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A design strategy based on topology optimization techniques for an additive manufactured high performance engine piston

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Abstract

In this paper, a methodology for the design of a motorcycle piston is presented, based on topology optimization techniques. In particular, a design strategy is preliminary investigated aiming at replacing the standard aluminum piston, usually manufactured by forging or casting, with an alternative one made of steel and manufactured via an Additive Manufacturing process. In this methodology, the minimum mass of the component is considered as the objective function and a target stiffness of important parts of the piston is employed as a design constraint. The results demonstrate the general applicability of the methodology presented for obtaining the geometrical layout and thickness distribution of the structure.

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1. Introduction

The piston represents the main alternating mass in an internal combustion engine mechanism. To minimize piston mass is therefore fundamental to contain inertial forces. Because of its low density, aluminium is the most common material employed for piston manufacturing. Unfortunately, aluminium exhibits low mechanical properties, which further decrease when it is exposed to high temperatures [1]. Turbocharging (downsizing), high compression ratios,

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advanced spark ignition strategies are some of the techniques employed in modern engines in order to increase engine efficiency to fulfil strict norms on engine pollution emissions and to minimize fuel consumption. Therefore, higher specific loads could be encountered, which lead to higher mechanical and thermal loadings of engine components [2, 3]. In this scenario, aluminium may not represent the best choice and steel may be considered as a valid alternative for piston manufacturing. Schreer et al. [4] analysed the consequences of employing a steel piston: a better kinematic behaviour of the crank mechanism, a comparable weight, more homogeneous surface temperatures, a lower dead volume at the top land, a lower blow-by and a more efficient combustion process are the main advantages registered. Nevertheless, traditional manufacturing technologies cannot be employed when steel is considered as the material for pistons. In fact, in order to obtain components with a comparable weight when compared with those produced by aluminium, the thickness of the different parts of a steel piston have to be reduced up to one millimetre. Additive Manufacturing represents a promising technology to obtain thin features. Bendsøe and Kikuchi [5] related optimization techniques to structural design, noting that the resulting complex shapes could be easily reproduced by Additive Manufacturing. Du and Tao [6] and Zhao et al. [7] adopted the topology optimization for an engine piston lightening, but they used the results only to understand which parts of the piston were redundant, without ascribe any focused design validity. Brackett et al. [8] analysed the main challenges and opportunities for topology optimization for Additive Manufacturing. The importance of mesh resolution, manufacturing constraints and the post-processing have been highlighted.

In this contribution, topology optimization analyses are coupled with Finite Element analyses in order to reach an optimum steel piston configuration. In particular, the minimum mass of the component is considered as the objective function and the displacements of specific nodes on the piston skirt, crown and bosses are employed as design constraints. Different load cases are considered and the results of the topology optimization are revised and discussed with the prospective to employ Additive Manufacturing as the production technique.

2. Design strategy

2.1 Topology optimization

A generic optimization problem can be written in the form [9]

$$\begin{aligned} &\text{minimize}_{\boldsymbol{x}\in D}\, f(\boldsymbol{x}) \\ &\text{subject to}\; c(\boldsymbol{x})\geq 0 \end{aligned} \tag{1}$$

where the vector $\boldsymbol{x}$ represents a suitable parameterization of the problem, $\boldsymbol{D}$ is the design space, $f(\boldsymbol{x})$ is the objective function, and $c(\boldsymbol{x})$ are the constraints of the optimization. The functions $f(\boldsymbol{x})$ and $c(\boldsymbol{x})$ are usually computed via a suitable numerical technique while the optimization algorithm iteratively looks for the best configuration.

In topology optimization, since gradient information is readily available from the Finite Elements analyses, a large number of variables can be easily handled, accepting that a gradient-based optimization algorithm is adopted.

The most popular methods for topology optimization are the homogenization methods. In particular, in this paper the solid isotropic material with penalization methods, SIMP, is employed.

The theory of this method is described extensively by Bendsøe and Kikuchi [5] and Bendsøe and Sigmund [10]. The main scope of the method is to find the optimum material distribution in a structure. Finite Element analyses are performed assuming as a parameters vector the element-by-element relative material density, which is allowed to vary with continuity:

$$x = \{x_i \in (0,1], \forall i = 1, \dots, N)\} \tag{2}$$

where N is the number of finite elements in the structure.

The density of the i-th element is given by: