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DESIGN OF CUTTING TOOLS FOR L-PBF MANUFACTURING AND FUNCTIONAL PERFORMANCES VALIDATION

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ABSTRACT

This paper reports the design of cutting tools for milling specifically addressed to additive manufacturing (AM) with associated validation with experimental tests. Laboratory tests under controlled conditions and operative tests on milling machine are conducted. The modified component is compared to the original version made by subtractive methods. The component includes an integrated lubrication system composed by reservoir chamber and channels. The modified version built with laser powder bed fusion (L-PBF) process has one single body in titanium alloy, with 33.9% mass reduction. The tests provide torsional stiffness validation and local surface strain, used for comparison with design modeling results. The parabolic-shaped channels provides uniform lubricant flow pressure and velocity, with more refined spraying and cooling performances.

Keywords: milling cutter, experimental mechanics, lubrication channels, L-PBF, SLM.

INTRODUCTION

Additive manufacturing (AM) of mechanical components already showed peculiar advantages over the traditional subtractive manufacturing, which led to increased applications in the last years. AM enables shorter lead time from design to market, flexible customization of products, standardization of the supply chain and flexible freeform design (Attaran 2020; Schniederjans 2017; Savolainen et al. 2020).

The traditional design of cutting heads for milling has the goal to optimize the static and dynamic behavior of the system composed by the milling machine, the cutting head and the workpiece. More recently, the technological evolution of milling processes is moving towards increased productivity and reduced energy consumption than in the past. The process throughput and the energetic needs of plants are inspiring innovative solutions in designing the cutting heads and the electronic controls of machines (Brecher et al. 2010; Wang et al. 2010; Hanzl et al. 2019; Hanzl et al. 2020; Yang et al. 2020). The complexity of the cutting head is due to the coexistence of structural features (responsible of torsional stiffness, stress, displacements, and mass) and functional features (linked to lubrication, cooling, alignment and stability of diamond inserts).

Considering the important aspect of engineering design and manufacturing, several studies have been conducted in order to create a better design related to machine tools or development of the existing component even with very complex shape. Brecher (Brecher et al. 2010) conducted a compact design for high precision machine tools. They proposed the model to satisfy the need of the micro-manufacturing process. They developed new machine tools, exemplify the dynamic and accuracy enhancement with a compact design. Wang (Wang et al. 2010) proposed the design and development of a precision machine tool using a counter-motion mechanism. They also focused on the manufacturing of high-quality miniature parts. The theoretical and practical background of the machine tool design and its control, including the measurement system, are deeply investigated.

Research in the design and development of complex part have also been conducted by several researchers. Tsiafis (Tsiafis et al. 2018) proposed a design method and the manufacturing of spiral bevel gears using CNC milling machines. The introduction of the design features showing the standard for the geometrical dimension of gear tooth was proposed. The five-axis machining tools were selected to study the manufacturing process. In the composite area, Mohammad Rouhi (Rouhi et al. 2018) conducted a study on the design, manufacturing, and testing of a variable stiffness composite cylinder. The activities involve a composite cylinder made by fiber steering. They mainly investigate the properties in terms of buckling capacity. In the area of additive manufacturing, Gebisa (Gebisa et al. 2017) analyzed the implication for design optimality and product sustainability between design for manufacturing to design for additive manufacturing. The analysis of the paradigm optimality of both manufacturing method was criticized. Zhao (Zhao et al. 2019) investigated the optimization design method of additive manufacturing-oriented porous structures and experimental validation. They proposed a novel method optimizes porous structures using embedded voids and incorporates two novel filters.

Additionally, the use of Finite Element Method and Computational Fluid Dynamics approach have been utilized widely in many disciplines of research (Adam at al. 2014; Hällgren et al. 2016; Hanzl et al. 2019; De Pasquale 2021; De Pasquale et al. 2022; Coluccia et al. 2021; Bertolino et al. 2019; Großmann et al. 2020).

Engineering design is defined as an iterative decision-making process in which the basic sciences, mathematics, and engineering sciences are applied to optimally convert resources to meet a stated objective. In terms of the design levels, the classification can be made as an adaptive design, new design, and development design. An adaptive design is when the activities encompass the adaptation of existing designs. Here, there is hardly anything left for designer to do except make a minor modification. Furthermore, the new design is named when the designer requires to generate a completely new concept. It involves mastering all the previous skills. The last classification is the development design. Considerably more scientific training and design ability are required for development design. The designer starts from an existing design, yet the outcome may be similar or completely differs from the initial product.

The goal of this paper is to apply a development design, optimizing an already existing product to be better in terms of functionality and topology. The progressive evolution of the initial design is made by considering some relevant functional target parameters of the device: the lightness, the lubricant management, the post-processing mechanical tooling, the powder extraction, the overall structural strength and stiffness, the local stress-strain distribution.

DESIGN FOR ADDITIVE MANUFACTURING

Problem recognition and definition have been made by the already existing problem definition from the original component. Then, the information finding of research and work related to the problem definition is performed. These two steps have been defined clearly at the beginning of the re-design process, Figure 1. It entails the connected combination of the systematic techniques applied, creativity, the feasibility, selection of the optimum configuration and the defining the optimization techniques. It is also essential to envisage the manufacturing constraint and construction techniques by considering, in this case, requirements of the model regarding the additive manufacturing process. Further, design analysis and evaluation are required to be performed. This includes the numerical modeling and simulation both the finite element method and the computational fluid dynamics (CFD) analysis.

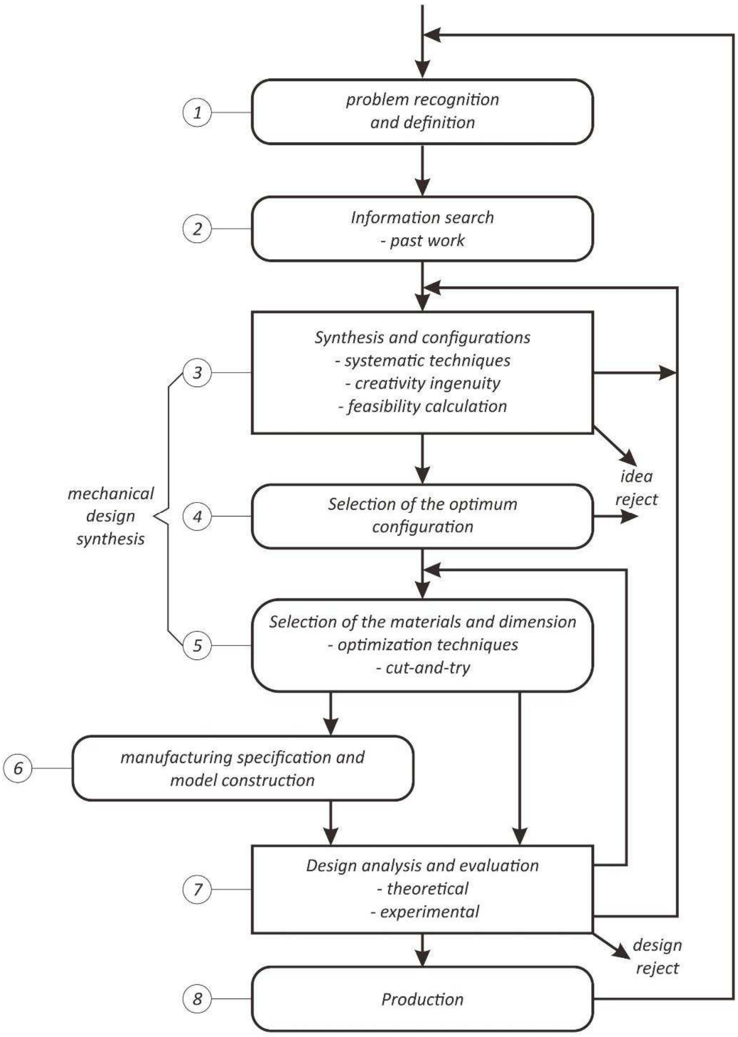

Fig. 1 – Design process map (Haik et al. 2011).

STRUCTURAL AND FLUDIC MODELING

The cutting head has 125 mm diameter, 58 mm height and eight inserts holding eight cutters. The overall masses of the cutting heads are 1941.3 g (original) and 1282.3 g (AM modified), the material is titanium Grade 5 (Ti6Al4V) with E = 104 GPa (De Pasquale et al. 2019; De Pasquale et al. 2018; De Pasquale et al. 2021) . The lubrication system includes eight radial channels directed towards the perimeter cutters and four axial channels directed to the top surface. All the channels start from a ring-shaped reservoir, with flat shape, situated inside the head that works as fluidic capacitance.

The structural FEM modeling of the cutting head tool is provided by means of tetrahedral element mesh. The element size is in the range 0.5-3 mm. The 3D geometry is created preliminary with SolidWorks, than the numerical simulations are conducted with HyperWorks.

The model accounts for three loads: the cutting torque, the compression of holding screws and the centrifugal rotation force. The first loads corresponds to eight cutting forces of 1600 N (the most severe operative condition). The main central screw (ISO M20) is tightened at 290 Nm prescribed torque, corresponding to 68.41 kN axial force applied through the central body and the cover. The inserts are held by eight ISO M8 and eight ISO M5 screws, tightened at 13 and 4 Nm torques respectively, corresponding to 9.85 and 4.85 kN. The axial forces generated by the screws are modeled by rigid virtual links connected to the structure surfaces. Finally, the nodal centrifugal forces are calculated from the instant angular velocity imposed to the component in the simulation. The structural model is represented in Figure 2a.

The CFD model included the two fluids present in the simulation: the lubricant and the air. The first one is a mixture of 85% water and 15% cutting fluid (density: 0.95 - 1.05 g/cm^3). The air properties are defined at 25 °C temperature with continuous fluid morphology. The standard k-epsilon model is used to describe the turbulence flow in the CFD calculation. The lubricant velocity at the channels is imposed by the pump of the milling machine (77.6-126.7 m/s). The maximum angular velocity of the tool is 1047 rad/s (or 10.000 rpm). The pressure boundary condition is defined at 1 atm or 101325 Pa at the lateral surfaces of the air volume. The fluidic model is represented in Figure 2b (detail of lubrication channels).

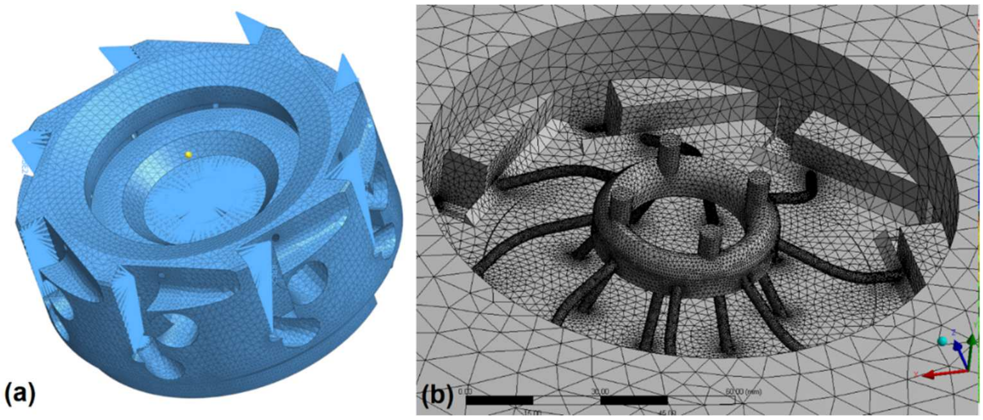

Fig. 2 – FEM model of the cutting head tool for structural simulations (a) and for CFD simulations of the lubrication system (b).

EXPERIMENTAL VALIDATION

The experimental setup has the goal to reproduce the steady state load applied to the tool in working conditions caused by the cutting torque and the screws compression. The tensile force generated by the universal testing system (UTS) Instron 8801 (100 kN load cell) is converted to the torsional torque, reproducing the cutting torque, by means of a customized clamping system as reported in Figure 3a. Two strain gauges with 120 Ω resistance, in half Wheatstone bridge configuration, are applied to the lateral surface of the cutting head. The strain gauges output is measured through the amplifier and analog-to-digital converter HBM QuantumX MX1615B and the software HBM Catman. According to the simplified torsional bar model, the sensors are oriented at 45° respect the axial direction. Differently from the theoretical cylinder, additional strain gradients induced by local geometrical details are present and they are included in the measurement. Nevertheless, the actual strain value is then compared to the calculation provided by the numerical simulations on the real geometry. The axial load ramp from 0 to 5 kN (corresponding to 685 Nm torque) and discharge is applied. Finally, the dynamic performance of the milling machine mounting the original and modified cutting tools are also observed. In particular, the qualitative lubrication spray is captured and stored by a fast sampling camera (Figure 3b). The FFT and power spectral density along the 3 axes are measured at variable rotating velocities in different operative conditions. The Campbell diagrams are also measured and compared.

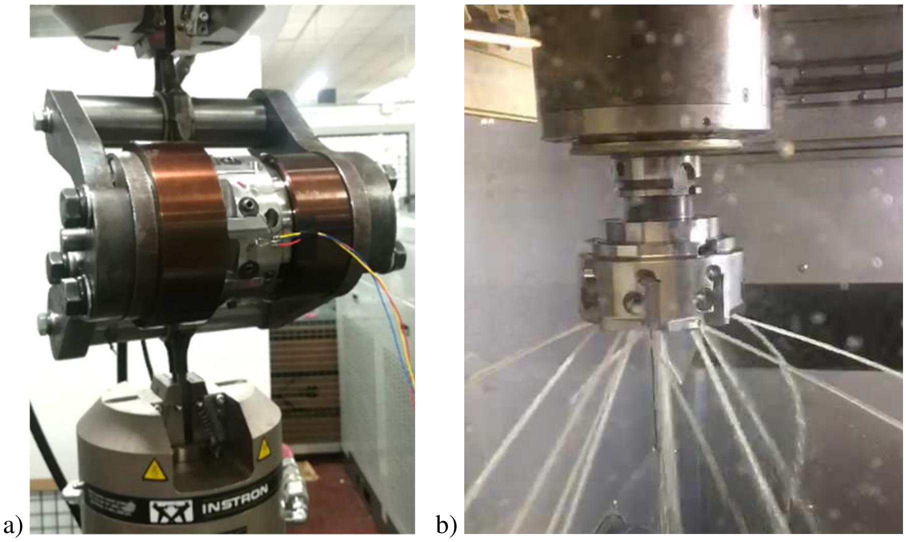

Fig. 3 – Experimental setup on testing machine (a) and qualitative lubrication spray observed on a milling machine during operations (b).

RESULTS AND DISCUSSIONS

The structural analysis conducted with the numerical model provides the results reported in Figure 4. The equivalent Von Mises stress distribution (Figure 4a) and the overall displacements (Figure 4b) are reported. The result is obtained under the combined effect of all the applied loads: cutting torque, screws compression and centrifugal force.

The results calculated from the CFD model about the lubricant spray, referred to the boundary conditions of 126.7 m/s inlet velocity and zero rotation speed, are reported in Figure 5.

The shape optimization of the component led to the configuration reported in Figure 6, which is obtained after a progressive reshaping of all the most relevant features, including the tool body and cover, and the internal lubrication reservoir and channels.

Finally, the experimental results provided by the static torque applied to the component are reported in Figure 7. The modified component, which is characterized by lower mass (-33.9 %), shows reduced torsional stiffness (-24.6 Nm/rad), but local increase of strength especially in correspondence of functional regions (e.g. the anchoring of cutters) and global reduction and uniformity of stress distribution.

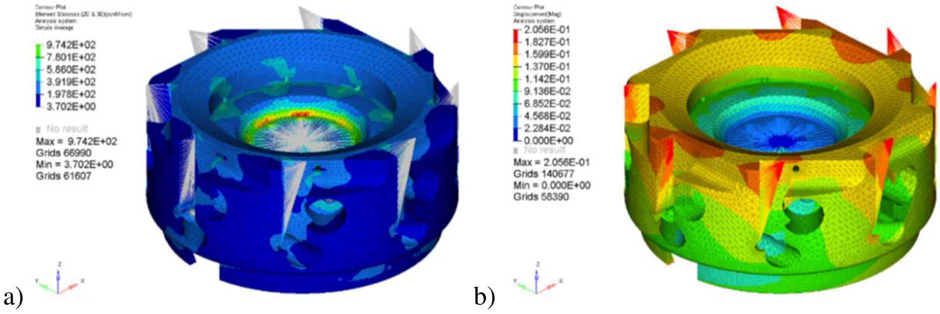

Fig. 4 – Von Mises stress in MPa (a) and equivalent overall displacement in mm (b).

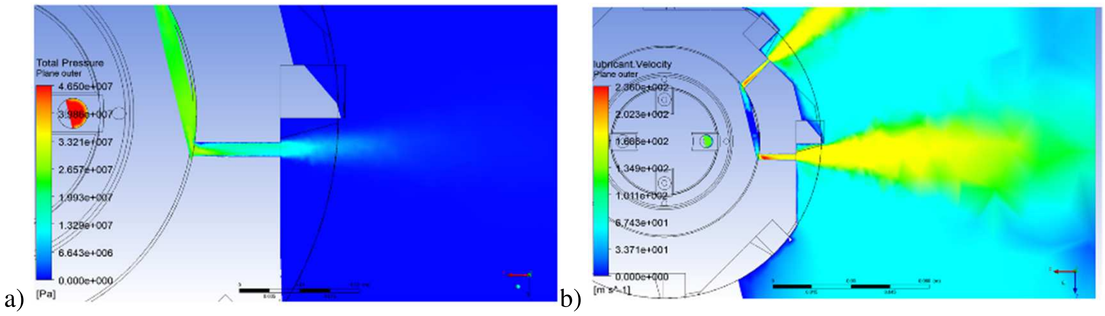

Fig. 5 – Results from CFD simulations related to lubricant pressure (a) and velocity (b) at the output of lateral channels.

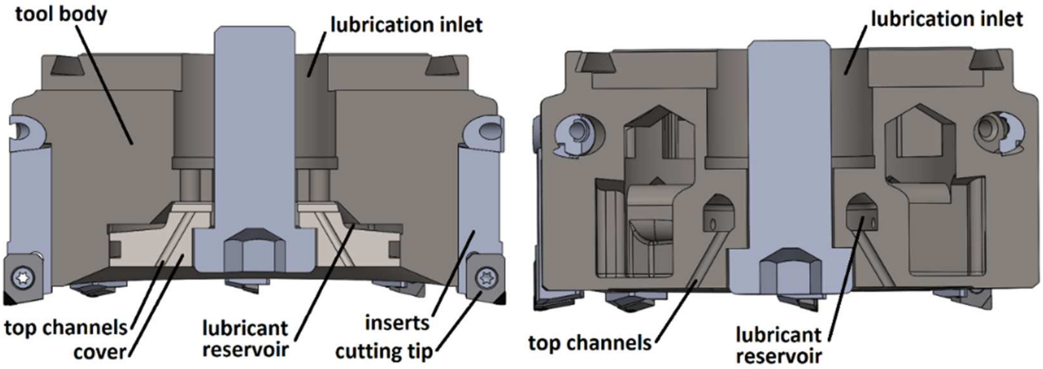

Fig. 6 – Original (left) and AM modified (right) versions of the cutting head tool.

From the experimental validation, it is observed that the maximum value of the strain measured on the re-designed head (77.41 μm/m) is 84% higher than in the original one (42.06 μm/m), as reported in Figure 3c.

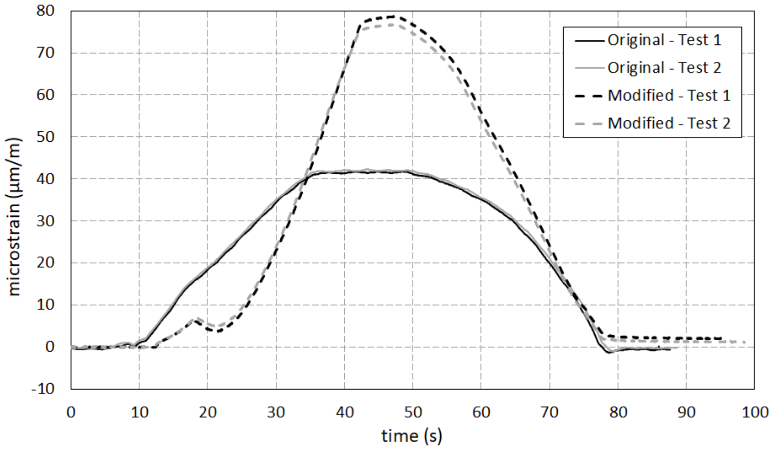

Fig. 7 – Strain measurements on the original and lightweight component.

CONCLUSIONS

This work has demonstrated the potential of dedicated design methods applied to the additive manufacturing processes to improve the functionality of consolidated components. The design for additive manufacturing (DFAM) accounts for the structural concepts in association to the manufacturing constraints and limitations. Generally, the evolution of complex components oriented to the functional optimization cannot be supported by automatic algorithms of topology optimization. In fact, the strong connection between the geometrical, process-related and functional parameters requires the progressive evolution of the design and of all the cross-linked effects.

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