DESIGNING ROBUST POWDER MIXES
FOR WARM COMPACTION

by

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Paper presented at the 1997 International Conference
on Powder Metallurgy & Particulate Materials
June 29- July 2, Chicago.

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ABSTRACT

The mechanical properties of high performance P/M parts depend heavily on the material composition and the processing route. In particular, the processing route together with the material formulation greatly affect the final density which is a key factor and currently much effort is spent on developing processing routes and adequate materials to reach high density at reasonable cost. The warm compaction technique is a relatively novel process developed in late 1980's [1]. It consists of pressing preheated powder in a heated die, taking advantage of the fact that increasing the compacting temperature favors part densification, leading to an improvement of their sintered properties [2,3].

Warm compaction requires powder mixes with specific physical characteristics to be adequately processed. Powder mixes should not only enable high densities, good flow rates and low ejection forces but should also provide very consistent and stable part to part characteristics. Mixes should also be robust to some specific factors inherent to warm compaction such as the retention time of powder at a given temperature, temperature fluctuations and other factors.

The consistency and properties of binder treated materials specifically designed for warm compaction and processed on an industrial press were investigated. Specific test programs were conducted to quantify the effects of powder temperature on the consistency and stability of the compacting pressure and the green and sintered characteristics of parts. The robustness of powder mixes to temperature fluctuation and production interruption were also evaluated.

INTRODUCTION

For numerous P/M applications, high sintered densities, typically over 7.3 g/cm³, are needed to achieve high mechanical strength and toughness. Such high densities are difficult to reach with standard compaction and sintering conditions and costly processing routes are usually needed to reach these densities. The warm compaction technique, which consists in pressing a preheated powder mix in a heated die [1], is a relatively novel technique which increases green density, and in turn, sintered density [2,3] at reasonable costs. Final sintered density ranging typically between 7.25 and 7.45 g/cm³ can be achieved by warm compaction with adequate powder mixes in a single compaction/sintering cycle at a compacting pressure and a sintering temperature not exceeding 50 tsi (690 MPa) and 2050°F (1120°C) respectively [3,4]. Still higher densities could be achieved by combining warm compaction with high temperature sintering [5].

The effect of key compacting parameters on the characteristics and properties of parts manufactured on a production scale with binder-treated materials specifically designed for warm compaction has already been investigated and presented in a previous paper [6]. It has been shown that the green density reached on a production press with more complex and/or heavier parts could be quite different from that reached with small specimens on a lab press. In particular, the optimum powder and tooling temperatures maximizing the green and sintered properties on a production scale depend heavily on part thickness, compacting pressure and stroke rate.

However, powder mixes used for warm pressing should not only provide good compressibility and flowability characteristics at the temperatures encountered during the compaction cycle but they should also give very consistent part to part characteristics. Parts produced with this technique should at least meet dimensional and physical tolerances similar to those obtained with the conventional cold compaction processing route. The ease of monitoring and control of the powder temperature is also a key factor to consider for the production of warm-pressed parts.

The objective of this work is to study the robustness of binder-treated powder mixes compacted on a production press. In particular, the effect of powder temperature on the green and sintered properties of parts and the process capability and robustness of FLOMET WP™ materials specifically designed for warm compaction are presented and discussed. The effect of temperature fluctuation and interrupted production on part to part characteristics are also discussed.

GENERAL CHARACTERISTICS OF WARM PRESSING MATERIALS

Powder mixes for warm pressing should be able to withstand the temperatures reached during the heating, delivery, compaction and ejection steps. A special high melting point lubricant combined with a binder-treatment properly designed for warm compaction are thus used in Warm Pressing materials to ensure good flowability, good compressibility and low ejection forces at the working temperature [6-8].

However, the density achievable by warm compaction is not only a function of the lubricant/binder system but also depends on the steel powder compressibility and mix formulation. In particular, the mix formulation determines the pore free density (PFD) which is the density of the mix when the porosity is completely eliminated. In practice, green densities up to 98% of PFD can be reached by warm compaction [6-8].

PFD is a function of the steel powder and the additives which are added to the mix. It is particularly affected by low density additives such as lubricant and graphite. Increasing their contents in the mix significantly reduced the PFD. For this reason, the amount of lubricant and graphite is kept as low as possible to enable high green densities. Additions of 0.6% lubricant or less for very thin parts are generally used. However, for long parts having large surface in contact with the die, the lubricant content may need to be increased to reduce ejection force and tool wear and improve the surface finish as is the case in cold compaction. Increasing the lubricant content for long part is not necessarily detrimental to density. Figure 1 illustrates the effect of increasing the lubricant content from 0.6 to 0.7% on the compressibility curves of FL-4205 mix processed by warm compaction on a production press. The die fill was about 1.5 in. (38.1 mm), giving a part thickness of about 0.75 in. (19.0) at 50 tsi (690Mpa). It can be observed that the density is higher with 0.7% lubricant than with 0.6% lubricant for compacting pressures lower than 52 tsi (717 Mpa). Green density at 50 tsi (690 Mpa) is about 7.22 g/cm^3 with 0.7% lubricant compared to 7.20 g/cm^3 with 0.6% lubricant. The increase in density below 52 tsi (717 Mpa) at 0.7% lubricant is thought to be related to a reduction of friction at die walls and between powder particles, leading to a better transfer of the compacting pressure throughout the part and better particle packing during compaction. The ejection force is also reduced by increasing the lubricant content.

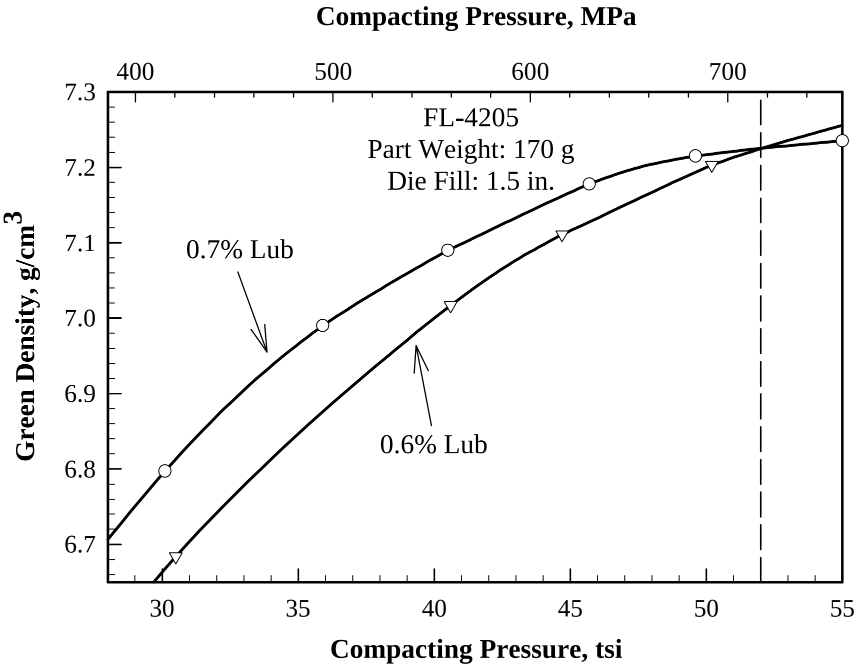


Figure 1. Compressibility Curves of FL-4205 Mixes Containing Either 0.6 or 0.7% Lubricant.

In a previous study [6], it has been demonstrated that the thickness of the part or the section of the part which necessitates a high densification also affects the optimum temperature to maximize green density. Figure 2 shows the effect of powder temperature on green density at 50 tsi for 0.22, 0.50 and 0.75 in. thick rings made from a FN-0205 mix. It can be observed that the powder temperature maximizing the green density decreases as the part thickness increases. In fact, thicker parts generate more heat during the compaction and ejection cycle requiring powder and tooling temperature readjustment to take this effect into account. Figure 3 shows the optimum powder temperature range as a function of part thickness for one level part at 50 tsi (690Mpa) when die, punches and core rod are heated to 250°F (121°C). The optimum powder temperature varies typically between 275 and 160°F (135 and 70°C) when part thickness varies from less than 0.2 in. to about 1.25 in. (32 mm).

EXPERIMENTAL PROCEDURE

Material Formulation

The following binder-treated powder mixes were prepared for cold and warm compaction tests:

Mix A: ATOMET 1001 + 2.5% Ni + 0.6% Graphite + 0.6% Lubricant
Mix B: ATOMET 4401 + 2.0% Ni + 0.6% Graphite + 0.35% MnS + 0.7% lubricant

Mixes were binder-treated with a patented blending technique [9-10]. Proper adjustment was made to the binder treatment to produce mixes suitable for warm compaction. The PFD of theses mixes is respectively 7.452 and 7.378 g/cm^3.

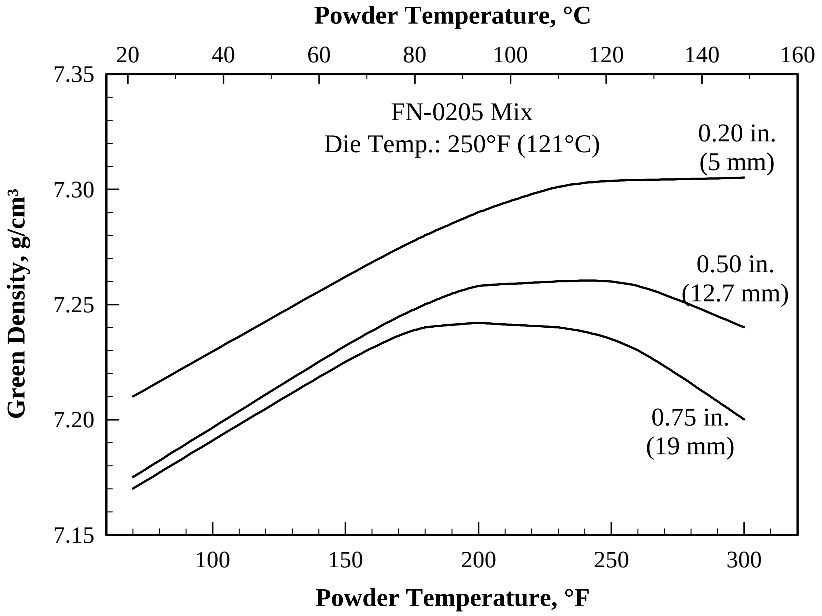


Figure 2. Relation Between the Green Density and the Powder Temperature for Different Part Thicknesses.

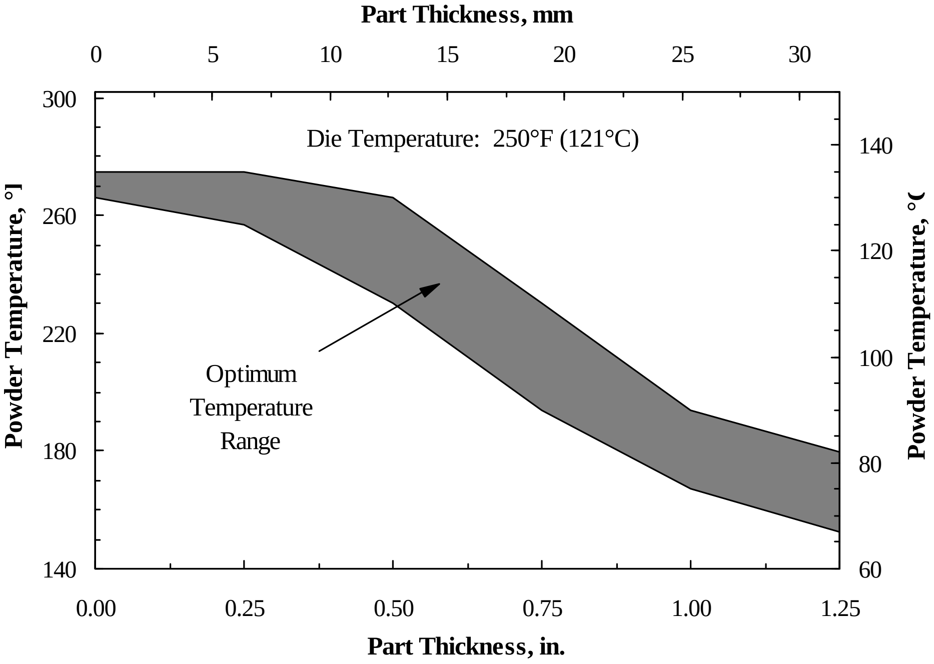


Figure 3. Relation Between the Part Thickness and the Optimum Powder Temperature.

Compaction Trials on a Production Press

Cold and warm compaction tests were carried out on a 220 ton Cincinnati mechanical press model # 220-DCII-6 equipped with powder and die heating systems [12]. One and two level tooling sets were used to press either rings or turbine hub parts. The diameters of the die and of the core rod of the ring tooling were respectively 2.148 and 1.490 in (54.6 and 37.8 mm). The turbine hub die had an hexagonal flange 2.50 in. (63.5 mm) wide and a hub with a diameter of 2.298 in. (58.37 mm). The core rod with a spline had a diameter of 1.876 in. (47.65 mm).

Die, punches and core rod were heated to a temperature of 250°F (121°C) for warm compaction trials and parts were pressed at a rate of 10 parts/min for parts less 0.8 in. (20.3 mm) thick and 8 parts/min above 0.8 in. The compaction parameters of each test were recorded with a portable computer and then transferred to a spreadsheet for analysis.

Characterization of Parts

Green and sintered characteristics of standard TRS specimens pressed at 302°F (150°C) and 50 tsi (690 MPa) on a hydraulic laboratory press were determined according to standard MPIF test methods. Sintering was done at 2050°F (1120°C) for 25 min. in a nitrogen based atmosphere. Several parts pressed with the production unit were collected during trials for determination of weight, green and sintered characteristics. Green and sintered density was evaluated by the water displacement technique and/or by measuring the physical dimensions of parts. Sintering conditions were identical to those used for parts pressed on a laboratory scale.

GREEN AND SINTERED PROPERTIES

The green and sintered characteristics of standard TRS specimens pressed on a lab press at 50 tsi (690MPa) and 302°F (150°C) are summarized in Table 1 for mixes A and B. A green density of 7.31 and 7.25 g/cm³ respectively was reached with these mixes on the lab press, which corresponds to about 98.1 and 98.5% of PFD. The lower density reached with mix B is explained by the higher amount of lubricant and the presence of MnS in that mix, leading to a reduction of PFD by 0.076 g/cm³ compared to mix A. Densities of 7.33 and 7.27 g/cm³ were respectively obtained after sintering at 2050°F (1120°C) for 25 min.

Rings were also pressed on a 220 ton Cincinnati press with the same mixes. The powder and tooling temperatures were kept constant at 250°F (121°C) and a die fill of 1.0 in. (25.4 mm) was used. Data at 50 tsi (690 MPa) are summarized in Table 1 while Figure 4 shows the green and sintered density as a function of compacting pressure. Green densities of 7.27 and 7.20 g/cm³ were respectively reached at 50 tsi (690MPa) with mixes A and B, which represents about 97.6 and 97.9 % of PFD. Lower green densities are obtained versus lab results mainly because part thickness and production rates were higher [6]. However, similar densities were obtained after sintering, namely about 7.33 and 7.26 g/cm³. The larger gain in density obtained with the rings versus TRS specimens is mainly related to the higher amount of energy stored in parts during compaction as explained elsewhere [6].

Table 1. Green and Sintered Characteristics of Mixes A and B.

	Properties	**Mix A**	**Mix B**
Lab Press 50 tsi - 300°F (690MPa-150°C)	Pore Free Density, g/cm³	7.452	7.378
	Green Density, g/cm³	7.31	7.25
	Relative Density (%PFD)	98.1	98.3
	Green Strength, psi (MPa)	3355 (23.1)	3320 (22.8)
	Sintered Density, g/cm³	7.33	7.27
Production Press 50 tsi - 250°F (698MPa-121°C)	Green Density, g/cm³	7.27	7.20
	% PFD	97.6	97.6
	Sintered Density, g/cm³	7.32	7.26

Sintering Conditions: 25 min. at 2050°C (1120°C) in a 90%N_2-10% H_2 atmosphere.

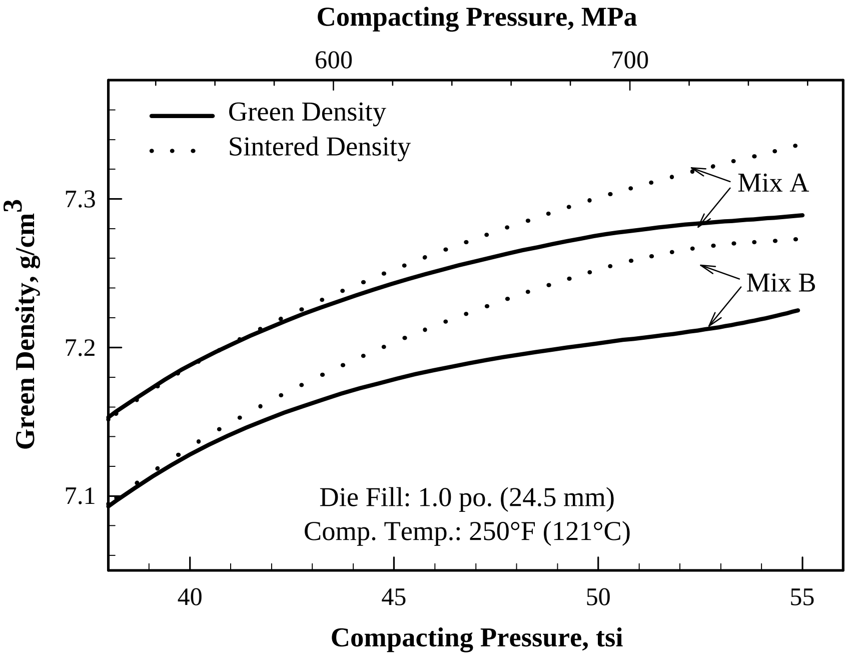


Figure 4. Compressibility Curves of Mixes A and B obtained on a Production Press with a Die Fill of 1.0 in. (24.4 mm) and a Compacting Temperature (Powder and Tooling) of 250°F (121°C).

ROBUSTNESS AND CONSISTENCY OF WARM PRESSING MATERIALS

As shown in Figure 2, the optimum powder temperature to maximize green density and minimize tool wear can vary typically between 170 to 270°F (80 - 135°C) for Warm Pressing WP mixes. In addition, even if it is highly recommended to control the powder and tool temperature within ±5°F (±2.5°C) when producing parts by warm compaction [12,13], the temperature variation during production may be greater. For example, temperature can vary significantly at the beginning of the run when tooling are properly adjusted and a stop and go process is used. Arrested production can also produce significant temperature fluctuation when the press is re-started. Mixes should therefore have the capability to adequately fill the die in this temperature range to obtain consistent part to part characteristics and withstand temperature fluctuations that may occur. The effect of powder temperature on mix robustness and consistency was investigated in greater detail.

Apparent Density versus Powder Temperature

Figure 5 shows the effect of powder temperature on apparent density of mixes A and B as measured on the production press with the ring tooling. Typical curves obtained with FN0205 Warm Pressing and regular mixes containing 0.6% lubricant are also given [6]. The apparent density of mixes A and B remains firmly stable between 160 to 300°F (70 - 150°C). The behavior of mixes A and B is very similar to that of Warm Pressing mixes tested in the past. It can also be observed that the apparent density of WP binder-treated mixes is much more stable than that of regular mixes as temperature varies. A much better weight stability will therefore be obtained with the binder treated mix, especially if some powder temperature variations occurred during processing.

Effect of Powder Temperature on Process and Parts Consistency

A series of special experimental trials were conducted to evaluate the effect of powder temperature and number of parts pressed on the robustness and consistency of mixes in terms of part to part green and sintered characteristics and compacting pressure. The turbine hub tooling was used for these tests. In the case of mix A, the powder temperature was varied by intervals of about 20°F (11°C) from 205 to 295°F

(95-145°C). In the case of mix B, the temperature was varied from 230 to 260°F (110-130°C) in steps of 10°F (6°C) , then brought back to 230°F (110°C) , then decreased to 210°F (100°C) by step of 10°F (6°C) and finally increased again to 230°F (110°C). For both mixes, 75 to 130 parts were pressed at each temperature plateau prior to changing the temperature setting of the powder heater in order to observe the consistency of mixes under stable conditions. The die and ram strokes were adjusted at the beginning of the test to have a total fill of about 1.5 in. (38 mm) and a compacting pressure of about 50 tsi (690 MPa) in the flange and the hub. No further adjustment was made throughout the test in order to evaluate only the effect of temperature and time on tonnage and part characteristics. Several parts were collected throughout the test to determine their green and sintered characteristics. Figure 6 shows the variation of compacting pressure and powder temperature as a function of part number for both mixes.

The results of the statistical analysis of data for each temperature plateau and for the entire test are summarized in Table 2 while Figure 7 illustrates the effect of powder temperature on the average values of compacting pressure, green part weight, green and sintered part height and density for both mixes. Error bars shown in Figure 7 correspond to the 3σ intervals while the medium and short dashed lines correspond to the average, upper and lower limit values for the entire test. The upper and lower limit values are those measured and correspond closely to the calculated 3σ limit values. It should be noted that the percentage of variation as used in the text corresponds to Range ÷ [2 x Average]x 100

It can be seen that the average compacting pressure is very stable as temperature varies for both mixes. The average compacting pressure varied from 51.4 to 49.6 tsi (709 to 685 MPa) as temperature was increased from 206 to 295°F (97 to 147°C) for mix A while the compacting pressure varied between 51.0 and 52.4 tsi (704-723 MPa) as temperature varied between 210 to 260°F (100 to 127°C) for mix B. Ranges for the compacting pressure obtained at each powder temperature plateau were between 1.4 to 1.9 tsi (19 to 26 MPa) for mix A and 1.8 to 2.3 tsi (25 to 32 MPa) for mix B. The maximum variation in compacting pressure obtained during the trials was only 3.5 and 4.0 tsi (48 and 55 MPa) for mixes A and B respectively, even if powder temperature varied by 89 and 53°F (49 and 29°C) respectively.

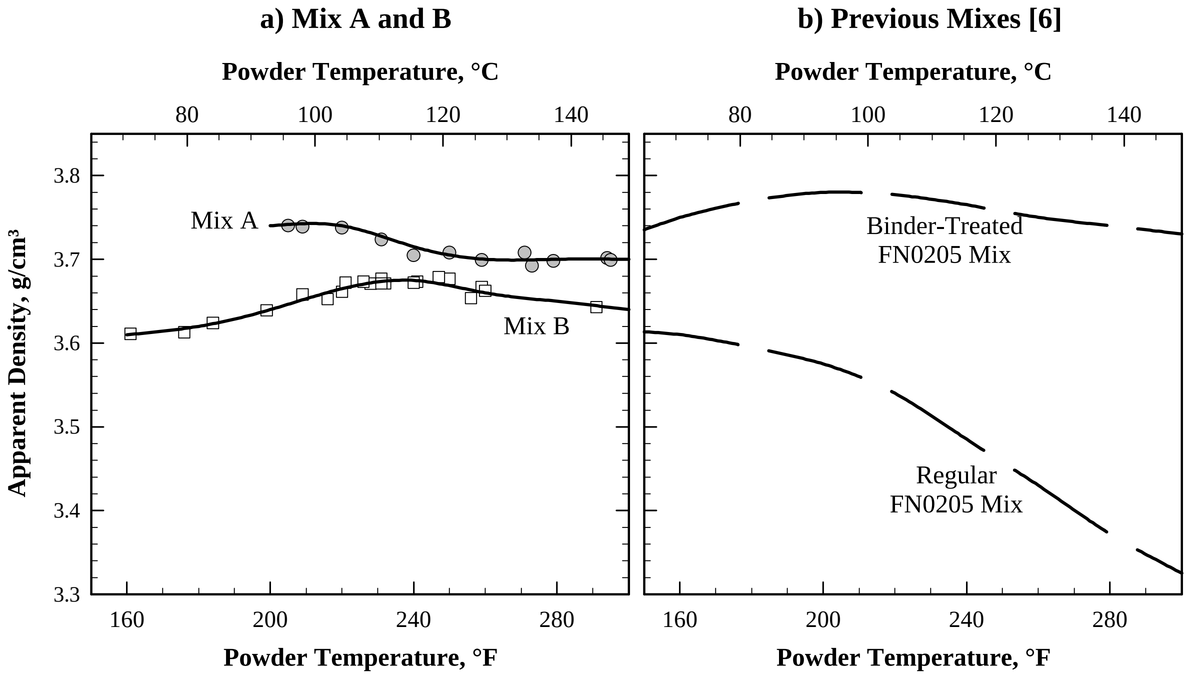
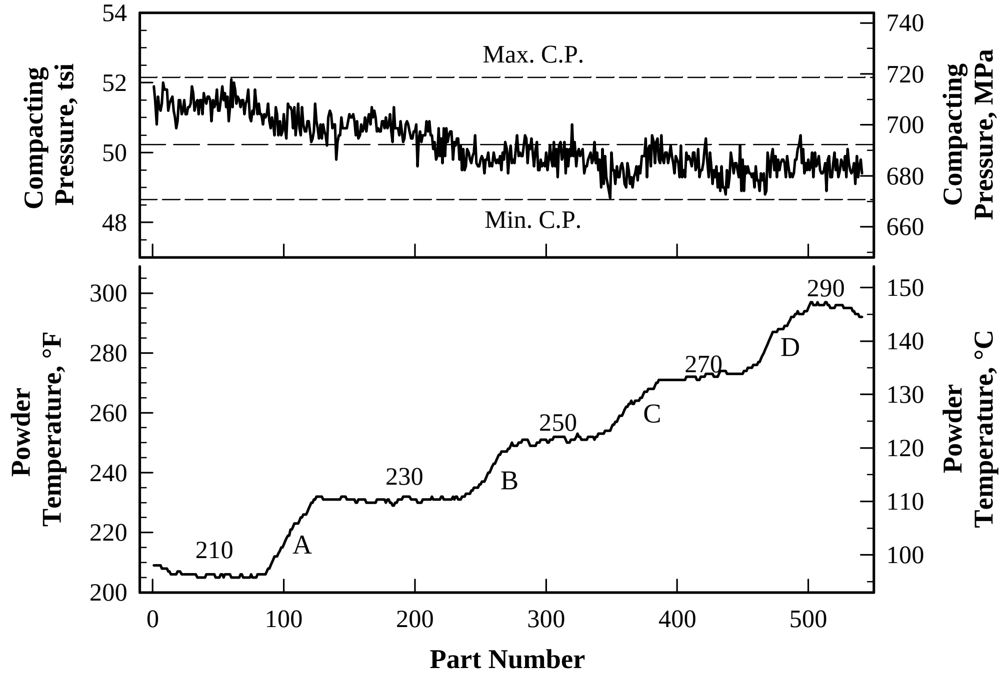


Figure 5. Apparent Density as a Function of Powder Temperature. a) Mixes A and B, b) Previous Work.

Tooling	Turbine Hub (2 levels)
Die Fill	1.5 in. (38 mm)
Tooling Temp.	250°F (121°C)
SPM	10 parts/min.

A) **MIX A**



B) **MIX B**

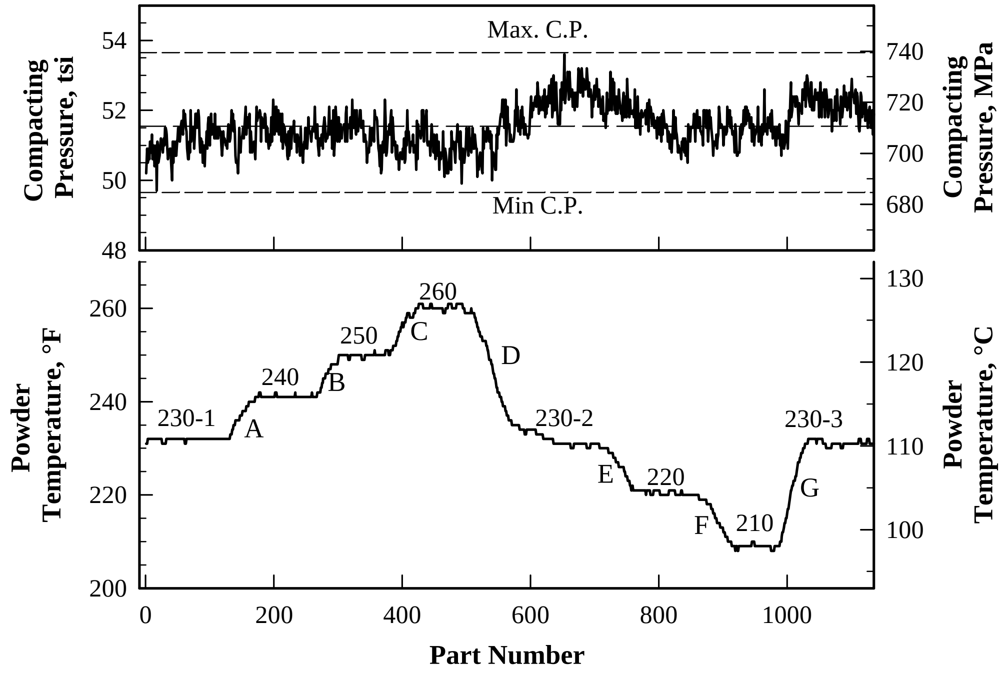


Figure 6. Variation of Compacting Pressure and Powder Temperature during Experimental Trials Carried Out to Evaluate the Effect of Powder Temperature on Robustness of a) Mix A and, b) Mix B.

Table 2. Results of Experimental Trials Carried Out to Evaluate the Effect of Powder Temperature on Robustness of Mixes A and B.

Test ID	Powder Temp. °F		Comp. Pressure psi			Part Weight g			Green Density g/cm^3			Sint. Dens. g/cm^3
	Avg	Range	Avg	σ	Range	Avg	σ	Range	Avg	σ	Range	
MIX A												
210	206	4	51.4	0.30	1.4	180.6	0.31	1.1	7.27	0.001	0.001	7.35
230	231	4	50.6	0.39	1.9	179.9	0.39	1.6	7.27	0.002	0.007	7.34
250	251	5	49.9	0.33	1.8	179.1	0.30	1.2	7.26	0.006	0.011	7.33
270	272	4	49.6	0.39	1.7	178.9	0.47	1.9	7.25	0.001	0.001	7.33
290	295	7	49.6	0.29	1.5	178.8	0.30	1.0	7.22	0.011	0.023	7.34
ALL	247	84	50.2	0.75	3.4	179.5	0.79	3.1	7.26	0.017	0.063	7.34
MIX B												
230-1	232	1	51.1	0.42	2.3	179.1	0.30	1.3	7.19	0.004	0.013	7.26
240	241	1	51.4	0.39	1.8	179.2	0.34	1.1	7.18	0.002	0.004	7.26
250	250	2	51.4	0.43	2.0	179.4	0.34	1.1	7.18	0.003	0.008	7.27
260	260	2	51.0	0.44	2.1	178.7	0.51	1.6	7.18	0.002	0.004	7.27
230-2	231	2	52.4	0.41	2.1	179.4	0.38	1.3	7.19	0.007	0.015	7.27
220	221	1	51.5	0.42	2.1	178.6	0.54	1.7	7.19	0.007	0.012	7.25
210	209	2	51.5	0.37	1.9	178.5	0.41	1.9	7.19	0.002	0.005	7.26
230-3	231	2	52.2	0.36	1.6	179.1	0.46	1.8	7.19	0.003	0.007	7.26
ALL	234	53	51.6	0.61	3.9	179.0	0.52	2.5	7.19	0.005	0.018	7.26

The very small variation in compacting pressure obtained under stable temperature conditions and even when temperature was varied is directly linked to the notable stability of part weight observed throughout the trials as illustrated in Figure 7. Indeed, ranges for the weight obtained under stable conditions were between 1.0 to 1.9 g for mixes A and B. This represents weight variations of about ±0.4%. It is worth mentioning that the part weight did not vary more than 3.1 and 2.5 g for mixes A and B respectively during the test. These results show clearly the excellent filling capability and the great stability of these mixes as temperature varies. This is also confirmed by the notable stability of powder temperature when a plateau is reached for both mixes, the temperature variation not exceeding 4°F (2°C) except at 290°F (145°C).

Figure 8 illustrates the effect of powder temperature on the percentage weight variation when powder temperature does not vary more than 10°F (5.5°C). The variation of part weight varies typically between ±0.20 to 0.60% for both mixes with an average value of 0.38% for mix A and 0.47% for mix B. As a comparison, a variation of part weight of ±0.50% was obtained during a standard cold compaction run of 700 parts having the same thickness carried out on mix B. Still larger weight variations would be obtained with non-binder treated mixes. It can be observed in Figure 8 that the powder temperature does not seem to affect the variation in weight which remains firmly stable over the range investigated. This shows clearly that excellent part weight consistencies will be obtained at any temperature in this range.

The effect of powder temperature on height and density of green and sintered parts is also shown in Figure 7. The average height of parts for all the tests is 0.692 and 0.699 in. (17.58 and 17.75 mm) respectively for mixes A and B. The higher height obtained for mix B is mainly due to the lower density reached after compaction. Variations in height measured for the entire run were about ±0.70% for both mixes.

Average green densities of 7.26 and 7.18 g/cm^3 were reached for the entire run for mixes A and B respectively. Such values are only slightly lower than green densities reached on 0.5 in. (12.7 mm) thick rings at 50 tsi (690 MPa). It can be observed in Figure 7 that green density remains very stable with temperature, except at about 295°F (147°C) for mix A where a drop of about 0.04 g/cm^3 compared to the average value was measured. This drop is related to a larger springback at ejection. Average densities of about 7.34 and 7.26 g/cm³ were respectively reached after sintering which are again comparable or slightly larger than values obtained on rings. It is interesting to note that sintered density remains stable with temperature for the entire range of temperature investigated. A larger gain in density after sintering was thus obtained at 295°F (147°C) for mix A, confirming previous results [6]. Ranges of green and sintered densities varying between 0.001 to 0.023 g/cm³ were measured when powder temperature was stable. These results show clearly that very consistent part to part green and sintered densities can be obtained when temperature varies between 200 and 270°F. For temperatures higher than 270°F (135°C), a reduction in green density should be obtained as temperature increases but sintered density should remain stable if adequate sintering conditions are used.

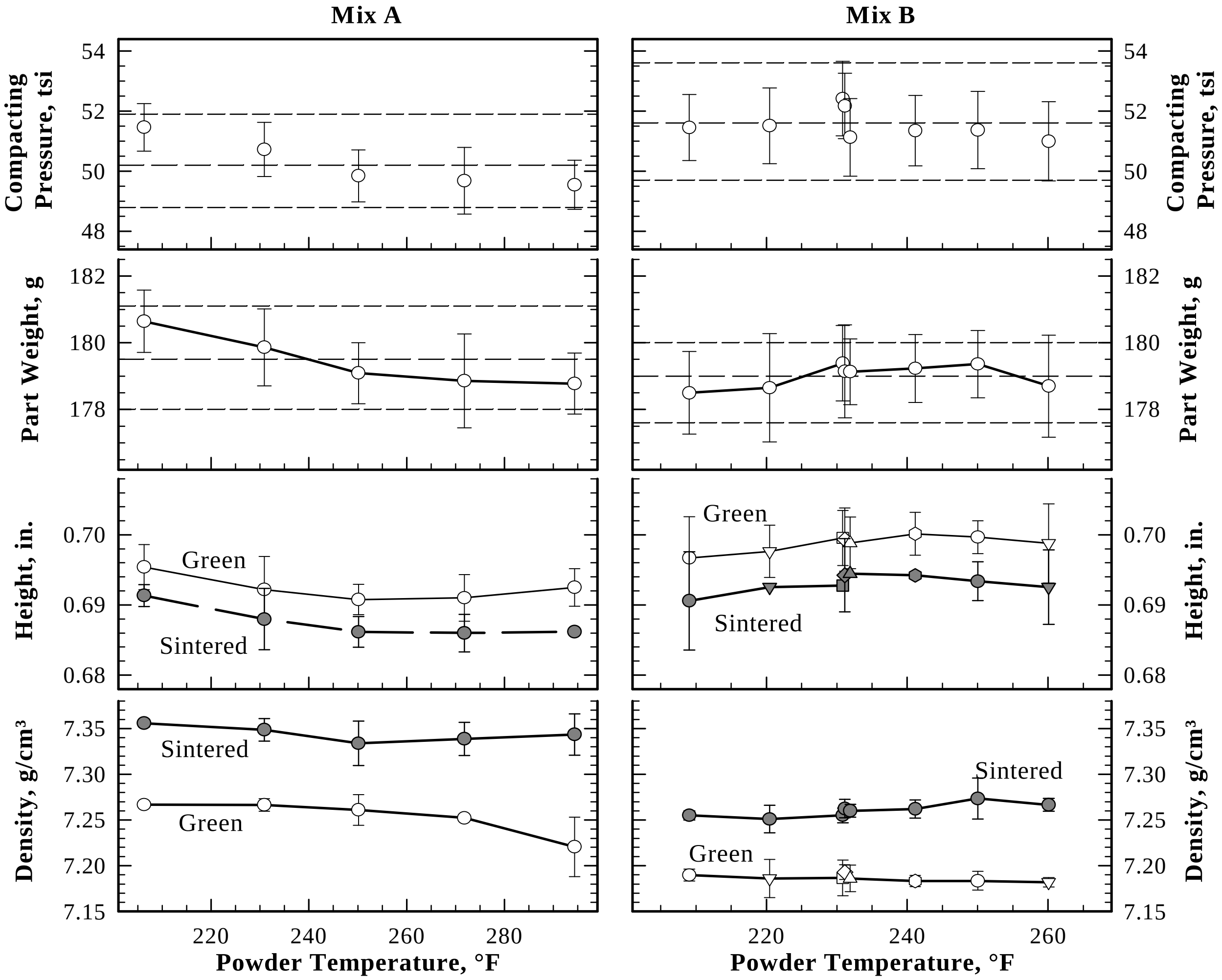


Figure 7. Effect of Powder Temperature on Compacting Pressure and Green and Sintered Characteristics of Parts.

Effect of Temperature Fluctuation on Part Weight Stability

The effect of a variation in powder temperature on the consistency of part weight was investigated from the data collected for mixes A and B. Figure 9 illustrates the relationship between the percentage of variation of weight and the fluctuation in temperature at different temperatures for both mixes. 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 for large temperature scattering. Indeed, the average part weight variation obtained in the temperature range investigated remains lower than 0.7% for a variation in powder temperature of about 50°F (28°C). Such variations in part weight are comparable to values usually obtained in the P/M industry.

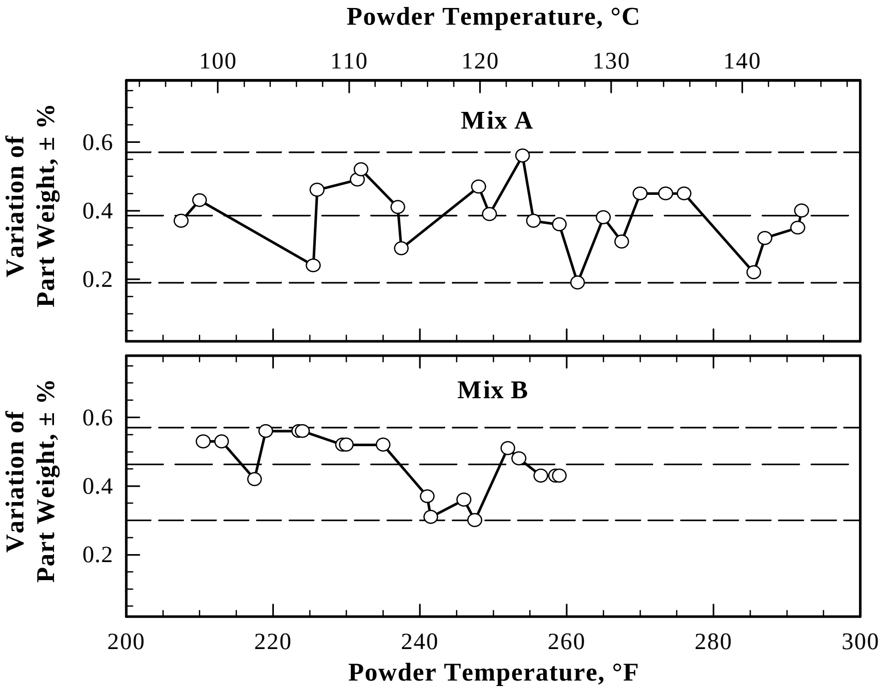


Figure 8. Effect of Powder Temperature on Percentage of Variation of Part Weight.

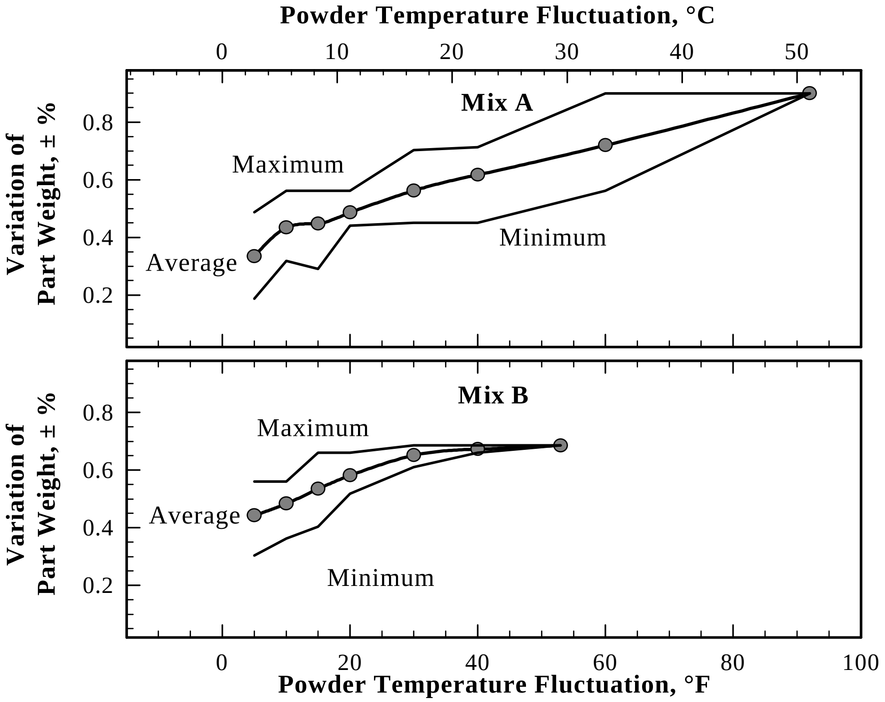


Figure 9. Effect of Fluctuation of Powder Temperature on Variation of Weight of Green Parts.

Effect of Production Interruption on Process and Part Characteristics

The effect of a production interruption on the compacting pressure and the green characteristics of parts was investigated with mix B on the production press. The powder heater and the ram punches were adjusted to reach a powder temperature and compacting pressure of about 230°F (110°C) and 50 tsi (690MPa). About 100 parts were pressed under these conditions prior to stopping the press. Production was stopped for exactly 18 minutes and re-started. No adjustment was made to the ram punches in order to observe the effect of this interruption on the compacting pressure and green characteristics of parts.

Figure 10 shows the variation of compacting pressure, powder temperature, weight and density as a function of time and the number of parts pressed before and after the production interruption. It can be observed that the interruption has caused a significant increase in compacting pressure due to an increase of part weight when the press was re-started. A part weight of 185.1 g was measured on the very first part pressed compared to an average weight of 177.1 g before the interruption, which represents an increase of about 3.6%. However, part weight and thus compacting pressure, dropped very rapidly with time to reach values similar to those obtained prior to the interruption. Indeed, the part weight was below 180 g after 10 parts and it took about 30 parts or 3 minutes to reach the steady state. This represents about 5.5 Kg of powder.

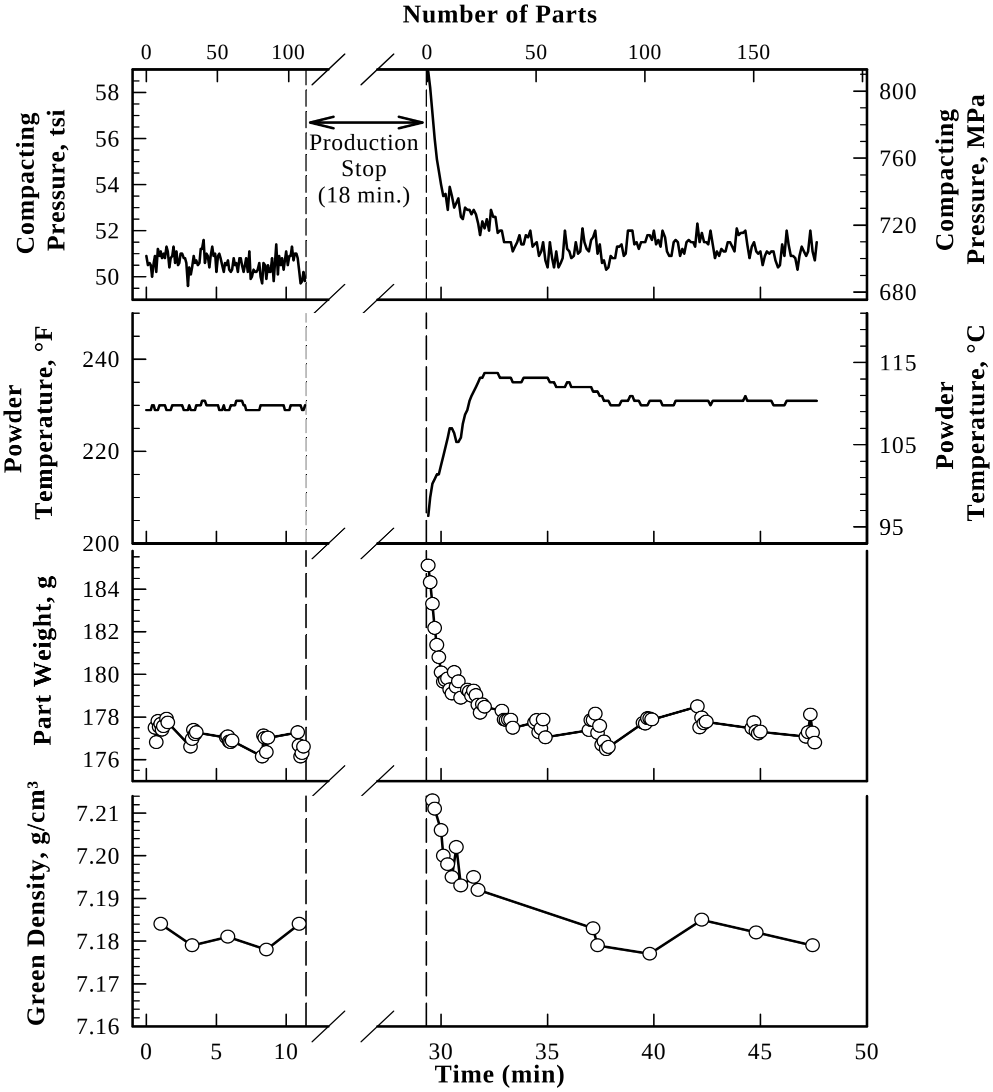


Figure 10. Effect of Production Arrest on Process and Green Parts Characteristics.

The increase in part weight observed after the interruption in Figure 10, which is about 3.6% for the very first part produced, can not be related to a longer pre-heating time. If this was the case, all of the powder in the system, which had been heated for a longer time would give similar weights. On the contrary, weight was found to drop very rapidly and reach similar values as those obtained prior to the arrest within 5.5 kg approximately, which represents only about 18% of the total amount of powder heated in the shoe, the feeding hose and the auger (about 30 kg of powder is heated). The increase is likely related to the packing of powder in the shoe during the arrest, leading in turn to a larger transfer of materials in the die when the press was re-started. It is worth mentioning that this phenomena of increasing weight when the press is re-started is also observed in cold compaction. The weight drops rapidly with the number of parts pressed due to the feeding of fresh powder into the shoe from the auger between each compacted parts.

Statistical analysis of data obtained during this test was performed. Ranges of 2.6 tsi (36 MPa) and 2.5 g for the compacting pressure and the part weight were estimated when considering parts produced from the 30th part after the production interruption. This corresponds to a weight variation of ±0.70%. A variation of ±0.53% in weight is obtained after production of 40 parts, which is identical to the variation obtained prior to the production stop. A weight variation of ±0.70% is obtained for all the parts produced before and after the interruption when eliminating the first 40 parts following the production interruption.

Finally, it can be observed that the green density remains very stable before and after the production interruption at 7.18-7.19 g/cm³, except for the first 20 to 30 parts where densities varying from 7.21 to 7.19 g/cm³ were reached due to the increase in compacting pressure. It can thus be concluded from these results that a production interruption has only a minor effect on the consistency of part to part characteristics and the number of parts to be rejected.

PRODUCTION RUN TRIALS

Longer production runs of 310 to 510 parts were carried out with mix B in order to evaluate the process capability and stability under different conditions. The turbine hub tooling was used for these runs. Parts with three different thickness ranging between 0.50 to 0.81 in. (12.7 to 20.6 mm) were produced at a compacting pressure of about 50 tsi (690 MPa) and at different powder temperatures. It should be mentioned that runs carried out at different temperatures were done continuously without stopping the press. Also, no adjustment was made to the ram punches as was the case for the special experimental trials discussed earlier. The tooling was set at a temperature of 250°F (121°C) for the 0.50 and 0.73 in. (12.7 and 18.5 mm) thick parts and 210°F (99°C) for the 0.81 in. (20.6 mm) thick parts. Parts were also pressed at room temperature. Five parts out of every 50 were collected for weight, density and size evaluation.

Table 3 summarizes the compacting conditions as well as the results obtained for these runs. The temperature ranges vary between 5 to 10°F (2.8 to 5.5°C) for all the runs. Part weight variations of ±0.26 to 0.61% were obtained for warm compaction runs while variations ranging between ±0.47 to 0.68% were obtained for cold compaction runs. These results confirm the excellent stability of Warm Pressing materials for parts having different thickness and pressed under stable conditions. It can also be observed that the part weight as well as the green density remained very stable from run to run for 0.5 and 0.81 in. (12.7 and 20.6 mm) thick parts, even if no adjustment was made to the press. This confirms results discussed in the previous section.

Finally, green densities of about 7.18 g/cm³ were reached for warm compaction runs compared to densities of about 7.10 g/cm³ for cold compaction. It is interesting to note that green density was not clearly affected by increasing the thickness from 0.50 to 0.81 in. (12.7 to 20.6 mm) and remained at about 7.18 g/cm³ for that thickness range. This result is likely related to the amount of lubricant in the mix, which leads to better transfer of tonnage throughout the part and to the tooling itself.

Table 3. Summary of Long Production Runs Carried Out with Mix B Under Different Conditions.

Part Thickness in.	Stroke rate	Die Temp. °F	nb of parts	Powder Temp. °F		Comp. Pres. tsi		Weight * g			Green Density g/cm^3	
				Avg	Range	Avg	Range	Avg	Range	Var. ±%	Avg	Range
0.50	10	-	510	Room	-	50.4	1.8	124.7	1.7	0.68	7.10	0.02
		250	510	228	6	50.2	1.9	128.4	1.4	0.54	7.19	0.03
			510	253	10	51.1	2.6	128.6	1.4	0.54	7.19	0.04
			510	269	5	52.0	2.2	128.8	1.4	0.54	7.19	0.03
0.73	10	-	510	Room	-	51.1	1.8	182.2	1.7	0.47	7.11	0.02
		250	310	231	10	50.3	2.6	187.3	2.3	0.61	7.17	0.04
0.81	8	-	510	Room	-	49.8	2.4	205.5	2.3	0.56	7.10	0.03
		210	310	230	7	49.6	1.5	206.9	1.1	0.26	7.18	0.03
			310	250	9	49.7	1.6	207.0	1.6	0.39	7.18	0.03

% Variation = Range ÷ (2 x Average) x100

CONCLUSIONS

Tests were conducted mainly on a production press equipped with warm compaction capability to evaluate the characteristics of parts and the stability and consistency of these characteristics from part to part. Two different FN0205 binder treated materials specifically designed for warm compaction containing either 0.6 or 0.7% lubricant were characterized. The effect of powder temperature, temperature fluctuation and production arrest on part to part green and sintered characteristics were specifically investigated. The following conclusions can be drawn from this study.

- Green densities corresponding to 98.1 to 98.3% of the pore free density were achieved on a lab press with both mixes while slightly lower densities were obtained on a production press with much thicker parts. However, similar sintered densities of about 7.33 and 7.26 g/cm^3 were respectively achieved on both lab and production parts with the 0.6% and 0.7% lubricant mixes.
- Apparent density of Warm Pressing mixes remained very stable when powder temperature varied from about 200°F (93°C) to 300°F (149°C), which ensured very stable part weight within this temperature range.
- Part weight variations ranging between ±0.2 to ±0.6% were typically obtained when powder temperature was set between 200 and 295°F and its variation did not exceed 10°F (5.5°C). Also, the powder temperature had only a minimal effect on part weight variation for the range of temperatures investigated.
- An excellent stability of part weight was obtained when high fluctuations of powder temperature were induced. Indeed, the part weight variation remained at about ±0.7% even with a variation of 50°F (28°C) of the powder temperature.
- A production interruption caused an increase of weight when the press was re-started for first few parts. However, weight dropped rapidly and reached similar values to those obtained prior the interruption within 10 to 40 parts., which represents about 5.5 Kg of powder for that specific part.

Finally, it can be concluded from all of these tests that WP binder-treated materials specifically designed for warm compaction give very consistent part to part characteristics over a wide range of temperature and are very resistant to temperature fluctuation and production interruption which may occur during production.

ACKNOWLEDGMENT

The assistance and support of all staff at QMP involved in this program, especially Mr. Pierre Houde, is gratefully acknowledged. We would also like to express our gratitude to the people of the Industrial Material Institute (IMI) and the helpful staff at the Technical Center of Cincinnati Incorporated. We wish to thank Cincinnati Inc. for the use of their facilities.

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