Powder Metal Gear Design and Inspection

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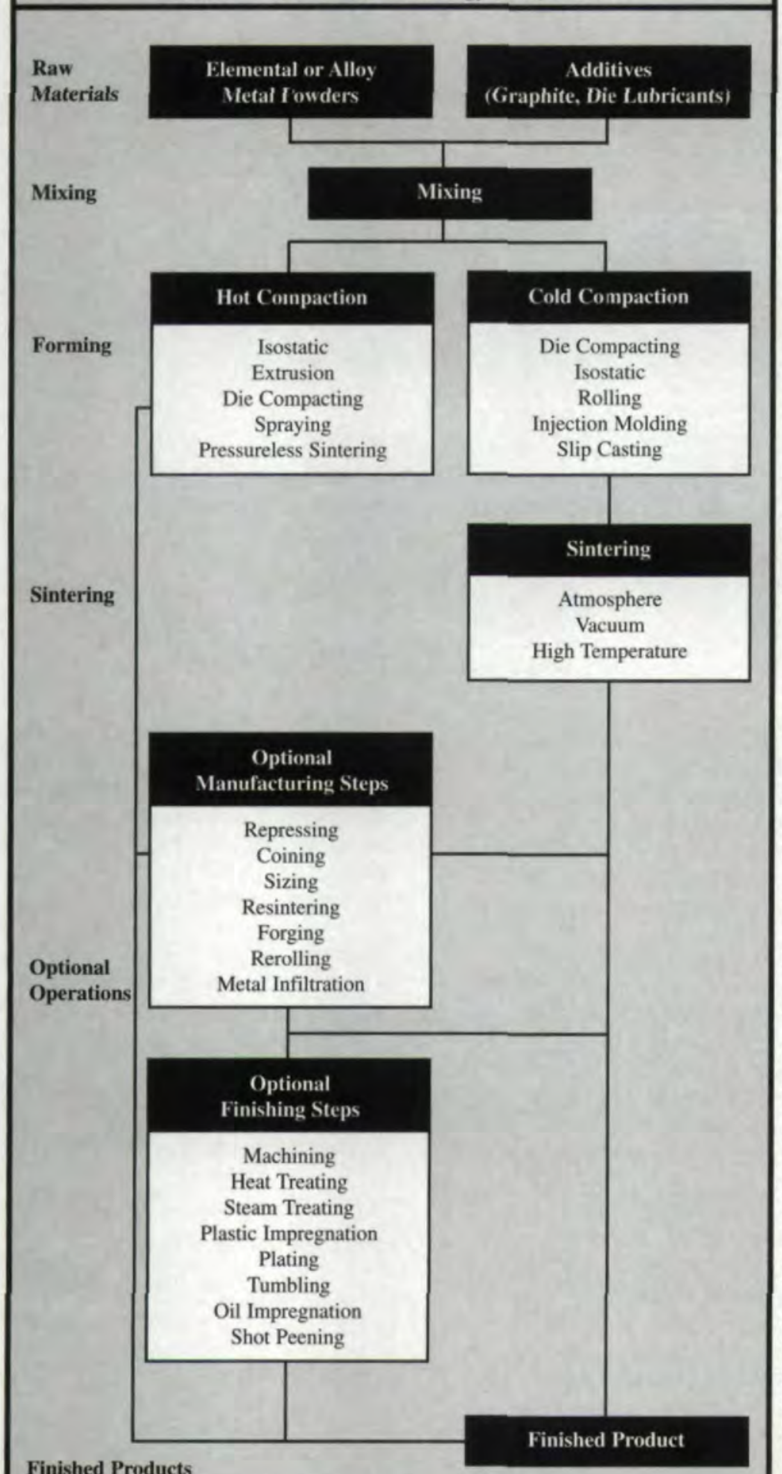
Table 1 — The Powder Metallurgy (P/M) Process



Powder metallurgy (P/M) is a precision metal forming technology for the manufacture of parts to net or near-net shape, and it is particularly well-suited to the production of gears. Spur, bevel and helical gears all may be made by powder metallurgy processing.

The P/M process is illustrated schematically in Table 1 (Ref. 1). There are three basic steps to producing parts: mixing, compacting and sintering. Variations to these basic steps, such as infiltration, double pressing/double sintering and powder forging, may be used to increase mechanical properties. Alternatively, a machining step may be added to qualify critical dimensions or to achieve a geometric feature not possible during rigid die compaction. Powder metal parts may be through-hardened or surface-hardened as required by the intended application.

In the pressing cycle, a charge of mixed powder is delivered to the die cavity by a feed shoe, and the upper and lower punches are used to compact the powder. After the upper punch is withdrawn, the pressed compact is ejected by the lower punch, and the feed shoe slides the part away from the die cavity. The cycle repeats as the feed shoe continues forward and refills the die cavity with another charge of powder.

Among the advantages of making gears by this process are that true involute gear forms are possible and that special features such as keyways, drive lugs, splines and cam contours may be incorporated during the compaction process. Lightening holes may be added to reduce part mass, and P/M gears can be made with blind corners, eliminating the undercut relief that is needed with cut gears (Ref. 2). P/M tooling provides consistent tooth form accuracy and surface finish over long production runs. Generally, because of their porosity, good surface finish and constant tool form accuracy, P/M gears reduce noise levels.

P/M gears can be made in a wide range of gear geometries for a number of applications, including gear motors for appliances, tractor transmissions, geared drives for cranes and a number of automotive applications.

Limitations of P/M Gears

Compared to wrought steel gears, P/M gears have lower impact resistance, fatigue strength and contact stress capability. This reduction in mechanical properties (due to the presence of porosity in the microstructure) may limit the same-size replacement of wrought and cast parts by P/M gears. However, it should be noted that the double-press/double-sinter process or warm compaction can overcome some of these limitations. Higher temperature sintering or case hardening can also improve the performance of P/M gears. Bending stress limitations may be overcome by using the versatility of P/M gear technology in the fillet radius design. If the design space permits, a larger P/M gear may be substituted.

For certain gear geometries, such as bevel and helical, the tooling motion cannot provide as high a tooth density as is possible in spur teeth. A portion of the applied pressure is lost to frictional effects in helical gears. Insufficient powder motion causes lower density in bevel gear teeth. Frequently copper infiltration is used to increase the density (and the corresponding mechanical properties) for both helical and bevel gears.

The face width of P/M gears is also limited. The constraints of the compaction process limit face widths to well under 3". Frictional losses between the powder and the die cause decreasing density along the face width, the lowest being at the midpoint. This is a reciprocal relationship, with greater face widths having larger density decreases. Dimensional variations can also occur during sintering and heat treating, which may lead to distortion, especially with larger gears.

Gear Design Data

P/M gear design data requirements are quite similar to those for machined gears. The AGMA Powder Metallurgy Committee has been working on the development of a new standard, "Powder Metallurgy Gear Specifications," for the past two years. This specification is expected to include sections for basic data, inspection data, calculation and process test data, as well as reference data.

Even after specifying the gear data in detail, certain geometric features or special notes should also be considered at the design stage:

1. Denoting the bore or central datum feature.

2. Providing a squareness of bore tolerance note if functionally critical.

3. Consideration of a tooling design to accommodate adherent burrs on the teeth edges.

a. Chamfers on teeth

b. A raised boss on the gear face to act as a 0.010" spacer between gears so small burrs do not interfere with proper rotation of the gears.

4. An allowance for minor surface defects, such as nicks or minor amounts of raised metal from a vibratory finishing operation.

5. Including an allowance for missing material (if possible).

6. An allowance for an identification mark on a gear face to assist in tool orientation during compaction and gear inspection after processing.

Proper consideration of these items during preliminary design discussions, either as specific design details on the part print or as off-line quality planning agreements, will ensure the P/M gear is specified correctly.

Mechanical Design Criteria

Once the geometric features of a P/M gear are determined, the next step is evaluating the mechanical loads on the product. Typically these requirements will include a normal operating load and a potential overload condition. Two types of failure modes should be considered:

- Tooth bending fatigue failure, and
- Tooth overload failure.

The AGMA Powder Metallurgy Committee is also reviewing methods of evaluating the mechanical operating characteristics of P/M gears. One of the goals of the committee is to provide a simple equation for determining the load capacity of P/M gears (spur, helical and bevel) once certain mechanical properties of the P/M steel materials are known. For instance, an equation of the form shown below has been suggested.

$$T = \frac{S\,K_1\,d\,F\,J}{2\,Pd\,K_2}$$

Where

T = torque load capacity (in-lbf)
S = design strength (lbf-in^2)
K_1 = constant
d = calculation diameter (in)
F = effective face width (in)
J = geometry factor
Pd = diametral pitch (in^{-1})
K_2 = constant

The design strength, S, would be the fatigue strength when determining the torque capacity under repeated loading or the yield strength when determining the torque capacity under a sudden, overloading condition. Once the material property, S, has been determined and the gear geometry is known, the torque load capacity, T, can be calculated. This value is then compared to the actual torque load expected by the gear. If the calculated T is less than the actual load, a failure is predicted; if T is greater than the actual torque load, then an acceptable material has been selected for the design conditions.

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Table 2 — Typical Manufacturing Tolerances for Heat Treated P/M Steel Gears					
P/M Gear Quality Manufacture Process					
Gear Size Pitch Diameter mm	Max Runout µm	Tooth-to-Tooth Error µm	Total Composite Error µm	AGMA Class (Approx.)	Secondary Operation
16	35 25 20	40 30 20	75 55 40	7 8 9	None Size Bore
40	45 35 25	40 25 20	85 60 45	7 8 9	None Size Bore
100	75 60 45	55 40 40	130 100 100	6 7 7	None Size Bore
Values for DP = 32 Module = 0.75 Finer pitch requires closer tolerances to meet same AGMA class.					

A second type of mechanical limit or failure mode encountered in gear designs is wear or pitting fatigue failure. This type of failure, also known as contact fatigue or surface fatigue, is normally associated with highly stressed, heat treated steel gears. Only recently has experimental work begun toward a systematic evaluation of the surface fatigue phenomenon as pertaining to P/M steel alloys (Ref. 3).

Until the AGMA Powder Metallurgy Committee completes its work in the area of mechanical performance characteristics, P/M gear designers will be forced to utilize other approximations for determining load capacity. One of the early studies of P/M gears (Ref. 4) suggested using the gear rating formula (as now found in AGMA 2001-B88), but modified for P/M steels. An approximation for the bending fatigue strength was to use 30% of the tensile strength. The approximation for the allowable contact stress was the tensile strength minus 10,000 psi.

These estimates are slightly conservative in light of more recent studies, which find the mean fatigue life closer to 32% of the tensile strength for heat treated P/M steels (Ref. 5), and the contact fatigue strength for a high density, heat treated nickel steel (FN-0205-180HT) about 10,000 psi greater than the tensile strength (Ref. 3). A recent Japanese study (Ref. 6) evaluated actual P/M gears for tooth bending fatigue. Contact fatigue limits were developed from a sliding roller test rig. Gear running tests were also conducted using a power circulating testing machine for comparison with these fatigue tests. Their results indicate improvement in bending fatigue strength through

- increased density,
- increased sintering temperature,
- shot peening after case hardening,
- heterogeneous microstructure.

The contact fatigue limit of about 190,000 psi for the 4% nickel steel in the Hirata study was lower than the value reported by Prucher et al. due to the lower density (7.1 vs. 7.4 g/cm^3) and difference in heat treatment (case-hardened vs. through-hardened). These investigators also noted that contact fatigue (spalling) was the predominant failure mode in the gear running tests, but that the contact fatigue life was increased 15–20% compared to the roller RCF tests. They concluded that the load bearing capacity of case-hardened P/M steel gears was higher than that of Tufftrided® AISI 1045 wrought steel gears.

P/M Gear Inspection

The quality of P/M gears is determined using the same type of inspection equipment as is used for machined gears:

- A rolling or composite gear checker for fine pitch gears,
- An involute or element gear checker for coarser pitch gears.

Typical manufacturing tolerances that can be expected for heat treated P/M steel gears are summarized in Table 2. As the size of the gear increases, the tolerance limits must also increase, since size changes in sintering and heat treatment are direct percentages of lineal dimensions. For small-to-medium size gears, an AGMA Q7 gear is quite feasible with no extra processing. A sizing or boring operation is needed to reach Q8 or Q9 tolerances. For much larger gears (4–6" pitch diameter), the as-manufactured tolerances are greater, resulting in a Q6 gear without any secondary operation.

Mechanical testing of a statistically representative sample from each production lot is used to demonstrate the mechanical quality of the product. Test methods include tooth torque tests or tooth breaking strength tests (either static or impact loading).

Advances to Further Improve P/M Gears

Efforts are already underway at specific P/M gear manufacturers, as well as at powder producers and process equipment suppliers, to improve both the dimensional control and the mechanical properties of P/M gears.

Dimensional Control. The dimensional consistency of gears can be improved either in the sintered condition or through the heat treatment process. One method, which is said to create AGMA Q9 gears from a Q6 gear, (Refs. 7–8) is the surface rolling of a sintered P/M gear against a master gear. Sinter-hardening P/M gears can reduce the distortion associated with more conventional quench and temper heat treatment processes.

Tooth Density Increase. Four primary methods to increase P/M gear tooth density are under study.

1. *Roll Densification*. This effective dimensional control method also densifies the gear tooth surface. Improvement in bending fatigue strength of 32% and a 3.5 times increase in contact fatigue stress has been reported for case-hardened 4600-type P/M steel gears subjected to this process (Takeya et al.). Contact fatigue strength of 96% of that of case-hardened wrought AISI 4118 steel has also been reported.

2. *Warm Compaction*. This process is much the same as conventional powder metal part compaction, except that both the metal powder and the tooling are heated to approximately 300°F before processing. In preliminary tests, gears manufactured using warm compaction showed an increase of 30% in tooth break load. When the process was coupled with high-temperature sintering, the improvement was over 50% (Ref. 9).

3. *Rotopressing*. The Rotopressing process, which subjects parts to large tangential stresses, causing intense, local plastic flow and densification, has been reported to give densities greater than 7.6 g/cm^3 in sintered P/M gear teeth, leading to excellent fatigue and wear properties (Ref. 10).

4. *Ausrolling*. This process combines surface densification and heat treatment (Ref. 11). Ausrolling of a conventional P/M steel is reported to have reduced the surface porosity from 14% to less than 2%, increased the rolling contact fatigue endurance by more than 10 times and led to substantial improvements in gear accuracy and surface finish (Ref. 12).

Conclusions

The powder metallurgy process can provide gear designers with a cost-effective alternative to machined, wrought steel gears. This net shape process offers dimensional tolerances and mechanical properties compatible with many market applications. As current process improvements and material developments are incorporated, more high performance transmission gears will be converted to powder metallurgy. ○

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Acknowledgements: *Longer versions of this material were presented at the 1995 AGMA Fall Technical Meeting and at the 1996 SME 1st International Advanced Gear Processing & Manufacturing Conference. They are available from AGMA as 95FTM13 and from SME as "Powder Metallurgy Gears—Expanding Opportunities" by James & Sanderow.*

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