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Densification laws and properties of sintered powder compacts in rotary forging process①

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Abstract: In order to obtain high property powder metallurgy products, at present rotary forging process has often been used to further densify the sintered powder compact, but the densification law and property analysis have very rarely been studied, therefore the densification laws of sintered powder compacts being composed of Fe-0.8%C-4.0%Cu-0.2% zinc stearate and formed as cylindrical shape by double action pressing, and then further densified as well in a rotary forging process was studied by orthogonal experiment and regression analysis. The experimental results show that the H/D ratio and the rotary forging force are major factors affecting the density of the sintered powder compacts in the rotary forging process. The effect of the H/D ratio and the rotary forging force on the density were discovered. By determining both the density and the hardness of compacts, it was found that the density distributions show no difference from the hardness distributions and that the gradients of the density and the hardness in the axial direction are larger than those in the radial direction.

Key words: sintering powder compact; rotary forging; densification; mechanical properties **Document code:** A

1 INTRODUCTION

A sintered powder compact is a porous material. The porosity lowers its mechanical properties. In order to obtain high property powder metallurgy products, a densification process must be added after the conventional powder metallurgy process, such as hot isostatic pressing, extrusion or hot forging[1,2]. The hot isostatic pressing can produce superior microstructure and properties, but the equipment is expensive. The hot forging and hot extrusion only meet massive production due to the high die cost, and hot working is very easy to cause interior oxidation defects of preforms. The rotary forging process not only has advantages such as small force, good surface quality and low installation investment, but also easily makes complete densification owing to the large shearing deformation. At present, much research work has been done in Japan, England and other countries[3~8], but those work concentrates more on application than on densification laws and property analysis of the compacts. The purpose of this paper is to study the foundation for later densifying powder metallurgy products by the rotary forging process and providing a reference for further research.

2 EXPERIMENTAL

In order to minimize the shrinkage during sintering, FG70Cu4 is used as raw material which belongs to typical material series Fe-Cu-C used in the field of powder metallurgy. The composition of the sample is as follows:

Fe-0.8%C-4.0%Cu-0.2% zinc stearate.

The samples were formed as cylindrical shape by the double-action pressing in order to reduce the non-homogeneity of density. Sintering atmosphere is decomposing ammonia. The machine used in the experiment was a 300 kN rotary forging press. Considering the poor plasticity and flowability of the sintered powder compacts, a set of flashless cold rotary forging dies was used.

3 LAWS OF DENSIFYING SINTERED POWDER COMPACTS BY ROTARY FORGING

3.1 Major factors affecting density

There are many factors affecting the density of the sintered powder compacts in the rotary forging process, i.e. the H/D ratio of samples, the draft per revolution, the initial density of samples, the rotary forging force, the forming time, lubrication condition and so on. The orthogonal experiment was made in order to find out the major affecting factors, the relationship between factors and index (i.e. the density), and the better experimental condition for the further experiment.

The average density was selected as the experimental index. The orthogonal experimental table $L_{16}(4^5)$ was selected. Every experimental factor and its four levels are shown in Table 1. Other experimental conditions are given below: rocking die's angle, 3°; rotary forging time, 5 s; rotational speed,

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298 r/min; lubricated condition, machine oil.

The initial density of the sintered compact and the density rotary forged were determined by dewatering method. The densities of the samples were calculated according to the following equation:

$$\rho = \frac{m_1}{m_3 - m_2}\rho' \quad (1)$$

where m_1 is the mass of the sample in air, m_2 the mass of the sample in water, m_3 the saturant mass of the sample taken from the water and then cleaned the surface, and ρ' is the density of water at measuring temperature t. The result of the experimental analysis shows that the ranges of the H/D ratio and the rotary forging force are larger than those of the initial density and the draft per revolution, as shown in Table 1. The index fluctuations of the H/D ratio and the rotary forging force at different levels are larger than those of the feed per revolution and the initial density. So it is clear that the H/D ratio and the rotary forging force are major factors affecting the density of the sintered powder compacts in the rotary forging process.

Table 1 Factors and their levels and values of ranges

Factors & Levels	H/D ratio	Feed per rev/mm	Initial density /(10^3 kg·m^{-3})	Rotary forging force/kN
I	1.5	1.43	5.80	75
II	1.0	1.66	5.95	150
III	0.75	2.15	6.10	200
IV	0.50	3.01	6.25	300
Ranges	0.55	0.10	0.11	0.57
Grade	2	4	3	1

3.2 Laws of densifying sintered powder compacts by rotary forging process

3.2.1 Effect of H/D ratio on density

The H/D ratio of the workpiece is a very important parameter in the rotary forging process. It affects not only the required rotary forging force but also the deformation homogeneity of the sintered powder compacts. Because the final density is affected by the non-homogeneous deformation of the sintered powder compacts in the rotary forging, the parameter H/D ratio seems very important.

Six series of different H/D ratios samples were forged on a 300 kN rotary forging press under the same other conditions. The curve of the density vs H/D ratio is shown in Fig. 1. The regression equation between the density and the H/D ratio is

$$\rho = 0.95080 - 0.041349\ln(H/D) \quad (2)$$

The regression coefficient $R = 0.961362$ (nearly equals 1.0) shows the accuracy of this equation is very high.

Fig. 1 and Eq. 2 show that the relationship between the reciprocal value of the H/D ratio and the density is logarithm, i.e. the density of the sintered powder compacts increases with the reduction of H/D ratio. When the H/D ratio is smaller than 0.35, the average density can rise to 99%; when the H/D ratio is smaller than 0.25, the density can approach to 100%.

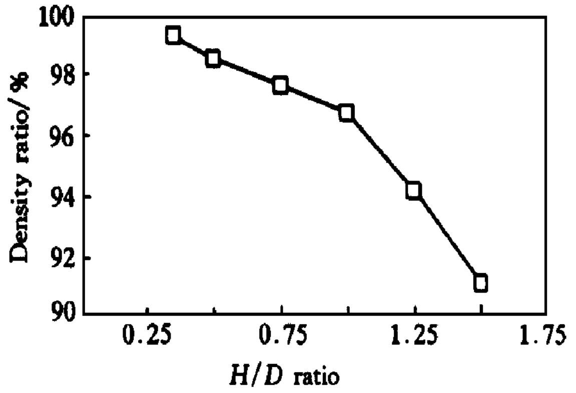

Fig. 1 Relationship between density and H/D ratio

The reason for the negative logarithm term between the H/D ratio and the density is illustrated as follows. A rotary forging process belongs to a process with the workpiece partially loaded and accumulatively deformed. The effective stress value decreases gradually along the loading direction with the increase of loaded area, so the top part of the workpiece first meets the yield criterion. The higher the H/D ratio, the larger the difference of the stress between the top and the bottom, thus the more non-homogeneous the density, i.e. the larger the density gradient in the height direction. As a result, the whole density can be raised. On the contrary, the lower the H/D ratio, the smaller the pressure loss caused by the friction between the die wall and the workpiece. Thus the deformation area almost permeates the whole height of the workpiece. So the density is very high and rather homogeneous.

3.2.2 Effect of rotary forging force on density

The range value of the orthogonal experiment shows that the effect of the rotary forging force on the density is much similar to that of the H/D ratio. In the same way, seven series of samples were forged by the different rotary forging forces under the same other conditions. The curve of density vs rotary forging force is shown in Fig. 2. The regression equation between the density and the rotary forging force is given below:

$$\rho = \frac{p}{1.008920 + 6.088029p} \quad (3)$$

where ρ is the relative density, p is the rotary forging force. The regression coefficient $R = 0.992417$ (≈ 1.0) indicates that the imitated result is rather accurate.

Fig. 2 and Eq. 3 show that the density gets higher with the increase of rotary forging force. The non-homogeneity of the density becomes more difficult to eliminate with increase of the rotary forging force because of the restriction of the H/D ratio. When

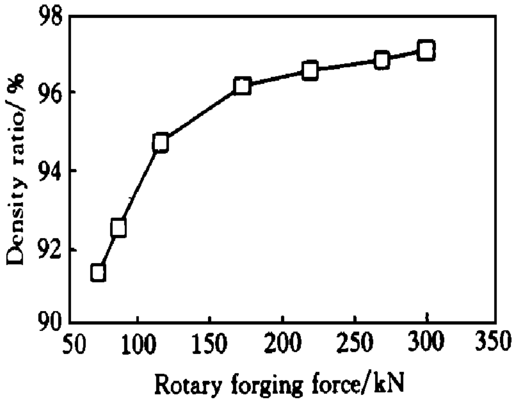

Fig. 2 Relationship between density and rotary forging force

the rotary forging force is raised to 300 kN, the density is only near 97%. In addition, from the curve of Fig. 2, we can see that the density increases fast when the rotary forging force is smaller than 200 kN and hardly increases when the rotary forging force continuously increases. The sintered powder compacts at low density are very porous. The yield stress of the compacts is very low so the yield criterion is rather easy to meet and the density increases fast. This phenomenon that the real loaded area increases with the decrease of the porosity is called "geometry-hardening". At the same time, the work-hardening also raises the further densification forming resistance gradually with the increase of the density. Because of these two types of hardening, the density is very difficult to increase with increasing rotary forging force.

4 PROPERTY ANALYSIS OF COMPACTS

A sintered powder compact has many properties. Care is usually given to the sintered construction products for their mechanical properties. In fact, the density and hardness can be regarded as the equivalent one of the mechanical property in the field of powder metallurgy. So the following property analysis focuses mainly on the density and hardness. The density distribution is obtained by cutting samples layer by layer and then calculating it with Eqn. 1. The results are shown in Fig. 3. The curves of the density distribution in the radial and axial directions are shown in Fig. 4.

	0.25*R*	0.5*R*	0.75*R*	1.0*R*
1.0*H*	6.05	6.17	6.20	6.33
0.8*H*	6.08	6.13	6.17	6.23
0.6*H*	6.20	6.12	6.10	6.06
0.4*H*	6.08	6.13	6.17	6.23
0.2*H*	6.05	6.17	6.20	6.33

	0.25*R*	0.5*R*	0.75*R*	1.0*R*
1.0*H*	7.79	7.81	7.90	7.71
0.8*H*	7.50	7.56	7.63	7.47
0.6*H*	7.35	7.36	7.38	7.21
0.4*H*	6.86	6.92	7.05	7.12
0.2*H*	6.82	6.85	6.95	7.05

Fig. 3 Density distribution of sintered powder compacts
(a) —Sintered only, $\rho = 6.18\times 10^3$ kg/m^3, $D = 1.0$, $H = 23.2$ mm;
(b) —As rotary forged to height reduction of 23%

Because a sintered powder compact is a porous material, the porosity can bring a gross error into determining the hardness. In order to reduce the error, the Ball hardness method was used. By dealing with the calculated results the hardness distribution curves in the radial and axial directions are shown in Fig. 5. The distribution of the hardness is similar to that of the density. They all show the same law that the axial gradient is larger than the radial one. The reasons lie mainly in two aspects, one is that the friction of the die wall makes the forming force generate an axial gradient, the other is that the loaded area expanded gradually makes the forming stress generate an axial gradient. The radial density gradient is much smaller

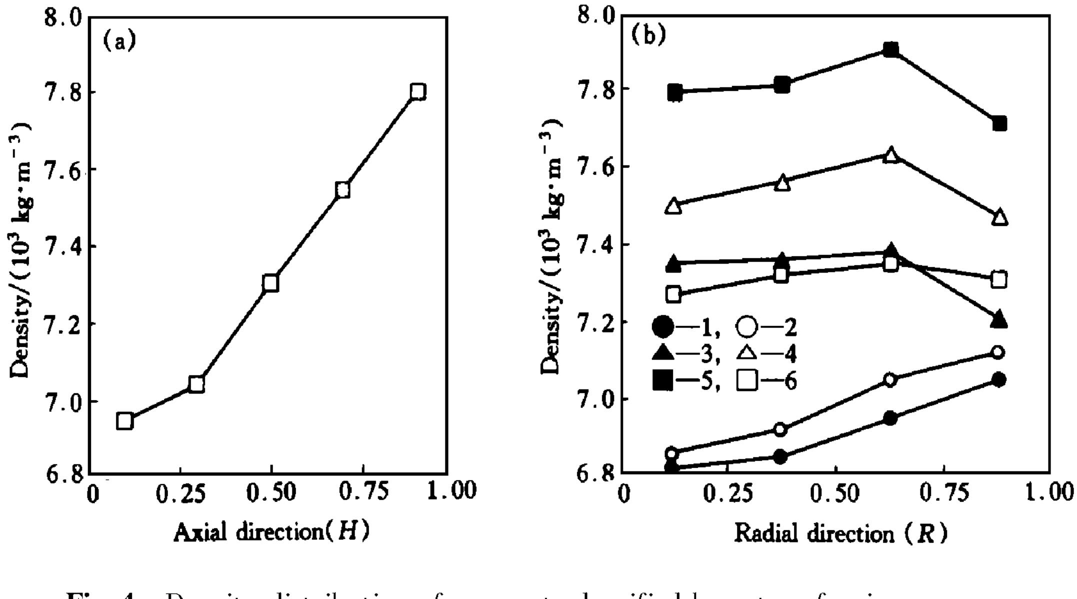

Fig. 4 Density distribution of compacts densified by rotary forging process
(a) —Average density distribution in axial direction; (b) —Density distribution in radial direction
(1, 2, 3, 4, 5 in Fig. 3(b) indicate each layer's radial density distribution respectively, 6 expresses the average density.)

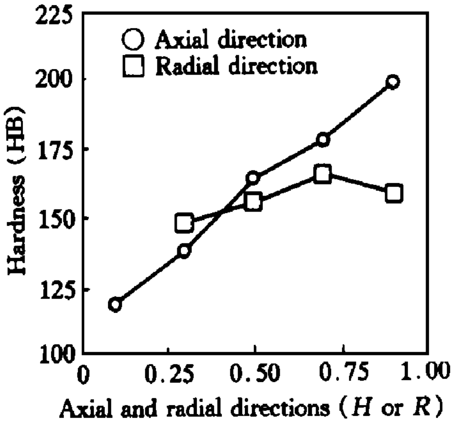

Fig. 5 Average radial and axial hardness distributions of sintered compacts densified by rotary forging

than the axial density. The reason for the non-homogeneous radial density (or hardness) is caused by the non-homogeneous radial stress distribution. It was reported that the maximum radial pressure is located at 0.25 R and the maximum tangential pressure at 0.73 R by Pei *et al*[9]. In Fig. 3(b) the peak value of the radial average density is also located between 0.50 R and 0.75 R. From Fig. 4(b) it is obvious that the peak value of curves 5, 4 and 3 all lie in 0.50 R ~ 0.75 R and one is more obvious than the next. It can be seen that the influence of the tangential stress on radial density distribution is remarkable. The closer to the top of the workpiece, the more remarkable the influence on the density. At the bottom of the workpiece there is no this influence. The density (or hardness) is the lowest at the central region of the bottom.

5 CONCLUSIONS

1) The H/D ratio of the processed compacts and its subsequent rotary forging force are major factors affecting the density of the sintered powder compacts in the rotary forging process.

2) The relationship between the H/D ratio and the density of the processed compacts is negatively logarithmic, i. e. the density of the sintered powder compacts increases remarkably with the decrease of the H/D ratio. The relationship between the rotary forging force and the density is hyperbolic, i. e. the density is higher and higher with increasing rotary forging force.

3) At a lower density of sintered powder compact, the effective means for increasing density is raising the rotary forging force; but at a higher density the further densification is only completed by reducing the H/D ratio.

4) The density and hardness distributions of compacts after the rotary forging, whether it is radial or axial, are non-homogeneous. The axial gradient is more remarkable than the radial one. The hardness distribution shows no difference from the density distribution.

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