

Warm compaction behaviors of iron-based powder lubricated by different kinds of graphite^①

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Abstract: Warm compaction behaviors and their affecting factors such as compaction temperature, compaction pressure and lubricant concentration were studied. Effect of die wall lubrication on the powder's warm compaction behavior was also studied. The use of smaller size colloidal graphite investigated can give a higher compact density and lesser spring-back effect than the use of flake graphite.

Key words: warm compaction behavior; iron-based powder metallurgy; spring-back effect

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1 INTRODUCTION

Conventional powder metallurgy (PM) processing can produce iron-based PM parts with a density less than 7.1 g/cm^3 (a relative density of approximately 90%). Their mechanical properties are substantially less than those of their full density counterpart. Increasing density is the best way to increase the performance of the PM parts. There are many processes that can produce iron-based PM parts with high density such as powder forging, double press/double sinter (DP/DS) and Cu infiltration, but warm compaction is the most economical and effective way. Its cost is about 25% higher than that of the conventional PM process but about 40% lower than that of forging and about 10% lower than that of DP/DS and Cu infiltration^[1]. Case studies on economic competitiveness of PM processing of gear components show that, with a comparable part density and mechanical properties, compared with DP/DS, warm compaction has a consistent cost saving over the entire range of production volume. Without compromising part performance, conversion to warm compaction from DP/DS, a 12% cost reduction for planetary gears and an 8% cost reduction for sun gears were achieved^[2].

Literatures focused on warm compaction were firstly published in 1994^[3, 4]. Industrialization of the technique matured in the mid 1990's. With minor modification on the conventional PM equipment, green compact density of 7.5 g/cm^3 can be obtained

by single pressing^[5, 6]. The only difference between the warm compaction and the conventional compaction is that the powder has to be treated with special lubricant, and then the powder was raised to the pre-set temperature and are pressed in the die, which was maintained at the warm compaction temperature with a deviation of $\pm 2.7 \text{ }^\circ\text{C}$ ^[6].

Special powder mix for warm compaction is available in world market. In China, CAO et al developed a series of iron-base powder for warm compaction^[7, 8]. Several other researchers studied the effects of processing parameters on the properties of the sintered iron-base alloys and studied the densification mechanism of warm compaction^[9-11]. Some researchers studied warm compaction route to prepare particulate reinforced iron-based materials^[12, 13]. LI et al studied the effect of die wall lubrication on the warm compaction^[14]. However, no literature reported the effect of different kinds of graphite on the warm compaction behavior of the iron-based powder. The aim of this paper is to study warm compaction behaviors of iron-based powders and to compare the results with those of conventional cold compaction.

2 EXPERIMENTAL

High purity water atomized iron powder with an average particle size of $75 \text{ }\mu\text{m}$ was used as raw material. Some characteristics of the iron powder

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Table 1 Chemical composition and property of iron powder

$w(C)/\%$	$w(O)/\%$	Apparent density/ $(g \cdot cm^{-3})$	Flowability/ $(20s \cdot kg^{-1})$	Particle size distribution/ $\%$			
				$\leq 45 \mu m$	$45 - 75 \mu m$	$75 - 150 \mu m$	$150 - 212 \mu m$
≤ 0.02	≤ 0.2	2.95	28	21.2	28.0	42.4	8.4

used in this study are listed in Table 1. Powders of carbonyl Ni ($3-5 \mu m$), electrolytic Cu ($< 75 \mu m$), reduced Mo ($< 75 \mu m$) and powder of flake graphite ($< 75 \mu m$) or colloidal graphite ($2-3 \mu m$) were used as alloying elements. The composition of the mixed powder in mass was 2.0% Cu, 2.0% Ni, 1.0% Mo and 0.6%–1.0% C. Unless specially mentioned, all compositions were reported in mass through out this paper. Additional 0.25% and 0.6% of polymeric lubricant were mixed with the powder for die wall lubricated and non-die wall lubricated experiment, respectively. The powder was mixed in a rotary mixing machine for 1 h. Approximately 29 of the mixed powder was raised to the assigned temperature in a mold, which was heated by a resistant coil. The powder was warmly compacted into standard tensile test bars (GB 7963-1987) or cylinders with diameter of 12 mm and height of 7 mm at a temperature ranging from ambient temperature to 160 °C, and with a pressure ranging from 500 to 800 MPa in a heated steel mold. For the die wall lubricated case, emulsified polytetrafluoroethylene (PTFE) was brushed on the inner die wall for lubrication. Green density and spring-back effect were measured.

Spring-back effect was determined by measuring the difference between the size of the sample and the inner size of the die. The sample size change after ejection was measured by micrometer according to GB/T 5159-1985. Size change percentage (Δd_{DC}) is defined as:

$$\Delta d_{DC} = [(d_G - d_D) / d_D] \times 100\%$$

where d_G and d_D are the size of the green compact and the inner size of the die, respectively.

3 RESULTS

Fig. 1 shows the relationship between the green compact density and the compact pressure for conventional compaction, warm compaction and die wall lubricated warm compaction. They all show an increase with increasing the pressure. Effect of compacting temperature on green density is more obvious for compaction with higher pressure. Compared with the conventional compaction, there is an increase of 0.19 g/cm^3 at 800 MPa and an increase of 0.1 g/cm^3 at 500 MPa by using warm compaction. An increase of 0.25 g/cm^3 can be obtained if die wall lubricated warm compaction is used.

Fig. 2 shows the relationship between the green

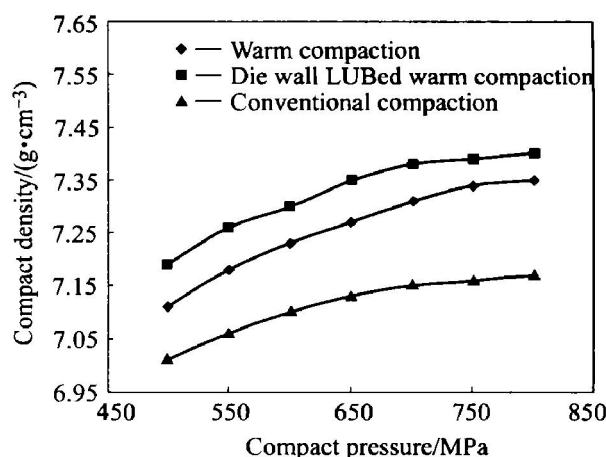


Fig. 1 Relationship between green density and compact pressure for conventional compaction, warm compaction and die wall lubricated warm compaction.

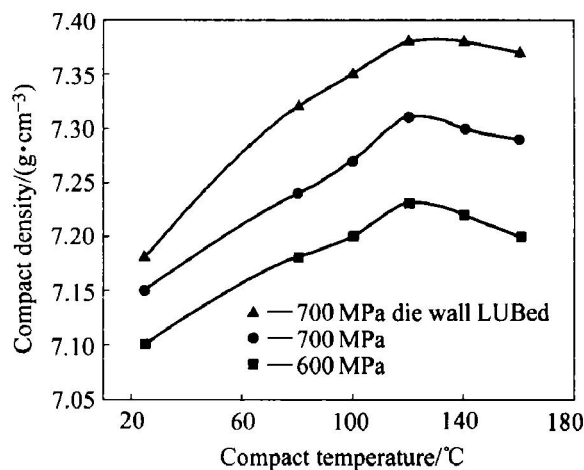


Fig. 2 Relationship between green density and compact temperature for warm compaction and die wall lubricated warm compaction samples

density and the compact temperature for warm compaction and die wall lubricated warm compaction samples. From Fig. 2, it is seen that green densities increase with the increase of temperature until the temperature reached 120 °C, then decrease gradually. For die wall lubricated warm compaction, the compact density seems to decrease at a higher temperature.

Fig. 3 shows the relationship between the green density and the compact pressure for warm compacted sample lubricated by different kinds of graphite. They all show a nearly linear increase with the in-

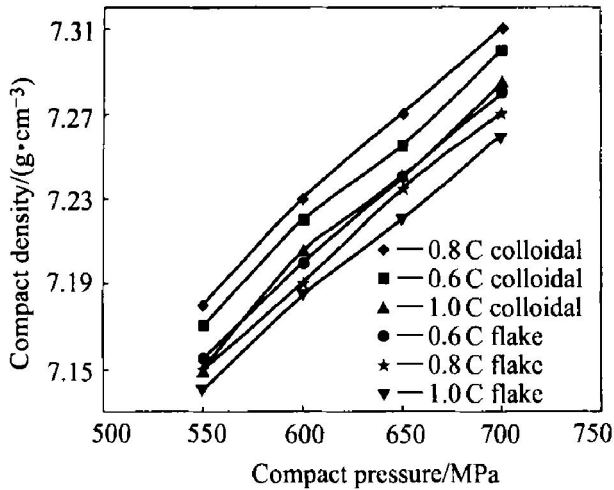


Fig. 3 Relationship between green density and compact pressure for warm compacted sample lubricated by different kinds of graphite

crease of pressure. The use of colloidal graphite can give a higher green density. For colloidal graphite there exists an optimal graphite content to obtain higher compact density, the optimal content in this study is 0.8%.

Fig. 4 shows the relationship between the spring-back effect and the compact pressure for warm compacted sample lubricated by different kinds of graphite. From Fig. 4, it can be seen that spring-back effect of all samples increases with the increase of pressure. Compacts lubricated by colloidal graphite show lesser spring-back effect. At high pressure the spring-back effects on die wall lubricated and non-die wall lubricated warm compaction samples are similar, but at lower pressure the die wall lubricated warm compaction samples show larger spring-back effect.

Fig. 5 shows the relationship between the spring-back effect and the green density for warm compacted samples with different carbon contents lubricated by colloidal graphite. They all show an increase with the increase of density.

4 DISCUSSION

The introduction of die wall lubrication enhances the effective pressure that exerts on the powder during the compaction. The shapes of the die wall lubricated and non-die wall lubricated curves in Fig. 1 are similar, with the die wall lubricated curve shifted upward. This similarity in shape indicates that the densification mechanism remains unchanged even the die wall is being lubricated. The maximum green density can be obtained at 120 °C because the lubricant used in this study melts approximately at 120 °C. As having been pointed out by LI et al.^[10], the decrease of lubricant's friction coefficient with the increase of

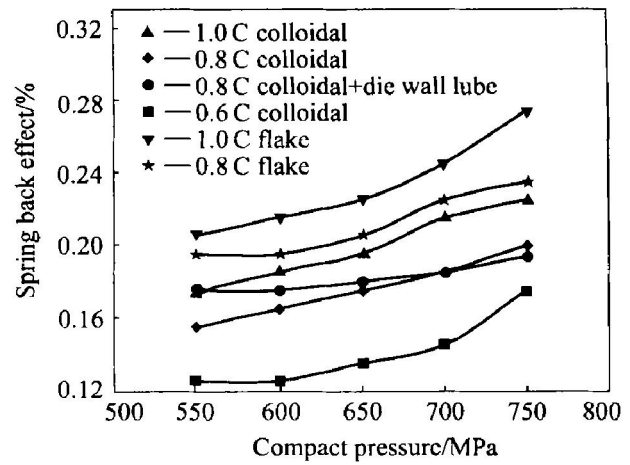


Fig. 4 Relationship between spring-back effect and compact pressure for warm compacted sample lubricated by different kinds of graphite

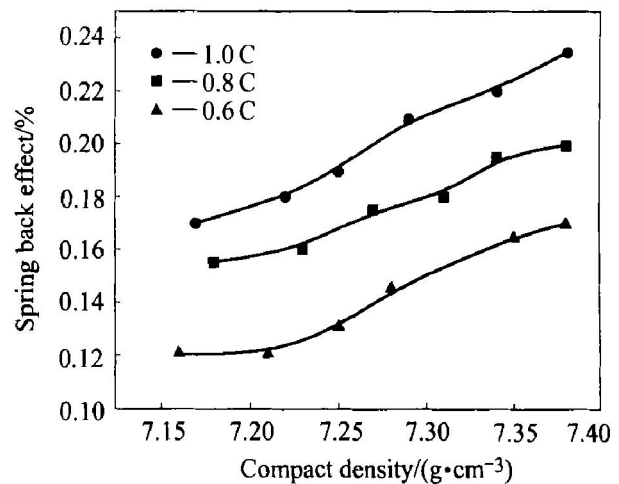


Fig. 5 Relationship between spring-back effect and green density for warm compacted samples with different carbon contents using colloidal graphite

temperature is the main reason to obtain higher green density at elevated compaction temperature. The melted lubricant spread out in the compact and modified the lubricating condition further during the compaction. When the temperature exceeded the melting temperature, effects of the lubricant diminish and the green density decreases accordingly. For die wall lubricated warm compaction the high melting point of PTFE can increase the effective pressure well beyond 120 °C.

Graphite is an effective solid lubricant. It has a high elastic modulus. When the compress stress releases after ejection from the die, graphite particles will at least partially recover from its compressive state and thus reduces the compact's density. The size of colloidal graphite is about 1/20 of flake graphite has. They can evenly fill in the interspaces inside the compact. The recovering of the compacted

graphite is therefore compensated by the available space and thus reduces the spring-back effect, while compacts containing flake graphite show larger spring-back effect since its large size stops it from filling the interspaces. Therefore, the high flake graphite content will decrease the compact's density. For colloidal graphite, since there are inter-spaces that can compensate the elastic recovering of the graphite particles, there exists an optimal graphite content to obtain the highest compact density. The optimal content is 0.8% in the study, as shown in Fig. 3.

No matter flake or colloidal graphite is used, it ignores the C content in the compact, and all the curves shown in Fig. 4 have similar slopes except for the die wall lubricated curve, which exhibits a gentle slope. Compared with the non-die wall lubricated sample, which also contains 0.8% colloidal graphite, die wall lubricated sample shows stronger spring-back effect at compaction pressure lower than 700 MPa and has a lesser spring-back effect at compaction pressure higher than 700 MPa. The major function for die wall lubricant is to reduce the friction between the die wall and the powder particles (or green compact). It can enhance the effective pressure that exerts on the powder during the compaction. It can be expected that the die wall lubricated case will shift the curves to the right side in Fig. 4.

The higher the density is, the larger the spring-back effect is, no matter flake or colloidal graphite is used. The higher density implies the lesser the available inter-spaces in the compact, the larger the energy stored in the severely deformed powder particles. The stored elastic energy will be released once the compact is ejected out from the die, leading to the expansion of the compact.

5 CONCLUSIONS

The die wall lubricated and the non-die wall lubricated warm compaction have the same densification mechanism. In this study, the maximum green density can be obtained at 120 °C. For die wall lubricated warm compaction PTFE, the high melting point can increase the effective pressure well above 120 °C. The use of smaller size colloidal graphite can give a higher compact density than that flake graphite can. No matter colloidal or flake graphite is used, spring-back effect increases with the increase of compaction pressure. Compacts using colloidal graphite show lesser spring-back effect. At high pressure, the spring-back effect for both die wall lubricated and non-die wall lubricated warm compaction samples are approximately

the same, but at lower pressure, the die wall lubricated warm compaction samples shows larger spring-back effect.

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