OPTIMIZING POWDER MIX FORMULATIONS AND PROCESSING CONDITIONS FOR WARM COMPACTION

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Warm compaction is a technique which uses moderate temperature, usually in the range of 90 to 150°C, to enhance densification of pressed components. The gain in density achieved with this process is typically of 0.001 to 0.0015 g/cm³/°C. However, powder mixes must show stable physical properties at the working temperature to maintain consistent part weight and density. Also, the base powder must show high compressibility and admixed elements must be properly selected to maximize both the green and sintered densities.

This papers studies the behavior of various powder mixes warm pressed at various temperatures. The effect of base powder grades, the influence of low density elements such as lubricant and graphite on green density, and the effect of admixed copper and nickel on sintered density is also reported.
KEYWORDS: WARM PRESSING, STEEL POWDERS, HIGH DENSITY.

I. INTRODUCTION

Reducing residual porosity in P/M components is the primary challenge to achieve high fatigue life. In cold compaction, the maximum green density that can be achieved is usually in the range of 7.15 to 7.25 g/cm³ depending on the compressibility of the base powder, the amount of lubricant and the compacting pressure. The double press and double sintering (DPDS) and forging techniques can also be used to further raise the density in the range of 7.4 to 7.5 g/cm³ for the DPDS process and to full density for the forging process but with significant effects on production costs. Warm pressing is an interesting avenue to achieve green densities in the range of 7.25 to 7.45 g/cm³ at a lower cost than DPDS and forging. However, this technology requires a good understanding of the mechanisms involved during the warm compaction and sintering stages in order to optimize the sintered density and hence the static and fatigue properties of the P/M parts. Indeed, the green density is not only closely related to the compressibility of the based powder but also to the type and concentration of the admixed lubricant. Also, the sintered density strongly depends on the degree of shrinkage during sintering which is very sensitive to the amount and type of admixed elements used to improve the strength of the P/M components. The objective of this paper is to review the critical factors affecting the final density of sintered components, including the effect of the base powder, of low density additives such as graphite and lubricant as well as of admixed elements like copper and nickel.

II. FACTORS AFFECTING DENSITY

The primarily objective of warm compaction is to reach the highest achievable density after sintering. This will be firstly met by selecting the base material, secondly by the mix formulation and finally the sintering conditions.

Effect of base material

Steel powders are generally selected as base material for warm compaction because of their better compressibility compared to sponge powders. However, steel powders can be produced over a wide range of compositions by either prealloying elements in the melt prior to atomization or by admixed them after the annealing treatment. Un-alloyed steel powders generally exhibit better compressibility than low alloy ones but show lower sintered properties due to a lack of hardenability. However, by properly selecting alloying elements that improve hardenability with minor effect on compressibility, it is possible to increase both the green density and the sintered properties. Figure 1 illustrates the difference in compressibility between un-alloy and low alloy steel powders. Raising the concentration in alloying elements increases the hardness of the steel particles and slightly deteriorates the powder compressibility [1]. On the other hand, alloying elements are required to increase hardenability and consequently the sintered properties. Therefore, alloying elements must be carefully selected to minimize their negative effect on compressibility. Molybdenum is very efficient to increase strength with only minor effect on powder compressibility [2]. This is the reason why molybdenum low alloy steel powders are widely used in warm compaction in order to achieve high green density after compaction and high strength after sintering.

Effect of compacting temperature

Raising the powder temperature during compaction reduces the yield strength and increases the ductility of the steel particles, favoring densification at a given compacting pressure [3]. This is well illustrated in Figure 2, where raising the compacting temperature from 20 to 150°C results in a gain of about 0.15 g/cm³ at 550 MPa and 0.12 at 690 MPa.
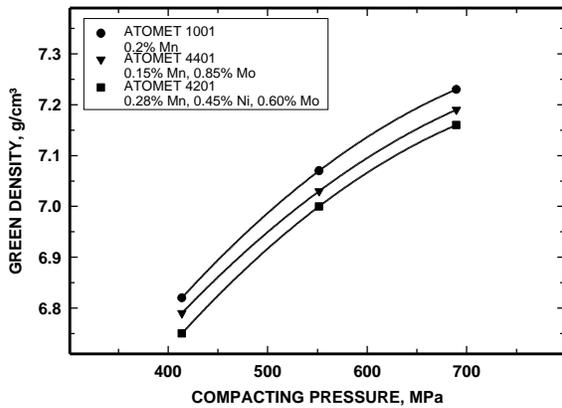
Figure 1. Compressibility of steel powders containing various concentrations of prealloyed elements (mixed with 0.5% lubricant pressed at room temperature), ref. 1.
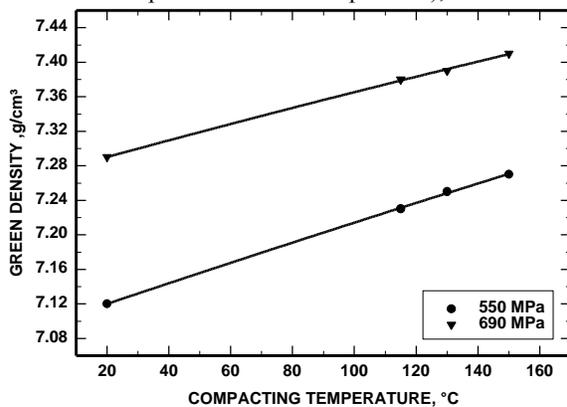

Figure 2. Effect of compacting temperature and pressure on green density (specimens pressed from ATOMET 1001 with 0.6% graphite and 2% Ni; die wall lubrication).

Effect of lubricant and graphite

Lubricants are admixed to steel powders to ease the ejection of P/M components after compaction but also to facilitate particle rearrangement during compaction. However, when the compacting pressure exceeds about 480 MPa, raising the lubricant concentration in powder mixes reduces the maximum achievable green density, as seen in Figure 3. This is due to the fact that the lubricant fills the available porosity and limits further increase of the density because of its much lower specific gravity relatively to steel [3]. This limitation is even more important in warm compaction because of the higher density achieved during compaction. As illustrated in Figure 4, similarly to cold compaction, higher green density values are achieved at lower compacting pressure when lubricant is added in the mix. Indeed, green density values of 7.28 g/cm³ are reached at about 600 MPa for mixes containing either 0.3 or 0.6% lubricant compared to 7.22 g/cm³ without lubricant. However, the green density of the specimens containing 0.6% lubricant starts to level off at about 7.4 g/cm³ because the pore free density for that mix formulation, 7.48 g/cm³, is almost reached. During warm compaction, the maximum achievable green density

is generally in the range of 98 to 98.5% of the theoretical density because the parts expand during ejection [4,5,6]. This behavior is defined as the springback and it generally increases with the compacting pressure, component height and high compacting temperature [4]. It is also worth noting that a minimum amount of lubricant is required to maximize the green density during compaction. From Figure 4, the highest green density at a given pressure is obtained with the mix containing 0.3% lubricant. Therefore, the addition of a small quantity of internal lubricant favors densification, probably because it promotes particle rearrangement during compaction.

Graphite is generally admixed to ferrous P/M materials formulations to increase the strength of the sintered components. However, because of its lower specific gravity relatively to iron, graphite also reduces the maximum achievable green density. This is well illustrated in Figure 5, where in spite of an increase of the compacting pressure of almost 40 MPa, the green density decreases with an increase of the graphite concentration. The magnitude of this effect corresponds to a density reduction of about 0.03 g/cm³ for each increment of 0.1% graphite.
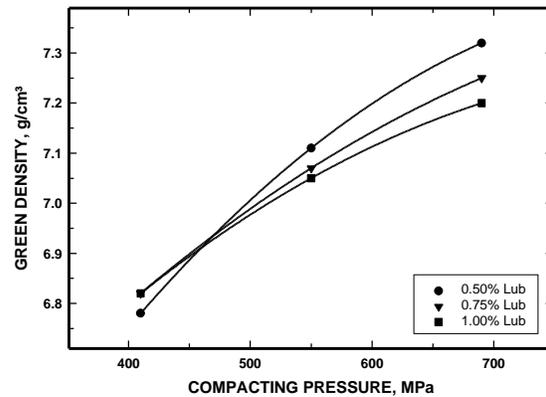

Figure 3. Effect of lubricant concentration and compacting pressure on the green density achieved after compaction (ATOMET 1001HP+zinc stearate, ref. 3).
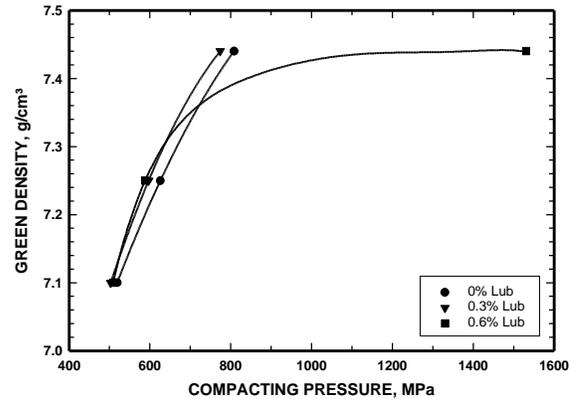

Figure 4. Effect of lubricant concentration on green density achieved during warm compaction (ATOMET 4401+0.6% graphite+4% Ni+lub; pressed at 150°C).
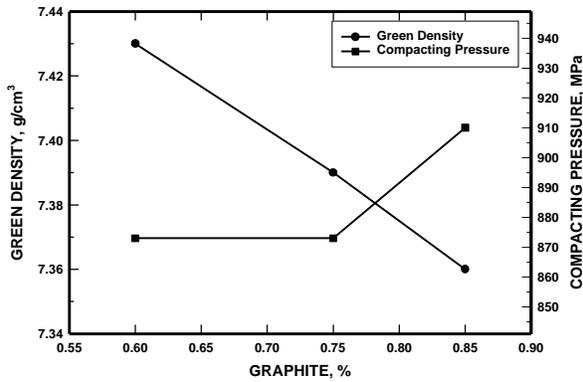
Figure 5. Effect of graphite concentration on the green density of TRS specimens pressed at 120°C (ATOMET 4401+4% Ni+1% Cu+ 0.5% lub).

Effect of copper and nickel

Copper and nickel are the most popular admixed elements in steel powder mixes to improve the mechanical properties of P/M components. Copper melts at 1085°C and easily diffuse into iron at 1120°C while nickel diffuses in solid state and requires higher sintering temperatures to fully diffuse in the iron particles [7,8]. However, because of the different diffusion mechanisms of these elements, their relative effects on sintered density are largely different. Indeed, copper additions cause growth during sintering and lowers the sintered density, particularly for low graphite mix formulations, as illustrated in Figure 6.
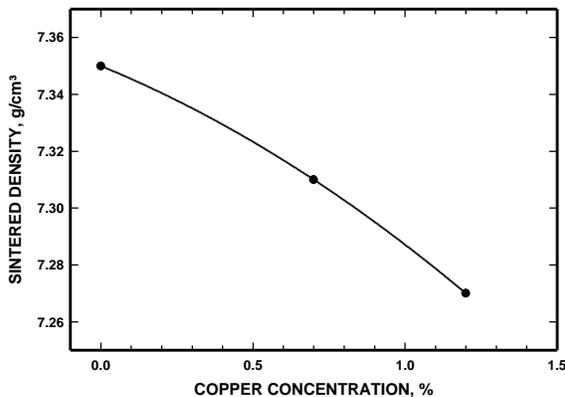

Figure 6. Effect of copper concentration on the sintered density of TRS specimens pressed at 130°C and 625 MPa (ATOMET 4401+3.5% Ni+0.3% graphite+Cu+0.5% lub; green density of 7.35 g/cm³).

On the other hand, as shown in Figure 7, the addition of nickel promotes shrinkage during sintering. Each increment of 1% Ni results in an increased shrinkage of about 0.01 g/cm³. The effects of Cu and Ni on dimensional change during sintering is also illustrated in Figure 8. The melting of copper at 1085°C causes the specimen to grow (black curve), while addition of nickel (gray curve) promotes diffusion and causes a larger shrinkage at the sintering temperature. Also, because

nickel is an austenite stabilizer, it reduces expansion during the ?? ? phase transformation.
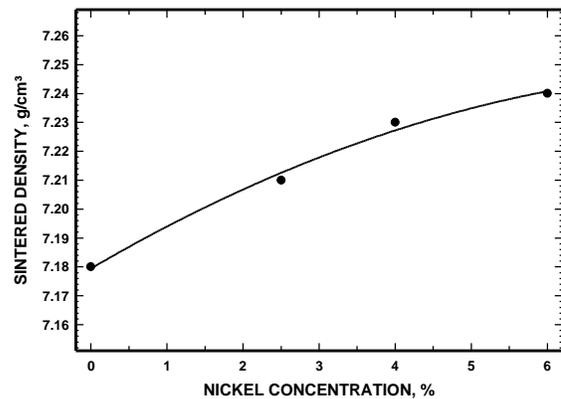

Figure 7. Effect of nickel concentration on the sintered density of TRS specimens pressed at 520 MPa and 130°C (ATOMET 4401+0.2% graphite+Ni+0.55% Lub; green density of 7.20 g/cm).
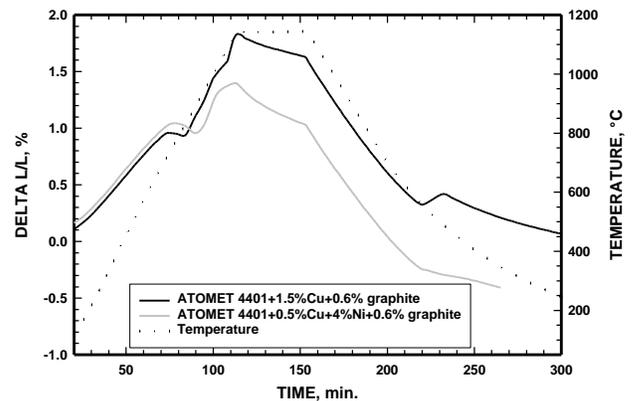

Figure 8. Effect of copper and nickel concentrations on dilatometric profiles of specimens sintered at 1145°C.

III. KEY FACTORS IN WARM COMPACTION

Once the basic characteristics of admixed elements in the powder mixes are understood, it is also important to characterize the behavior of these mixes during compaction on a production scale.

Powder temperature

Mixes used in warm compaction must be designed to perform efficiently at the temperature at which the compaction is carried out. This means that the mix must keep good flowability and consistent apparent density in the compacting temperature range while keeping its lubricating properties to maintain low ejection forces and ensure good surface finish of the parts. Therefore, a binder treatment is generally made to bond the additives to the steel particles in order to promote the mix flowability. Figure 9 and 10 respectively illustrates the effect of the temperature on the flow rate and apparent density of powder mixes. The binder treatment improves flow rate

and increases apparent density. Also, in the temperature range of about 90 to 110°C, the flow rate and apparent density values of the binder treated mix are relatively constant. This represents an interesting feature because in that temperature range, this system would show a consistent operation on a production press.
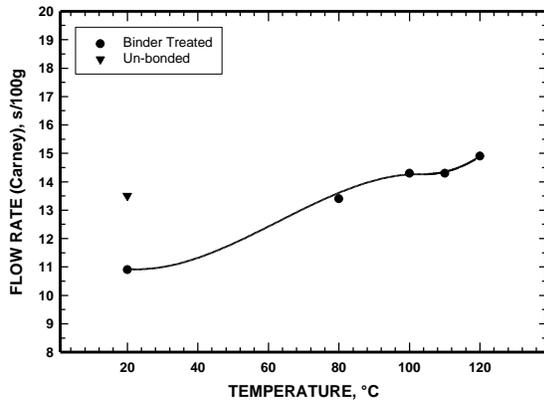

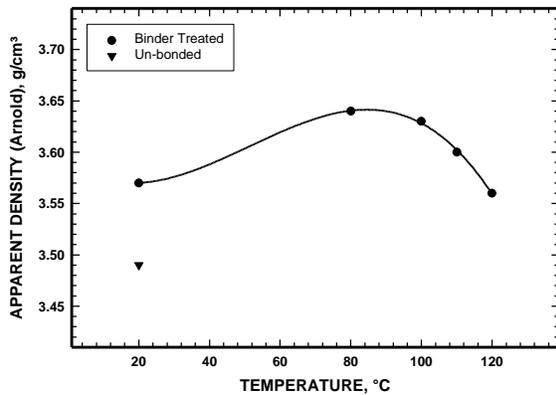Figure 9. Effect of temperature on flowability of warm compaction mixes (ATOMET 1001+0.6% graphite+2% Ni+0.6% Lub).

Figure 10. Effect of temperature on apparent density of warm compaction mixes (ATOMET 4401+4% Ni+1% Cu+0.85% graphite+0.6% Lub).

Die temperature

The die temperature during warm compaction must be adjusted to maintain low part-to-part weight variation and good surface finish. This temperature varies with the size and height of the part which determine the surface area in contact with the die walls. Increasing this surface area will result in a raise of the part temperature. During operation this temperature increase is generally in the range of 5 to 30°C [9]. The maximum part temperature to maintain low ejection pressure and good surface finish for mixes previously discussed is about 125°C [9]. This temperature is easily achievable with large parts when the die temperature is set at 110°C. Therefore, larger parts will require a lower die temperature compared to smaller ones in order to maintain the ejection temperature below 125°C.

This temperature range will generally fall between 90 and 115°C, depending of the dimension of the parts.

IV. CONCLUSIONS

Warm compaction requires a good understanding of the effect of the base powder, admixed elements and compacting and sintering conditions in order to maximize the sintered density. The amount of admixed and/or prealloyed elements that reduce either the compressibility or lower the density during sintering must be carefully selected to minimize any detrimental effect of the final density. Finally, the mix formulation must be designed to show good flow properties and consistent behavior at the compacting temperature.

V. REFERENCES

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