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# Warm compacting behavior of stainless steel powders①

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**Abstract:** The warm compacting behaviors of four different kinds of stainless steel powders, 304L, 316L, 410L and 430L, were studied. The results show that warm compaction can be applied to stainless steel powders. The green densities and strengths of compacts obtained through warm compaction are generally higher than those obtained through cold compaction. The compacting behaviors in warm compaction and cold compaction are similar. Under the compacting pressure of 700 MPa, the warm compacted densities are 0.10-0.22 g/cm$^3$ higher than the cold compacted ones, and the green strengths are 11.5%-50% higher. The optimal warm compacting temperature is 100-110 ℃. In the die wall lubricated warm compaction, the optimum internal lubricant content is 0.2%.

**Key words:** stainless steel powders; warm compaction; die wall lubrication; lubricant

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## 1 INTRODUCTION

It is well-known that stainless steel parts possess excellent corrosion resistance and good comprehensive mechanical properties. They have been widely used in various industrial sectors such as automobile, ship-building, chemistry, food, watch, medical appliance. Powder metallurgy, as a net or near net shaping method with high materials utilization and low cost, can be used to produce stainless steel parts in volume and eliminate or reduce machining operations. However, low density and porous structure of sintered stainless steel parts lead to low mechanical properties and corrosion resistance, which severely restrains the development of sintered stainless steel parts.

In powder metallurgy, there are mainly two ways to reduce the pore concentration and thus to improve the performance of sintered materials: 1) increasing the green density; 2) activating sintering. In the past, a great deal of work has been focused on the sintering process such as how to eliminate oxides, how to select the protective sintering atmosphere, how to enhance and activate the sintering process. However, little work has been done on how to improve the compressibility and the green density of stainless steel powders.

Warm compaction is a new single-pressing and single-sintering technology developed in 1990s. The feature of warm compaction is that it can achieve high green density (beyond 7.3 g/cm$^3$) at relatively low cost through pre-heating the die and mixed powders and adopting special lubricant[1-5]. Warm compaction has been successfully applied to iron based mixed powders and some partially pre-alloyed powders[6-9], but its application in stainless steel powders has not been reported. On account of their high alloy content, stainless steel powders are generally less compressible than pure or low alloy steel powders. Consequently, little work has been done on the warm compaction of stainless steel powders.

However, through our research on warm compaction process and its densification mechanism, it is believed that warm compaction also can be applied to stainless steel powders. The aim of this study is to study the effects of warm compaction on stainless steel powders, in hope to obtain powder metallurgy stainless steel materials with high green density and strength.

## 2 EXPERIMENTAL

In this study, four kinds of stainless steel powders including 316L, 304L, 410L and 430L, which were made by water atomization in Handan Steel Company with size of < 0.106 mm, were employed. Its particle size distribution and physical properties are shown in Table 1. The lubricant was a macromolecule polymer prepared by ourselves with the merit of very little ash left after burning.

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**Table 1** Particle size distribution and properties of stainless steel powders

| Type of powder | Particle size distribution/ % | | | | Flowability (50 g) / s | Apparent density/ (g•cm⁻³) |
|---|---|---|---|---|---|---|
| | ≤45 μm | 45 − 75 μm | 75 − 106 μm | ≥106 μm | | |
| 304L | 75.1 | 16.65 | 8.15 | 0.1 | – | 2.63 |
| 316L | 69.24 | 19.23 | 10.07 | 1.45 | – | 2.56 |
| 410L | 65.58 | 20.63 | 12.14 | 1.64 | 40.3 | 2.78 |
| 430L | 71.46 | 18.50 | 9.07 | 0.97 | 42.3 | 3.04 |

The rectangular samples with the dimensions of 30 mm × 12 mm × (5.5 − 6.0) mm were prepared by uniaxial pressing. The green density was tested by Archimedes method according to the National Standard of GB5163-1985 and the green compact strength was tested according to GB/T5160-1985. Unless mentioned, all the experimental data were the average of five samples.

## 3 RESULTS AND DISCUSSION

### 3.1 Effect of temperature on green density

Temperature is essential to warm compaction. In order to examine the effect of temperature on warm compacting behavior and select the optimal compacting temperature, compacts of 316L, 410L and 430L powders have been made at different temperatures. The lubricant content was 0.7% (mass fraction) and the pressure was 700 MPa. The experimental results are shown in Fig. 1.

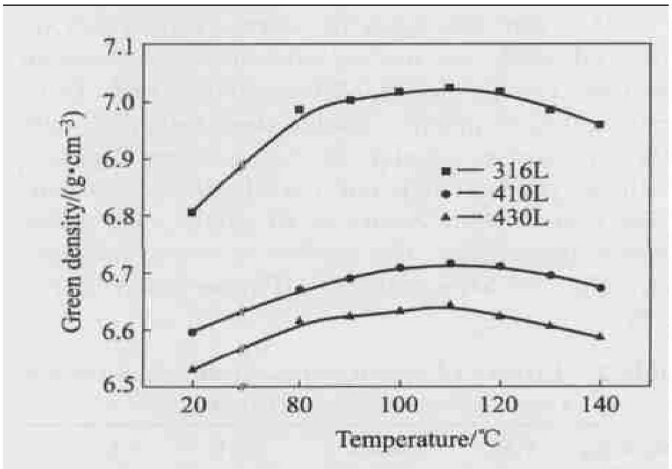


**Fig. 1** Effects of temperature on green densities (700 MPa, 0.7% lubricant)

From Fig. 1, it can be seen that warm compact densities are all higher than cold ones. The profiles of the three curves are similar. The green densities first increase with the rising temperature. After reaching the highest point, the densities then begin to decrease slightly. At 110 ℃, the green densities reach the highest. The highest density is 7.02 g/cm$^3$ for 316L, 6.72 g/cm$^3$ for 410L and 6.64 g/cm$^3$ for 430L, which are higher than those compacted at room temperature by 0.21 g/cm$^3$, 0.12 g/cm$^3$ and 0.11 g/cm$^3$, respectively.

Another important thing worthy of our attention is that warm compaction can be carried out within a fairly wide temperature range, which is significant for the application of warm compaction. From Fig. 1, we can learn that the temperature has no significant impact on the green density when the temperature is between 100 ℃ and 120 ℃. As we know, most of the current patent powder mixture for warm compaction have severe restriction with the warm compacting temperature which should be controlled within the range of ±2.5 ℃[10−12]. However, in this experiment the change of density is very little within the temperature range of 100 ℃ to 120 ℃. The fluctuation of density is no more than ±0.02 g/cm$^3$. That is to say, warm compaction can be practiced in a very broad temperature range. In this study, the optimum temperature is 110±10 ℃. When the temperature is beyond 130 ℃, the heated powder mixture begins to be sticky and the ejection force obviously increases with severe scores appearing in the surface of green compacts.

### 3.2 Effect of pressure on green density

In general, the green density increases with the rise of compacting pressure. Therefore, raising pressure is a common and useful way to improve the green density. For stainless steel powders, the green density and strength are usually very low in conventional powder metallurgy due to their low compressibility. So, in production, the compacting pressure is rather high. However, too high pressure may have adverse effect on the quality of compacts and also reduce the life-span of the forming die. When selecting the compacting pressure, the capacity of equipment and the burden limit of the die should be considered. In addition, the degree of effect of pressure on green density should also be taken into consideration. For this purpose, green densities of four different types of compacts prepared by both warm compaction and cold compaction at different pressures have been tested. The results are shown in Fig. 2.

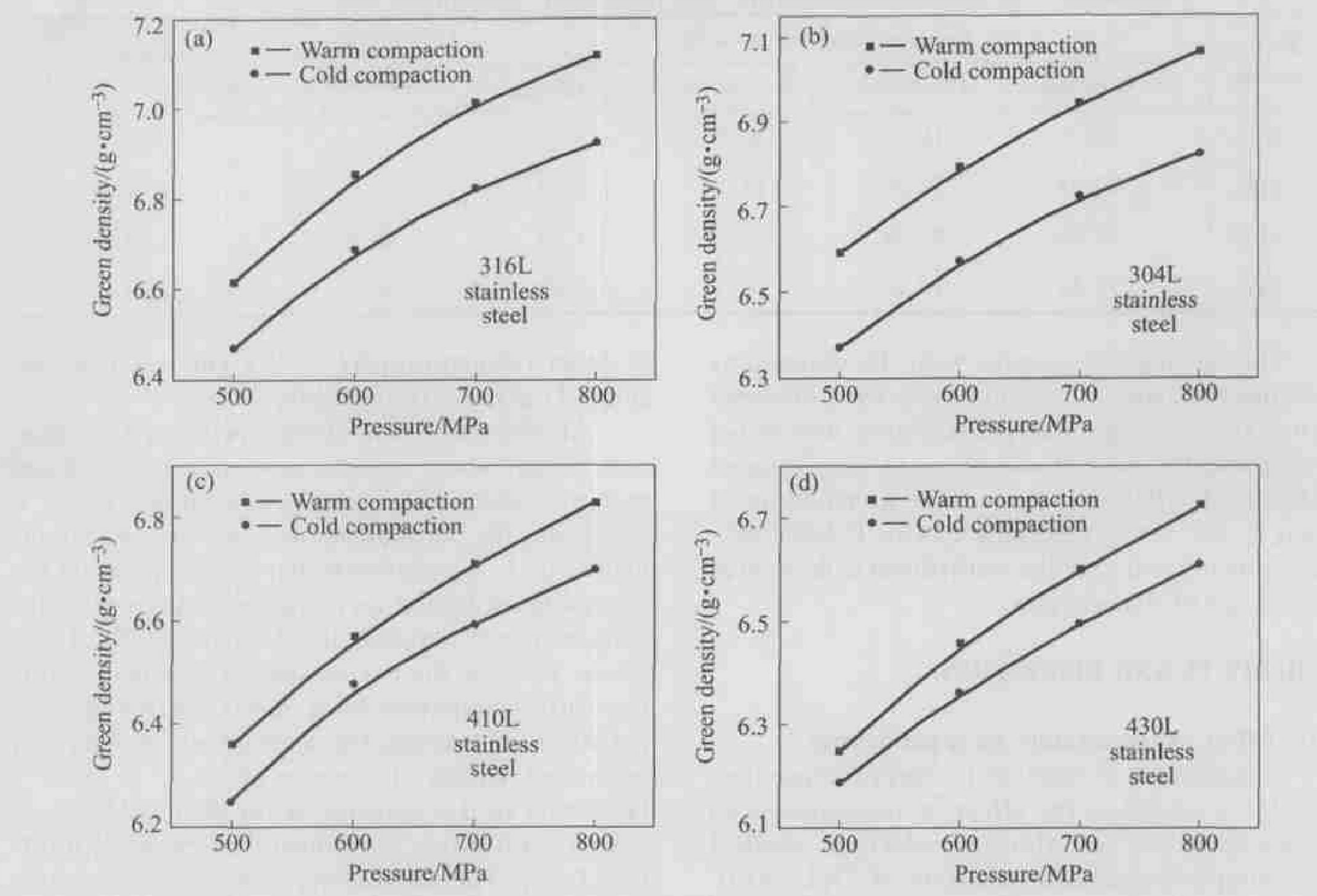


**Fig. 2** Effects of pressure on green density (110 ℃, 0.7% lubricant)

Fig. 2 indicates that the green densities of both warm and cold compacts go up almost linearly with the ascending of pressure below 800 MPa. The green densities of warm compacts are all higher than those of cold compacts. The superiority of warm compaction is further widened with the increase of pressure. This can be explained by the densification mechanism of compacting process. In fact, the densification of metal powders progresses through two ways: one is the rearrangement of particles; the other is the plastic deformation of particles. During compaction, these two densification mechanisms always coexist, but their proportions of contribution to densification change in different conditions. Under low pressure, the plastic deformation of particles is on a small scale and the densification is mainly caused by rearrangement of particles. While under high pressure, deformation on a large scale is possible although rearrangement still exists. In this case, the role of temperature to reduce the yield limit and enhance the plastic deformation of metal powders becomes more significant. Consequently, the density difference between warm and cold compacts is broadened.

From Fig. 2, it can also be seen that the advantage of warm compaction for powder mixture of 316L and 304L is distinct. Under the pressure of 700 MPa, warm compaction can enhance the green density by 0.19 g/cm$^3$ for 316L, and 0.22 g/cm$^3$ for 304L. But the roles of warm compaction on 410L and 430L are not so obvious, whose green densities are only improved by, respectively, 0.12 g/cm$^3$ and 0.10 g/cm$^3$. Under the pressure of 800 MPa, the green density of 316L is the highest, which can reach 7.12 g/cm$^3$, while the lowest density is that of 430L, only 6.73 g/cm$^3$. For more obvious illustration, the results of warm compaction under 700 MPa and 800 MPa are listed in Table 2.

**Table 2** Effects of warm compaction on different types of stainless steel powders

| Compacting pressure/MPa | 316L | | 304L | | 410L | | 430L | |
|---|---|---|---|---|---|---|---|---|
| | $\rho_W$ | $\Delta\rho$ | $\rho_W$ | $\Delta\rho$ | $\rho_W$ | $\Delta\rho$ | $\rho_W$ | $\Delta\rho$ |
| 700 | 7.01 | 0.19 | 6.95 | 0.22 | 6.71 | 0.11 | 6.60 | 0.10 |
| 800 | 7.12 | 0.20 | 7.07 | 0.24 | 6.83 | 0.13 | 6.73 | 0.12 |

$\rho_W$ is warm compact density, g/cm$^2$; $\Delta\rho$ is the increase in density between warm and cold compacts, g/cm$^3$

### 3.3 Compact strength

The compact strength is an important index of compact's properties, which indicates the ability to keep in shape and resist damage during subsequent processing. The improvement of compact strength can reduce the defective ratio in transportation. It's reported that warm compacts can even be machined directly[12]. This is very helpful to improving the effectiveness of cutting operation, reduce the cost, and broaden the application prospect of warm compaction. This is more significant for stainless steel parts which is hard to machine. In this study, the green strengths of warm and cold compacts have been examined. The results are shown in Fig. 3.

Fig. 3 shows that the green strengths of warm and cold compacts both steadily move up with the rise of pressure. The green strength of warm compacts is much higher than that of the cold compacts especially under high pressure. Like the trends in Fig. 2, the difference of green strength between warm and cold compacts is also widened with the rising pressure. The reason is, as stated before, there is more plastic deformation of particles in warm compaction under high pressure, thus, the binding of particles is firmer. Under the pressure of 700 MPa, the green strength of 316L warm compact is 30.7 MPa, which is 50% higher than that of cold compact and for 304L that is 32.9 MPa, which is 26.5% higher than that of cold compact. For 410L, the warm compact strength is 29.6 MPa, improved by 23%, and 27.6 MPa for 430L, enhanced by 11.5%.

### 3.4 Effect of lubricant content on green density

Lubricant is a decisive factor for warm compaction. It can improve the flowability of powder mixture and reduce the internal and external friction and ejection force, thus enhance the green density and the life span of the die. However, lubricant in compact is harmful to the mechanical properties of sintered materials and must be eliminated in the later sintering process. So, a proper content of lubricant is necessary. If the lubricant is too little, the lubrication will be poor. On the other hand, if the lubricant is too much, it may lead to deformation of sintering parts and forming bubbles in the surface of parts due to dissociation or evaporation of lubricant during sintering. In addition, more ash may be left in the parts if the lubricant is too much, which is very harmful to the mechanical properties. In order to determine the optimal content of the admixed lubricant, the effect of lubricant content on green density has been investigated. The results are shown in Fig. 4.

From Fig. 4, it can be seen that between 0.5% and 0.9% of lubricant content there is no notable change in green density. As pointed out by many researchers, the most important role of lubricant is to overcome the die wall friction rather than interparticle friction[13]. For 316L, the green density reaches

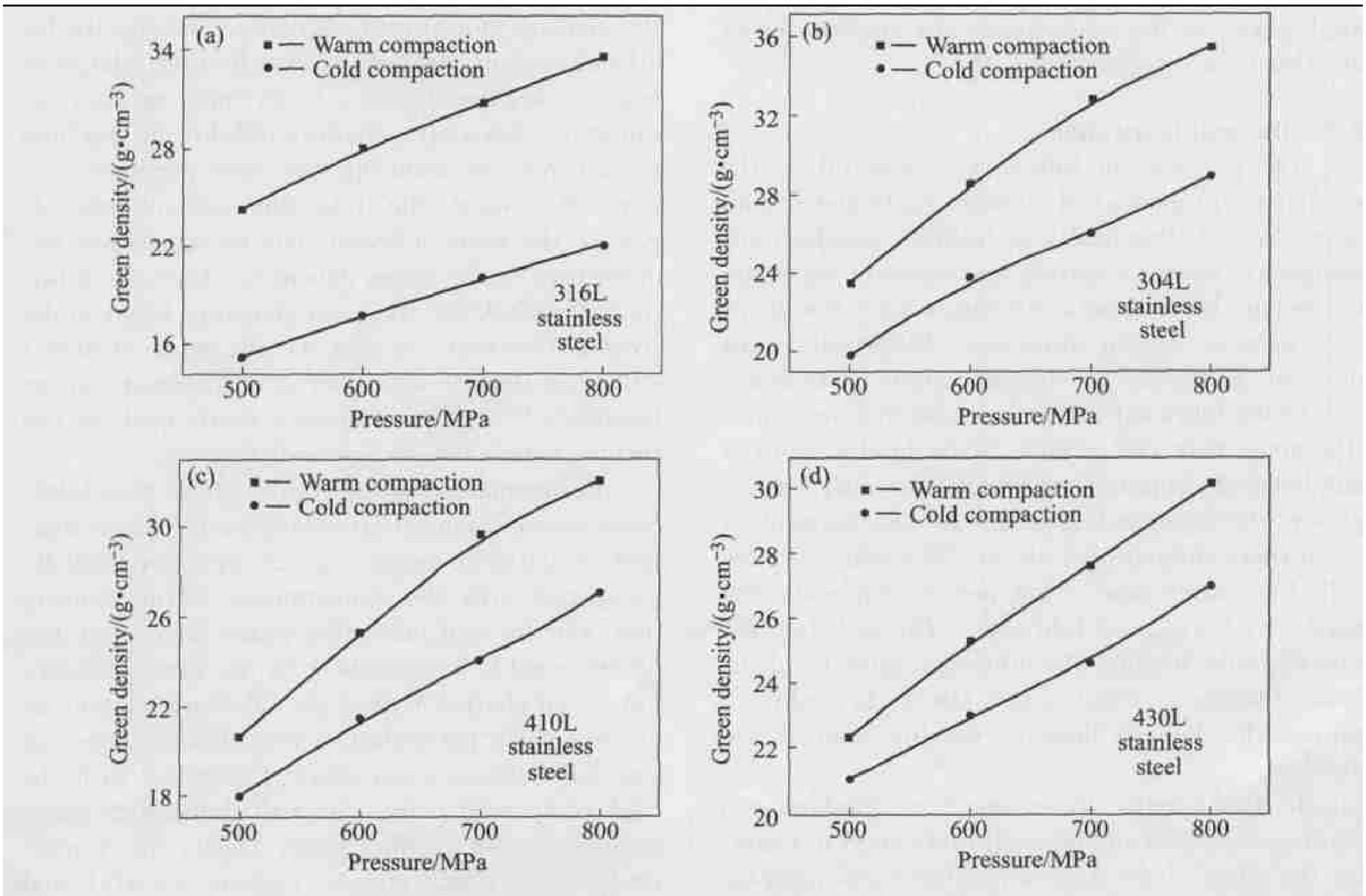


**Fig. 3** Comparison of green strength between warm and cold compactions (110 ℃, 0.7% lubricant)

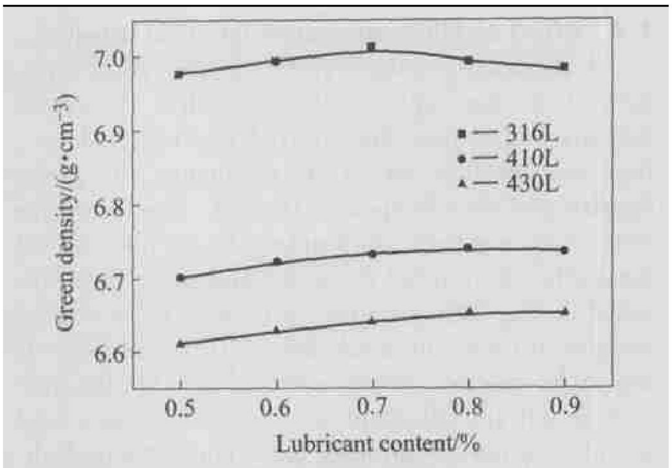


**Fig. 4** Effects of lubricant content on green density (110 ℃, 700 MPa)

maximum when the lubricant content is 0.7%. For 410L and 430L, the warm compact densities slightly climb with the increase of lubricant content. After the lubricant content rises to 0.8%, the green densities become relatively stable. This can be explained by that the green densities of 410L and 430L are relatively low and there are more pores, which can hold the redundant lubricant. In this study, we think that the proper lubricant content admixed in 316L powder blend is 0.7% while it is 0.8% in 410L and 430L. Using these contents, on one hand, the green densities are higher, on the other hand, the ejection forces are also relatively low.

### 3.5 Die wall lubrication

The presence of lubricant is harmful to the mechanical properties of sintered parts and should be minimized. Practically no lubricant can burn off completely during sintering and remnant ashes are left inside the compact, thereby, hinder the diffusion process during sintering. Meanwhile, gas pressure generated by decomposition or evaporation of the lubricant during pre-sintering and sintering stage may create more voids in the compact and lower the compact's dimension stability. In addition, the vaporized lubricant is also harmful to the furnace and pollutes the air. Therefore, the die wall lubrication was developed to eliminate the need for admixed dry lubricants. Die wall lubrication not only diminish the lubricant content and enhance the green density, but also is favorable to protect the die and improve the life span of the die[14-16].

In this study, we attempt to combine the warm compaction and die wall lubrication to examine the effect of die wall lubricated warm compaction on the compacting behaviors of stainless steel powders. Mixture of alcohol and EBS was brushed on the inner surface of the die wall as die wall lubricant. The experimental results are showed in Fig. 5.

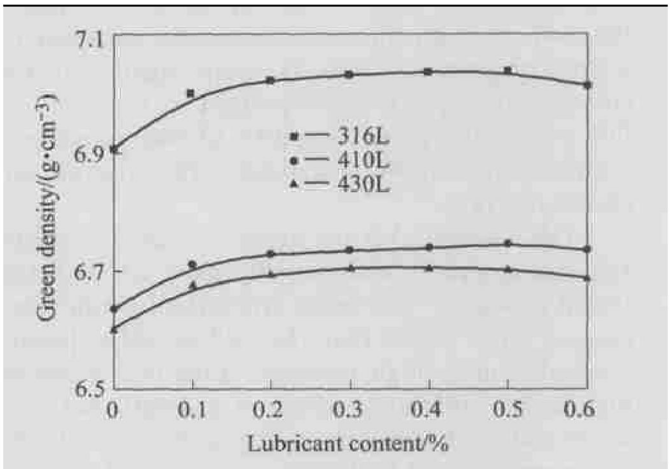


**Fig. 5** Effects of lubricant content on green density in die wall lubricated warm compaction (110 ℃, 700 MPa)

It can be known from Fig. 5 that the green density is very low when no lubricant is admixed in stainless steel powders. But, when a little lubricant is admixed in the powders, the green densities sharply move up. After the lubricant content gets to 0.2%, the green densities tend to be stable. Then, the green densities increase very little with the increase of lubricant contents. But after the lubricant content reaches 0.5%, the green densities begin to decline slightly. From these results, we can know that a little quantity of lubricant has high effectiveness in reducing the inter-particles friction. But after the lubricant content exceeds 0.2%, the more lubricant has no significant improvement in the green densities. After the lubricant reaches 0.5% the green densities begin to decrease. However, in Fig. 4, the green densities still grow slightly with the rise of lubricant content beyond 0.5%. This is because more lubricant can further reduce the particle-wall friction.

For comparison, the results of die wall lubricated warm compaction, conventional warm compaction and cold compaction are listed in Table 3. Compared with the conventional warm compaction, the die wall lubricated warm compaction has no remarkable improvement in the green density, but it can sharply reduce the lubricant content by 0.5%, which particularly has significant effect on sintered stainless steel parts. Compared with the cold compaction, the die wall lubricated warm compaction can enhance green density by, respectively, 0.20 g/cm$^3$ and 0.19 g/cm$^3$ for 316L and 430L powders while only 0.13 g/cm$^3$ for 410L powders.

**Table 3** Comparison between die wall lubricated warm compaction, conventional warm compaction and cold compaction

| Technology | Lubricant content/ % | Green density/ (g•cm⁻³) | | |
|---|---|---|---|---|
| | | 316 L | 410 L | 430 L |
| Die wall lubricated warm compaction | 0.2 | 7.02 | 6.73 | 6.69 |
| Conventional warm compaction | 0.7 | 7.01 | 6.71 | 6.60 |
| Cold compaction | 0.7 | 6.82 | 6.60 | 6.50 |

## 4 CONCLUSIONS

1) The green density and strength of the compacts of stainless steel powders sharply increased with the rising pressure. The green density and strength of warm compacts were generally higher than those of cold compacts, but their trends were almost alike.

2) With a lubricant content of 0.7% and warm compaction at 100 - 110 ℃ under a compact pressure of 700 MPa, the green densities of 316L and 304L warm compacts were 0.19 g/cm$^3$ and 0.22 g/cm$^3$ higher than those of cold compacts respectively, and the green strengths were 50% and 26.5% higher respectively; the green densities of 410L and 430L warm compacts were 0.12 g/cm$^3$ and 0.10 g/cm$^3$ higher than those of cold compacts respectively, and the green strengths were 23% and 11.5% higher respectively.

3) The temperature employed for warm compaction in this study had a wide optimal temperature range, which was properly within 100 - 110 ℃.

4) The die wall lubricated warm compaction had no significant improvement in green density compared with the conventional warm compaction, but it could greatly reduce the lubricant content. The die wall lubricated warm compaction with 0.2% lubricant could achieve the results higher than or equivalent to that of conventional warm compaction.

5) The warm compaction could be applied in stainless steel powders if correct lubricant and process parameters were adopted.

## REFERENCES


[1] Capus J, Pickering S, Weaver A. Hoeganaes offers higher density at lower cost[J]. Metal Powder Report, 1994, 49(7/8): 22 - 24.

[2] Rutz H G, Hanejko F G. High density processing of high performance ferrous materials[J]. Int J Powder Metall, 1995, 31(1): 9 - 17.

[3] LI Yuan-yuan, XIAO Zhi-yu, NGAI Tungwai Leo, et al. Warm compacted NbC particulate reinforced iron-based composite (Ⅰ) —Effect of fabrication parameters [J]. Trans Nonferrous Met Soc China, 2002, 12(4): 659 - 663.

[4] NGAI Tung-wai Leo, CHEN Wei-ping, XIAO Zhi-yu, et al. Warm compaction of $Al_2O_3$ particulate reinforced powder metallurgy iron-based composite[J]. Trans Nonferrous Met Soc China, 2002, 12(5): 886 - 889.

[5] XIAO Zhi-yu, LI Yuan-yuan, NGAI Tung-wai Leo, et al. Warm compaction behavior of iron-based powder using different kinds of graphite[J]. Trans Nonferrous Met Soc China, 2003, 13(5): 1181 - 1184.

[6] Degoix C N, Griffo A, German R M. Effect of lubrication mode and compaction temperature on the properties of Fe-Ni-Cu-Mo-C[J]. The Inter J of Powder Metallurgy, 1998, 34(2): 29 - 33.

[7] Capus J. Warm compacted turbine hub leads new PM thrust[J]. Metal Powder Report, 1997, 61(9): 9.

[8] LI Yuan-yuan, XIAO Zhi-yu, NGAI Tungwai Leo, et al. Effect of sintering parameters on warm compacted iron-based material[J]. Trans Nonferrous Met Soc China, 2003, 13 (6): 1333 - 1337.

[9] CAO Shun-hua, YI Jian-hong, Qu Xuan-hui, et al. Design of high density powder mixtures for warm compaction[J]. J Central South University of Technology, 2000, 31(6): 532 - 535. (in Chinese)

[10] Unked R F. Additional application of cincinnati El-temp systems[J]. Advance in Powder Metallurgy and Particulate Materials, 1995(1): 2 - 3.

[11] Weaver A. QMP looks at high density products[J]. Metal Powder Report, 1994, 49(7/8): 23.

[12] Engstrom U, Johansson B, Jacobsom O. Properties and tolerances of warm compacted P/M materials[J]. Powder Metallurgy Industry, 1997, 7(2): 10 - 15. (in Chinese)

[13] Yarnton D, Davies T J. The effect of lubrication on the compaction and sintering of iron powder compacts[J]. Int J Powder Metall, 1972, 8(2): 51 - 57.

[14] LI Yuan-yuan, NGAI Tungwai Leo, ZHANG Da-tong, et al. Effect of die wall lubrication on warm compaction powder metallurgy[J]. J Mater Process Technol, 2002, 129(1 - 3): 354 - 358.

[15] Leopold P M, Nelson R C. The effect of die-wall lubricant on the compaction of sponge-iron powder[J]. Int J Powder Metall, 1965, 1(3): 7 - 12.

[16] NGAI Tungwai Leo, CHEN Wei-ping, XIAO Zhi-yu. Die wall lubricated warm compaction of iron-based powder metallurgy material[J]. Trans Nonferrous Met Soc China, 2002, 12(6): 1095 - 1098.


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