Two-step PM forging for precise fabrication of carbon fiber reinforced engineering plastic gears

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Keywords: Carbon Fiber Composites, Engineering Plastics, Gears, Powder Metallurgy, Green Compaction, Sinter-Forging, Die Technology

Abstract. Carbon fiber reinforced engineering plastic (CFREP) small-sized parts were fabricated by PM (Powder Metallurgy)-oriented forging process. This manufacturing procedure consisted of the green compaction and sinter-forging steps. In the first step, the CFREP powders were consolidated to a green compact with high density. This preform was further sinter-forged into a final product by hot stamping with the use of the induction heating unit. Hardness distribution was measured to describe the consolidation behavior with increasing the compression load, and to optimize the sinter-forging conditions for solidifying the green compact to the sintered product. X-ray tomography was utilized for non-destructive diagnosis on the residual pores and defects. The eight-teeth gear model was fabricated to demonstrate that two step procedure wrought well to yield the dense and defect-free gear with sufficient strength and integrity.

Introduction

The composite materials have been used to improve its mechanical and functional properties by combining the secondary phase materials and the matrix [1]. In particular, CFRP (Carbon Fiber Reinforced Plastics) and CFRTP (Carbon Fiber Reinforced Thermo-Plastics) have been widely used to produce the light-weight and high strength structural parts and members [2,3]. In those composite materials, their intrinsic properties are controlled not only by the fiber orientation and density in reinforcement but also by the selection of matrix plastics [3,4]. The normal CFRP is made from the epoxy-resin matrix and the carbon long-fibers; the CFRP ply and woven cloth are also used as a staring material for near-net shaping of parts and members. Most of those CFRP parts and members have been fabricated by using the autoclave processing [5] and the hot/warm stamping [6] with the finishing step. In particular, the small-sized parts and structural members are often yielded by hot stamping the laminated ply sheets [7]. The carbon short-fiber reinforced plastics are injection molded into various small- to medium-sized products from the pelletized feedstock [8]. Those processes work well when the composite matrix is made from relatively low glass transition temperature plastics such as epoxy. Most of engineering plastics (EP) have much higher glass transition temperature than normal matrix plastics; they are difficult to be molded or compressed into products. In addition, their feedstock is usually made of powders and particles; a new manufacturing process is necessary to fabricate the small sized EP and CFREP parts from this feedstock.

The mechanical gears are a typical element to transfer the applied load from input to output, to reduce the rotational speed in reducer, and to construct the mechanism of movement [9]. As reported in [10], the light-weight gears with high stiffness play an important role in the reducer at the robot arms and joints and in the automatic mechanics for electric vehicles. In addition, the gears with high radiation resistance are also needed in the robotics working in decommissioning operations [11]. Most of engineering plastics have sufficient radiation resistance and high specific strength to provide a solution to those demands.

In the present study, the carbon fiver reinforced engineering plastic (CFREP) powders are selected as a feedstock to fabricate the CFREP gears with sufficient hardness and integrity. Two-step powder metallurgy oriented procedure is developed for this fabrication. First, the CFREP powders are poured into a die cavity to consolidate them into the green compact with relatively high density. This green compact is further sinter-forged to an eight-teeth gear-model product. The hardness distribution is measured to describe the green compaction behavior and to investigate the effect of holding temperature and applied load on the sinter-forging process. The X-ray tomography is also employed to make non-destructive evaluation on the defects and porosities left in the green compact and sinter-forged gear. Three dimensional profilometer is used to measure the dimension of gear teeth with reference to the CAD (Computer Aided Design) data.

Methods and Materials

Two-step PM (Powder Metallurgy) oriented method is stated in details on the green compaction step for cold forging the CFREP powders to a green compact and on the sinter-forging step to consolidate the green preform to the final product. How to characterize the green compact and sinter-forged gear product, is also explained in the following.

Two-Step PM-Oriented Procedure.

Two-step PM-procedure to fabricate the CFREP product consists of the green compaction step in cold and dry and the sinter-forging step in hot. As illustrated in Fig. 1, the feedstock powders were poured into a die cavity in the die set. In the green compaction step, the load was applied to the punch to consolidate them into a green compact with the specified density in cold and dry. The incremental compression mode was utilized to deliver the powders to every branch of cavity for uniform consolidation. This green preform was fixed into the other die set to sinter-forge this preform into a sintered product at the elevated temperature. The indirect heating method was employed to preserve the hot forging condition by using the high-frequency induction heating (HF-IH) system (YS-Electrical Industry, Co., Ltd.; Kofu, Japan). In both steps, the CNC (Computer Numerical Control) system (Precise Stamping Laboratory, llc.; Tokyo, Japan) was commonly utilized.

The solid lubrication was utilized to reduce the friction on the contact interface between the punch/core surfaces and the work in these two-step processes. The h-BN sprayed film was formed onto the punch and die surfaces before each operation. After green compaction, the punch is first released and the core-die was reloaded to move down for ejection of formed compact. In nearly the same manner, the sintered work was also ejected from the die-set.

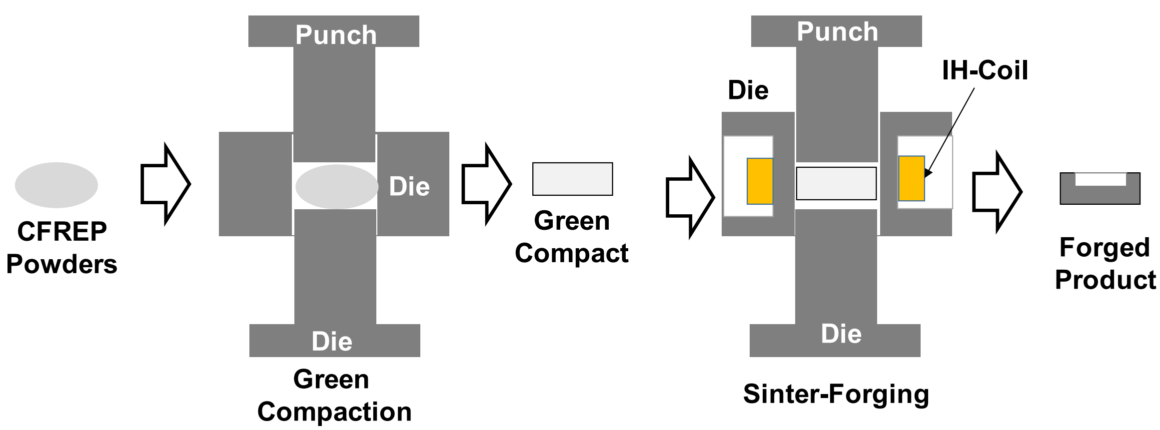


Fig. 1. A schematic view on the two-step PM-oriented procedure from the feedstock powders to the product. a) Green compaction step, and b) sinter-forging step.

Green compaction.

Among several materials, the CFREP powders (Aurum-PD450; Mitsui chemicals, Co., Ltd.) were selected as a feedstock for fabrication of gear models by the two-step procedure. This Aurum-PD450 was a thermoplastic polyimide with Tg (Glass transition temperature) of 518 K (or 245°C) and Tm (Melting temperature) of 661 K (or 388°C). When using the injection molding, the mold temperature could be higher than 673 K; this PD450 must be difficult to be shaped into products by using the injection molding. Table 1 summarized the mechanical properties of this Aurum-PD450. Compared to normal thermoplastic polymers such as PP (polypropylene) and PC (polycarbonate), higher strength and modulus characterizes this feedstock.

Table 1. Mechanical properties of Aurum-PD450.

Item	Typical data	Testing method
Tensile strength	90 MPa	ASTM D 638
Ultimate elongation	90 %	ASTM D638
Bending strength	140 MPa	ASTM D 790
Bending modulus	3 GPa	ASTM D790
Izod impact strength	90 J/m	ASTM D256

Fig. 2 depicts the CFREP powders as an initial material for green compaction. The carbon short-fibers were included into each powder at the preparation of powder feedstock.

Fig. 2. CFREP powders as a feedstock for consolidation via the cold, dry stamping to a green compact.

In the normal powder metallurgy (PM) processes, the original powder feedstock was poured into a die cavity and consolidated by stamping in cold. As stated in [12], the metal and alloyed powders with lubricants were mixed and compressed in the die to build up the green compact. This green compact was further processed to degrease the lubricants from the green compact before sintering and sinter-forging processes. In the present two-step PM procedure, no lubricating oils and waxes were utilized in green compaction and sinter-forging steps to minimize the contamination.

In this consolidation process, the relative density of green compact is controlled by varying the applied load. As stated in [12], this relative density of green compact has significant influence on the homogeneity and uniformity of products in the sinter-forging step. Hence, the hardness of green compact is measured by varying the applied load. Figure 3 shows an experimental setup for consolidation of CFREP powders to a green compact, corresponding to its schematic view in Fig. 1a. The load cell was embedded into the lower die. Owing to the programmable loading sequence in the CNC stamping system, the stoke schedule of upper die set was controlled to densify the green compact through the incremental loading sequence.

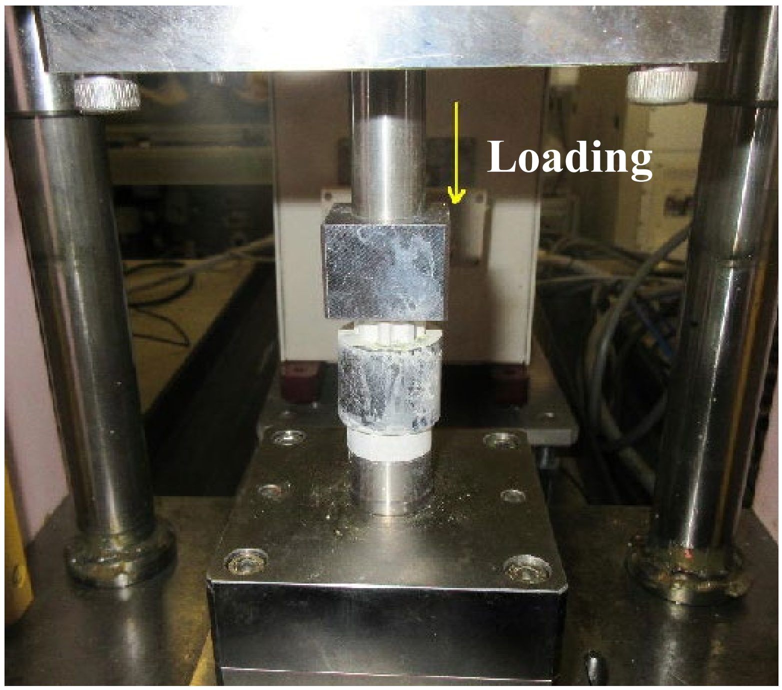


Fig. 3. Experimental setup for consolidation of CFREP powders to green compact in correspondence to its schematic view in Fig. 1a.

Sinter-Forging.

The green compact preform was fixed into the die-set for sinter-forging, as shown in Fig. 4. The HF-IH coil was placed to surround the die set with the designated clearance to optimize the spatial impedance between the dies and the coil. The load was first applied to 2 kN before heating the die set. The load was increased to the holding load at the specified temperature. The holding duration was constant by 600 s. In the following experiment, the holding temperature and applied load were varied to optimize the sinter-forging conditions by measuring the surface hardness. The sprayed h-BN film was also used for solid lubrication on the die surface.

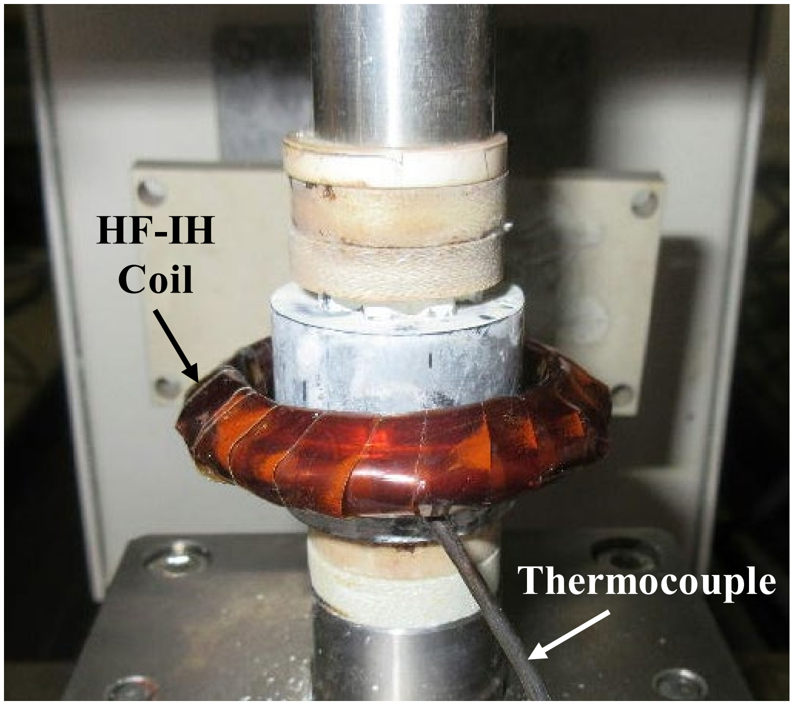


Fig. 4. Experimental setup for sinter-forging of the green compact to the forged gear product in correspondence to the schematic view in Fig. 1b.

Characterization.

A table-top X-ray tomography apparatus (X-1; Ueda, Japan) was employed to make non-destructive evaluation on the residual pored and defects in the green compact as well as the sinter-forged products. The intrinsic spatial resolution is 50 – 100 μm; however, the X-ray penetration capacity must be optimized to improve the spatial resolution in practice. Otherwise, no X-ray images are obtained when the applied power is too much or too low. Through the learning step, the optimal conditions were fixed and used in the following diagnosis. Three dimensional profilometer was also used to measure the part dimension of each tooth in the sintered gear with reference to the original CAD data and to discuss the dimensional accuracy of sintered CFREP gears.

Results

The cold and dry consolidation process is described by measurement of the average and maximum hardness in the teeth of green preforms in each loading condition. The sinter-forging behavior is also described by hardness measurement to search for the optimal processing conditions. The X-ray tomography is utilized to validate the dense green compacts and sinter-forged products. Three dimensional profilometer is utilized to measure the tooth profile and configuration for practical usage as a gear with reference to the standard.

Green compaction behavior.

The CFREP powders were consolidated in cold and dry to green compact preforms, the hardness of which was measured in each green compaction conditions to determine the appropriate load. A typical green compact was depicted in Fig. 5a when the applied load was 3.2 kN. The X-ray tomography was utilized for non-destructive evaluation on the density distribution in the inside of preform. As shown in Fig. 5b, no pores and defects were detected by this diagnosis. Three cross-section X-ray tomographic images proved that the preform had homogeneous density distribution.

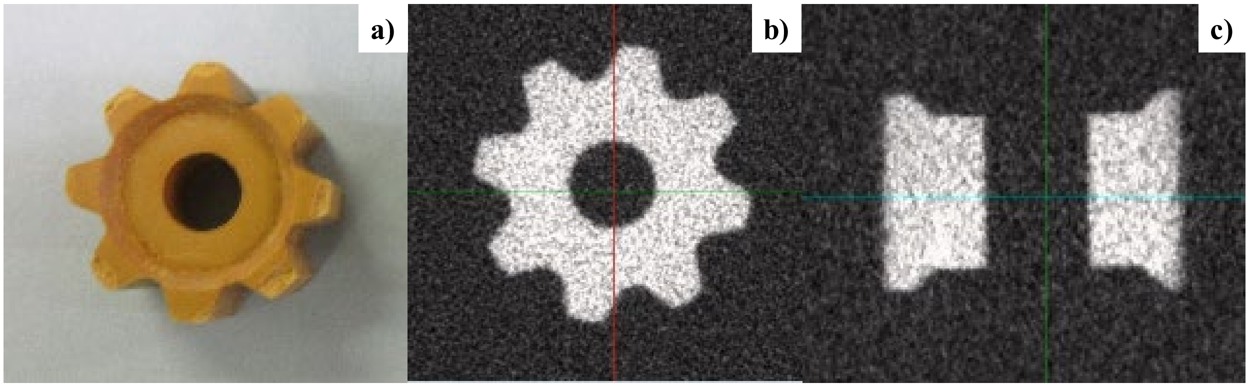


Fig. 5. A green compact after cold, dry stamping by applying the load of 3.2 kN. a) Overview of the green compact, b) X-ray tomographic image on the green compact from the top view, and c) X-ray tomographic image on the green compact from the side view.

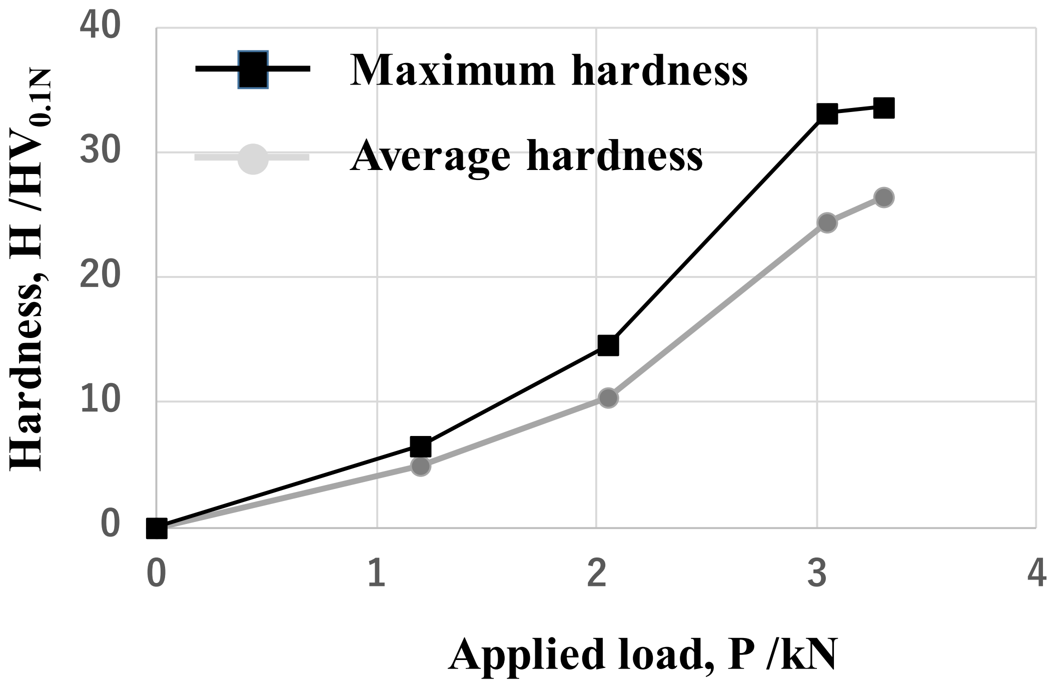
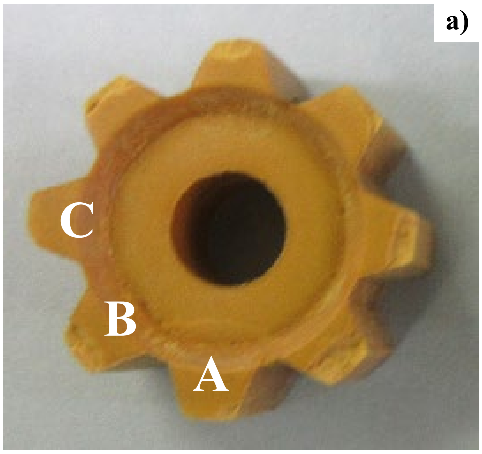


Fig. 6. Variation of the average and maximum hardness with increasing the applied load in the green compaction.

The average and maximum hardness were measured at each tooth of eight-teeth green compact preform. The applied load and duration were constant by 0.1 N (or 10 gf) and 10 s, respectively. As shown in Fig. 6, both hardness increased monotonously with increasing the applied load (P) up to P = 3 kN. This reveals that densification of CFREP powders advances with increasing the applied load during this consolidation process. The deviation of the maximum hardness from the average one increased with increasing P. This might be because of the friction on the surface of dies. When P > 3 kN, both hardness turned to be nearly constant; the green compact is near-fully consolidated in dry and cold. Several green preforms were fabricated by applying the load of 3.2 kN to investigate the hardness distribution among teeth of gear preforms.



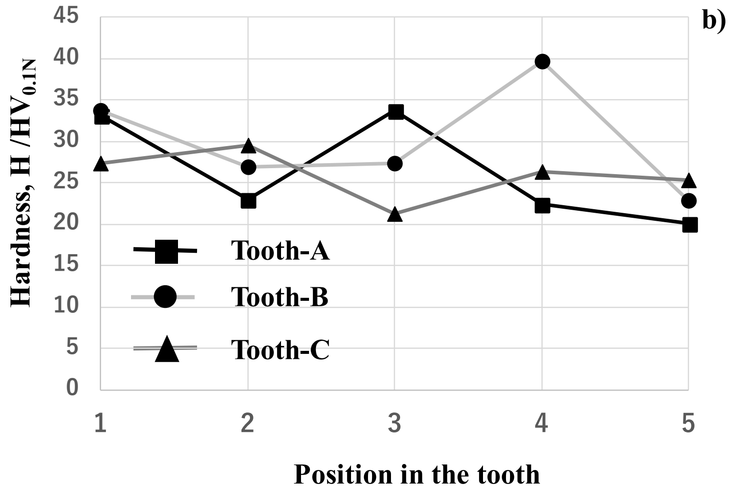


Fig. 7. Deviation of the surface hardness among the teeth of green preform gear when applying the load by 3.2 kN. a) Selected three teeth for measurement in the gear preform, and b) deviation of surface hardness among five positions in each tooth.

Three teeth (A, B, C) of green compact were selected to measure the hardness at the five positions in each tooth as depicted in Fig. 7a. The center point of tooth was denoted by No. 2. No. 1 and No.3 points were located away from this center point in the upper and lower directions by 0.075 mm, respectively. No. 4 and No. 5 points were also located away from No. 2 in the right and left sides by 0.075 mm, respectively.

Fig. 7b shows the hardness distribution in each tooth for A, B and C teeth. Since the average hardness is 27 $HV_{0.1N}$ in Figure 6, the deviation in each tooth ranges from 21 $HV_{0.1N}$ to 34 $HV_{0.1N}$ excluding the extraordinary high hardness. That is, the feasible hardness of green compact is estimated to be 27 $HV_{0.1\,N} \pm 7$ $HV_{0.1N}$; the statistical deviation is controlled to be less than a single standard deviation from the average hardness.

Most of this dimensional deviation comes from the powder flow and deformation behavior under compression. After [13], the rearrangement of CFREP powders by powder flow has more influence on the density of green compact than the deformation of CFREP powders. The incremental compression mode might be necessary to make more uniform densification in the green compact.

Sinter forging behavior.

The green compact specimens were fixed into the die cavity for sinter-forging. The specimen was first compressed and held by 2.0 kN during induction heating as shown in Fig. 4. The die temperature was inline monitored by using the thermocouple, which was embedded into the die. The holding temperature (T_H), the loading sequence, and the holding duration (τ) work as a main parameter in this sinter-forging process. T_H must be higher than Tg; T_H could exceed Tm since the actual specimen temperature might be less than Tm due to the thermal conductivity through die wall and the gap conductance between the specimen and die surface.

At first, the parameters were fixed at T_H = 668 K (or 395°C) and τ = 600 s, the sinter-forged preform was fabricated as shown in Fig. 8a. The X-ray tomography was also employed to investigate the sintering behavior; the X-ray irradiation intensity was lowered to distinguish the pores and defects left after sintering. Figure 8b shows the cross-sectional view of sinter-forged specimen. No pores and defects were seen in the inside of preform.

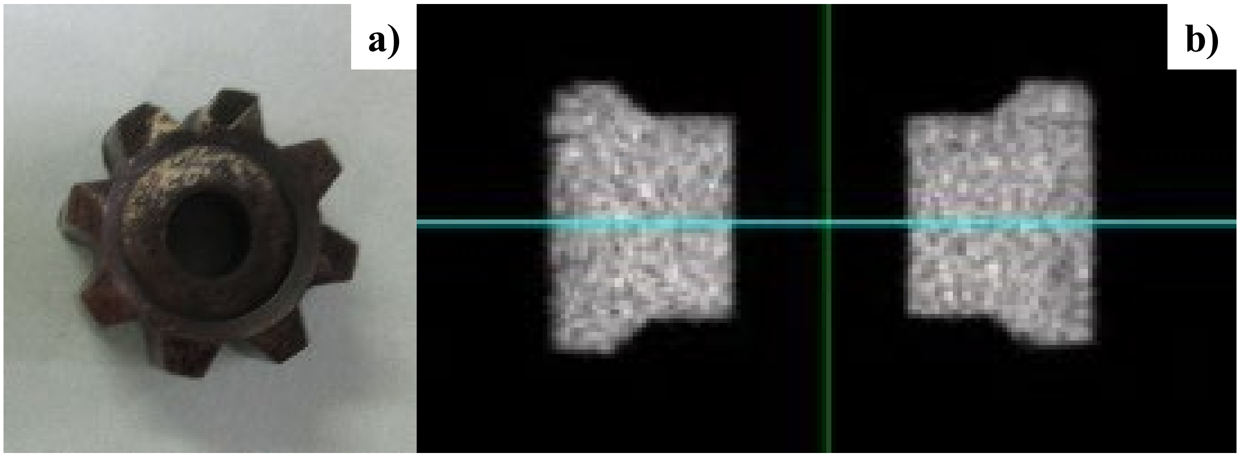


Fig. 8. A sintered gear after hot forging at 668 K for 600 s by 2 kN. a) Overview of the sinter-forged product, and b) X-tomographic image on the sinter-forged product in Fig. 5a with three cross-sectional images.

Table 2. Variation of the maximum hardness by varying the holding temperature just below Tm and the applied load in the sinter-forging.

Specimen	Holding Temperature (T_H) °C	Applied load (P) kN	Hardness (HV0.1N)
#1	381	2.5	41
#2	387	3.0	38
#3	389	4.0	47

Let us investigate the effect of T_H and applied load (P) on the sintering behavior. T_H was varied below T_m of polyimide matrix. Table 2 summarizes the variation of measured maximum hardness by varying T_H and P. Compared to the hardness distribution of green compact in Fig. 7b, higher hardness was attained by sinter-forging. Different from the sinter-forging of electrically conductive metallic powders [14], the loading schedule must be controlled and optimized to attain much higher hardness at the sinter-forged gear-teeth of non-conductive CFERP.

Table 3. Dimensional measurement of sinter-forged CFREP gear by three dimensional profilometer.

Item	D_c (mm)	D_{cic} (mm)	D_{coc} (mm)
Sinter-forged CFREP gear	4.963	15.969	11.981
Die for sinter-forging	5.02	16.06	12.04

Quantitative evaluation on the CFREP gear.

Three dimensional profilometer in the projector-type (CALYPSO) was utilized to measure the center hole diameter (D_c), the diameter of circumscribing inner and outer circles (D_{cic} and D_{coc}) were measured for the sinter-forged CFREP gear at T_H = 450 °C, by P = 3 kN and for 300s. Table 2 compares the measured data and original dimensions of die. In every dimension of gears, a negative deviation of 0.5 % is commonly measured in the sinter-forged CFREP gear. This deviation can be improved by optimization the sinter-forging conditions.

Discussion

As stated in [15], most of engineering plastic gears are made from polyacetal (POM) and MC Nylon, which is essentially polyamid resin, U-PE (Ultra High Molecular Weight Polyethylene), and PEEK (Poly-Ether-Ether-Ketone). Although they are characterized by the lightweight, the non-rusting, the quiet operating, and the injection molding enabling low cost, they suffer from the low strength, the tendency to hold heat, and the large dimensional change. In particular, the thermal distortion by relatively large coefficient of thermal expansion influences on the gear performance working in operation, in addition to the geometric distortions by the resist temperature change, the moisture absorption rate and the resistance to chemicals. The present CFREP gear has higher strength, chemical and thermal stability than those normal engineering plastic gears. Especially, this gear is free from the thermal distortion and dimensional change. To be noticed, those normal engineering plastic gears have no ways in hardening and strengthening. This CFERP gear is made from high strength polyimide matrix and carbon short fibers. This high strength composite design reflects on the high hardness even for the green compact.

Let us discuss the radiation resistance of CFREP gears. As discussed in [16], the CFRP has a risk of microstructural damage without CNT modification; this damage might come from the interfaces between the carbon fiber and epoxy matrix. The carbon fiber – poly imide interface is enough strong to reduce the risk of microstructural damage even under γ-irradiation conditions. This superiority in the radiation resistance is attractive to the gear box in reducer and in mechanical control unit of robots working in decommissioning operations.

The PM processing has been utilized to make mass production of small-sized and middle sized automotive parts. Its merits for fabrication of CFREP gears by the two-step PM processing, are as follows: 1) easiness to yield the complex shaped gears as a spur-gear, milter and bevel gears, screw gears and warm gears, 2) adaptivity to join the two gear units into a single working gear by sintering under compression, and 3) strengthening of gear teeth by homogeneous distribution of CFREP powders including the short carbon fibers.

In the present study, the green compaction and sinter-forging is performed in the uniaxial compression mode so that this two-step procedure has no ways to control the short-fiber orientation in the consolidation and forging. The CFREP powder flow control as well as the incremental loading in sinter-forging must be effective to make fiber-orientation control around the tooth part of CFREP gears.

Summary

Two step powder-metallurgy manufacturing procedure is proposed to fabricate the carbon reinforced engineering plastic gears from the powder feedstock. Through the green compaction step, the original powders are consolidated in cold to a solid gear-preform with relatively high density without significant pores and defects. This preform is sinter-forged at the holding temperature below the melting point for 600 s under the applied load to fabricate the CFREP gear with dimensional accuracy. In the further optimization of the processing parameters, the dimensional accuracy is improved with sufficient tolerance within the requirement of highly qualified gears.

Acknowledgements

The authors would like to express their gratitude to S-I. Kurozumi (Nano-Film Coat, Co., Ltd.) for his help in experiments, and, to Mitsui Chemical, Co., Ltd. for his help in feedstock. This study was financially supported in part by METI, Japan on the Go-Tech Program at 2022.

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