak and a smooth sliding with continuously decreasing pressures while Lub-B10P with the same ejection peak value shows a more difficult sliding with flat pressures that could even increase for longer parts exiting the die cavity.

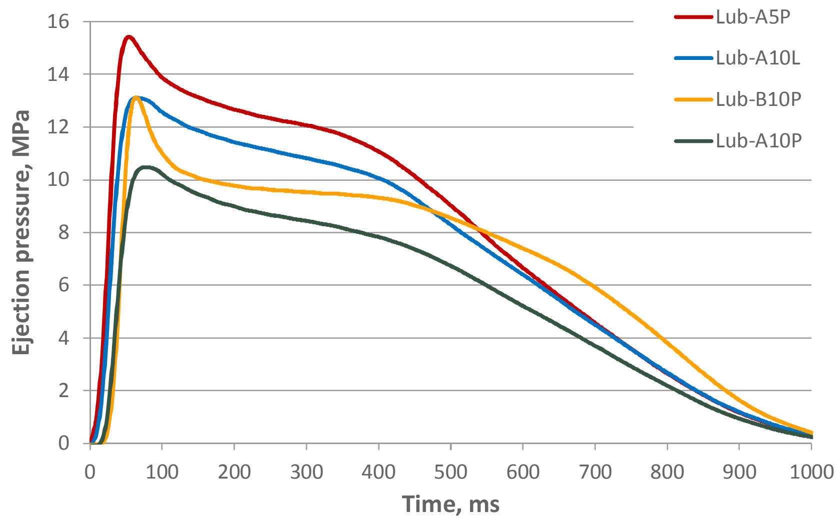


Figure 4. Ejection curves for EM-1 thick bars (30 mm) pressed to 7.20 g/cm³ using different composite lubricants sprayed on the die walls heated to 80°C.

These results suggest that different composite lubricants are available for spraying on the die walls (here a tool steel die) with a good ejection performance. Depending on the mix composition and the material of the tooling (tool steels or carbides), the lubricants exhibit different ejection behavior.

DWL process stability or part-to-part consistency

In order to evaluate the DWL process stability, a series of 500 regular thick EM-1 bars was pressed to 7.15 – 7.20 g/cm³ in automatic mode at a stroke rate of five parts per minute with the die heated to 80˚C. The compaction and peak ejection forces were recorded for all bars and the series was sampled every 10 bars for weight and geometric measurements. The temperature of the bars exiting the press was also measured at a lower frequency. These readings (compaction force, peak ejection force and part temperature) are reported graphically in Figure 5. The straight bars, approximately 35 mm high, were pressed by spraying 0.452 cm³ of an external composite lubricant on the die walls except for a short period of time during which the lubricant volume was increased to 0.804 cm³. Note that only a fraction of these lubricant volumes effectively stick to the die walls, the overspray being recovered and recycled in the DWL machine.

A first important observation is a sinusoidal pattern in the compaction forces and more obviously in the stripping ejection forces. This pattern proved to be related to the die temperature which is reflected in the bar temperature readings reported on the bottom graph in Figure 5 (secondary Y-axis). With the die heating system in place for this trial, a temperature variation of 10˚C could be measured for the parts (between 80˚C and 90˚C). In more recent tests, this variation in temperature has been reduced (within

5˚C). As shown in the bottom graph, the low stripping ejection forces correspond to the highest part temperature values. It is likely that a larger fraction of the lubricant volume sticks to the die walls when temperature increases, further reducing the compaction and ejection forces.

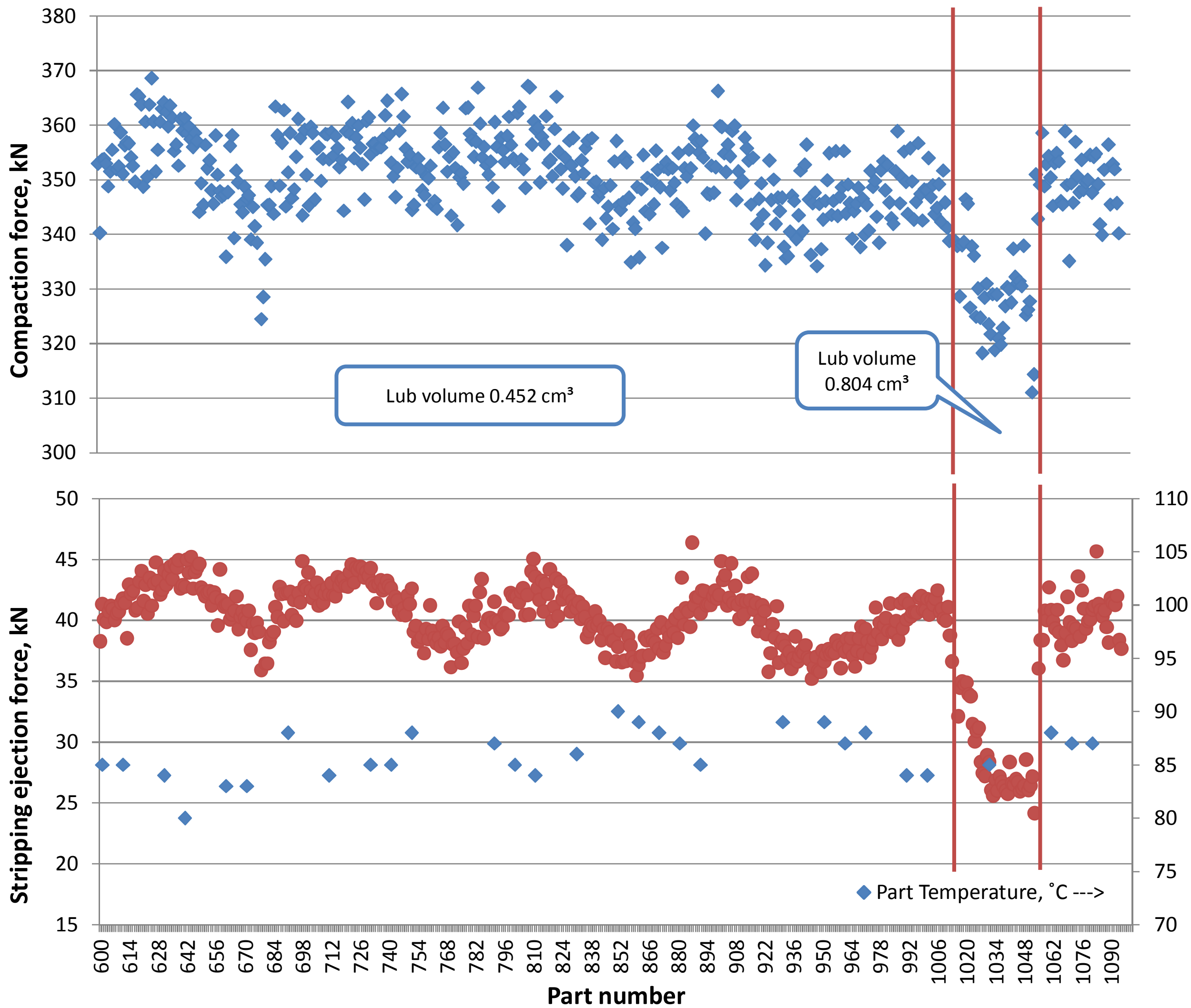
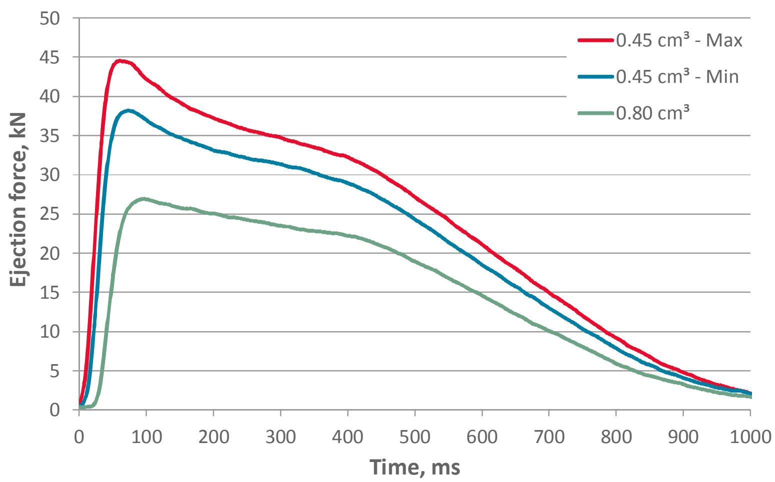


Figure 5. Compaction force (top) and striping ejection force (bottom) for the 500 ATOMET EM-1 bars pressed by spraying 0.452 cm³ of a composite lubricant on die walls (except for the #1015 to #1053 parts sprayed with 0.804 cm³ of the same lubricant). The temperature is also reported for some parts on the secondary Y-axis (in ˚C).

The second observation is the effect of increasing the injected composite lubricant volume: it further decreased both the compaction and ejection forces. For instance, typical ejection curves are plotted in Figure 6 for three cases: one high and one low ejection force curve (reflecting the variation range) for two bars pressed with 0.45 cm³ of composite lubricant sprayed on the die walls and a curve for one bar pressed with 0.80 cm³ of composite lubricant. Again, ejection was easy in all cases with no high stripping force at the start of ejection (almost no peak – only sliding forces).

Figure 6. Typical ejection curves for three of the bars pressed in the series: one curve from the high end and one curve from the low end of the ejection forces for two bars pressed with 0.45 cm³ of composite lubricant sprayed on the die walls and one curve for one bar pressed with 0.80 cm³ of composite lubricant.



However, this larger amount of composite lubricant sprayed on the die walls affected the pressed parts by decreasing the weight by about one gram and the density by about 0.05 g/cm³. In order to get relevant statistical data on the process stability, the analysis was carried out by excluding the data in the period of time where the lubricant volume was increased. The results of the statistical analysis are reported in Table 1 for 454 compaction and ejection data points and 47 weight, height and density data points.

Table 1. Statistical results for the series of ATOMET EM-1 thick bars pressed to 7.15-7.20 g/cm³ using DWL with the die heated to 80°C*: compaction and peak ejection forces (454 data points) and part weight, height and density (47 data points).

	Compaction force kN	Peak ejection force kN	Weight g	Height mm	Density g/cm³
MIN	342	35	115.4	34.95	7.15
MAX	369	46	116.5	35.10	7.19
Mean ± Std Dev	351 ± 7	40 ± 2	116.0 ± 0.3	35.03 ± 0.04	7.17 ± 0.01
Relative Std Dev	2.0%	5.5%	0.25%	0.12%	0.10%

* Tooling temperature variation of about 10°C.

At first sight the variation in compaction and peak ejection forces seem relatively high (up to 5.5%) but this variation includes the bias caused by the temperature variation (sinusoidal trend). By improving the temperature control, this relative variation would decrease, likely below 3%. Statistics obtained for the parts are much better with a relative variation in the weight of the parts of 0.25%. It is even better for the part height with half of this variation (0.12%). These results indicate that the DWL technology with the use of composite lubricants is well suited for the compaction and ejection of this type of SMC material with no internal lubricant. The process stability is good with data variation comparable to the conventional compaction process of press-ready mixes.

Effect of the part shape and die filling mode

Several trials were made using the same tooling with one of the two punches bevelled at an angle of 60° in order to measure the effect of non-symmetric shape (here a wedge) on the compaction and ejection behaviour as well as the density gradient in the parts. A schematic of the bevelled bar or wedge is shown in Figure 7 with the bevelled punch and die filling configurations. The bevelled punch could be installed in the top or bottom position and the feed shoe was modified in order to be able to partially fill in the cavity distributing more powder in the tip of the wedge were more powder is suitable. The three configurations were tested and their effects on the compressibility, ejection and density gradient measured.

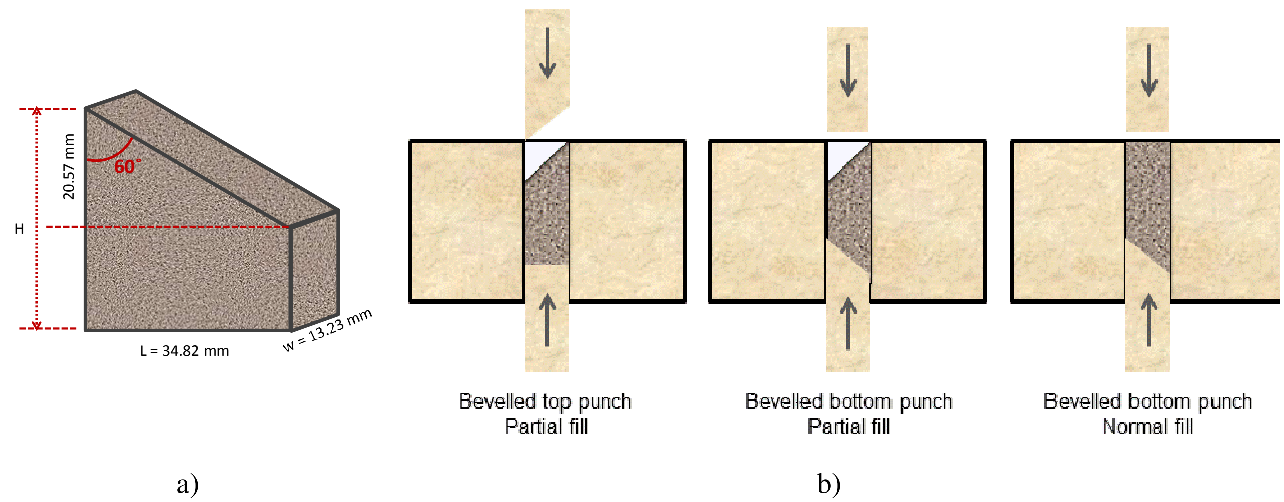


Figure 7. Bevelled bar schematics and dimensions (a) and the three configurations tested for the compaction of bevelled bars (wedges) (b): bevelled punch installed on top or bottom of the die and cavity filled completely (normal fill) or partially using a modified feed shoe.

With the bevelled punch installed upward (bottom punch), the effect of a partial or normal die filling on the compressibility and peak ejection pressure is illustrated in Figure 8. In all cases, the ejection was easy but slightly higher stripping pressures were measured for the normal fill mode (approximately 10% higher). The trials were made using the maximum achievable die fill height and consequently more powder could be fed in the cavity using the normal fill mode: 102 g and 40.9 mm high wedges versus 97 g and 39.4 mm high wedges for the partial fill mode. It was thus slightly more difficult to extract the larger wedges. However, the compressibility was not significantly affected by the die fill mode with densities in the 7.25-7.30 g/cm³ range achieved at high compacting pressures for both. In fact, the compressibility curves for these wedges are similar to that for straight bars (see Figure 3). It is noteworthy that the DWL system used with the same coating head and

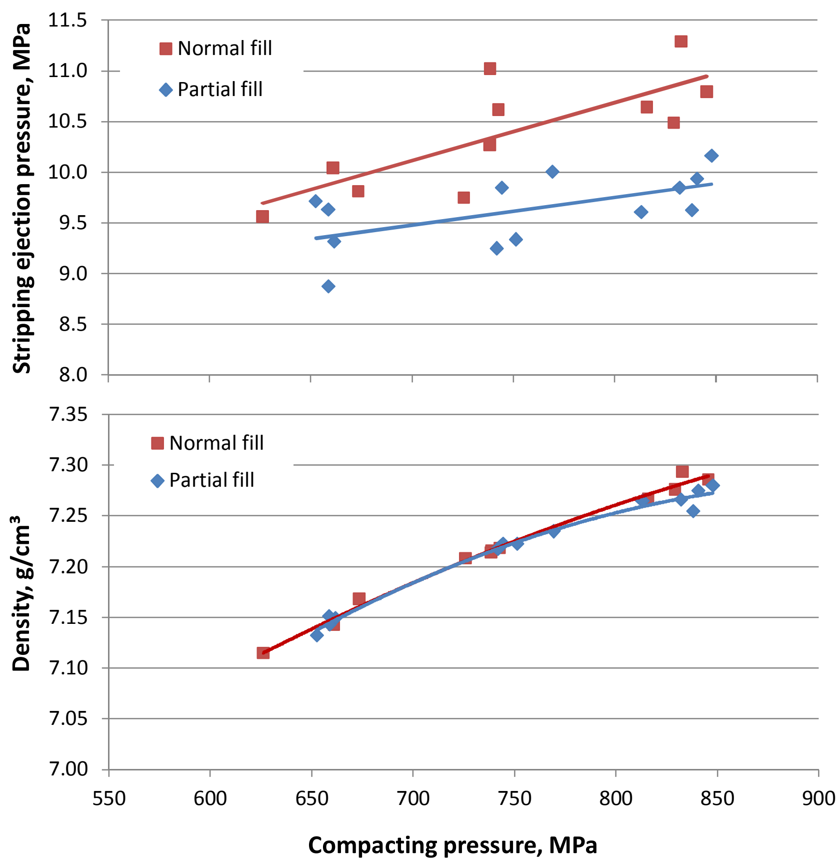


Figure 8. Effect of the compacting pressure and die filling mode (partial or normal) on the stripping ejection pressure (top) and density (bottom) of wedges pressed using a bevelled bottom punch.

composite lubricant produced an efficient lubricant layer on the die walls for the compaction of wedges. Recall that the SMC powder contains no internal lubricant.

The effect of having the bevelled punch installed on top or bottom side of the die on the densification (compressibility) was also measured. The effect of the position of the bevelled punch and die filling mode on the compressibility curve of the EM-1 wedges is illustrated in Figure 9 together with an embedded graph showing the effect on the ejection curve for wedges pressed to 7.25 g/cm³.

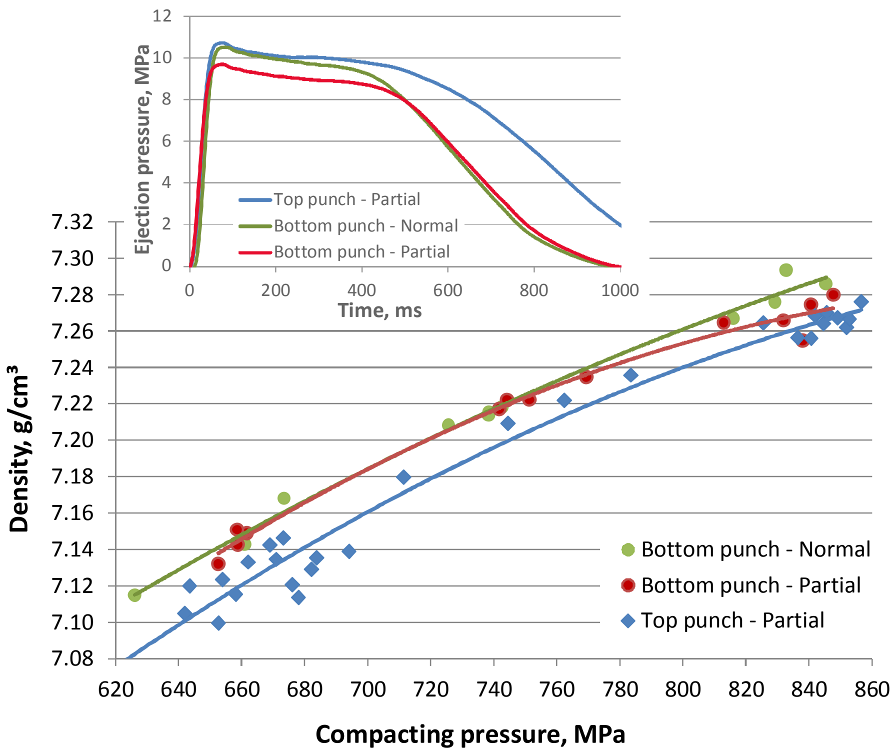


Figure 9. Effect of the position of the bevelled punch (top or bottom) and die filling mode (partial or normal) on the compressibility curve of the EM-1 wedges. The embedded top graph shows the effect on the ejection curve for the wedges pressed to 7.25 g/cm³.

Compressibility curves are very similar for all conditions but it is slightly easier to press EM-1 wedges with the bevelled punch in the bottom position; it requires approximately 20 MPa less compaction pressure to achieve a given density in the 7.0 to 7.2 g/cm³ density range. At higher densities (7.25 to 7.30 g/cm³), differences are even smaller.

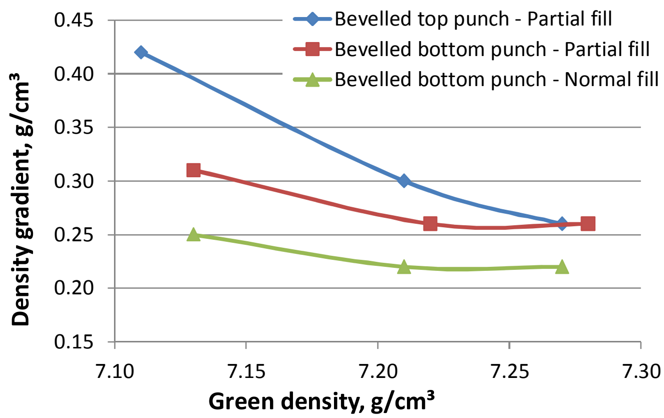
Regarding the ejection (embedded ejection curves), as seen previously, with the bevelled punch installed upward (bottom punch), it is slightly easier when a partial fill mode is used. It is noteworthy to see that the part ejection remains smooth with this angled punch which tends to induce lateral forces on the die walls during ejection. With the bevelled punch installed downward (top punch), the ejection is still easy but slightly more difficult due to the fact that the massive part of the wedge (large base) travels longer along the die walls during ejection. The peak ejection pressure is about the same but the sliding pressure remains high longer resulting in a larger amount of energy required to extract the wedges completely.

The effect on the density gradient within the pressed part of having the bevelled punch installed on top or bottom side of the die was also evaluated. This was done by cutting the wedges in four sections, as illustrated in Figure 10, and measuring their density in water. As expected, the highest density values were measured in the small height of the wedges (section 1) and lowest density values in the tip of the wedges (section 3), for all bevelled punch positions and both powder filling modes. This is due to the fact that the tip of the bevelled punch travels longer in the powder causing more densification in section 1. Indeed, there is some extent of powder transfer in the die during initial compaction but this does not

Figure 10. Identification of the 4 sections cut in the wedges.

result in a complete density homogenisation. This phenomenon is more obvious when using a normal fill mode and this is the reason for testing a partial fill mode which could compensate for the lack of powder transfer during compaction. The density gradient is defined as the difference in density between the small height and the tip sections of the wedges (sections 1 and 3). The effect of the position of the bevelled punch and die filling mode on this density gradient in the EM-1 wedges is given in Figure 11 as a function of the average part density.

Figure 11. Effect of the position of the bevelled punch (top or bottom) and die filling mode (partial or normal) on the density gradient in EM-1 wedges (difference between sections 1 and 3) as a function of the average part density.



The density gradient is larger with a bevelled punch installed in the top position. The smallest gradients were obtained with the bevelled punch in the bottom position and using a normal fill mode. It was expected that a partial fill mode would have reduced the density gradient but finally it did not; the density was found more uniform within the parts with a normal fill mode. This being said, whatever the configuration, the density gradients decrease with an increased overall density.

<u>Part II: Compaction of mixes for high density applications</u>

This case study was a continuation of previous studies [6,7] where formulations were tested for high density applications using another DWL system equipped with a confining block. Here, five FD-0205 formulations were prepared using ATOMET DB46, a diffusion-bonded steel powder containing 0.5% Mo, 1.75% Ni and 1.5% Cu manufactured by Rio Tinto Metal Powders, mixed with 0.5% graphite and different lubricants. The mixes and compaction parameters are described in Table 2. The first two mixes were pressed without lubrication of the die walls with the die heated to 60°C for reference purposes. The Ref mix with 0.7% wax serves as a benchmark for conventional compaction while the HD mix containing 0.5% of a higher performance lubricant serves as a reference mix for high density applications.

Table 2. Description of the FD-0205 type mixes and their compaction parameters.

Mix	Internal lubricant	Die temperature °C	Die wall lubrication	Bar height mm
Ref	0.7% Wax	60	No	25.4
HD	0.5% HD Lube			
DWL-L	0.1% Wax	80	Yes	25.4 & 38.1
DWL-H	0.25% Wax			
DWL-BT	0.25% Wax/Binder			

For the trials with die wall lubrication, the die was heated to 80°C and three mixes were pressed which contained a low level of internal lubricant: 0.1% or 0.25% admixed wax (in DWL-L or -H) and a binder-treated mix with 0.25% wax/binder (DWL-BT).

Effect of the amount and type of internal lubricant

The compressibility and stripping ejection pressure of the five mixes are compared in Figure 12 for 25.4 mm thick bars pressed according to their respective parameters. The less compressible material is the Ref mix (0.7% wax) pressed without die lubrication with a maximum achievable density of ~7.23 g/cm³ at 825 MPa (60 tsi). The HD material (0.5% HD lube), also pressed without die lubrication, reached a higher density at ~7.29 g/cm³. Now by spraying a composite lubricant on the die walls, the three mixes with a low level of internal lubricant (DWL-L, H and BT) reached a density of 7.30, 7.33 and 7.34 g/cm³ respectively at 825 MPa (60 tsi). As expected, by lowering the quantity of internal lubricant, higher densities could be achieved assuming the lubrication of the die walls was sufficiently effective. For the DWL-L mix with only 0.1% internal lubricant, it was even possible to press bars at a pressure as high as 1075 MPa (78 tsi) and reach a density of 7.47 g/cm³. The binder-treated mix appears slightly more compressible than the regular premix at low compacting pressures but less compressible at high compacting pressures.

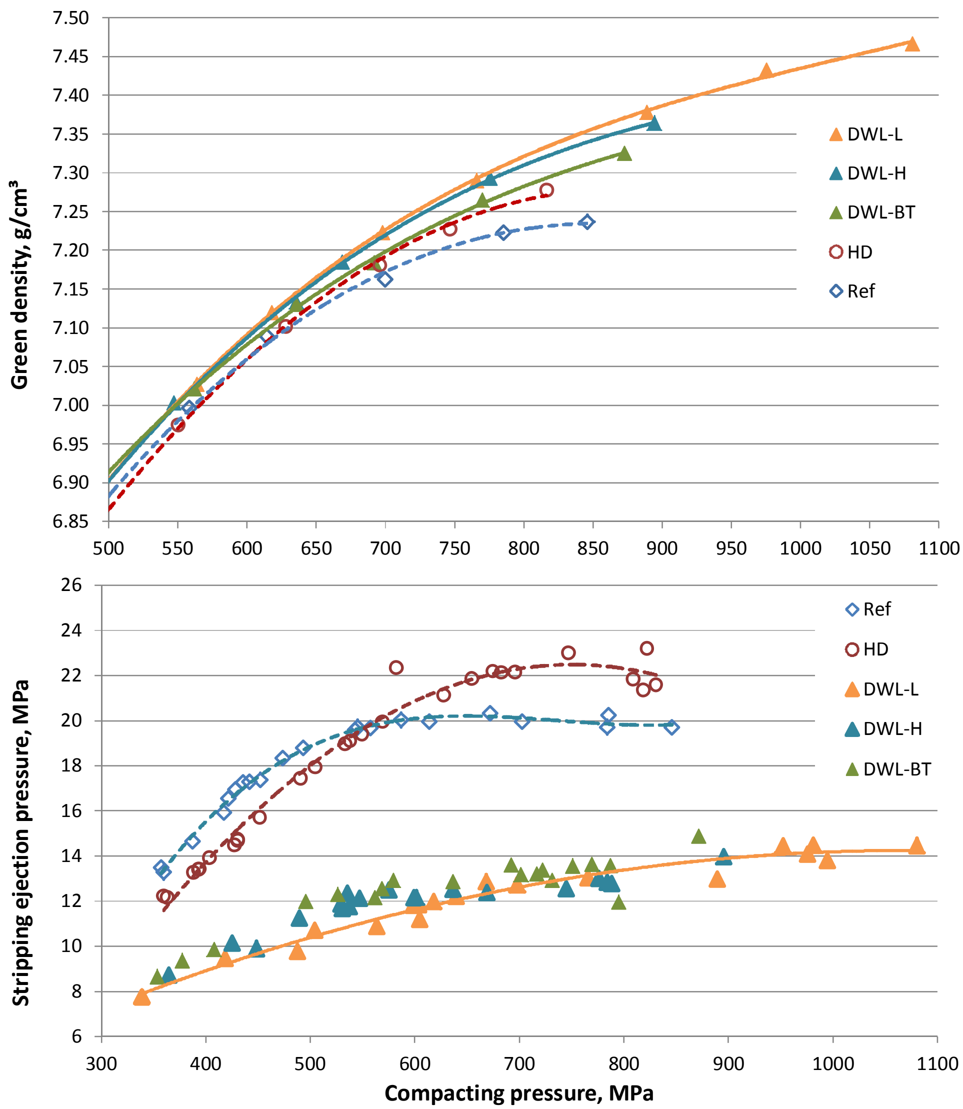


Figure 12. Compressibility (top) and stripping ejection pressure (bottom) as a function of the compacting pressure for the five FD-0205 mixes of the study pressed into 25.4 mm thick bars: the two mixes pressed without die lubrication (Ref & HD) and the three with die wall lubrication (DWL-L, -H & -BT).

There is a significant difference in compressibility between the mixes but the difference is much more striking in terms of their ejection behaviour, as can be seen on the bottom graph of Figure 12. This graph highlights the effect of lubricating the die walls with an important decrease of the stripping ejection pressures. For the two reference mixes, the stripping ejection pressure increases rapidly with the compacting pressure up to a maximum of about 20 MPa for the Ref mix and 23 MPa for the HD mix which contains a lower amount of internal lubricant (0.5% versus 0.7% for the Ref mix). On the other hand, with die lubrication, stripping pressures increased slowly with the compacting pressure and topped around 14 MPa for the three mixes. This represents a decrease of 40% in stripping pressure compared to the HD mix or 30% compared to the Ref mix. In order to better appreciate the differences in ejection behaviour, a typical ejection curve is shown in Figure 13 for four of these mixes pressed at around 800 MPa.

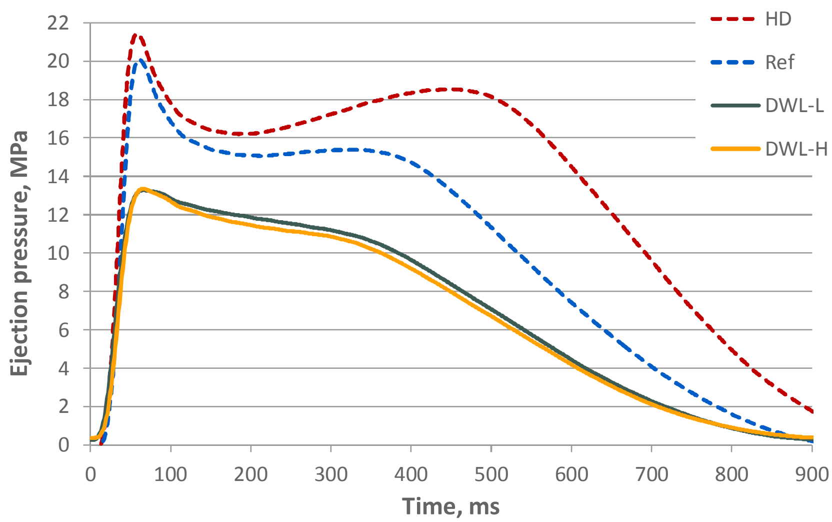


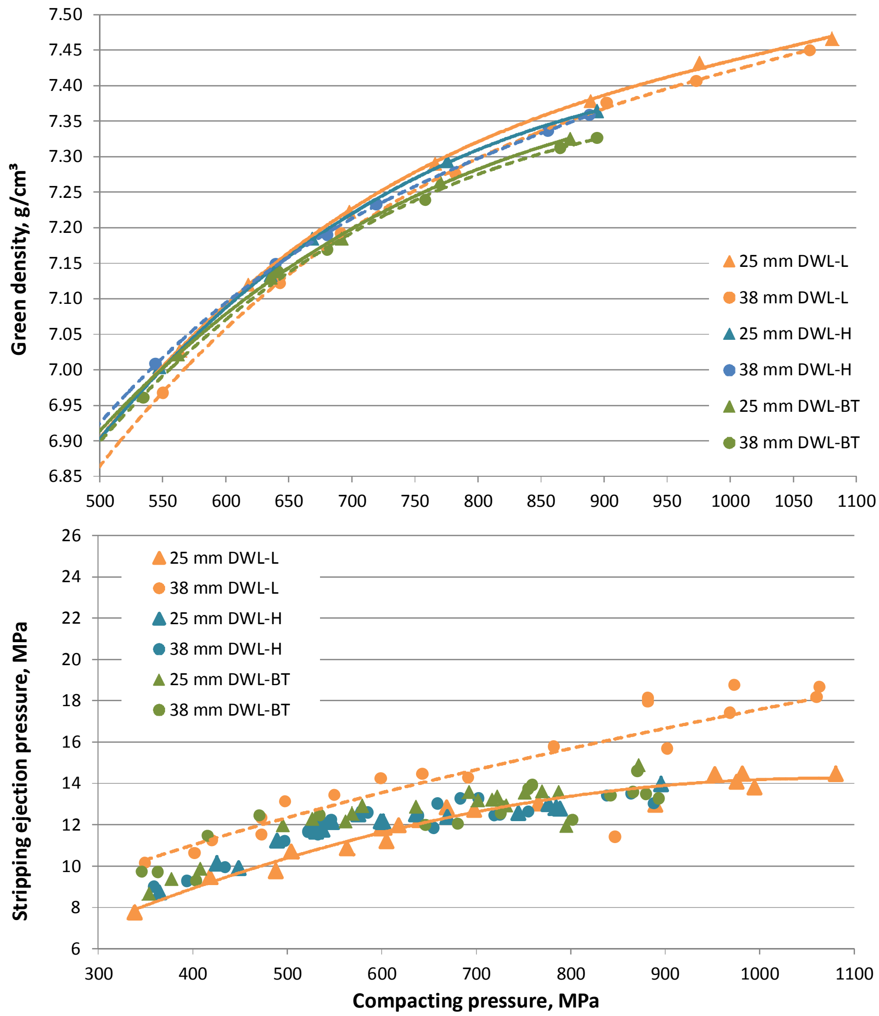
Figure 13. Typical ejection curves for the two reference materials (Ref & HD mixes without DWL) and two materials with DWL (DWL-L & -H) for 25.4 mm thick bars pressed at around 800 MPa (58 tsi).

The ejection curve for the Ref mix is typical of conventional press-ready mixes, e.g., a well-defined peak pressure (stripping) at start of ejection movement followed by a constant sliding pressure corresponding to the movement of the bar inside the die and then an out-die sliding pressure continuously decreasing as the part exits the die cavity. For the HD material, the start of the ejection is similar but the increase in sliding pressure is indicative of a lack of lubrication at die walls during ejection. It appears that a level of 0.5% of the HD lubricant was not sufficient for these bars pressed in a tool steel die (better results were obtained in a previous study for the compaction of rings in a carbide die) [7]. Note that a slight increase in the sliding pressure could be observed for the Ref mix also. Now by lubricating the die walls, the peak pressure disappeared and a continuously decreasing ejection pressure was measured all along the ejection movement indicating an easy and smooth ejection of the parts.

Effect of increasing the part thickness

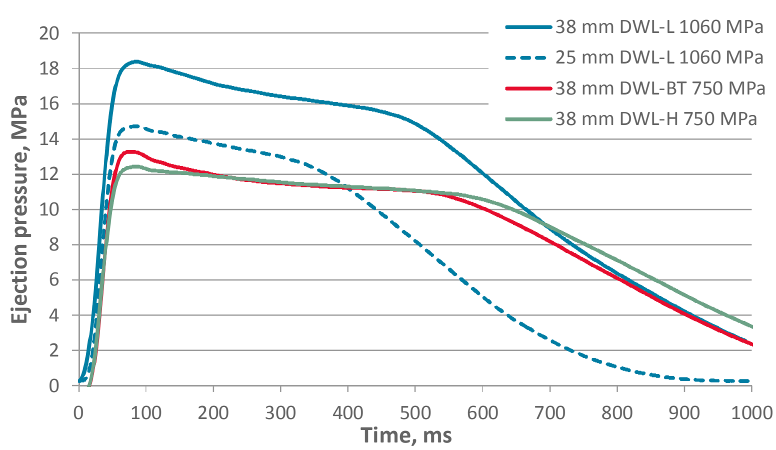
As stated earlier, the part thickness could not be increased for the two reference mixes (Ref and HD); the lubrication was not good enough. However, for the three mixes containing a low content of internal lubricant and use of the DWL technology, the ejection was easy and the part thickness was increased to 38.1 mm. Note that this represents a challenging ejection with an M/Q ratio of 7.9 (compared to 5.3 for the previous 25.4 mm thick parts). The compressibility and stripping ejection pressure for the three DWL mixes pressed into 25.4 and 38.1 mm thick bars are compared in Figure 14.

Figure 14. Effect of the part thickness (25.4 or 38.1 mm) and compacting pressure on the compressibility (top) and stripping ejection pressure (bottom) for the three FD-0205 mixes pressed using the die wall lubrication technology (DWL-L, -H & -BT).



It appears that the compressibility is little affected by an increase in the part thickness suggesting that the lubrication at the die walls is very efficient. Again, the maximum achievable density is dictated by the level of internal lubricant. Regarding the ejection (bottom graph), the two mixes containing 0.25% internal lubricant (DWL-H and -BT), exhibit very similar stripping pressures for 25.4 or 38.1 mm thick bars. The DWL-L mix with only 0.1% internal wax exhibits the same behaviour for 25.4 mm thick bars but higher stripping pressures for the 38.1 mm thick bars. In order to visualize how the ejection behaviour of these mixes used in combination with the DWL technology differs, a typical curve is shown in Figure 15 for four cases.

Figure 15. Ejection curve for four parts pressed from the three DWL mixes: two 38 mm thick bars pressed at 750 MPa from DWL-BT and -H mixes and two bars, 25.4 and 38.1 mm thick, pressed at 1060 MPa from the DWL-L mix.



In all cases, the ejection is smooth and easy with no peak ejection pressure as typically observed for conventional compaction with press-ready mixes. At 750 MPa compacting pressure, the ejection is very similar for all mixes (same curve for the DWL-L mix, not shown). By increasing the compacting pressure to 1060 MPa, even the most difficult ejection (38.1 mm thick bars) with the DWL-L mix is still easy (in comparison with the mixes pressed without DWL in Figure 13). The curve for the 25.4 mm thick bar is in the middle of the spectrum of the ejection curves confirming that the part thickness is not that critical when DWL is used.

CONCLUSIONS

Two case studies were presented in which an improved DWL system was used for the compaction of SMC and high density parts. The emphasis was put on their compaction and ejection behaviour as well as the DWL system performance. With the first case study where the ATOMET EM-1 containing no internal lubricant was pressed, different parameters were varied and the results show that:

- It was possible to press thick bars at the maximum achievable thickness allowed by the press, e.g., 36 mm high corresponding to an M/Q ratio greater than 7.
- The compaction and ejection were easy with ejection curves showing no high peak stripping pressure and smooth sliding of the bar out of the die (ejection pressure continuously decreasing during ejection).
- Different composite lubricants are available for spraying on the die walls with ejection performance depending on the mix composition and tool material (tool steels or carbides).
- The composite lubricants are sprayed on the walls of a heated die and the compaction and ejection pressures vary with the die temperature. This was observed for a span of 10°C in temperature variation of the pressed parts.
- In these conditions, the part-to-part variation was comparable to the conventional compaction process of press-ready mixes with a value of 0.25% in part weight variation and 0.12% in part height variation. It is expected that a better control of the die temperature would further reduce these variations.
- Changing the configuration of the punch (60° bevel) and die filling mode (partial and normal fill) did not affect the compaction and ejection behaviour significantly. In order to reduce density gradients in such cases, the best results were obtained with the bevelled punch in the bottom position and using a normal fill mode. As expected, in all cases, density gradients decrease with an increased part density.

For the second case study where high density parts were pressed, conventional compaction of press-ready mixes was compared to compaction of mixes with a low level of internal lubricant and use of DWL. The results show that:

- By using DWL, the maximum achievable densities increased due to the fact that the mixes contained a lower level of internal lubricant and the compacting pressure could be further increased. For instance, for the compaction of 25.4 mm thick parts, densities in the 7.25 to 7.30 g/cm^3 range were achieved using conventional compaction while 7.30 to 7.45 g/cm^3 were achieved using DWL (enabling application of compacting pressures up to 1075 MPa).
- In addition to increased density, the most beneficial effect of using DWL is related to the ejection behaviour with an important decrease of the stripping and sliding ejection pressures. For the three DWL mixes (-L, -H and -BT) a decrease of 40% in stripping pressure was obtained compared to the HD mix or 30% compared to the Ref mix.

- By using DWL, it was possible to increase the part height from 25.4 mm up to 38.1 mm with a smooth and easy ejection (this could not be done in conventional compaction using Ref and HD mixes).

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