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Design Guidelines for Additive Manufactured Particle Dampers: A Review

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Abstract

Recently, additive manufacturing has been used to integrate particle dampers into structural components, particularly by means of laser powder bed fusion (LPBF), in order to significantly reduce component vibrations. The advantage over previous damping mechanisms is that these can be functionally integrated directly into the component during the additive manufacturing process by leaving unmelted powder in the component. This allows local damping effects to be adjusted and low-vibration lightweight structures to be developed and manufactured. In addition, the damping properties act over a wide frequency range and are insensitive to temperature. Despite the positive damping properties, the use of laser beam melted particle dampers is limited at the present time, since there are not yet sufficient design tools available due to the numerous non-linear influences. This is where the current contribution comes in, by developing design guidelines for laser beam melted particle dampers. The results were finally summarised in a design catalogue and support a suitable design of laser beam melted particle dampers.

Keywords: Additive Manufacturing (AM); Design Guidelines; Particle Damping; Lightweight Design; Functional Integration; Laser Powder Bed Fusion (LPBF)

1. Introduction

In the context of product development, lightweight design is playing a key role as a result of increased sustainability aspects [1]. However, the challenge arises that with increasing lightweight design, the individual components become more susceptible to vibrations [2]. Particularly in the case of lightweight structures subject to vibration, the integration of external mass-loaded damping elements is an unsatisfactory option. In contrast, additive manufacturing offers the possibility of producing lightweight structures with integrated damping elements without additional mass ("Damping for Free") [3, 4, 5]. Especially in laser powder bed-based processes, unmelted powder can be incorporated into cavities during the manufacturing process to produce an integrated particle damper, see Fig. 1 [6, 7, 8]. With these particle dampers, component vibrations can be reduced by more than a factor of 20 [9, 10, 11]. By integrating the particle-filled cavities in the area of the neutral fiber, the component strength is hardly affected so that the conflict of objectives between high stiffness and high damping can be resolved [12]. Other advantages of particle dampers include broadband damping, long service life, low maintenance, low wear, temperature resistance, and simple and inexpensive implementation [13, 14, 15].

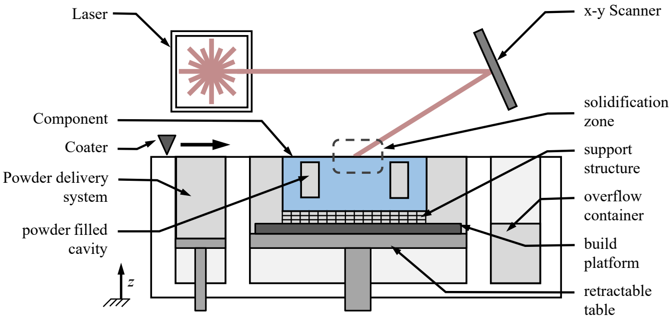

Fig. 1. Laser powder bed fusion of a particle damped component, acc. to [3].

Despite these advantages, the use of laser beam melted particle dampers is limited. One reason for this is the highly nonlinear damping characteristics, which complicate component design, as a result of numerous design parameters [13]. The relevant design parameters include, for example: Particle mass, cavity shape and cavity dimension, etc. [13, 16, 17]. In addi-

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tion to the design parameters, the type and level of excitation influence the effect of particle damping [3, 4, 17].

As a result of the high experimental and numerical effort, only individual design parameters can be investigated in the respective research work [3, 4, 5, 17, 18]. Thus, the knowledge on laser beam melted particle dampers is decentralized and a summary of the current knowledge on the design of laser beam melted particle dampers is missing.

Within the scope of this work, the current state of knowledge on the design of laser beam melted particle dampers is prepared in the form of design guidelines. According to Pradel et al. [19], design guidelines refer to context-dependent guidelines that give direction to the design process in order to increase the chance of a successful solution. Their validity is demonstrated by empirical evidence and/or extensive experience. Compared to design rules, design guidelines are more abstract and the cause-effect relationship is less well understood.

The design guidelines are categorized and sequenced so that a systematic design of laser beam melted particle dampers is supported. Furthermore, these findings can serve as boundary conditions for further methods or be a basis for building design tools.

2. Methodology

The design guidelines for laser beam melted particle dampers are to be derived from the current state of research. For this purpose, a literature search was conducted on Google Scholar. In addition, for each identified paper, the literature was analyzed and considered for pre-selection if there was a match. In total, 49 papers on laser beam melted particle dampers were identified for pre-selection. Of the 49 papers, 25 were screened out due to lack of reference to design guidelines or lack of quality assurance, leaving 24 papers to be analyzed in detail for this work. Table 1 shows the results of the literature search. The papers are sorted according to the research institutions. It can be seen that the Air Force Research Laboratory (AFRL) shows the most research activity. In general, with the exception of the TU Dortmund University (TUD), primitive geometries or test specimens are investigated, and the focus of the investigations is predominantly experimental in nature. In addition, modeling is addressed in some papers. Here, the focus is often on the creation of regression analyses to represent the experiments. A total of four different materials have been investigated so far. Here, the focus is primarily on Inconel 718, followed by stainless steel 316L, tool steel 1.2709 and AlSi10Mg. In general, it must be noted with design guidelines that they are sometimes contradictory and mutually dependent. For this reason, it is advantageous to establish an order for their application and to apply first those design guidelines that influence as little as possible subsequent design guidelines [20, 21]. Table 1 shows that the design guidelines can be primarily divided into the following five categories:

Positioning: Positioning is used to a large extent to determine the effectiveness of the particle damper.

Determine cavity geometry: Cavity geometry affects both damping and the stiffness and strength of the component.

Dimensioning: Sizing is used to fine-tune the effect of particle damping.

Orientation and support: To ensure the manufacturability of the particle-filled cavity, the part orientation on the build platform plays a crucial role. Furthermore, the orientation of the cavity can have an influence on the effect of particle damping.

Post-process: Finally, limitations and influences resulting from the post-process have to be considered already in the design phase of the particle damper.

From the current state of research, it appears that initial work is being done on the design of laser beam melted particle dampers. However, no collection of design guidelines comprehensively reflecting the current state of knowledge is yet available. Thus, the focus is on developing design guidelines for the design of laser beam melted particle dampers that can be derived from the current state of research, knowing that they will need to be continuously developed and adapted. Furthermore, due to the highly nonlinear properties, the degree of concretization will be lower compared to design rules of additive manufacturing, e.g. production-oriented design. However, a high degree of transferability can be assumed due to the lower degree of concretization.

3. Design guidelines

The five categories of design guidelines are described in detail below and finally summarized in the form of a flow chart, shown in Fig. 2.

3.1. Positioning

To have little effect on stiffness and strength, the particle damper should be located near the neutral fiber [3, 6, 9, 12]. Furthermore, for high damping, the cavity should be integrated in the region of maximum vibration amplitude, since this is where particle interactions are greatest [4, 7, 22, 24, 25, 26, 27]. To identify this position(s), a modal analysis can be performed, for example.

3.2. Determine cavity geometry

State-of-the-art research indicates that a continuous versus a subdivided cavity results in higher damping [29, 34]. However, it must be taken into account that a subdivided cavity can have advantages in terms of stiffness, strength or other component requirements [11, 18, 28]. Thus, it should be decided individually, depending on the problem, whether a continuous or subdivided cavity should be used. In terms of cavity geometry, cuboid cavities generally result in higher damping, whereas, cylindrical and spherical cavities result in broader band damping [17].

3.3. Dimensioning

So far, only limited mechanical equivalent models or discrete element methods exist that can be used as design tools to

Table 1. Current state of research on design guidelines of laser beam melted particle dampers.

#	Reference	Institution	Demonstrator	Material	Design guidelines Positioning	 Determine cavity geometry	 Dimensioning	 Orientation and support	 Observe post process
1	[7]	AFRL	Beam	Inconel 718	x				
2	[22]	AFRL	Beam	Inconel 718	x				
3	[23]	AFRL	Beam	Inconel 718				x	
4	[16]	AFRL	Beam	Inconel 718		x			
5	[24]	AFRL	Beam	Inconel 718	x				
6	[25]	AFRL	Beam	Inconel 718 / 316L	x				
7	[26]	AFRL	Beam	Inconel 718 / 316L	x				
8	[4]	AFRL	Beam	Inconel 718 / 316L	x		x		
9	[27]	AFRL	Beam	Inconel 718	x				
10	[8]	UTK	Cylinder	Aluminum			x		
11	[5]	UTK	Wall	316L			x		x
12	[11]	UTK	Wall	316L		x			
13	[28]	UTK	Beam	316L		x			
14	[29]	DMRC	Beam	316L		x	x	x	
15	[17]	DMRC	Beam	316L		x	x		
16	[18]	TUD	Tool holder (turning)	1.2709		x			x
17	[30]	TUD	Tool holder (turning)	1.2709		x			x
18	[31]	TUD	Tool holder (turning)	1.2709		x			x
19	[32]	TUD	Tool holder (turning)	1.2709					x
20	[33]	TUD	Tool holder (milling)	1.2709					x
21	[34]	WU	cubic unit cells	316L		x	x		
22	[3]	LUH	Beam	AlSi10Mg			x	x	
23	[6]	LUH	Beam	AlSi10Mg / 1.2709			x	x	
24	[9]	LUH	Beam	AlSi10Mg			x	x	

Air Force Research Laboratory (AFRL); University of Tennessee, Knoxville (UTK); Direct Manufacturing Research Center (DMRC); TU Dortmund University (TUD); Waseda University (WU); Gottfried Wilhelm Leibniz Universität Hannover (LUH)

evaluate the force- and frequency-dependent damping response [24, 34, 35]. In addition to simulation, design curves or regression analyses derived from experiments are used for component design [25, 26]. What both the experimental and the simulative models have in common is that they have so far shown limited transferability and are therefore of limited use as a dimensioning tool. In general, however, a large compared to a small cavity leads to higher damping [4, 5, 8, 17, 29]. A noticeable damping effect can already be realized at a void ratio of 3 %, and increases sharply up to a void ratio of 10 % and only slightly beyond that [4, 9].

With the void ratio fixed, the void cross-section perpendicular to the neutral fiber should be maximized, whereas the void length can be reduced [9]. Furthermore, minimum hole diameters, gap widths and wall thicknesses, especially for filigree structures, should be considered when dimensioning. These minimum structure sizes can be looked up from the literature on general design guidelines for additive manufacturing [20, 36].

3.4. Orientation and Support

To maximize component damping, the cross-section perpendicular to the neutral fiber should be oriented so that the side with the smallest void dimension points parallel in the direction of vibration [9]. In the case where a vibrating load acts on the particle damper in multiple spatial directions, anisotropic damping characteristics must be considered for cuboid cavity cross-sections with a large aspect ratio of >4:1 [9].

Furthermore, the orientation of the cavity on the build platform influences the subsequent damping properties [3]. The background is that during the additive manufacturing process, the powder layers on top compress those below. This compression of the powder layers is higher the more powder layers are applied. This ultimately results in a higher packing density and thus higher damping in the case of a cavity printed upright compared with one printed horizontally [3].

Furthermore, for the orientation of the cavity the building process must be taken into account in order to realize a self-supporting cavity structure. Self-supporting structures are defined in this context by maintaining maximum overhangs and critical down-skin angles. In addition to the orientation of the cavity within the component, the component orientation can also be adjusted. For example, beams with rectangular cross-sections can be oriented on the build platform such that the down-skin angles are exactly 45°, making the down-skin surfaces self-supporting [3, 6, 9, 34]. In sum, this results in an iterative procedure of component and cavity orientation, whereby various boundary conditions such as anisotropy, self-supporting structures or construction time have to be taken into account.

If it is nevertheless not possible to realize self-supporting structures, load-adapted internal structures must be provided [11, 18, 33]. Internal structures should be preferred to support structures in order to minimize the risk of detaching under load, which can change the damping and component properties. Internal structures can be created by repeating unit cells (honeycombs, tetrahedrons, etc.) or on the basis of topology optimization and are more massive in total than support structures [37, 38]. Internal structures also have a higher relative density, since every layer is melted during the additive manufacturing process and not only every second layer, as is the case with support structures.

3.5. Consider post-process

In the post-process, the choice of post heat treatment can have a decisive influence on particle dynamics and damping. At high temperatures and over a longer period of time, the powder can become sintered and consequently agglomerates can form. However, no further statements can be made on this yet, since only as-built particle dampers have been characterized so far.

Powder outlets are integrated as standard in components with cavities, in order to remove the powder after the manufacturing process. In cavities that function as particle dampers, however, no powder outlet openings must be provided.

It must also be taken into account that no mechanical post-processing of the cavities is possible. Down-skin surfaces in particular are characterized by increased surface roughness [3, 39]. Sometimes, the down-skin angles or the length of the overhangs in the cavity must be adjusted here.

One alternative to minimize or solve these challenges is multi-material printing using LPBF or powder exchange [40]. During multi-material printing, particles with a high melting point, such as tungsten [13], can be deposited in the cavity, reducing the risk of agglomeration of the powder at high temperatures. Furthermore, particles with a higher hardness can also be deposited so that the rough surfaces of the main structure can potentially be smoothed during operation.

The other alternative is to empty the cavity of powder after the manufacturing process [18, 30, 31, 32, 33]. This can be followed by post heat treatment and mechanical or chemical finishing of the rough surfaces, for example by flow grinding. The powder can then be filled into the cavities, which are then sealed [18, 30, 31, 32, 33]. However, it must be taken into account that the accessibility for the powder filling and the closing mechanism must be given.

Finally, it must be taken into account that no visual inspection of the cavities is possible, making the detection of component defects more difficult. In particular, care must be taken to ensure that there are actually cavities inside the component. An analysis of CAM data or CT scans, for example, is suitable as a quality assurance measure.

Fig. 2 summarizes the previously described design guidelines in the form of a flow chart. Depending on the problem, it may be the case that not all design guidelines are applied. On the other hand, other design guidelines may have to be applied, e.g. for production-oriented design or for internal structures. In addition, there are other influencing factors such as the machine, the manufacturing process, and the material that affect the design guidelines [20, 41]. Among the influencing factors of the manufacturing process are the process parameters, layer thickness and inert gas. Those of the material include the grain size distribution, melting temperature, moisture, proportion of recycled powder, and the alloy itself [20].

4. Conclusion and outlook

Within the scope of this paper, the current state of research on the design of laser beam melted particle dampers was presented. A collection of design guidelines was derived from the resulting findings and prepared in the form of a flow chart. The flow chart on design guidelines represents a systematic approach to the design of laser beam melted particle dampers by establishing a sequence that influences subsequent design guidelines as little as possible. Overall, the design guidelines could be divided into five categories (positioning, determine cavity geometry, dimensioning, orientation and support, post-process), and are formulated as generally as possible to realize a high transferability. This should make it possible in the future to systematically integrate the effect of particle damping into any vibration-loaded structural components that are to be manufactured using LPBF. In the long term, further methods must be assigned to the individual categories in order to further specify the design guidelines that are generally valid here. This includes, for example, multi-objective optimizers for positioning and defining the shape of the cavities for the embodiment design and mechanical substitute models for precisely quantifying the effect for the detailed design. Further questions also need to be answered regarding the influence of material and manufacturing process on the effect of the particle damping.

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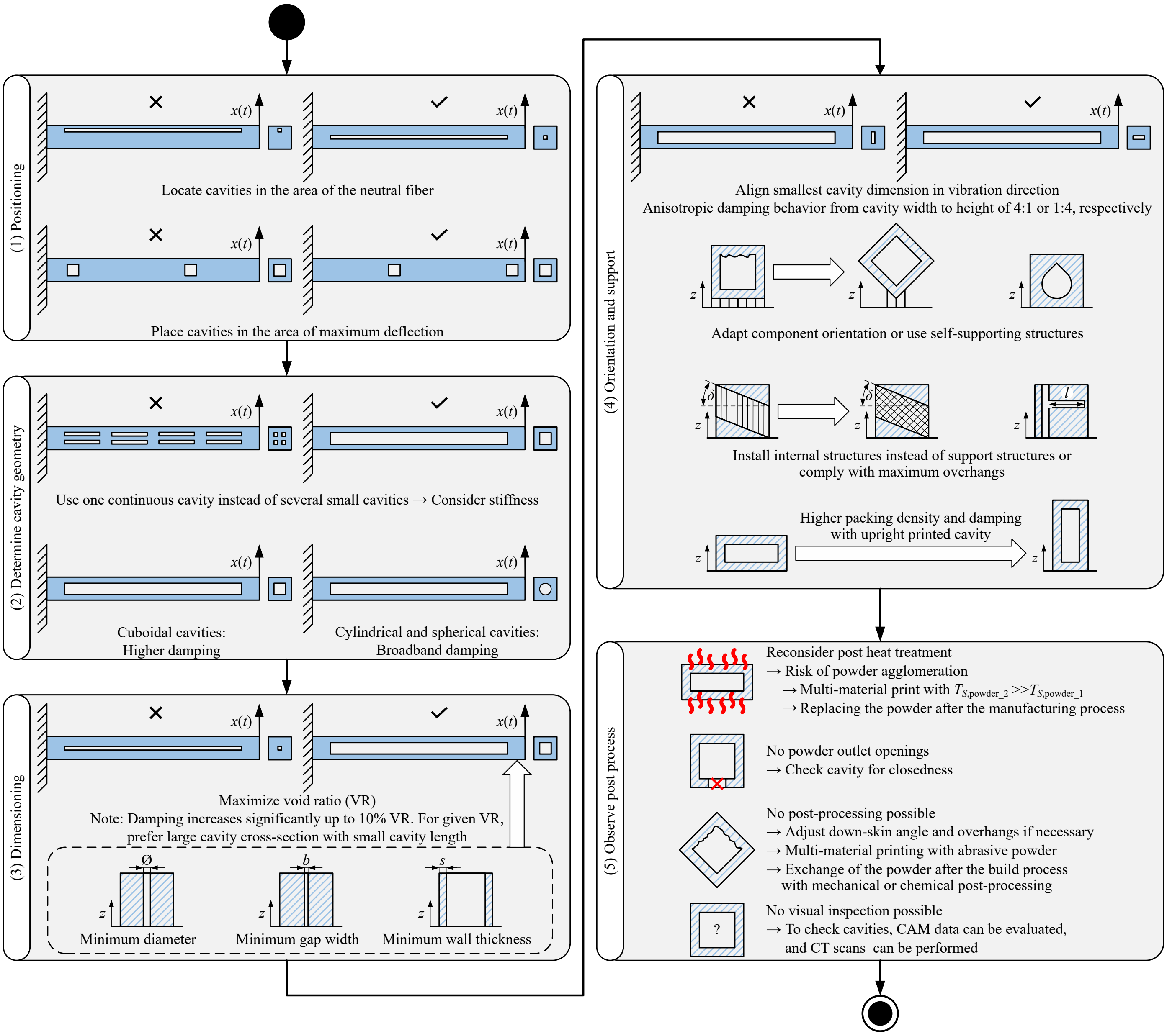

Fig. 2. Design guidelines for laser beam melted particle dampers.

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