State of the Art on Robust Design Methods for Additive Manufacturing

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Abstract. Additive Manufacturing (AM) technologies allow to produce functional parts with complex geometries that cannot be manufactured by conventional processes. However, the complexity of the product is increased and causes new constraints in the manufacturing process. Therefore, these new processes lead particularly to new needs in design methods. The objective of this paper is to explore and form an overall view of design methods, especially, robust design (RD) methods. Robust design is defined here as a methodology that enables to design a product with optimal performances and insensitivity to small variations of the inputs of the manufacturing process. In this contribution a state of the art of robust design methods applied to AM will be carried out.

Keywords: Robust design · Additive manufacturing · Design for additive manufacturing (DfAM) · Taguchi method

1 Introduction

AM groups a set of technologies that allows parts to be manufactured by adding material, usually layer upon layer [1]. In the last few years, AM processes have evolved quickly from rapid production of prototypes into manufacturing processes enable to produce end-use products [2]. This could significantly reduce the high funding in injection moulding tooling of small series production and thus, decrease cost and time to market within the product production [3]. Therefore, these processes are fully mature for industrial production. Research has indicated that the industries have begun strongly using the AM technologies such as selective laser melting (SLM) for example to directly produce end-use parts [4]. However, all AM technologies still require significant developments, especially at the design level. In addition, the skills of designers need to be completely developed in this field and guidelines must be set up. Hence, there is a necessity to develop and implement RD methodologies for AM processes to assist designers. The aim of these methodologies is to optimize products performances, i.e. guarantee robustness of the product against all the unwanted performance variations that could be generated due to the part geometry or process variables such as machine technology or material...etc. This article will present the existing RD methodologies applied in several fields, in particular AM field. In order to develop a robust design for AM, a state of the art will be conducted. Thus, various works related to this framework will be cited. First of all, the

research methodology consisted in selecting the articles that best explained the robust design of the mechanical parts. Then, an analysis of the articles will highlight their strengths. Afterwards, the authors will propose a vision of robust design for AM.

2 State of the Art

This section presents two main subjects. The first one is about RD and its existing methods. The second deals with RD methods with adaptation to AM processes.

2.1 Robust Design

The first English version of the Taguchi's robust design concept has been published in 1979 [5]. In fact, Taguchi has developed a statistical method for carrying out experimental designs. It is mainly used for the product quality improvement. On the one hand, [6] and [7] have applied Taguchi's method based on design of experiment (DOE) to simplify and limit the experimental approaches of their studies and therefore, reduce time and resources. On the other hand, RD means that a system's design is done in a way that sharply reduces variations, i.e. getting the best solution that will behave as expected by the designers [8]. In addition, [9] have identified that the main principles of RD methodology are insensitivity to noise factors, awareness of variation and finally continuous applicability. Indeed, these principles need to be achieved in order to guarantee a RD methodology. Otherwise, a manufactured product will present unwanted performance variations, as a result, it shows that the robustness of a design depends entirely on its performance variations. To avoid or at least decrease these variations, design engineers must consider them in the early stages of the design process in order to predict their effects on the product's performance and therefore, be able to control and limit them as much as possible.

In this context, [8] have presented a set of methods whose objective is to predict the effects of variations of the system to be designed. Firstly, they have identified independently a deterministic analysis of variations based on the conditioning of a matrix and afterwards, a statistical approach to analyze dimensional and geometric tolerances. According to the authors these methods are used for both technical and economical reasons. However, they are based on very precise assumptions such as the linearity of the objective functions.

Furthermore, particularly in structural dynamics, [10] proposed a RD methodology based on the coupling of stochastic multi-objective optimization with a robust condensation method with respect to structural modifications and uncertainties. The idea of this methodology is to integrate robustness as an additional objective function to be maximized. In addition, [10] have demonstrated the efficiency of their methodology in two different simulations. Firstly, the simulation of a bracket made up of an assembly of two reinforced plates and then, of a curved plate reinforced by five stiffeners. The results of this methodology present very slight performance variations caused by the uncertainties in the design parameters and a significant gain in terms of calculation time. However, this methodology remains limited only to structures. Besides that, [11] confirmed that the main intention of RD is to design a system with less performance variations and even

insensitive to the process inputs variations such as material properties and operational conditions. Currently, the robustness is applied to simple forms, such as thin-walled shells like cylinders, cones and spheres [12]. However, the forms with non-uniform geometry such as the optimized parts for AM remains non-studied. Furthermore, the integration of robustness in the iterations of topological optimization might be a strong point for AM parts, however, it still applied only for conventional designs [13].

2.2 Robust Design for Additive Manufacturing

In this section, RD methods with adaptation to AM which mainly focus on functional improvements and the limitation of geometrical defects are presented.

In the recent years, AM processes have offered enormous manufacturing capabilities and reduced manufacturing costs. However, it is often difficult to have high levels of geometric and dimensional precision with some of these processes. For instance, the quality of parts manufactured by AM depends on several variables, such as the material used, process parameters and the machine technology. Due to the numerous additive processes and their rapid proliferation, designers suffer from a lack of design guidelines and standardization of best practices [14]. Numerous works have been done before in this framework to develop RD methodologies for AM in order to produce high quality parts.

[7] have conducted a detailed research to optimize the 3D printing (3DP) manufacturing processes. This research focused particularly on numerous process parameters, such as the layer thickness and binder setting saturation value...etc. According to the authors, these parameters mainly influence the final part quality and accuracy. In order to limit the number of experiments of their study, the authors have used the Taguchi's method based on DOE. The main idea of this work was to improve the quality of the produced 3DP parts and reduce their building time while keeping optimal manufacturing costs. The results were relevant whether at the level of building time and accuracy error which have been reduced, beside the increasing of the flexural stress at the level of strength. Despite these improvements, this study still only adapted for rapid prototyping parts, an extra effort is therefore needed to extend it for end-use parts. Another RD methodology was proposed by [3] which combines three concepts; Taguchi design of experiments (DOE), multi objective optimization and statistical process control (SPC). The authors have demonstrated the effectiveness of their combined methodology to assess AM feasibility and robustness for direct component manufacturing of a typical ABS injection moulded plastic part. This work has better encompassed almost all the contributions of RD for AM by providing relevant case studies results about three different AM processes. However, this work needs to be completed by projecting it on multi-components products, while considering the noise factors and interaction between the process variables.

AM technology and structural optimization technology have been recently well integrated in the works of [15]. Thus, they have demonstrated the effectiveness of their structural optimization design approach based on SLM for thin-walled antenna bracket. The proposed design approach for the antenna bracket might be further improved in the future by exploiting Wang's work [13]. Besides that, [16] have proposed the concept of topological optimization loops for multi-components product. Based on a case study, several topological optimization paths are compared. Thus, certain optimization principles are

suggested to choose the most suitable path according to the designer's objectives (e.g. minimize the calculation time, obtain the best mechanical behavior or obtain the lowest mass). The results obtained during this work were relevant for mechanisms with an open loop kinematic chain and to minimize mass as an objective and minimize displacement as a constraint. To complete this research, it would be more interesting to conduct a study of complex systems with closed loop kinematic chains with other objectives and constraints of topological optimization.

To sum up, the Table 1 gives an overview about the works previously cited.

Table 1. Summary of the state of the art.

Reference	Methods type	Proven for AM?	For which AM process?	Advantages	Drawbacks	Applicable to an assembly?
[3]	Robust design & Taguchi method	Yes	Stereolithography; Polyjet and laser sintering	Give guidelines for machines Automation of process parameters selection	Does not include noise factors Limited for simple parts	No
[7]	Taguchi method	Yes	3D printing	Optimize process parameters Consider noise factors	Limited for simple parts Limited for RP technologies	No
[8]	Robust design method	No	–	Predict the effects of variations of a system	Based on very precise assumptions	Yes
[10]	Robust design method	No	–	Integrate robustness as an objective function to maximize	Need to be adapted for AM products	Yes
[11]	Robust design method	No	–	Provide guidelines for the designers	Need to be proven for AM technologies	Yes
[12]	Numerical design approach	No	–	Analyze the buckling behavior of critical shell structures	Need to be proven for AM's optimized parts	No
[15]	Structural optimization design	Yes	SLM	Improve the natural frequency and dynamic characteristics	Need to be applied for multi-body components	No

3 Conclusions and Perspectives

This paper presents a state of the art of robust design methods for simple parts and products and gives some definitions and principles of RD and the Taguchi method. Firstly, this contribution has presented a set of robust design methods applied in different domains such as dimensional and geometric tolerances domain, structural dynamics and tolerance compensation. The second part of this state of art dealt with RD methods with adaptation to additive manufacturing. Generally, it is clearly noticed that some

of the exiting RD methods are not adapted to multi-body systems (e.g. [3, 7, 12] and [15]), and some of them are not proven yet for AM technologies (e.g. [8, 10–12] and [13]). In addition, the majority of these methods have not been combined yet. Table 1 visualizes the characteristics of the different methods presented in this work and gives their advantages and drawbacks. Obviously, this article has highlighted the gaps in the literature, this will offer new perspectives of research. That is why the next work will be focused on the development of a robust additive design methodology allowing to achieve all the advantages of most AM processes. This methodology will be studied at the first time on a simple part, in which an industrial case study will be carried out and then, this methodology will be improved in order to perform multi-components systems design.

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