BEHAVIOUR OF STEEL POWDER MIXES
PROCESSED BY WARM COMPACTION

by

S. St-Laurent and F. Chagnon

Quebec Metal Powders Limited

Paper presented at the 1998 PM World Congress & Exhibition
October 18-23, Granada, Spain.
Behaviour of Steel Powder Mixes Processed by Warm Compaction

S. St-Laurent and F. Chagnon
Quebec Metal Powders Ltd

Warm compaction is a technique which takes advantage of temperature to favour densification during compaction. Warm compaction requires powder mixes with specific physical characteristics to be adequately processed in the temperature range involved in warm pressing. The powder mix formulation, especially the lubricant/binder system, should provide good compressibility and lubrication of the die walls to ensure high green densities and low ejection forces. In addition, powder mixes should also provide good flowability and give very consistent part to part characteristics during production runs. Parts produced with this technique should at least meet similar dimensional and physical tolerances to those obtained with the conventional cold compaction processing route. This paper discusses powder mix characteristics required for warm compaction and how the part density is affected by the compaction parameters. Compacting conditions to optimise density, surface finish and part to part consistency are also discussed.

INTRODUCTION

Achievement of high sintered densities at reasonable cost is one of the major objectives of the P/M industry. Much effort is spent to develop and/or improve the densification techniques to achieve this goal. The warm compaction process, which was developed in the late 1980’s [1], is a densification route which consists of pressing a preheated powder mix in a heated die. It takes advantage of the fact that moderately increasing the temperature favours densification of parts [2,3], leading to an improvement of sintered densities [4,5]. Sintered density typically ranging between 7.25 and 7.45 g/cm³ can be achieved by warm compaction for compacting pressures not exceeding 690 MPa followed by a normal sintering. Still higher densities can be achieved with slightly higher compacting pressures and high temperature sintering [6].

However, powder mixes for warm pressing applications, especially the lubricant/binder system, should have specific physical characteristics. The lubricant/binder system should provide good compressibility and lubrication of die walls to enable high densities, low ejection forces and good surface finish. It should also ensure an excellent feeding of the die to obtain consistent part to part characteristics and meet dimensional and physical tolerances similar to those obtained with the conventional cold compaction processing route.

This paper reviews the major characteristics required for warm compaction and presents the behaviour of warm pressing mixes processed on lab and production scales. The influence of compacting parameters on green and sintered characteristics of parts made on a production scale and the part to part consistency are discussed.
GENERAL CHARACTERISTICS OF WARM PRESSING MIXES

It is well known that increasing the compacting temperature lowers the yield strength of steel particles and increases their ductility, leading to an increase of densification for a given applied pressure [3]. However, as for cold compaction, lubrication is needed to lower the internal friction between particles and the friction at die walls in order to enable high densification and ensure good transfer of the compaction force, low ejection forces and good surface finish. Therefore, the choice of the lubricant is of prime importance. This is illustrated in Figure 1 which shows the applied pressure needed to reach a density IN die of 7.25 g/cm³ as a function of temperature for three different high melting point lubricants. The density IN die is the density of compact under load. It is seen that lubricant C requires much lower applied pressures than lubricants A and B between 90 and 150°C. It is also seen that the applied pressure decreases with temperature with lubricant C while it remains stable for lubricant A and increases slightly with lubricant B. Therefore, lubricant C exhibits a much better aptitude for warm compaction than the two other lubricants.

The green density is also intrinsically related to the pore free density (PFD) which is the theoretical density if all the porosity is eliminated. It determines the upper limit which can be achieved during warm compaction. In practice, green densities up to 98% of PFD can be reached. The pore free density is strongly affected by the amount of low density additives such as lubricant, binder and graphite. Increasing their content in the mix significantly reduces the pore free density, and thus the green density achievable at high pressures. As a rule of thumb, each addition of 0.1% lubricant/binder decreases the pore free density by about 0.05 g/cm³. In the case of high densification processes such as warm compaction, the amount of organic materials should be kept as low as possible to maximise PFD. An addition of 0.6% lubricant suitable for warm compaction is a good compromise between the pore free density, the compressibility and the lubrication of die walls.

Powder mixes for warm pressing should also provide a good and consistent feeding of the die at the pre-heating temperature. The binder treatment plays a key role in the capacity of a powder mix to fill a die. It is already known that binder treatment improves the flow rate substantially [7]. The binder also favourably affects the apparent density as shown in Figure 2. First, it is seen that the apparent density as measured on a production press is very stable between 80 to 140°C with the binder treated mix while it varies for the regular mix. The binder treated mix is therefore more robust to temperature fluctuations which could occur during a production run and provides a larger working temperature range with the same apparent density. This is particularly important since the optimum compacting temperature, which is a function of part size, also varies in that temperature range. Secondly, a higher apparent density is obtained with the binder-treated mix compared to the regular mix due to the improved flowability. A higher apparent density is beneficial for densification since it lowers the die fill needed to reach a given weight and reduces the punch motion distance needed to reach a given density. This should help to reduce friction at the die walls during compaction and the energy needed for compaction. Finally, binder helps to stabilise the powder temperature by homogenising and regulating the heat absorption capacity of the powder. It is therefore much easier to control the powder temperature during production with binder-treated mixes, which reduces the time needed to set the conditions.

---

**Figure 1.** Variation of the applied pressure required to reach a density IN die of 7.25 g/cm³ as a function of temperature for FN-0205 mixes.

**Figure 2.** Variation of the apparent density as a function of powder temperature for binder-treated FLOMET WP and regular mixes [8].
for production.

**EFFECT OF COMPACTING PARAMETERS ON THE PROPERTIES OF GREEN AND SINTERED PARTS**

Most of the data on the compressibility of warm pressing mixes published so far were obtained on thin laboratory specimens, according to P/M standards. However, the properties and behaviour of powder mixes processed on a production scale is quite different than those obtained in lab equipment as shown in a previous study [8].

It is known that increasing the compacting temperature leads to a continuous increase of the green density of standard specimens pressed in the lab. However, the behaviour of powder mixes processed on a production scale is not necessarily the same. The compacting pressure as well as the part height also have a strong influence on the material response. Figure 3 shows the effect of the powder temperature on green density of FLOMET WP FN-0205 mixes for different compacting pressures. It can be seen for a compacting pressure of 550 MPa that green density increases continuously as powder temperature is raised. However, at higher compacting pressures such as 690 and 760 MPa, green density increases first, reaches a maximum in the range of 100 to 125°C and then decreases beyond that temperature. The reduction in green density above the optimum temperature is larger at 760 MPa than at 690 MPa. It is also interesting to note that the gain in density obtained by warm compaction decreases as the compacting pressure increases.

Figure 4 shows the variation of green density reached at 690 MPa as a function of powder temperature for three different part thickness. The relation between density and temperature obtained in the lab on 6 mm thick TRS bars is also shown. It is seen that the behaviour of specimens having a thickness of about 6 mm pressed both in lab and in production is similar, the green density increasing as temperature increases up to 145°C. A maximum density of about 7.30 g/cm³ is reached in both cases, which corresponds to 98% of theoretical density. However, increasing the thickness significantly modifies the behaviour of powder mixes. First, it leads to a reduction in green density at any temperature. Secondly, as was the case at high compacting pressures, green density reaches a plateau as temperature increases and drops when the powder temperature exceeds a certain value. It is clear that the optimum temperature range maximising green density, decreases when part thickness increases. It varies typically between 90 and 140°C. It should be noted that the temperature of parts ejected from the die is always higher than that of the powder entering the die as well as the tooling. In addition, pressing thicker parts generates more heat during the compaction and ejection cycle mainly due to the friction loss. This effect must be taken into account when pressing thicker parts and powder and tooling temperatures should be readjusted accordingly to consider these temperature changes.

The behaviour of powder mixes as part thickness and/or compacting pressure increases is somewhat surprising considering that the ductility of steel particles, and thus their compressibility, is improved. However, green density is not only a function of the compressibility of the steel particles. Lubricant also
plays a key role in compaction as shown in Figure 1. In addition, green density also depends on the volume expansion that parts undergo at ejection. This latter phenomenon, likely linked to the lubricant itself, is crucial in warm compaction at high stroke rates. Figure 5 shows the influence of powder temperature on springback and density for 13 mm thick parts pressed at 690 MPa. It is seen that the springback remains constant between 20 and 110°C while it increases beyond that temperature. This explains the reduction in green density shown on the top graph of Figure 5. It should be noted that temperature has a greater effect on springback when compacting pressure and/or part thickness increase. However, it is also seen that the reduction in green density due to an increase of springback has no detrimental effect on sintered density, which increases continuously with temperature. In fact, the loss in green density due to the springback is recovered after an adequate sintering.

Figure 6 shows the effect of thickness on springback and density of parts pressed at 120°C. Increasing the thickness leads to a significant increase of the springback. The same trend is observed at any temperature, the effect being however enlarged as the temperature is increased. Again, the increase in springback explains the reduction in green density when thickness is increased as shown on the top graph of Figure 6. However, as it was the case with the temperature, the sintered density is not adversely affected by the part size, contrary to the green density. Indeed, densities of 7.32 to 7.33 g/cm³ were achieved after sintering for all the parts, which is typical of the density achieved on TRS specimens pressed in the lab at 150°C and sintered under the same conditions.

It is clear from results in Figures 5 and 6 that the gain in density during sintering is a direct function of the springback. This indicates that springback is not only a function of the elastic deformation released at ejection but is also a measure of the energy stored in parts during compaction. This energy likely acts as a driving force for diffusion and densification during sintering. It is worth mentioning that springback is not significantly affected by the temperature or part thickness on a hydraulic press. The compaction rate plays a key role in the behaviour of powder mixes. Indeed, increasing the stroke rate on a mechanical press contributes to increase the springback and reduce the green density. However, the density loss is recovered during sintering.

**ROBUSTNESS AND CONSISTENCY OF FLOMET WP MIXES**

Achieving of high sintered density is the main goal pursued when using warm compaction. However, warm pressing mixes used in production should provide consistent part to part characteristics and meet the physical and dimensional tolerances typical of the P/M industry. This aspect is critical for parts manufacturing. It was already shown in Figure 2 that the apparent density of binder-treated mixes was quite stable in a range of 80 to 140°C, which corresponds to the optimum compacting temperature range to optimise green density and surface finish. The process capability and stability of warm pressing (WP) mixes processed under...
different conditions were evaluated in detail in a previous study [9].

Figure 7 shows the part weight variation obtained with FN-0205 and FL-4405 FLOMET WP mixes processed by cold compaction and warm compaction on a Cincinnati 220 TON press. The part pressed was a two level turbine hub with an overall thickness of about 18.5 mm for the FN-0205 and 12.7 mm for the FL-4405. The tooling temperature was set at 121°C for all the warm compaction runs while the powder temperature was controlled within ±2.5°C. The part weight variation, measured by dividing the range by two and by the average weight, varies between ±0.36 to ±0.54% for the warm compacted parts pressed between 100 and 145°C. These variations are typical of values obtained with other binder-treated WP mixes used to press different parts. For comparison, a part weight variation slightly higher at 0.68% was obtained with material B processed by the conventional cold compaction route. It should be mentioned this variations slightly higher than that are usually obtained with non binder treated materials processed by cold compaction.

The effect of thickness on the part weight variation of a FL-4405 mix processed by cold and warm compaction is shown in Figure 8. Warm compacted parts were pressed with a powder and tooling temperature of 110 and 121°C respectively. Again, an excellent stability of part weight was achieved by cold and warm compaction, the maximum variation obtained being ±0.68% for the cold pressed parts and ±0.61% for the warm pressed parts.

All the results shown in Figures 7 and 8 were obtained by controlling the powder temperature within ±2.5°C. However, the temperature variation during production may be greater for different reasons. Figure 9 shows the effect of powder temperature fluctuation on the part weight stability obtained with a FN-0205 and FL-4405 warm pressing mixes. It should be noted that temperature was intentionally varied during the production run. It can be observed that an increase of the powder temperature variation leads to a larger variation in part weight. However, the variation in part weight remains relatively low even when a large temperature fluctuation is induced to the powder. Indeed, the part weight variation obtained in the temperature range investigated remains below 0.7% even for a variation in powder temperature of about 30°C. This is comparable to the part weight variation measured on the cold compacted parts made with the FL-4405 mix, Figure 7. It can thus be concluded from these results that FLOMET WP is very robust to temperature fluctuation that may occur during a production run.

CONCLUSIONS
The characteristics required for warm compaction and the influence of different compacting parameters on the properties, behaviour and process capability of binder-treated Warm Pressing (WP) mixes were discussed in this paper. To summarise:

* The behaviour of WP mixes processed on a production scale is different than that obtained on a lab press mainly due to a higher compaction rate.
* Contrary to the lab results, green density does not necessarily increase with temperature on a production press. The optimum temperature to reach maximum green density is a function of the compacting pressure and part height. Increasing the compacting pressure and/or the part thickness lowers the optimum compaction temperature.
* The reduction in green density beyond the optimum temperature is directly related to an increase of the springback. However, a good sinter ensures recovery of density loss due to springback at ejection.
* Binder treatment improves flowability, stabilises the apparent density between 80 and 145°C and allows a much better temperature control by regulating the heat transfer to the powder.
* Part weight variations typically ranging from ±0.2 to ±0.6% are obtained when powder temperature varies in the optimum range.
* WP mixes are extremely robust to powder temperature fluctuation, part weight variations do not exceed ±0.7% even when temperature varies by 30°C.

**ACKNOWLEDGMENT**

The authors would like to express their warmest thanks to the people of QMP, Cincinnati Incorporated and the Industrial Material Institute of Canada who have contributed to this work.

**REFERENCES**