Advancements of Powder Metallurgy in Gear Manufacturing

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MEEG 453: Manufacturing Processes and Systems

Homework 7

November 15, 2018

Summary: Powder metallurgy is a net-shape or near-net-shape process that compresses metal powder in a mold, then heats (sinters) the compacted powder to just below the material's melting point to cause bonding between the particles. Advances in powder metallurgy, including warm compaction and double-action presses, have enabled powder metallurgy to produce many spur, beveled, and helical gears at a comparable quality to wrought steel gears but at a fraction of the cost. Due to similar mechanical properties at a reduced cost, advances in powder metallurgy have been heavily implemented in the automotive industry.

Powder Metallurgy and Gear Manufacturing

Overview

Powder metallurgy (P/M) has recently become a popular manufacturing method for many types of gears. To compete with traditional gear manufacturing techniques, P/M must deliver gears that have comparable mechanical properties to wrought steel, and the process must be able to achieve the high tolerances associated with many American Gear Manufacturer's Association (AGMA) standards/applications.

Achieving Desirable Mechanical Properties with P/M

Steel gears produced via P/M must have similar mechanical properties to gears machined/cut/hobbed from wrought steel. The most important of these mechanical properties include tensile strength, contact fatigue strength, and elastic modulus. These desired mechanical properties directly result from achieving the proper **density and porosity** of the green compact after it undergoes compaction [1]. The compaction step in the manufacturing process plays a key role in achieving the necessary density, therefore also achieving the desired mechanical properties.

Wrought steel has an average density of about 7.6 g/cm^3, therefore becoming the target density for a gear produced via P/M. Traditionally, a mixture of steel powders and binding agents are fed into a mold and compacted by a single-action press at pressures ranging from 70 MPa to 800 MPa depending on the material and part size [2]. In a single-action press, a piston compresses the powder downward into a stationary die (see Figure 1). Because the force applied to the powder is only applied to one side of the part, a density "gradient" develops in the part; the top of the green compact has a higher density relative to the bottom of the green compact. Single-action presses typically generate average densities less than 7.1 g/cm^3 that are non-uniform throughout the gear [3] (see Figure 2). After sintering at a temperature (~1200º C) around 70-80% of the melting point of steel to metallically bond the particles, the gear's key mechanical properties can be evaluated [2]. Due to the non-uniform density distribution created by the single-action press and lower average density compared to wrought steel, traditional press-and-sintered gears often have a contact fatigue life about 1/3 lower than wrought steel gears and impact resistance of about 50% that of wrought steel [1].

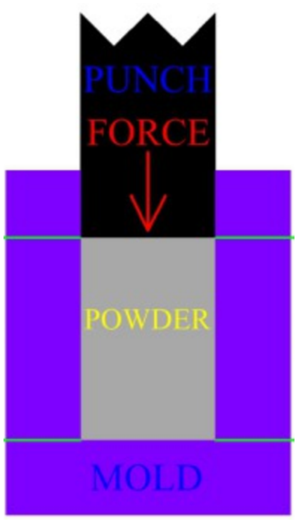

Figure 1: Single-action press with stationary mold/die

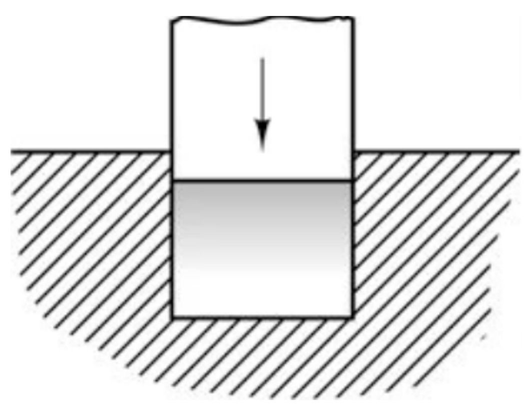

Figure 2: Compaction with a single-action punch, showing the resultant non-uniform density (shaded gray)

Advancements in P/M to Improve Gear Density

The first solution to improving the compaction density generated by a single-action press involves adding a second press to minimize the density "gradient". Double-action presses utilize a second press instead of a stationary die/mold (see Figure 3). The powder can be compressed more evenly than in a single-action press. This results in higher core densities near 7.4 g/cm^3 and higher overall average densities of 7.5 g/cm^3 [3]. The density "gradient" also begins to disappear as the top and bottom surfaces of the green compact are pressed equally (see Figure 4). Note the increased uniformity in density (shown in gray) of Figure 4 compared to Figure 2.

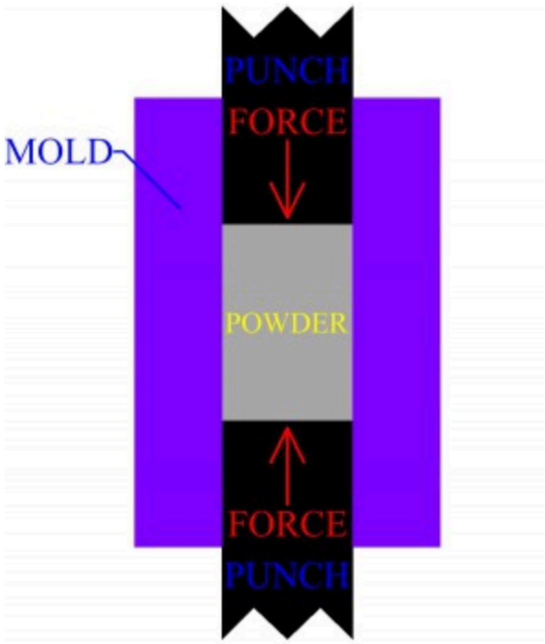

Figure 3: Double-action press

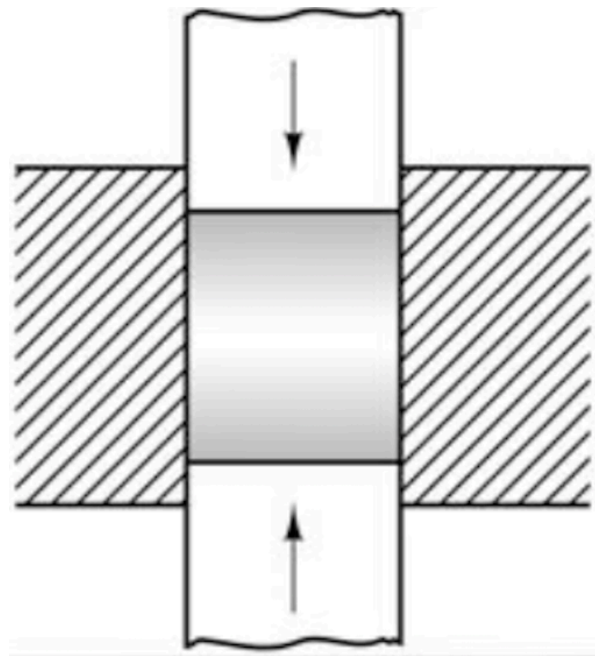

Figure 4: Density distribution (seen in gray) obtained with a double-action press and two moving punches.

Further developments to the compaction process strive to eliminate the need for a double-action press to simplify the process and ultimately decrease tooling costs. Warm compaction involves heating the powder to about 150º C prior to entering the mold. The press and the mold often are also heated to maintain a consistent compaction temperature near 150º C. At this temperature, the compressive yield strength of the powder can be reduced by up to 30% when compared to room temperature, allowing the powder to compact tightly and attain pore-free densities of up to 98% [6]. Warm compaction can also achieve average densities of up to 7.5 g/cm^3 using a single-action press [1].

Additional research has been conducted regarding the binders used in the powder. A patent-pending process called AncorMax D focuses on improving the lubricants and binders used in compaction to achieve higher densities using single-action presses. AncorMax D uses polymer binders to prevent desegregation of the powder, which is a mixture of several powders that each have different particle sizes and weights. The process successfully increases the density of the final sintered gear by as much as 0.15 g/cm^3 using a single-action press. However, a relatively high compaction pressure of 550 MPa and minimum compaction temperature above 150º C has deterred many manufacturers from using this process.

Tolerances and AGMA Standards

In many high-speed or high-torque applications, the gear teeth must mesh almost perfectly to prevent accelerated wear, increase gear lifetime, and decrease noise/vibration levels. The American Gear Manufacturer's Association (AGMA) measures quality of a gear from a Q3 rating to a Q15 rating. The ratings take into account the tolerances surrounding tooth lead/alignment, involute profile variation, pitch variation, and radial run-out. Q3 indicates the lowest accuracy geometry, while Q15 represents incredibly precise tolerances less than one-thousandth of an inch [5].

P/M produces surprisingly precise gears. P/M is a **net-shape process** that can achieve AGMA Q6 ratings *without additional machining.* This level of quality without additional machining makes P/M a lucrative production method for many industries. The quality of the P/M gear can also be improved by roll-forming operations, where the P/M gear is rolled against a master gear. This simple finishing operation can further improve the gear rating from a Q6 to a Q9 [1].

Roll-forming operations also have the added bonus of increasing the tooth surface density, where stresses on gears are typically highest. The minor increase in density at the tooth via roll-forming can lead to an increased contact fatigue life as much as 32% higher (compared to a P/M gear without roll-forming) [1].

Technical Summary

Powder metallurgy has the capability to produce net-shape parts with mechanical properties comparable to traditional wrought steel gears. Advances such as double-action presses, warm compaction, and polymer binders have enabled P/M to produce gears with densities of 7.5 g/cm^3 (compare to wrought steel with density of 7.6 g/cm^3). AGMA quality ratings of Q6 are achievable via P/M, and simple, inexpensive finishing operations can produce gears with qualities ratings up to Q9. P/M is a favorable production process for gears because it is ultimately cheaper than traditional manufacturing methods; P/M produces net-shape products that require little-to-no machining, uses almost 100% of raw materials, and can easily incorporate complex geometries. The recent advances now enable gears to be produced at nearly the same quality as wrought steel gears but at a fraction of the cost.

Business Impact

Perhaps the most attractive aspect of P/M is its ability to produce high quality gears at significantly lower costs compared to traditional manufacturing methods. P. Ramakrishnan estimates that a typical P/M gear costs about 20% to 25% less than its traditional counterpart [4]. Because of this cost savings, the automotive industry has become the largest consumer of P/M parts; approximately 70% of P/M parts are ultimately used in the automotive industry. P/M gears are quickly becoming popular in transmissions, where high surface hardness, fatigue resistance, high density, and small tolerances are required. As the auto industry grows to a net worth of over a trillion dollars, the cost savings from P/M gears can translate to multi-million-dollar savings for consumers and automotive industries.

A secondary impact of P/M gears involves improving the environmental footprint from the auto industry. Although the P/M gears have comparable densities to wrought steel, the P/M process readily incorporates lightening holes, providing the option to easily reduce weight. By decreasing weight, P/M indirectly leads to higher gas mileage. P/M also uses nearly 100% of raw materials, thus reducing scrap and improving the environmental footprint of the auto industry. As the environment becomes a growing concern, P/M's positive environmental impacts allow auto companies to promote green initiatives and appeal to consumers.

Relevance for Engineers

The significance of P/M for young engineers is to recognize the versatility and quality of P/M. More generally, young engineers should realize that manufacturing techniques are rapidly improving to create high quality products efficiently and in a more cost-effective way. While traditional manufacturing techniques can get the job done, chances are that newer technologies are being discovered that can make a product much more competitive in the marketplace. The advancements in P/M are just one of many newer technologies that should be considered as alternatives to traditional techniques. Specifically, P/M can now be considered for metal parts that experience high stresses, undergo many cycles, and/or require complex geometries.

The significance of advances in P/M for experienced engineers is to show that processes can always be improved. The core principles of a process (e.g. compaction and sintering in P/M) may remain the same, but minor adjustments to the process (e.g. warm compaction with polymer binders vs. room temperature compaction) can result in huge differences. A working process/product does not necessarily mean that it's perfect; there's always room for improvement. An experienced engineer must realize, however, that minor adjustments to the process could just as easily ruin it. Therefore, any engineer should always be mindful of the effects (both positive and negative) that certain decisions may cause.

Learning

During this project, I learned how much effort and engineering analysis goes into something as simple as a gear. An engineer cannot implement a gear system by simply specifying dimensions, pitch, number of teeth, etc. like we generally learn in machine design classes. Much consideration must go into the material selection and manufacturing process to ensure that the gears have *all* the necessary mechanical properties. Even after coming up with a design, an engineer must spend extensive time analyzing the tolerances of the gear and specifying AGMA standards to ensure the gear is manufactured correctly for the application.

Before researching P/M gears, I knew press-and-sintering was a great process because it's net shape, uses almost 100% of material, and can produce complex parts. As I read several articles about P/M, I learned that another added benefit of P/M is that it can achieve surprisingly small tolerances. That led me to research AGMA standards to compare the tolerances achievable by P/M to those achieved by traditional machining. I learned how AGMA quantifies some of the basic gear tolerances/standards and that P/M can easily achieve most commercial AGMA standards.

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