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Affecting Transmission NVH-Behaviour by Implementing a Damping System Using Additive Manufacturing

Matthias Schmitt[a,*], Tobias Kamps[a], Christian Seidel[a,b], Gunther Reinhart[a,b]

[a] *Fraunhofer Insitute for Casting, Composite and Processing Technologies IGCV, Beim Glaspalast 5, Augsburg 86153, Germany*
[b] *Institute for Machine Tools and Industrial Management, Boltzmanstr. 5, München, Germany*

Abstract

Additive manufacturing, especially powder bed-based technologies, like Laser Beam Melting (LBM), provides a suitable technology for manufacturing complex parts. This permits an innovative product design for resource efficiency and effectiveness via lightweight design or functional integration. To exploit this potential, the presented project focuses on improving the NVH (Noise, Vibration, Harshness)-behaviour of gear transmissions by implementing particle damping into a gear wheel through additive manufacturing. Particle damping is widely used in the suppression of vibration in translational motions, but is less described for the use in circular motions. Nevertheless, there are reports qualifying the effectiveness of particle damping in gear wheels. Kinetic energy is dissipated through inelastic collisions and friction between the particles, thereby making particle damping a passive technology for vibration reduction. The efficiency of particle damping is determined by various parameters. Those include powder material density, size and form of particles, number and form of cavities and filling rate of such cavities. LBM is a suitable production technology to manufacture gear wheels with particle damping due to the offered design freedom and due to the possibility of including particles in closed cavities as a result of the layer-by-layer production principle.

Within this contribution, a method to include particle damping in gear wheels via additive manufacturing is described. Variated particle sizes will be determined and the feasibility for particle damping will be rated. As a second step, the issue of extracting remaining powder in the cavities will be addressed. Furthermore, a rating of possible cavity forms will be shown. The results are graded in order to show the manufacturability of particle damping systems using additive manufacturing.

Keywords: additive manufacturing; laser beam melting; gear wheel; NVH- behaviour; particle damping

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* Corresponding author. Tel.:+49-821-90678-147; fax.:+49-821-90678-55.
E-mail address: matthias.schmitt@igcv.fraunhofer.de

1. Introduction

Additive manufacturing enables new freedom in the design process of parts by creating opportunities conventional tooling does not allow. Design opportunities in additive manufacturing arise in many ways, depending on the used process and materials (Thompson et al. 2016), and allow for potential exploitation in multiple business models (Lutter-Guenther et al. 2015). Regarding highly functional parts with the purpose of transferring forces, the usable design opportunities can be summarized in the two areas of functional integration and lightweight design. In stationary parts many approaches for lightweight design have been developed to minimize mass. One of these approaches is using a lattice structure instead of a massive body to save material (Reinhart & Teufelhart 2011). Another further advancement of this idea is to orientate the lattice structure along the flux of the affecting force. This enables a part design with even less material (Reinhart & Teufelhart 2013). Further approaches use topology optimization to achieve lightweight design. This method is commonly used in industries like the aviation industry contributing in high mass savings (Seabra et al. 2016). Classic lightweight design approaches are extended by using nature as an example and mimicking successful tools of the evolution (Emmelmann et al. 2011). Employing the mentioned approaches in trying to minimize the mass of moving parts, such as gears, has not been commonly applied yet, although minimizing the mass of moving parts holds significant potentials in saving energy in accelerating or decelerating systems. One of the rare approaches has been the implementation of biomimetic part design in additive manufactured gears, which has proven to possess significant weight reduction potential (Kamps et al 2016).

Integrating additional functions by using additive manufacturing has led to the development of conformal cooling which uses the design freedom of additive manufacturing by deploying cooling channels near surface areas in geometries, patterns and distances, which cannot be achieved by conventional tooling (Sachs et al 2000). This concept has been commonly used in molds resulting in a reduction of cycle time in the injection molding process (Brooks & Bridgen 2016). Fig. 1 provides an overview on the use of the given design freedom applied in additive manufactured gears.

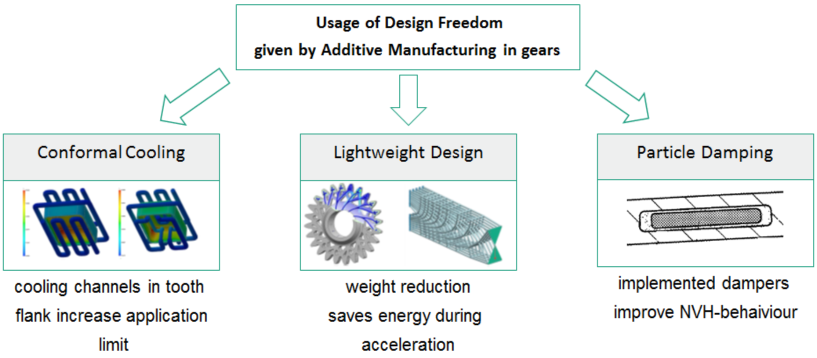

Fig. 1. Design Freedom through Additive Manufacturing for gears (Sachs et al 2000, Kamps et al 2016, Reinhart & Teufelhart 2011 and Erno 2015)

Additionally to conformal cooling only a limited amount of options on adding further functions in gears has been described. One of these options is the integration of damping elements in parts by using additive manufacturing (Erno 2015). During the manufacturing process, a cavity is created which is filled with unsolidified powder. This powder has the ability to work as a particle damper. Kinetic energy is absorbed through inelastic collision as well as friction between particles and cavity wall and between the particles itself (Friend & Kinra 2000).

This paper will focus on the advantages given by additively manufacturing particle dampers into gears. Therefore, traditional approaches integrating particle damping into parts are compared and evaluated against the possibility of adding them via additive manufacturing. Finally, the integration of particle damping into gears will be discussed and the feasibility of additive manufacturing different characteristics for particle damping will be rated.

2. Integration of particle damping

Up to now, there are two ways of linking particle dampers to a body that should be dampened. The first possibility is to attach a shell with an arbitrary kind of geometry, e.g. box or cylinder, holding the particles to the body by using a capable joining technique, e.g. gluing. This provides an easy way to introduce particle damping to a body after all production steps are finished. Moreover, the placement of the particle damper can be chosen quite freely on the body. Depending on the used joining technique, joints can be altered if the achieved suppression effect is not satisfactory. Attaching particle dampers as described, results in one additional manufacturing step to receive finished product, which increases production time and cost. Additionally, it has to be ensured that the joint between body and shell withstands all occurring forces in all load-cases so that no failure will occur. The required production steps are shown in Figure 2 together with further integration possibilities.

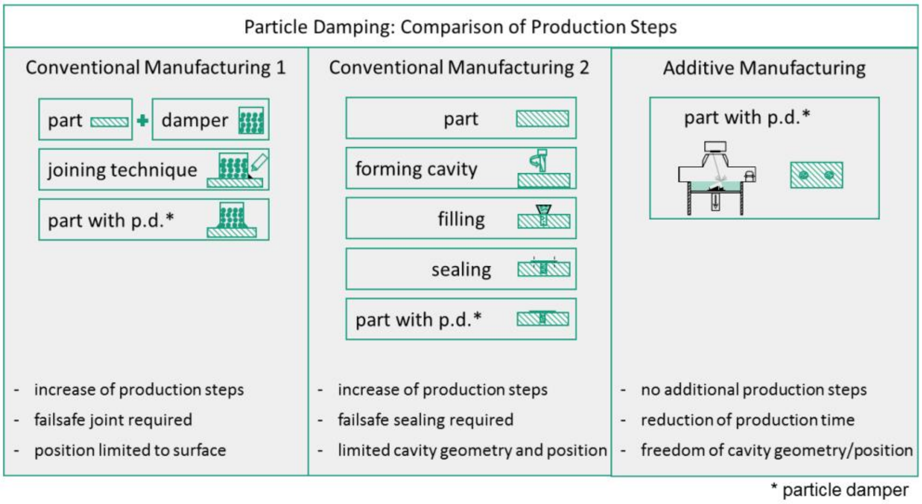

Fig. 2. Comparison of production steps to include particle damping in parts

A second possibility is including particle dampers in the body itself. This leads to a strong rise in production steps using conventional manufacturing methods. To secure the required particles, some kind of cavity needs to be created. Traditionally, this is done by drilling or milling the cavity in the body. Depending on the used manufacturing technique the creatable geometry of the cavity is limited. Furthermore, orientation and placement are restricted by manufacturing constraints. After creating a cavity, it has to be filled with particles. The final production step is sealing the cavity with the aim of retaining the particles in the cavity for a predefined time. A loss of particles during the lifetime of the product will affect the damping performance and especially hold the threat of causing system failures. Today, additive manufacturing, e.g. through laser beam melting, poses an alternative. Integrating the build of cavities in the build-up of parts does not increase the amount of necessary production steps. Especially powder bed-based technologies provide the opportunity of creating an already filled cavity within the part build-up. In further parts of this work, possible filling options will be discussed and rated. These options include leaving unsolidified powder in the formed cavities, which does not affect production time since there is no laser exposure time in those areas.

An evaluation of the production steps shows that conventional manufacturing of parts with particle damping always requires additional steps. This leads to an increase of production time and cost which ultimately reduces the broad implementation. In contrary, additive manufacturing provides the possibility of including particle damping in the production of the part itself without adding additional production step.

3. Adding particle damping to gears

Gears are typically classified as highly stressed and functional parts with the task of transferring forces during operation. Adding particle damping to gears opens the possibility of addressing the field of Noise-Vibration-and-Harshness (NVH)-behaviour in gear boxes if gears with damping elements are used. Especially vibration causes problems in transmissions, can reduce lifetime, and increases the probability of breakdown. Main contributors to vibration and noise in gear boxes are cyclic time-varying mesh stiffness (TVMS), loaded static transmission errors (LSTE) and non-load static transmission errors (NLSTE) (Hui et al 2016). Extensive research has been done on reducing the vibration through changes in the tooth geometry, e.g. tip relief profile modification, profile modification or flank modification (Aski et al. 2014 and Inoue & Kurokawa 2017). However, there is research on suppressing vibration in the centrifugal field of gear transmissions by dissipating energy through particle damping (Xiao et al. 2016). The main objective of the research carried out by Xiao et al. (2016) is to introduce particle damping as an alternative to other passive vibration damping systems, like frictional dampers and viscoelastic dampers which show decreasing damping effects at high temperatures (Zhong et al. 2017). The incapability to withstand high temperatures while still maintaining proper damping effects, eliminate those damping systems for the use in harsh conditions, and therefore the use in gears. Until know, particle dampers have been included into gears by drilling holes in the gear body and filling those with particles (cf. Fig. 2). To save production steps, additive manufacturing is a suitable production method. So far, additive manufacturing has been used as a fast production method for gear prototypes and for introducing lightweight design in gears (Bouquet et al 2014 and Kamps et al. 2016). Adding particle dampers within the production step of the gear gives additive manufacturing a unique advantage and has the ability to compensate higher production costs. Nonetheless, it is not clear that additive manufactured particle dampers have proper damping abilities. In particle damping, inelastic collision and friction dissipate energy and those depend greatly on the characteristics of the particles and cavity like size, geometry and material of particles, orientation and geometry of cavity and the interaction between particles and cavity.

Within this contribution, the crucial attributes of those characteristics are determined for particle damping in gears by reviewing literature. Furthermore, the possibility of using additive manufacturing to manufacture those attributes in the gear body during production is outlined by rating the manufacturability. As a basis, the rating is done by applying manufacturing properties of the laser beam melting process and assuming a typical case hardening steel, which is commonly used in gear production, e.g. 16 MnCr5 (1.7131).

4. Characteristics of particle damping for gears

4.1. Particle material

The damping effect of particle dampers is determined by its ability to dissipate energy through either collision or friction. The particle materials density increases the energy, which can be dissipated through collision, by increasing the contact forces through higher masses of particles at equal sizes (Xiao et al 2016). This connection was shown for translational movements by carrying out experiments with particles made of tungsten carbide, stainless steel and aluminum alloy (Veeramuthuvel et al. 2016). The used particles only differed in material. Size and shape of the particles were identical, as well as the used cavity. Tungsten carbide showed the greatest damping capability. These results were verified by Booty et al. (2014) in comparing the damping effect of lead and steel particles. Again the damping effect of particles with higher density proved to be higher. For the use of particle dampers in centrifugal fields, e.g. the integration of such dampers in gears, the effect of particles densities on the damping effect was studied by Xiao et al. (2016). Gears with drilled cavities in the gear body were filled with spherical particles made out of magnesium alloy, aluminum alloy, steel alloy, lead alloy and tungsten alloy. Filling rate, particle size and shape were identical. It showed that similar to translational movements, particles with high density provide better damping effects. Tungsten alloy particles were best. Nevertheless, it showed that besides the density differences of lead and steel alloy the achievable energy loss did not variate much.

The results show that powder bed-based technologies, like laser beam melting, are a suitable technology to manufacture particle dampers in gears. Using a case hardening steel, provides a high density of the unsolidified powder, which has shown sufficient damping effects. To increase the damping effect a powder with higher density than steel (e.g. lead or tungsten) would have to be filled in the cavity. This would create the necessity of handling multiple materials in one process chamber and the ability to process multi materials. Traditionally powder bed-based technologies operate only with one material at a time but there is research carried out in the development of multi material processing (Anstaett & Seidel 2016). Applying these developments to the integration of particle dampers via laser beam melting opens the opportunity to create cavities filled with particles of higher density than the density of the base part. Therefore, multi material processing has the ability to increase the damping effect of particle damping significantly in the near future.

4.2. Particle geometry

Until know the term ‘particle’ has been used as a general term for the damper filling. For a better understand a distinction will be made between particles and structures. The term particles will be used for objects of small sizes (diameters 15-90 µm) e.g. powder particles whereas bigger objects will be named as structures. This distinction is necessary as powder bed-based technologies allow the creation of structures by solidifying powder particles.

In particle dampers, energy dissipation is caused either by friction or by collision between the filling objects themselves or between the filling objects and the cavity wall. As such, the objects geometry influences the damping efficiency. Using unsolidified powder as damping particles limits the particle geometry to the powder shape as provided for production. Depending on powder production principle, the particle shapes differ greatly. Gas atomized powder possesses a spherical shape while water atomized powder has an irregular shape (Li et al. 2010). Pourtavakoli et al., 2016 simulated the performance of various structures shapes in particle dampers using the discrete element method. The structure shapes ranged from simple spherical structures with diameters of 4 mm to more complex shapes like rods, model squares, rings, crosses and L-shaped particles. To rule out any mass effects on the damping performance all structures had the same mass and the same cavity was used. The results indicate a dependency between damping efficiency and structure shape, showing that spherical structures lead to higher energy dissipation compared to more complex shaped structures. Additionally to the simulations, testing shows that irregular structures can achieve comparable damping effects to spherical structures at very specific frequencies but perform worse in the overall view (Booty et al. 2014). Considering the outlined studies, it becomes clear that spherical structures provide the best damping efficiency for particle dampers with big structures. No recommendation can be projected towards the choice between gas or water atomized powder since all studies were carried out with large spherical structures with diameters of around 4 mm, while the average particle size of additive metal powder is at around $40\,\mu m$. Decreasing diameters lead to a great increase of collisions numbers, which changes the dampers behaviour, making the results less transferable. The effect of particle size on damping performance will be discussed in the following section.

Nevertheless, spherical-shaped structures give advantages in damping performance over a wide frequency and are to be preferred when creating solidified structures. Manufacturing spherical parts via laser beam melting possesses the challenge of creating smooth curves along the built axis because the layer-wise build-up leads to a staircase effect (Kranz et al. 2015). Spherical structures with small diameters are prone to the staircase effect because there are fewer layers with a higher thickness compared to the structure diameter to achieve the curved surface needed for spherical structures. This culminates into structures with very high surface roughness and only spherical-like shapes. Structures with big diameters compared to the layer thickness, achieve better spherical shapes and lower surface roughness. However, the surface roughness of laser beam melting parts is high compared to machined parts. Usually post-process manufacturing steps like shot peening or polishing are used to smoothen the surface. Those post-process steps are unavailable if the structures are left in the cavity to create particle damping leading to structures with high surface roughness. However, this is no disadvantage since Xiao et al. (2017) showed that spherical structures with high surface roughness achieve higher damping performances compared to spherical structures with low surface roughness. All in all, it shows that laser beam melting is a suitable manufacturing technique for the production of enclosed particle dampers by either leaving unsolidified powder in cavities or by creating spherical-shaped structures in such cavities. The high surface roughness of laser beam melted parts is used as a benefit to increase the damping effect.

4.3. Particle size

The particle size has great effect on the characteristic of particle dampers. Energy dissipation in particle dampers is caused by four means; friction between the particles, friction between particles and the cavity wall, collision between particles, and collision between particles and the cavity wall. Decreasing the particle size increases the possible collisions greatly. In horizontal vibrating systems, small spherical structures improve the damping efficiency compared to lager structures (Saeki 2002). By replacing spherical copper structures of 4 mm diameter with copper powder the occurring vibrations were damped better, indicating that an increase in collisions leads to an increase in damping efficiency (Booty et al., 2014). Contradicting to these results, Els 2009 showed that particle damping of rotating and horizontally vibrating beams is better when using structures with a diameter of 4 mm instead of structures with a diameter of only 2 mm. More research on the size effect of structures in centrifugal fields was carried out by Xiao et al. 2016. The movement of spherical-shaped structures of diameters ranging from 1 mm up to 8 mm in centrifugal fields of gears in a consistent cavity were simulated and validated in experiments. It showed that optimum damping was achieved by diameters of 4-5 mm.

Based on these findings, it seems clear that the size of the filling has a great influence on damping efficiency and is dependent on the predominant kind of motion. For merely translational movements small structures (diameter < 2 mm) and powders achieve best damping performances. For damping in centrifugal fields bigger structures (diameter > 4 mm) have better damping performances. The increase in collisions using small structures is less dominant in centrifugal fields through the occurring centrifugal force, which presses the structures to the outside of the cavity. At high speeds the dominant energy dissipation mechanic shifts towards friction instead of collision, leading to better damping effects of bigger structures.

Considering that particle dampers and the included filling in gears are exposed to a centrifugal field during their use, the recommendation for the filling size leads to structures with diameters of around 4 mm. These promise best damping efficiency. For manufacturing particle dampers with the laser beam melting technique this result has adverse effects because the questions of extracting powder and necessary support structures arise. To avoid these effects, it might be beneficial to accept lower damping abilities and use particle dampers with unsolidified powders. These points are addressed in more detail in chapter 5.

4.4. Cavity orientation, geometry and filling ratio

Besides the particle characteristics, properties of the enclosing cavity influence the damping efficiency. Decisive properties are cavity filling ratio, orientation and geometry. The filling ratio is determined by the ratio between the volume of enclosed particles and the overall volume of the cavity (see equation 1).

$$\rho_{filling} = \frac{V_{Particles}}{V_{Cavity}} \tag{1}$$

Within equation 1 RhoFilling represents the filling ratio, VParticles the volume of enclosed particles/structures and VCavity the total volume of the cavity. In particle dampers with high filling ratios the ability to dissipate energy through collision is low. Energy dissipation happens mainly through friction. In contrast, particle dampers with low filling ratios dissipate energy mainly through collision. Research in translational and rotational moving particle dampers showed that there is an optimum filling ratio where best damping performance can be found (Veeramuthuvel et al. 2016 and Dragomir et al. 2012). The filling ratio should not be less than 40% but should not exceed 80% to secure good damping performance. At these filling rates the relation of energy being dissipated through friction or collision is well-balanced to achieve highest damping.

Consequently, the question of what filling ratios can be achieved by creating particle dampers with laser beam melting has to be addressed. If unsolidified powder is used as damping particles the filling ratio is strongly connected to the packing density of the powder bed. The packing density varies with the used material, particle geometry and particle size (Gennan 1984). Powder used for additive manufacturing has a specific grain size distribution with usual grain sizes of $20 - 63\,\mu m$ which leads to packing densities of 40-55 % (Karapatis et al., 1999). By adding fine particles to the powder the packing density can be increased up to 80% (Karapatis et al., 1999). Nevertheless, this step is not necessary because the normal packing density of additive manufacturing powders result in a sufficient filling ratio to provide good damping properties. When solidifying powder to create damping structures, the filling ratio has to be considered during the design process. Another option would be the use of big spherical structures and unsolidified powder in one cavity. In this way the filling ratio can be designed more freely. Unfortunately, up to now there is no data available on the performance of such mixed filled particle dampers but they are an interesting possibility for generating particle dampers via laser beam melting and further studies should be considered. Another possibility to influence the filling ratio is to integrate a suction module into the laser beam melting machine allowing for partial removal of particles within foreseen cavities and refilling the cavities with particles of different sizes. Obviously, it should be avoided to influence resulting part quality. Proof of concept for this approach can be considered as provided because Glasschroeder et al. (2014) demonstrated that cavities can be generated with an accuracy of about 50 µm in powder bed-based processes in order to pick-and-place screw nuts.

Cavity orientation influences the behaviour of particle dampers too. This counts especially when looking at particle dampers in centrifugal fields because those particles experience centrifugal forces which influence position and movement of the particles. Zhang et al. (2016) predicted the damping performance of particle dampers in centrifugal fields depending on their orientation using the discrete element simulation method. A cylinder was used as a cavity, mimicking a drilled cavity. The orientation was altered between alignments of the cylinder axis with the x-, y- and z-axis of the rotating field which performed its rotations around the z-axis. The orientation of the cylinder can be seen in Fig. 3 part a)-c).

It showed that orientating the cylinder along the x-axis (Fig. 3. a)) lead to low damping performances. Meanwhile, orientating the cavity along the y- and z-axis proved much higher damping. Only a small difference in damping was seen between the orientations along the y- and z-axis with the z-alignment leading to slightly higher damping performance (Zhang et al. 2016)

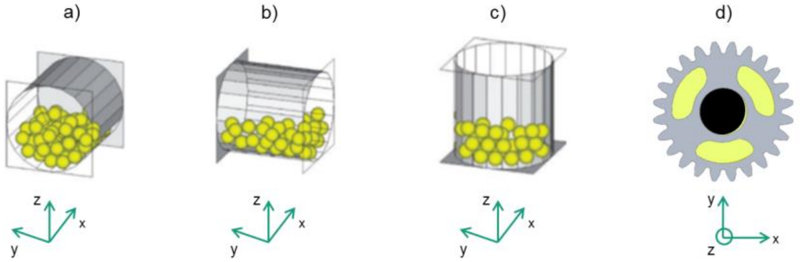

Fig. 3. a) - c): Cavity orientations by Zhang et al. 2016 d) proposed cavity geometry and orientation for particle dampers in gears

Since additive manufacturing enables great freedoms in part design, there is no longer the need to restrict the cavity geometry and orientation by conventional manufacturing restraints. Cavity orientations along the y- and z-axis showed good damping properties for cylindrical particle dampers in centrifugal fields. By using laser beam melting both orientations of the cavities can be merged to radially bent pockets in the gear body as seen in part d) of Figure 3. The proposed cavity design has a larger surface area on the outer side of the cavity giving the particles more area to engage in contact with the cavity walls. Aim of the design is to increase the possible dissipation of energy through friction. Favourable cavity shapes along the built axis will be presented in the following chapter.

5. Manufacturability

The manufacturability of particle dampers in gears depends greatly on the chosen damper properties (cf. chapter 4). Figure 4 gives an outline on possible combinations of those properties, especially addressing the particle filling with the possibilities of the sole use of unsolidified powder, solidified structures, a mix of both and the cavity geometry in building axis. Those properties have the biggest effect on the manufacturability since using a sufficient dense material for the particles is already reached by using the basic case hardening steel as particle material and since a sufficient filling ratio of 40% is reached easily. Manufacturing solidified structures raises the challenge of what kinds of support structures are needed. Self-supporting structures of the filling structures would be beneficial. Additionally, those support structures need the ability to be removed easily with the removal of the powder. For that purpose, holes in the cavity have to be created. The cavity geometry in x- and y- direction can be chosen freely but in z-direction (building axis) the geometry is restricted by occurring overhangs, which need additional support (Kranz et al. 2015). Cavity geometry Nr. 1 has fewer constraints because no support is needed. In a rating of manufacturability the combination of filling Nr. 1 and geometry Nr. 1 (1|1) comes first, whereas the combination filling Nr 3. and geometry Nr. 3 (3|3) rates last. A full rating can be seen in Fig. 4. With an increasing number of the cavity filling and geometry the difficulties in manufacturing increase.

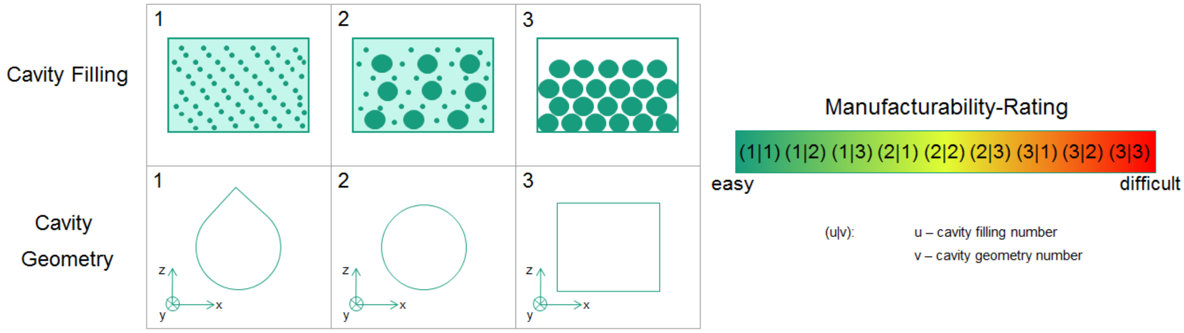

Fig. 4. Possible combinations of cavity filling and geometry with manufacturability rating

6. Summary and Conclusion

It was laid out that particle dampers are an innovative function that can be easily integrated by utilizing additive manufacturing methods with the potential of saving production steps compared to conventional tooling. Within this contribution, suitable properties for particle dampers in gears were determined by reviewing literature. Based on the performed analysis, the potential for best damping performance in gears are given by a combination of rough spherical structures with a diameter of 4 mm, a filling ratio of at least 40% and radially orientated elongated cavities in the gear body. However, this combination is expected to be hard to manufacture. For easy manufacturing unsolidified powder qualifies best as damper filling. Future work foresees an experimental validation of these findings.

To achieve vibration suppression in gears particle dampers are a suitable method and easy to integrate in the production when using powder bed-based technologies. Manufacturing dampers with good properties for gears is expected to be challenging because the questions of powder removal and support structure have to be addressed. For a next step, suitable support structures and powder removal strategies have to be developed. At the same time, testing should be carried out to determine the damping performance of particle dampers with unsolidified powder in centrifugal fields, since there is no data available yet. If suitable damping performances are obtained, manufacturability is given.

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