A Study on the Powder Forging of Aluminum Alloy Pistons

Jong-Ok Park[1], Chul-Woo Park[1] and Young-Ho Kim[2]

[1] Dept. of precision mechanical engineering, Pusan National University, graduate school, Pusan, South Korea
[2] School of mechanical engineering, Pusan National University, Pusan, South Korea

ABSTRACT

Powder forging technology has been introduced to manufacture the parts for vehicles. This paper describes the process conditions for the powder forging of aluminium alloy piston for vehicles including the determination of composition of aluminum alloy by experiment, preform design by FEM simulation, cold compaction of aluminum alloy powder, sintering of preform, and the experiment of powder forging. The mechanical properties such as hardness, tensile strength, and elongation of the formed piston were invested and compared with casted piston and forged piston. The tensile strength and hardness of the piston formed by powder forging technology were much more excellent than other pistons.

Keywords: Powder forging, Sintering, Compacting, Preform design, Aluminum alloy piston

1. Introduction

By containing 10-20% of pore, the products manufactured by powder metallurgy have defects such as lower ductility, fatigue strength, and impact strength.[1] Therefore, there are a lot of limitation in the size and application of product. Powder forging technology has been introduced as an idea to overcome such defects. In the powder forging process, the products manufactured by powder metallurgy are forged in order to remove pores contained in them. Powder forging is a technology that can expand the limited application of powder metallurgy by minimized flash, reduced number of stage, and possible grain refinement. Moreover, manufacturing cost and weight of product can be decreased by the net-shape forging and less number of forming process comparing to conventional hot forging technology.

Recently, related works have been reported on the various technological aspects of the industrial processing of powder forging. Iwata[2] carried out the investigations concerning the development of aluminum alloy powder forged piston. Daninger[3] studied on the sintering characteristics and process of aluminum alloy belt pulley for cam shaft and the influence of several composites on wear resistance. Crawford[4] investigated on pressure transmission in metal powder material by slab method, and Sutradhar[5] applied slab method to cold closed forging with sintered aluminum preform and carried out the experimental study. Domestically, various studies such as the application of powder forging technology to the parts for vehicles[1], preform design technology with FEM simulation[6], the FEM simulation on plastic deformation through the prediction of density distribution when sintered metal is deformed[7], the analysis on forging limit of sintered metal[8], and the theoretical study on the yield function of sintered metal[9] have been carried out. But still, the studies on sintering and forming technology and theoretical study with aluminum alloy powder have not been achieved enough.

The purpose of this study is the development of piston for vehicles as shown in Fig. 1 including the determination of optimal composition by experiments, preform design by FEM simulation, and the characteristic analysis of the product by several test methods.

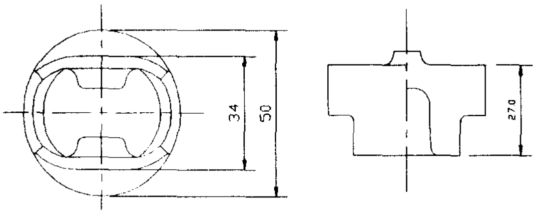


Fig. 1 Schematic diagram of piston

2. Determination of composition

Generally, comparing to wrought material, the material of preform formed with metal powder has some problems such as cracks and fractures during forging process due to porosity. Therefore, in determination of composition, not only the characteristics of material such as mechanical strength but the forgeability of the material should be considered.[6]

2.1 Mixing and compaction

The powder used in experiment is produced by ECKART, co. ltd. in Germany and 200mesh (less than 150 μm in diameter) in size. The powder was mixed in V-type mixer and compacted by 200 ton hydraulic press. Generally the compacting of aluminum powder is carried out 2~4/cm^2 in pressure, which was fixed as 2/cm^2 in the experiment.

The floating die shown in Fig. 2 was designed and fabricated for the compacting of metal powder. This is needed for the uniform distribution of density in compacted part.

2.2 Sintering

The sintering experiment was carried out to determine the composition of aluminum alloy for the development of proper piston material for vehicles. Considering the working atmosphere of high pressure and temperature, Mn and Ni were added. The compositions of other metal powders except Si were fixed. 1~2%(mass) of Si was added in order to increase hardness and wear resistance and 4.5% of Cu was added in order to improve sintering ability and strength.

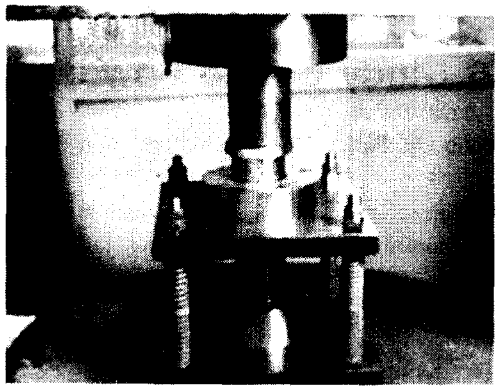
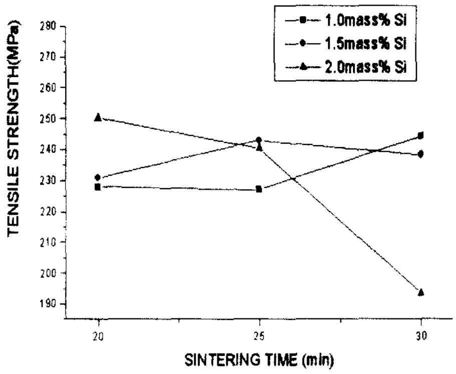


Fig. 2 Floating die for compaction

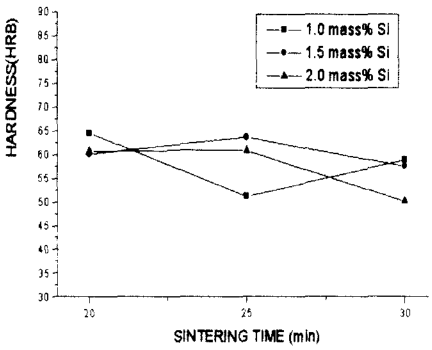
In order to establish the sintering condition according to alloy composition the percentage of Si, temperature, and time for sintering were set for parameters. 1, 1.5, and 2% of the percentages of Si, 560, 580, and 600℃ of the sintering temperatures, and 20, 25, 30 minutes of the sintering time were set so as to have the experimental condition of 9 times with 27 process parameters. In the process, the green compacts were hold 30 minutes in 400℃ for dewaxing, 20~30 minutes in 560~600℃ for sintering and 20~30 minutes in 150℃ for cooling. Finally the temperature of materials became 40℃ in air. N_2 was used as the atmospheric gas. The sintered materials were T6 heat treated for the estimation of mechanical characteristics. The mechanical properties and characteristics according to each process parameter such as tensile strength, elongation, hardness, and micro-structure were estimated.

2.3 Results of experiment

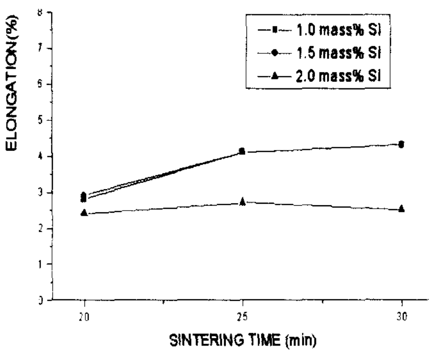
After compacted ϕ84 × 20mm in cylinderical shape, the green compacts were sintered in various conditions. The variations on tensile strength, hardness, and elongation according to 580℃ of sintering temperature are shown in Fig. 3. As the sintering time is increasing, the tensile strength and elongation are also increasing while the hardness is generally decreasing. The determined composition of aluminum alloy metal powder for the engine piston of vehicles is shown in Table 1.



(a) Sintering time - Tensile strength



(b) Sintering time - Hardness



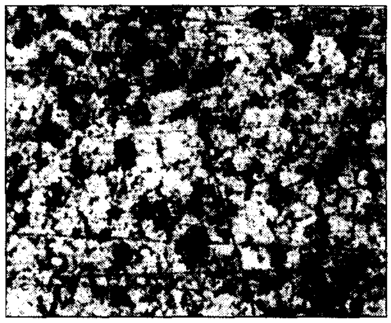
(c) Sintering time - Elongation

Fig. 3 Mechanical strength and characteristics of sintered specimens (sintering temp.: 580℃)

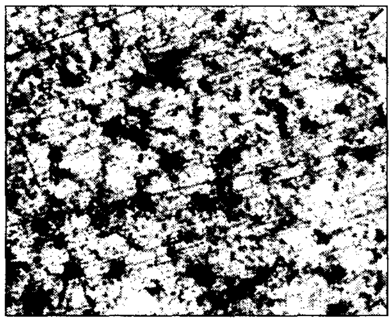
Table 1 The determined aluminum alloy composition for the engine piston

Compos-ition	Al	Cu	Si	Ni	Mn	Mg	micro-wax
mass%	89.8	4.5	1.5	2.0	0.5	0.5	1.2

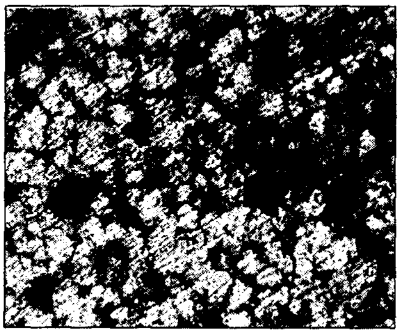
The micro-structures(magnification 50×) of sintered materials in the condition of 25 minutes of sintering time and each sintering temperatures are shown in Fig. 4. As sintering temperature and time increase, the effect of melted chemical compound becomes more activated. The distributed eutectic structures are thick, exhibited the minute distributed precipitation and cavities in surface. In manufacturing process, aluminum powder has a stable alumina(Al_2O_3) layer. After sintering process, the abrasion resistance becomes increased because the alumina acts as a dispersion strengthening substance.



(a) 560℃



(b) 580℃



(c) 600℃

Fig. 4 Micro-structure according to sintering temperature(Si 1.5%, sintering time 25min)

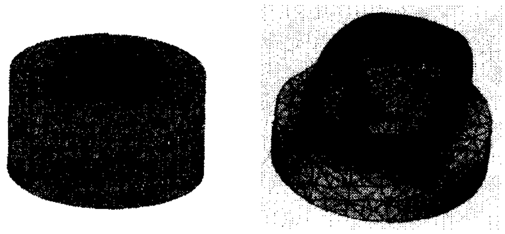
The optimum condition of sintering is determined as 1.5% of Si, 580℃ of sintering temperature, and 25 minutes of sintering time.

3. Preform design by FEM simulation

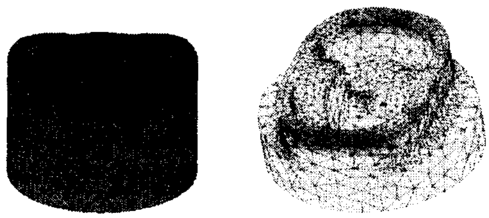
The FEM simulation by DEFORM, one of mostly used softwares in analysis of metal forming, was carried out. The relative density test(KS standard D0033) and ring compression test were carried out in order to estimate the relative density and friction coefficient of the preform. The relative density of 0.92 and friction coefficient of 0.28 were obtained from ring compression test and used as the input parameter in FEM simulation. The flow stress of specimen at 450℃Ėwas assumed as a function of strain-rate, and it was acquired from MTS(Material Test System) test. The equation is shown as follows.

$$\bar{\sigma} = 36.5\,\bar{\varepsilon}^{0.115}\,(\mathrm{MPa})$$

Fig. 5 shows the preforms and results of FEM simulation with each shape of preform, and the computational results show good agreement with the experimental results. For the preform Fig. 5(a), die filling was not accomplished at the end of boss. The preform Fig. 5(b) reduces the tensile strain from 0.9 to 0.45 through the endowment of boss portion.



(a) Cylindrical preform and the result of simulation



(b) Modified preform and the result of simulation

Fig. 5 Designed preform and the result of simulation

4. Forging experiment

4.1 Experimental method

The forging experiment was carried out using 200 ton hydraulic press with closed forging die. The die temperatures were 250℃ and 300℃, and the material temperatures were 420℃, 450℃, 480℃. Specimens for the tensile test and hardness test were T6 heat treated after forming. The specimens for tensile strength were prepared according to KS standard 14(A). The schematic diagram of powder forging die is shown in Fig. 6.

Fig. 7 shows various preform shapes used in experiment. In the case of preform Fig. 7(a), the end parts of skirts was not filled completely because of the wrong shape of preform. In the process with the preform Fig. 7(b), the crack was found on the end region of skirts. As the preform is ejected, micro cracks might appear on the skirts by abrupt spring back. Accumulated micro cracks may cause macroscopic defect. To avoid the defect such as folding at the final stage compression, sudden geometric change in the shape of preform should be kept out. The preform Fig. 7(c) designed for the reason is better than others.

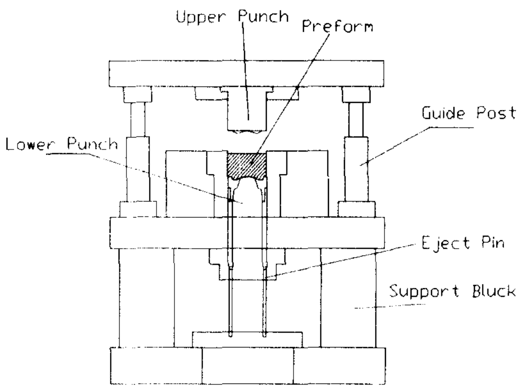
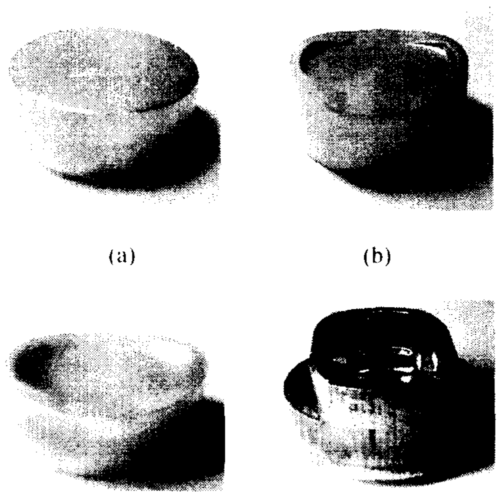


Fig. 6 Schematic diagram of powder forging die



(a) (b)

(c) (d) the forging product

Fig. 7 Preforms and forged piston

4.2 Estimation of forging product

Table 2 shows tensile strength, elongation, and hardness according to each temperature of die and preform. When the temperature of die and preform is low, the higher tensile strength and hardness were acquired. But if they are too low, defects appear at specimens. The experiment shows that the die temperature 250℃ and the preform temperature 420℃ are the optimal condition.

Table 2 The mechanical properties and strength of powder forged piston according to forging condition

Die temp. (℃)	Preform temp.(℃)	Tensile strength (MPa)	Elongation(%)	HRB (avg.)
250	420	630	8.0	77.5
	450	580	7.2	75.8
	480	600	7.0	74.2
300	420	560	6.4	75.8
	450	530	5.5	71.2
	480	530	5.9	68.0

Table 3 shows the comparison on tensile strength and hardness of pistons manufactured by casting, forging, and powder forging technology[10]. The tensile strength and hardness of the piston by powder forging technology are much more excellent than other pistons.

Table 3 Comparison of pistons on mechanical properties

Products \ Properties	Tensile strength (MPa)	Hardness (HRB)
Casted Piston	232	69~73
Forged Piston	299	70~80
Powder Forged Piston	630	77.5

5. Conclusions

In this study, the determination of the composition for the aluminum alloy metal powder by experiment, preform design by FEM simulation, analysis on deformation behavior for sintering, and evaluation of mechanical characteristics and workability through forging experiment for high strength aluminum alloy piston were performed. The conclusions are summarized as follows.

1. The most efficient aluminum alloy composition

of powder forged piston was proposed, which provides high mechanical strength and characteristics.

2. Through the FEM simulation and experiments, the preform design method taking accounting of densification of whole regions of piston, die filling, and removal of defect was proposed.

3. Mechanical properties of aluminum alloy piston were evaluated by the extensive experimental and theoretical analysis, including FEM simulation.

4. Optimal process condition with the used material was determined for powder forging through the experiments ; 1.5% of Si, 580℃ of, 25 minutes in sintering condition, 250℃ of die and 420℃ of material temperatures in forging.

References

1. J. H. Lee, Y. S. Lee, and H. S. Chung, "Development of Bevel Gear by Powder Forging Process," Journal of Korean Powder Metallurgy Institute, Vol. 4, No. 4, pp. 258-267, 1997.
2. Y. Iwata, S. Mae, Y. Urai, and T. Tsunoda, "Aluminium Alloy having an Excellent Forgibility," United States Patent[19], P. N. 4889557, Dec. 26, 1989.
3. H. Danninger, "Sintered Aluminium camshaft belt pulleys," M. P. R. June, pp.46-52, 1993.
4. R. J. Crawford, and D. Paul, "Pressures transmitted through Polymetric powders subjected to solid phase compaction," Polymer, Vol. 21, pp. 138-139, 1980.
5. G. Sutradhar, A. A. Bashashwan, A. K. Jha, and S. Kumar, "Closed die axisymmetric forging of sintered aluminium preforms," J. Materials Processing Technology, Vol. 68, pp. 19-22, 1997.
6. J. J. Park, J. H. Lee, and H. S. Chung, "Preform Design for Forging of a P/M Connecting Rod," Journal of Korean Powder Metallurgy Institute, Vol. 2, No. 1, pp. 19-28, 1995.
7. H. S. Kim, H.N. Han, K.H. Oh, " Thermo-Elasto-Plastic Finite Element Analysis of Powder Hot Forging," J. Korean Powder Metallurgy Institute, Vol. 4, No. 2, pp. 83-89, 1997.
8. J. J. Park, "A Yield Function for Sintered Porous Metals," The Korean Society of Mechanical Engineers, Vol. 17, No. 5, pp. 1115~1122, 1993.
9. H. K. Oh, J. K Lee, "A Study of the Extrusion of Sintered Porous Metal," J. Mechanical Working Technology, Vol. 11, pp. 53-69, 1985.
10. Y. H. Kim, W. B. Bae, H. S. Kim, H .S. Byun,, "An Experimental Study on the Manufacturing Technology of an Engine Piston," Korean Society of Precision Engineering, Vol. 15, No. 11, pp. 13-22.