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Review

Topology optimization and additive manufacturing: Comparison of conception methods using industrial codes

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ABSTRACT

Additive manufacturing methods provide an increasingly popular industrial means of producing complex mechanical parts when classical methods are not suitable. The main advantage of these methods is the great freedom they give designers. At the same time, theoretical and numerical topology optimization tools can be used to simulate structures with complex shapes which exactly meet the mechanical constraints while requiring as little material as possible. Combining topology optimization and additive production procedures therefore seems to be a promising approach for obtaining optimized mechanical parts. Nonetheless structures obtained via topology optimization are composed of parts of composite densities which can not produced via additive manufacturing. Only numerical structures made of full or empty spaces only can be produced by additive methods. This can be obtained at the end of computational optimization through a penalization step which gives the composite densities from 0 to 1 the values 0 or 1. This means that the final part is different from the best solution predicted by topology optimization calculations. It therefore seemed to be worth checking the validity of an engineering approach in which additive methods are used to manufacture structures based on the use of industrial topology optimization codes. Here the authors propose to study, in the case of a simple mechanical problem, that of a metal cube subjected to a given pressure, three procedures, which differed in terms of the code and type of topology optimization calculations performed and the level of penalization applied. The three structures thus obtained were then produced using additive methods. Since all three structures proved to be mechanically resistant, the three procedures used can be said to be valid. However, one of them yielded better compromise between the mechanical strength and the amount of material saved.

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1. Introduction

One of the traditional manufacturing methods most widely used in the mechanical industries consists of removing excess of material from a block until only the desired shape remains. However, although computer aided manufacturing tools and machine tools are being constantly improved, it is sometimes very difficult or even impossible to produce parts with complex shapes such as intertwined, imbricated, assembled and alveolar parts only by subtractive manufacturing. *Additive Layer Manufacturing* (ALM) methods, which are commonly known as "3-D printing" methods, are a set of mechanical procedures which can be used to overcome the technical limitations of classical approaches while giving greater freedom of design. These methods can be applied using metallic or plastic materials in the form of powder or threads, which are melted and soldered layer by layer, depending on the Computer Aided Design (CAD) trajectory of a laser or electron beam, an electric arc or a thermal resistance. After being developed in the 1960 as a means of producing prototypes and scale models, additive manufacturing processes were gradually improved in order to meet the demand for more functional mechanical parts and tools [1]. These processes can be used either to improve and lighten previously existing parts, or as a means of quickly manufacturing new products with complex shapes at a similar cost to that of conventional procedures [2]. In view of these advantages, many studies are now being performed to further improve these methods and give greater design freedom and precision and a wider range of materials while reducing the production time to a minimum. The best-known ALM methods include FDM (*Fused Deposition Modeling*) [3], DMD (*Direct Metal Deposition*) [4] and SLS (*Selective Laser Sintering*) [5] methods, which are faster than classical methods but do not always meet the requirements of mechanical strength, fatigue resistance, porosity and surface rugosity.

Selective Laser melting (SLM) methods, in which a laser is used to selectively fuse a layer of powder according to a specific pattern, seem to provide an attractive means of overcoming the problems inherent to classical methods because the fast cooling speeds make it possible to produce complex parts with very fine microstructures. These methods can be applied to various materials such as polymers, ceramics and metallic materials. During the production of a metallic component, the laser melts not only the powder bed, but also part of the underlying layer, so that metallurgical bonds are formed between the laser weld seams and the previous layers. These method give similar mechanical properties as those obtained using conventional procedures. However, since the machine parameters adopted during the production process directly affect the mechanical properties of the components obtained, these parameters have to be finely adjusted in order to obtain high-quality mechanical parts. SLM manufacturing is conducted in controlling first the laser parameters: the power, the scanning velocity and the beam diameter. Then system parameters have to be defined. They correspond to the density and depth of the powder bed, the seam width, the hatch distance between two adjacent seams, the scanning trajectory and the hatch angle [6–8]. The environmental parameters which have to be regulated include the protective gas and the pre-heating temperature.

If several studies [9–13] have shown that the final quality of SLM parts depends strongly on the laser parameters, it is possible to obtain a relative density of almost 100% by optimizing the laser parameters [14]. In the same way, the residual loads and the distortion can be highly reduced by adjusting some of the environmental parameters [15–17]. The SLM method, after calibration, can be so seen as a real means to produce parts of high mechanical quality comparable to or even better than those obtained using traditional methods.

Once all the parameters have been calibrated, the cost of additive manufacturing processes will depend directly on the mass of the material to be fused. The cost therefore depends on the volume of the final part rather than on its complexity, contrary to what occurs in the case of subtractive manufacturing. To ensure greater cost efficiency and better performances, it is therefore necessary to lighten the part by decreasing the amount of material to be deposited and encourage designers to increase the complexity. One way of achieving this is to combine ALM processes with intelligent design based on topology optimization methods.

Topology optimization methods [18] provide an ideal numerical tool for automatically determining optimum shapes without having to take the manufacturing process into account, based on specifying one or two mechanical criteria to be minimised and a given design space. The optimization potential of these methods is much greater than that of classical optimization methods of size [19,20] or shape [21–26]. Indeed topological optimization allows changes to be made not only in the geometry of the structure, but especially in its topology, modifying the number and connectivity of components and creating in the medium some boundaries, branches and holes. With topology optimization methods, the aim is not so much to look for the most suitable shape, but rather for the optimal distribution of material and void regions inside a predefined design domain for a given set of loads and boundary conditions. In the continuous case, the design variables are the number, connectivity, shape and location of voids (Fig. 1a) whereas they are the thicknesses or cross-sectional areas of structural members (Fig. 1b) in the discrete approach.

In most industrial cases, this approach yields satisfactory solutions, which are fairly complex and not always very intuitive. Contrary to conventional manufacturing, ALM methods give near-complete freedom of design and makes it possible to benefit from the powerful numerical solutions which can be "printed out" directly without any restrictions. The significant decrease in the volume of material used immediately shortens the production time and makes for considerable savings.

During the last few years, modules of topology optimization have been integrated into the industrial calculation codes. The main software programs providing topology optimization modules include Optistruct, which comes with *Hyperworks* (Altair), *Tosca* (FE-Design), which comes with the Abaqus code (DS Simulia), MSC-Nastran (MSC Software), Genesis (VRCreo (PTC), PLM Software, which comes with NX/CAE (Siemens), and Inspire (SolidThinking).