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Investigating the Fabrication and Application of Powder Forging Components Using Experimental Methods for Quality Assurance

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Abstract

The goal of this study was to examine the fabrication and application of powder forging components using experimental methods to assure their quality. This study found that the ultimate forged surface of a powder component pertained to the ultimate surface of a forging tool. Later, it was found that the microscopic structure of most powder forging components were combined with carbon to yield hardened and quenched stresses. In the meantime, a cam clutch converter has been a primary powder forging means used in the industry. The inner ring gear of powder forging is used in the autonomous transmission of trucks with gross weights of 22.700 kg (50000lb). On the other hand, engines are getting smaller but have higher rpm. Thus, there is a need for a connecting rod with enhanced fatigue strength to be economically produced.

Keywords: Powder forging components, Cam clutch, Connecting rods, Fatigue strength, Gear

Introduction

An investigation of magnetic particles reveals surface defects such as cracks and overlaps. Forged carbon and oxygen amounts are specifically focused. There is a need for a certain amount of carbon to yield a desired heat treatment response, as forged oxygen amounts have significant effects on dynamic properties. Density measurements are performed to ensure that there is sufficient density in key areas. Convective density tests, performed in ASTM B311, are usually complemented by microscopic structure tests to assess residual porosity levels. These tests are used to assay components to have a higher density in specific areas than what is needed in less important areas. As for a certain level of porosity, a measured density depends on the chemistry, heat conditions, and microscopic structures of samples. Under hardened conditions and relaxed stresses, an identical sample will have a lower density than when it is fully softened by heat and gradually cooled down in a furnace. Density amounts need to correspond to component specifications. Experiments to estimate the density of powder forging materials were proposed by Cundill [1]. Recently, Smith developed ways to estimate the non-porous density of α iron plus iron carbide ($\alpha+Fe_3\ C$) and the intact microscopic martensitic structures of low-carbon and low-alloy steels [2]. The estimations were primarily based on the basic considerations of the crystal volume of a unit cell and the mass of each phase in steels, which are considered for measured or estimated values. Estimation methods cannot be considered for the residual austenite or the presence of alloy carbides. Also, estimations of non-porous density consider powder forging materials (P/F) containing mixed copper to be insignificant if there is a considerable number of compounds in the materials.

Smith and Mashl compared measured and estimated values of the density of powder forging steels [3], demonstrating that it was very difficult to achieve a fully intact martensitic microscopic structure even in smaller sections rapidly hardened. They showed that the microscopic structure of α iron plus iron carbide ($\alpha+Fe_3\ C$), which can be produced by the gradual cooling of austenite or balls developed from a microscopic martensitic structure, should be used to assay the residual pores and voids of powder forging materials.

The reason why powder forging was selected for competitive processes was that it could reduce fabrication costs by 58% compared to conventional machining processes. Powder forging cams are made of water-atomized steel powder (P/F-4200), including molybdenum (0.6% wt), nickel (0.5% wt), manganese (0.3% wt), and graphite (0.3% wt). The Performs weighs 0.33kg (0.73lb) and is compressed to a density of $6.8\frac{\mathrm{gr}}{\mathrm{cm}^3}$. The preforms are hardened at 1120ºC (2050ºF) at an endothermic gas atmosphere with a dew point of +2ºC (+35ºF). Before being induction heated, hardened preforms are coated with graphite and forged by using both axial and lateral flows until a near-full density of >0.2% porosity. By modifying forging, the frontal facing of the cam clutch converter is combined with carbon to a depth of 1.78 mm, with the surface is induction hardened. This modified component needs a higher density to withstand a stress that the inner surface of a cam experiences in practice. Machining is only performed once on the powder forging cam. The production of powder forging cam started back in 1971. Since then, over 30 million powder forging (P/F) cam clutch converters have been fabricated without even a single simple crack.

On the other hand, the connecting rods working in internal combustion engines are subjected to higher tensile and compressive loads. These rods should be able to transmit axial, tensile, and compressive loads. They should also withstand bending stresses, caused by the axial and tensile pressure on pistons and by the eccentric force of the rotating crankshaft. The invention of connecting rod-crankshaft systems has resulted in the invention of various machines, such as internal combustion engines.

With the launch of the Buick V-6 engine in 1962, the General Motors (GM) Company produced 50 million perlite-molded malleable (flexible) iron connecting rods to be used in 11 various engines. Due to various cross-section requirements, little design modifications were applied compared to the existing forging designs, with the I-shaped beam cross-section getting larger and a much larger radius assigned to the end of the rods, which were fitted around the crankshafts. These connecting rods were cast in green sand molds, heated at 1750ºF for 18 h, and then cooled by air. After being cooled off by air, they were reheated at 1600ºF. Later, they were submerged in oil to form a hard and brittle structure and were then quenched for 3 to 4 h at 1150 to 1180ºF. Specifications of this section included tensile strength of at least 100 ksi, yield strength of 80 ksi, and elongation of 2%. The cast (molded) connecting rod was economically competing with its forged counterpart.

Powder forging connecting rods were first produced for the Porsche 928 autos back in 1970 when the advantages of a powder forging connecting rod were the reduction of machining operation and the control and withstanding of a higher weight. In 1970, raw materials required to produce powder forging connecting rods were significantly more expensive than drop forging connecting rods involved in soft metals, which initially limited the expansion of powder forging connecting rods to other engines. In the mid-1980s, Toyota used and produced the powder forging process for its connecting rods, and sought to reduce costs by using Fe-Cu-C (Carbon-Copper-Iron) as raw materials. Ford also introduced the first connecting rods in its vehicle production back in 1987, with GM and Chrysler adding powder forging to some of their engines over five years. Some European countries, such as BMW and Jaguar, used powder forging connecting rods for their gas-burning engines, though using such rods had already been limited in Europe.

This study aimed to investigate the quality of powder forging components, including component dimensions, density, metallurgy analysis, surface oxides, microscopic structures, etc. Meanwhile, the applications of powder forging components were investigated, which included a cam clutch converter, cam/inner loop, inner ring gear, powder forging roller bearings, etc. In sum, this paper discussed a brief history of connecting rods and then introduced various production methods, including sand casting, forging (soft formability), and powder metallurgy. In the end, it focused on forging and powder metallurgy to provide an accurate analysis of the forging fatigue strength and powder metallurgy.

Methodology

Quality Assurance of Powder Forging Components (P/F)

Many of the quality assurance tests of components are similar to the tests used for powder forging components. The ASTM B848 Standard includes material signs, chemical compound limits, and appropriate testing methods for powder forging components. Table 1 below gives a list of material signs and chemical requirements.

Table 1: Chemical compounds required for powder forging components (wt%)

Elements	P/F_10xx	P/F_10Cxx	P/F_11xx	P/F_11Cxx	P/F_42xx	P/F_46xx	P/F_44xx	P/F_49xx
Nickel (max)	0.10	0.10	0.10	0.10	0.40_50	1.75_2.00	0.10 max	0.10 max
Molybdenum (max)	0.05	0.05	0.05	0.05	0.55_0.65	0.50_0.60	0.80_0.95	1.4_1.6
Manganese	0.10_0.2	0.10-0.25	0.30_0.60 (a)	0.30_0.60 (a)	0.20_0.35	0.10_0.25	0.08-0.18	0.08-0.18
Copper	0.30 max	1.8_2.2	0.30 max	1.8_2.2	0.15	0.15	0.15	0.15
Chrome (max)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Sulfur (max)	0.025	0.025	0.23(a)	0.23(a)	0.03	0.03	0.03	0.03
Silicon (max)	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Phosphorus (max)	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Carbon	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)
Oxygen	(c)	(c)	(c)	(c)	(c)	(c)	(c)	(c)
Iron	Bal	Bal	Bal	bal	Bal	Bal	bal	bal
(a) Manganese sulfide coatings from 0.3 to 0.5% wt, manganese in a solution similar to P/F_10xx or P/F10Cxx wt%. (b) the carbon content assayed by the purchaser and (c) the time needed, the maximum oxygen content must correspond to the amount specified by the purchaser.								

Table 2: Types of tolerance of powder forging components

Specifications or dimensions	Description	Types of tolerance		Min. tolerance	
		$\frac{in}{in}$	$\frac{mm}{mm}$	In	Mm
(a)	Linear dimension perpendicular to the pressure axis	0.0025	0.0025	0.003	0.08
(b)	Linear dimension parallel to the pressure axis	0.10±	±0.25	0.008	0.20
(c)	External dimensions of concentric holes	...	...	0.004	0.10
(d)	Quality level	...	...	Usually better than 0.8µm(32µin)	
Source: 90					

This study carried out several tests on two types of forging connecting rods of powder metals and soft metal forging. The chemical composition of these two materials is given in Table 3.

Table 3: Chemical composition with a weight percentage (Iron is in balance) of connecting rods used in the study

Elements	Forged steel of soft metals	Forged steel of powder metals
Carbon	0.33	0.04-0.64
Phosphorus	0.02	00.04 max
Silicon	0.4	00.03 max
Nickel	0.07	0.01 max
Copper	0.21	1.8-2.2 max
Vanadium	0.084	...
Manganese	0.99	0.3-0.6
Sulfur	0.04	0.18 max
Chrome	0.47	0.09 max
Molybdenum	0.03	0.05 max

Findings

1. Quality Assessment of Powder Forging (P/F) Components

The allowable content of surface decarburization is usually assayed in a forged component. The decarburization depth can be estimated by metallographic testing, however, it should be assayed by micro-hardness measurements, as described by the ASTM E1077.

Surface oxides are defined as oxides that follow the boundaries of the previous part to the forged component of the surface, but cannot be defined by physical instruments such as rotating finishing. Figure 1 below illustrates surface oxides. Meanwhile, metallographic techniques are used to assay the maximum penetration depth of surface oxides, consistent with the ASTM B797 standard.

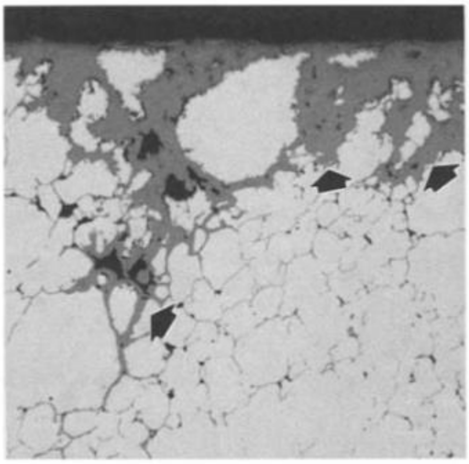

Figure 1: Surface oxides (arrows near the top right) and inter-particle oxide networks (the arrow near the bottom left) in a powder-forged material (Powder Forged Steel, p. 820).

Inter-particle oxides follow the boundaries of the previous part and can sometimes form a consistent 3D network; however, they mostly appear inconsistently on a 2D polish plate. Figure 1 shows an example of this. Metallographic techniques are used to detect inter-particle oxides (ASTM B797).

A non-metallic inclusion amount in a powder forging component can be assayed by using image analysis in the “Material Considerations” section. However, if the section of the selected component is not without pores or voids to be assayed for inclusion, image analysis methods are not used, as the presence of pores and voids makes it difficult to estimate the quantitative-visual estimation of inclusion sizes. Thus, the ASTM B796 Standard cannot be used.

2. Applications of Powder Forging Components

Powder forging and automatic transmission components are widely applied in the automotive industry. One of the most important elements of powder forging used in this industry is the cam clutch converter. A component that is represented by complex forms and can be formed on both the inner and outer surfaces of a powder forging component is a cam or an inner loop, illustrated in Figure 2 [4]. This component is a central piece of automatic transmission converters in cars.

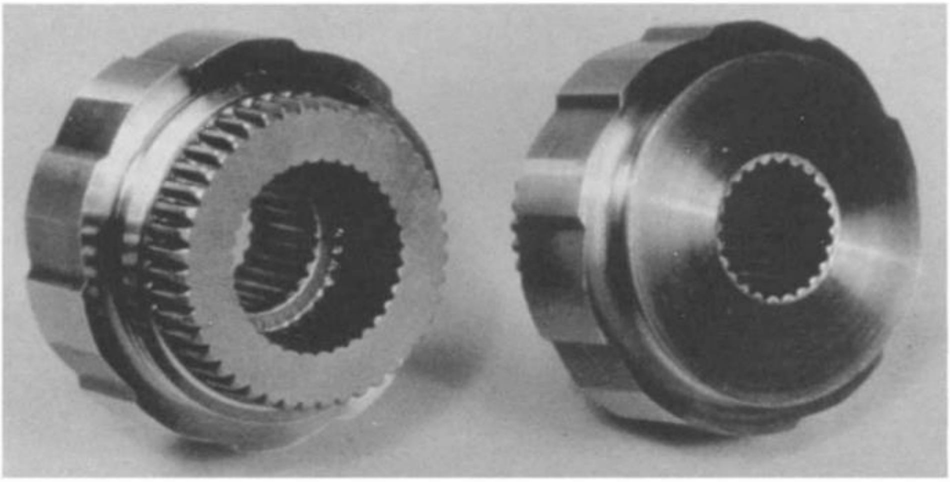

Figure 2: Powder forging cam/inner loop for automatic transmission in cars (Powder Forged Steel, p. 821)

The cam is forged to a minimum density of 7.82$\frac{\text{gr}}{\text{cm}^3}$ of the P/F-4662 material. The component has a minimum hardness and relaxed stress of 58HRC and tensile strength of 2070Mpa (300ksi).

Initially, the gear is fabricated by forging a hollow tube (AISI 5140M). The empty space is arbitrarily forged and thus goes through the following stages: rough machining (roughing), gear tooth formation, core heat treatment, combination with carbon, and deburring. The secondary treatment process required for powder forging components includes surface sanding, roughing, blast pulse, and vibrational finishing (polishing). The P/F-4618 ring gear is fabricated to a minimum density of 7.82$\frac{\text{gr}}{\text{cm}^3}$. The component is selectively combined and hardened with carbon using a specialized process. The minimum hardness of the surface is 57HRC (2070 Mpa (ultimate tensile strength of 300 ksi)), while the core hardness is 25 HRC (825 Mpa (ultimate tensile strength of 120 ksi)). The inner teeth of the gear are fabricated by the V-class AGMA method.

3. Crankshaft-Connecting Rod System

According to Figure 3, samples of the tension test in the I-shaped beams of connecting rods were subjected to machining consistent with ASTM E8 standards. Table 17 gives the tension test results of each element. As noted, the yield strength of the forged steel of soft metals was 19% higher than that of the forged steel of powder metals, with the ultimate tensile strength of the forged steel of soft metals being 8% higher than that of the forged connecting rods of powder metals.

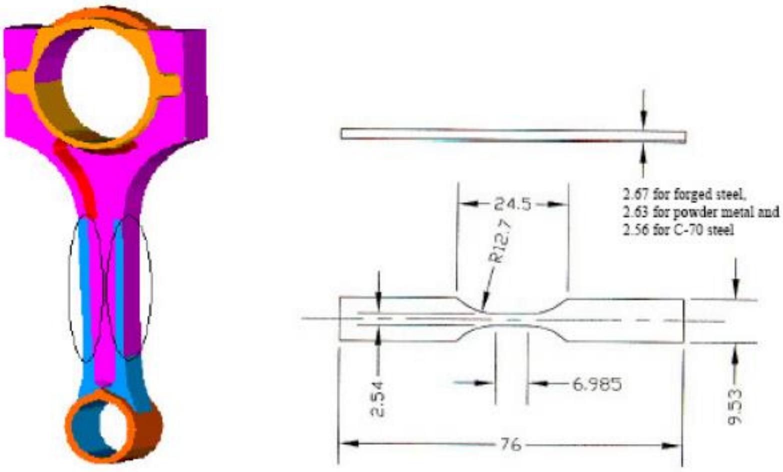

Figure 3: Position of two samples from every connecting rod and sample geometry (dimensions in mm) [4].

Table 4: Mechanical properties of the forged steel of soft metals and the forged steel of powder metals

Properties	Soft metal forging	Powder metal forging
Modulus of elasticity (Gpa)	201	199
Yield strength (2% offset) (Gpa)	700	588
Ultimate tensile strength	938	866
Elongation	24%	23%
Surface finishing	42%	23%
Strength	1400	1379
Hardness strain capacity	0.122	0.152
Real fracture strength	1266	994
Flexibility to real fracture	54%	26%
Hardness HRC	28	20
Brittle hardness	272	223

The weights of the forged connecting rods of soft metals range from 454 to 456 gr., while the same rates for the forged connecting rods of powder metals range from 571 to 577 gr. Powder-forged connecting rods are 25% heavier than the forged connecting rods of soft metals on average. Axial fatigue tests of forged connecting rods and powder metal rods were carried out at room temperature. Fatigue tests were carried out in three load amounts for each of the two types of forged rods, which yielded a fatigue life from 4×10^4 cycles to $>3\times10^6$ cycles. The fatigue strength of the connecting rods of soft metals, defined in 10^6 cycles, was 387 Mpa, while the same rate for the powder connecting rods was 282 Mpa. Therefore, the connecting rods of the forged steel demonstrated a fatigue strength of 37% higher than that of the powder metal connecting rods. When rupture (failure) occurs in the forged connecting rods of soft metals, their sub-surface failures indicate that the quality of the forged surface does not affect the fatigue behavior of the forged steel connecting rods.

The subsequent analysis compared C-70 with the above data, with the fatigue strength of C-70 being 20% less than that of the forged metallurgical steel of soft metals. Cost savings in C-70, as well as its ability to adapt to production requirements, motivated many DEMs in North America to apply C-70 for their connecting rods.

Conclusion

The goal of this study was to examine the fabrication and application of powder forging components using experimental methods to assure their quality. This study found that the ultimate forged surface of a powder component pertained to the ultimate surface of a forging tool. Later, it was found that the microscopic structure of most powder forging components were combined with carbon to yield hardened and quenched stresses. In the meantime, a cam clutch converter has been a primary powder forging means used in the industry. The inner ring gear of powder forging is used in the autonomous transmission of trucks with gross weights of 22.700 kg (50000lb). It is concluded that advancements have enabled the auto industry to develop more powerful and reliable engines while reducing the special volume they occupy. It is also noted that the two main methods to mass-produce cars involve the forged connecting rods of powder metals (with cracks) and the forged connecting rods of soft metals. On the other hand, engines are getting smaller but have higher rpm. Thus, there is a need for a connecting rod with enhanced fatigue strength to be economically produced.

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