Materials Research Proceedings 31 (2023) 299-305 https://doi.org/10.21741/9781644902592-31

Using powder metal gears in industrial applications- A review

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Keywords: Gears, Powder Metal (PM) Technology, Sintered PM, PM Gears

Abstract. Due to the high performance, lightweight, competitiveness and net shape of the parts produced using sintered Powder Metallurgy (PM), PM-based products are used in different industrial applications. PM method offers high precision and repeatability, maximum material utilization, tailored shape properties, freedom of design, cost efficiency, and sustainability. These advantages are driving the ongoing demand for PM products and for the PM method as a good alternative to the conventional gear production methods. The use of PM is confirmed as an applicable technology for gear production. However, the strength and NVH characteristics of PM-products still require more investigation. In the current paper, the mechanical properties, strength and NVH characteristics are presented and discussed. The paper concludes based on the presented overview of the applicability of PM gears in the industry, further research investigation is needed on both the system and component levels to improve the durability and NVH behavior which are important for extending the PM parts' application. Moreover, the sustainability aspects of powder metallurgy technology should be emphasized.

Introduction

In the industry, optimizing fuel efficiency and minimizing weight while increasing power density is challenging. However, the industry still needs to optimize the applied manufacturing methods and reduce investment and manufacturing costs for the upcoming powertrain operations.

Each method that can be applied for structural parts production has certain limitations and offers certain advantages. The Powder Metal (PM) method as compared to other manufacturing methods has the ability to produce complicated structural shapes of parts of high dimensional accuracy in large series without chip formation at reasonably low costs. PM method offers a unique and important facility to generate shapes which are not achievable with other methods or can only be achieved with difficulties and at high costs [1]. Different research works were presented to review the use and application of powder metal gears.

During the last two decades, the use of PM technology has gained a lot of attention in the automotive industry to investigate the possibility of producing gears with the attributes of PM. Transmission synchronizer hubs were produced using PM and used at different gear speeds. More recently, PM gears were introduced for the low-load gears to prove the applicability of this technology to survive under the applied transmission load and meet the durability requirements [2].

The recent developments in the manufacturing of gears were presented in [3]. Due to international competitiveness and environmental regulations, industries are forced to adopt economical, ecological and efficient means of producing products. The availability of financial and technical data which is needed for economic analysis of PM gear production was reviewed in [4]. The author concluded that the operational cost of PM gear manufacturing is comparable to that of conventional gear manufacturing methods. However, further research is needed for proving the benefits of adopting PM gear manufacturing including the economic benefits as compared with the conventional methods.

In the literature discussed in the above-mentioned references, the use of PM is confirmed as an alternative method for gear production. However, the strength and NVH characteristics of PM still require more investigation. In this paper, the mechanical properties, strength and NVH characteristics are discussed to give a good overview of the applicability of PM gears.

Benefits and limitations of PM gears

In general, the main advantage of applying PM technology in production is the possibility of producing complicated parts of high dimensional accuracy in large series at reasonably low costs [1]. PM technology has been applied for gear production to use the advantages of optimizing the tooth root shape for better stress distribution, reducing gear weights, adding additional design features, and reducing structural-borne vibrations, which means reducing gear noise, due to the damping effect [5]. Fig.1 [5] shows how the use of PM can change the stress distribution due to the possibility of optimizing the tooth root shape, in contrast to the conventional hobbed gear. Moreover, the product weight is relatively lighter than if it is produced from wrought steel [1]. New techniques of adding alloys to the steel PM for having lighter weight were discussed in [6,7].

The strong ongoing trend of electrification in the automotive industry introduced the challenges of increasing the input speed of the transmission and increasing the required power density. Furthermore, the generated gearbox noise is of high importance, since the noise of the gearbox is no longer masked by the combustion engine sound. PM could be a good alternative to meet those requirements. Due to the internal porosity PM gears can be of lighter overall weight and can have a dampening effect on the noise and vibration [8].

However, the current manufacturing of powder metallurgical steel has also limitations. In general, PM gears have limitations in strength and size. PM gear teeth as compared to wrought steel ones have approximately 50% lower impact resistance and 33% lower contact fatigue strength due to the porosity of the PM structure. In manufacturing, this limitation can be partially made up by increasing the density of the produced PM gear teeth. This can be achieved using double pressing and double sintering. Also, high-temperature sintering or case hardening can be used. Another important limitation of PM technology is the gear face width. The amount of the used powder in most of the compaction presses determines the gear face width to about 3 inches. Furthermore, frictional losses between the die and the powder cause decreased density along the gear face width, where the lowest density is at the mid-point. The wider the gear face width, the more density reduction. The density variation along the face width can result in dimensional variations during sintering and also when it is subjected to heat treatment. High-density variation leads to distortion, especially in big gears [9].

One new technology of Nanotechnology Enhanced Sintered Steel Processing works on enhancing the PM gear strength to reduce the applicability difference between conventional steel and powder metallurgical steel. One of the significant benefits of this technology is that the density can be increased with the inclusion of nano-powder particles [8].

Applying PM technology involves sustainability aspects which can be of great environmental benefit if the approach of recycling materials can be applied. Höganäs AB in Sweden presented its new sustainable Cr pre-alloyed metal powder. The new powder (Astaloy® CrS) is recyclable and also it can be used as a raw material for the next product when the first product has reached its end of life [10]. PM technology can be applied for converting oxidized ferrous metal scrap into usable parts [11]. An optimized PM-based recycling process is studied in [11] to obtain significantly higher mechanical and physical properties of PM products. Recycling or reusing materials involves environmental and also economical benefits, due to the increasing material disposal costs and the lack of land fields, in addition to the raw material extraction costs [12].

Further research on the sustainability aspects of gear manufacturing processes including powder metallurgy is needed to enhance this approach.

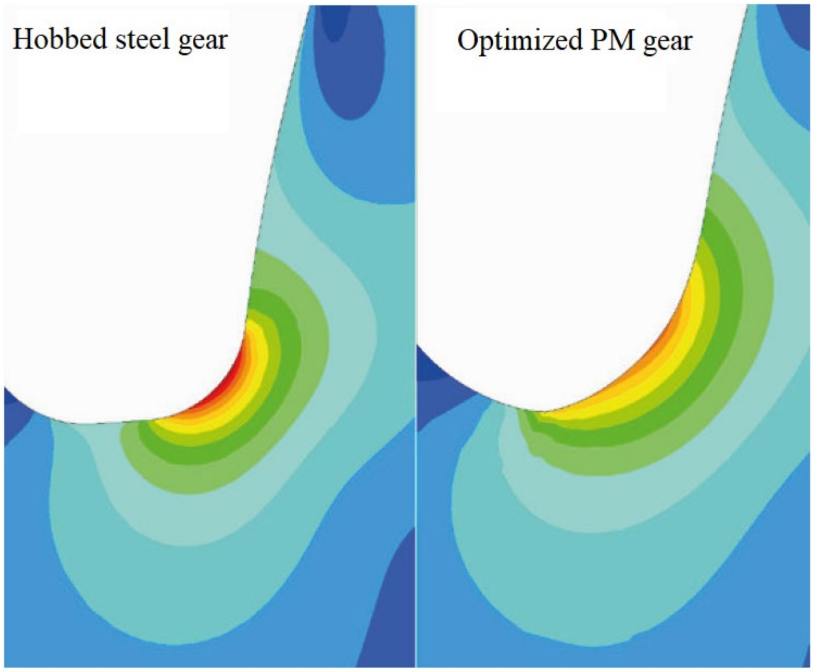

Fig.1 Tooth root stress distribution in a PM gear as compared to a hobbed gear [5].

Mechanical properties and strength of PM gears

In general, the flank load-carrying capacity of the PM gears is lower than the wrought steel gears because of the porous structure. In the PM parts of the porous structure, every pore can be considered a weak spot where a crack can be initiated. Therefore, the tooth flank surface of the highly loaded PM gears is usually densified to reduce the porosity in the surface region to ensure a sufficient load-carrying capacity. The material properties such as Poisson´s ratio and Young´s modulus are mainly affected by the local porosity [13]. The material properties were typically reported to be, for example, for copper powder (Young´s modulus =110-120 GPa, Poisson´s ratio = 0.35) [14,15] and for stainless steel powder (Young´s modulus =190-200 GPa, Poisson´s ratio = 0.29) [14,16]. The normalized Young´s modulus magnitude for spherical copper and stainless-steel powders shows similar dependence on the normalized density, Fig. 2 [14].

Efforts made by tooling manufacturers and PM parts producers have shown significant improvement in helical gear compaction. Although this technology is expensive and limited to a few specialist companies, it is applied in the powder metallurgy industry. The possibility of compacting a helical gear with a 33° helix angle using conventional alloy steel powders is proofed at a density close to 7.2 g/cm3. In addition to compaction complexity in PM production and the difficulties of high core density, PM gear blanks should get deep surface densification in order to maximize the strength in the root fillet and on the active tooth surfaces [17].

A comparison of the contact fatigue of hobbed wrought steel gears and surface-densified gears using a powder metallurgy process is presented in Fig.3 [17]. As shown in the figure, surface-densified PM gears have an endurance limit of around 1764 MPa as compared to 1839 MPa for the hobbed gears. The difference in fatigue life, below 5 per cent in this case, makes the surface-densified gears a good and applicable alternative to the ordinary hobbed gears with respect to performance in applications of high contact stress [17].

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In the production of PM parts, the rolling densification process was processed using a rolling machine provided by Escofier as illustrated in Fig. 4 [18]. In the densification rolling process, two rolling wheels of the same speed are spinning in the same direction [18]. However, the Fe-base PM parts that are produced using the conventional PM production methods have a porosity of about 5% to 15%, and their application range in the automotive industry is then limited due to the relatively low wear resistance, strength, and hardness caused by the existence of pores [19]. The mechanical properties of Fe-base parts can be comparable to wrought steel parts when the porosity is made close to 0%, which can be obtained using new technologies to produce PM parts with low porosities. In this way, the applicability of PM-products can be expanded in the industry [18].

The impact of the precipitation-hardened structures and the heterogeneous grain structures are combined by processing a certain dual-phase microstructure based on the Ti-2448 alloy. Actually, several microstructural features have been investigated and modified by changing the processing parameters, e.g. grain sizes in both shell and core, chemical concentrations, and phase precipitation [20].

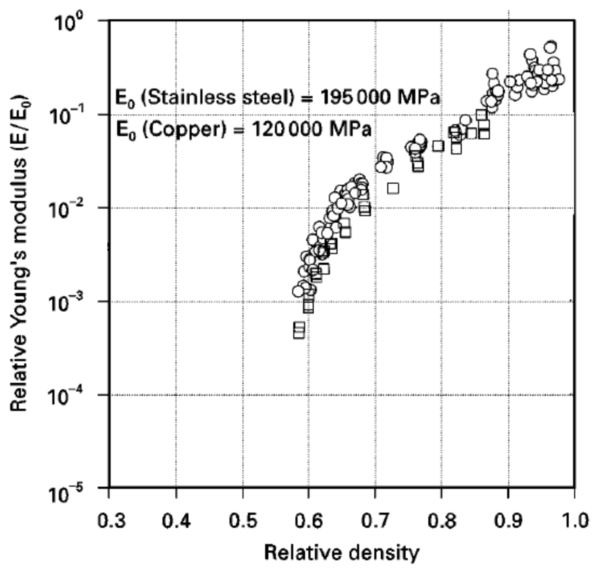

Fig.2 Relative Young's modulus for spherical copper and stainless-steel powders with relative density [14]

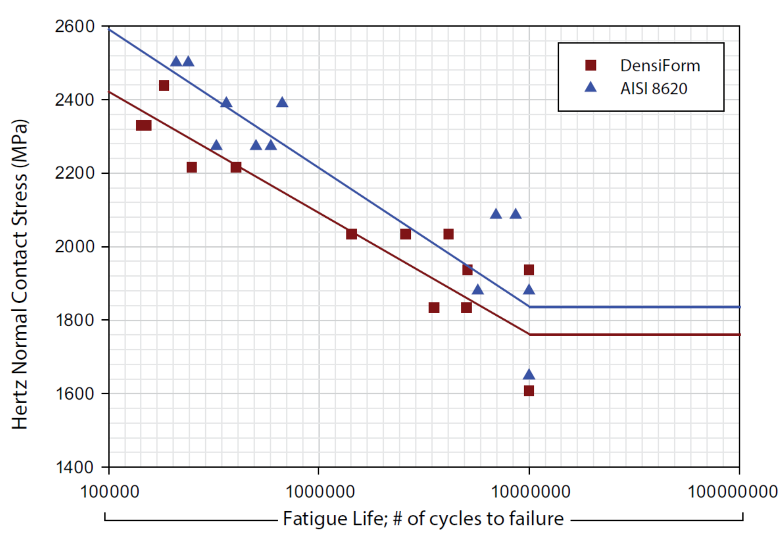

Fig.3 Contact fatigue of surface-densified PM gears and broached gears [17]

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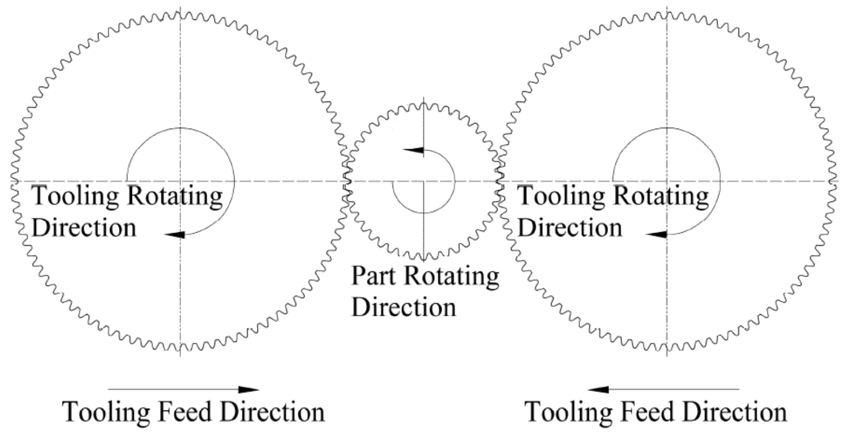

Fig.4 Schematic view of the experimental apparatus [18]

Noise and vibration NVH characteristics

In the new era of electrification in the automotive industry, reducing the generated noise from gearboxes is of high importance since the noise of the gearbox is no longer masked by the combustion engine. Hybrid electric vehicles (HEV) and electric vehicles (EV) are facing different challenges, like the need for performance enhancement to meet the durability requirements and also the increasing NVH requirements for minimizing the generated noise and vibration. PM gears can be a good alternative to be investigated for meeting those requirements.

Examining different PM densities, it is observed the damping property increases while decreasing the gear density and a more increase can be obtained in damping when further decreasing in PM density [21,22].

Using the original geometry of a steel gear to a PM gear leads to a higher excitation, but the optimized PM gear geometry results in a lower excitation at the applied torque range. As a result of this, gear micro-geometry optimization, in addition to tooth root area optimization, should be included in the design process for PM gear surface densification [21].

In the current stage, testing is important to further investigate the improvement in the NVH by using the PM. Damping potential is examined on the component level, but the impact on NVH is still not obviously evaluated, especially on the system level. On both the system and component levels testing is needed to improve the NVH behavior which facilitates further potential to apply PM Gears in the current and future gear transmissions and machines [21].

PM gear parts with an overall density of 6.8g/cm³ give a significant change in the NVH behaviour, where the change in material density and porosity has an impact on the obtained Eigen frequencies. Depending on the applied torque and rotational speed, the structure-borne noise could be reduced by about 3dB [23].

The porosity due to the process leads to difficulties and challenges in the manufacturing of PM gears but also can be good in terms of offering the potential for higher damping and then an improvement of the noise, vibration, and harshness (NVH) behavior can be obtained. PM gears offer the feasibility of an optimized gear design for better NVH behavior. To evaluate this feasibility, tests and experimental investigations were conducted, and both the excitation and the structure-borne noise emission were measured and evaluated. In terms of gear damping and noise reduction properties of the materials, the structure-borne noise emission of the produced PM gears is proportional to the density of the gear structure. By reducing the density of the gear structure, the NVH behaviour is improved. [24].

Conclusions

- Powder Metallurgy (PM) method offers lightweight, high precision and repeatability, maximum material utilization, tailored shape properties, freedom of design, cost efficiency, and sustainability.
- PM gears have limitations in strength and size, so further work is needed to improve the applicability of PM gears in terms of strength and size.
- Highly loaded PM gears are usually surface-densified to reduce the porosity in the surface region to ensure a sufficient load-carrying capacity. So, improving the surface densification process is important to close the gap, in terms of durability, between the PM gears and those from wrought steel.
- The NVH behavior is affected by the change in material density and porosity and thus system Eigen frequencies are affected. In general, the higher porosity will result in higher damping effects.
- Further investigation is needed on both the system and component levels to prove the applicability of PM gears for more industrial applications in terms of durability and NVH behavior.
- Further research on the environmental benefits of applying PM technology is needed to enhance the sustainability aspects.

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