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Designing die inserts by additive approach: a test case

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Abstract

The die manufacturing industry is widely based on the use of conventional machining tools. However, several studies have proposed Additive Manufacturing (AM) for molds and die inserts in the last ten years. The AM flexibility allows designing and manufacturing complex surfaces. This flexibility can be used to optimize the cooling channels of die inserts (conformal cooling). The research aims to evaluate whether Design for Additive Manufacturing commercial tools can be employed in redesigning die inserts. Besides, the paper describes a method to redesign a die insert for High-Pressure Die Casting using Selective Laser Melting. A test case is proposed to analyze an AM die insert's redesign process for improving the thermal exchange and the material distribution. The simulation of the AM process supports the drafting conclusions from the results.

Keywords: Metal Additive Manufacturing; Rapid Tooling; Additive Design; 3D Printing; High Pressure Die Casting; Conformal Cooling; Lattice Structure

1. Introduction

Additive Manufacturing (AM) is a very challenging technology for the industry. Even if this technology is costly, if compared with traditional machining, it shows essential advantages. Some of these advantages are the high flexibility, the possibility of producing lightweight shapes with complex geometry [1]. The AM flexibility is related to designing complex shapes while reducing the number of operations involved in the manufacturing workflow. Moreover, the AM can provide customized products through a full digital design and manufacturing process. The digitally controlled process enhances the system's flexibility and responsiveness to react quickly to changes [2].

The 3D printing process digitalization allows this technology to be fully integrated into the paradigm of Industry 4.0 [3]. The interest in this technology is becoming more and more relevant. A new design approach called Design for Additive Manufacturing (DfAM) has been recently introduced in the literature for optimal selecting design and process parameters (such as thicknesses and overhang surfaces) [4]. The DfAM approach focuses not only on the design framework but also on improving the product functionalities by implementing the AM features [5].

The early applications of AM were mostly related to the production of customized parts of lightweight engineering. AM technologies have been used mainly for the Rapid Prototyping of concepts and pre-competitive platforms [6]. Typical applications such as biomedical [7], aeronautics, and automotive have been long studied in the literature. As Pradel et al., nowadays, the use of AM is still mainly dedicated to the manufacturing of prototypes and tooling [8]. This study also proposed a survey to understand the current level of knowledge and practice about AM design in the industry. The results of that survey provided exciting statistics about the perception of the advantages and disadvantages. A majority of the interviewees indicated that AM had changed their design process and practices because designers are more focused on concepts than product functionality. As outlined by Vaneker et al., AM is a field that is rapidly evolving; therefore, many challenges remain in terms of additive process and design methods [9].

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Focusing on Rapid Tooling, AM is used to support the customization of inserts for molding and die casting. The flexibility of designing complex shapes allows conformal cooling to be optimized into die inserts. Even if this field has been well analyzed for injection molding, there are fewer applications in the field of High Pressure Die Casting (HPDC).

The paper aims to analyze the employment of DfAM tools in the redesign of die inserts for HPDC. In this context, a method is proposed to describe how each tool interacts inside the design workflow. This method has been used to describe a case study. The remainder of the paper introduces the state-of-the-art about AM and their application in tooling. After that, the method is described, and then the test case is analyzed in detail. The paper ends with conclusions and discussions.

2. Background research

Additive manufacturing technologies are opening fresh opportunities in terms of production paradigm and manufacturing possibilities [10]. The AM process is also well known as 3D printing because it creates 3D solids by an additive layered approach [11]. AM is a digital manufacturing process because the digital STL file (CAD geometry) is rapidly converted layer-by-layer into a machine code (G-code) for the 3D printer. While traditional machining tools require CAM analysis and simulations, digital data can be directly built in the case of AM.

Focusing on the printing technology, in the case of Selective Laser Melting (SLM), a layer of powder is iteratively spread over a building platform and processed with a laser (powder bed fusion technology). According to the CAD geometry, the laser scans over each layer to melt each powder layer [2].

Even if AM is a direct digital manufacturing process, simulation activity can be carried out to improve the built parts' quality and optimize cost and time. Therefore, virtual prototyping tools and methods can be applied to simulate all the additive production phases [12]. The virtual analysis shows the relation between the built project and the results regarding deformation and stress. Other tools can support engineers to define the supporting structures' geometry and the best part orientation.

The part's strength could be a weakness of AM parts; however, the optimization of processes parameters and design can increase it [3]. Another drawback is the necessity to reduce the amount of material [13]. Topology optimization is a solution to reduce part weight while preserving most of the strength of a part. The design configurations are elaborated by the Finite Element Method (FEM). The topology optimization analysis removes elements from the mesh volume until the desired mass objectives are achieved [13]. The outcome of topology optimization is innovative lightweight and high-performance structures that are difficult to obtain with conventional design methods [14]. Several researchers adopted topological optimization with additive manufacturing to decrease light-weighted parts' design efforts [15]. To improve the lightweight of the built components, lattice structure [16] and porous microstructures have been well analyzed in the literature [17]. These approaches have achieved significant results. However, lattice structures should provide a 3D homogenization to approximate the non-continuum periodic composites to continuum ones [18].

During the last 5-6 years, additive manufacturing has been applied to produce metal parts in several fields, such as aerospace [19] and automotive [20]. In such sectors, customization and lightweight are essential product features. The 3D printing of metal parts is also called Metal Additive Manufacturing (MAM) to distinguish from generic AM.

2.1. Tooling production with MAM

The design of tooling such as molds and die inserts by Additive Manufacturing is recent activity. SLM is the MAM process used in the literature for providing printed parts of dies. Petrovic et al. analyzed the fabrication of free-form cooling channels with AM technologies in 2010 [21]. More recently, Wu et al. were pioneers in defining an optimization framework for the molds design [22]. Generally, for die inserts, AM technology enables adaptive cooling design (conformal cooling). Since the cooling channels can follow the mold cavity, the heat exchange is more homogeneous [21]. This solution decreases the manufacturing cycle time (faster cooling) with benefits on the product quality [2] [21].

Stolt et al. studied an approach to integrate the AM insert design in the die assembly design [23]. This study deals with implementing SLM die inserts with separate cooling inside a traditional HPDC die assembly. The conventional design workflow has been compared with the design phase for SLM inserts. While both methods start with the CAD model analysis, the design of SLM inserts requires additional considerations about material usage, conformal cooling creation, part orientation, supports modeling, etc. Their study confirms the opportunity to design a lightweight die insert by AM process, keeping the stress within the permissible range. However, additional machinings to tolerance have been proposed because, in this study, the class 6 tolerance (ISO 286) cannot be achieved with SLM. Even if the SLM inserts post-processing is the bottle-neck, Armilotta et al. highlighted that the temperature distribution in HPDC molds could be improved using AM [24].

When manufacturing SLM inserts, design steps such as deciding the part's orientation and supporting structure are necessary. Therefore, it is suggested to use traditional molds with AM inserts to reduce the overall design effort. This solution seems to be the right compromise between design time and flexibility because the DfAM activity is only focused on the die insert [25]. In this case, the other parts of the die assembly are fabricated with traditional machining.

The benefits of AM for manufacturing inserts are contrasting. Stolt et al. have discussed the additional time to design and optimize AM parts [23]. Brøtan et al. have affirmed that AM inserts' design can be faster than traditional approaches [26]. Brøtan et al. also confirmed the benefits of conformal cooling channels in AM molds used for casting [26]. This aspect allows the quality of injected and cast parts to be improved. The optimization of the conformal cooling can also improve thermal fatigue resistance; however, the designer should consider the die insert's thermal expansion feature. The thermal expansion can be enhanced by applying lattice structures in some sections of the mold.

Generally, the convenience of using 3D printing over traditional manufacturing processes is a current research topic in the literature [27]. For about ten years in the injection molding industry, hybrid molds have been studied to evaluate practical convenience [11]. In hybrid molds, the most used solution consists of prefabricated parts (the inserts holder plate) and built ones (inserts). For several researchers, as analyzed in the literature, the mixing use of traditional machining and 3D printing is a practical and convenient solution for the design of molds.

3. Method

The methodology used to analyze the redesign-workflow of die inserts is described in Fig. 1. This method is focused on the development of die inserts for HPDC to be built by the SLM process. The tools employed are representative of commercial software used in DfAM. Examples consist of CAD tools with advanced features for designing AM supports, FEM applications for simulating the structural behavior and the AM processes.

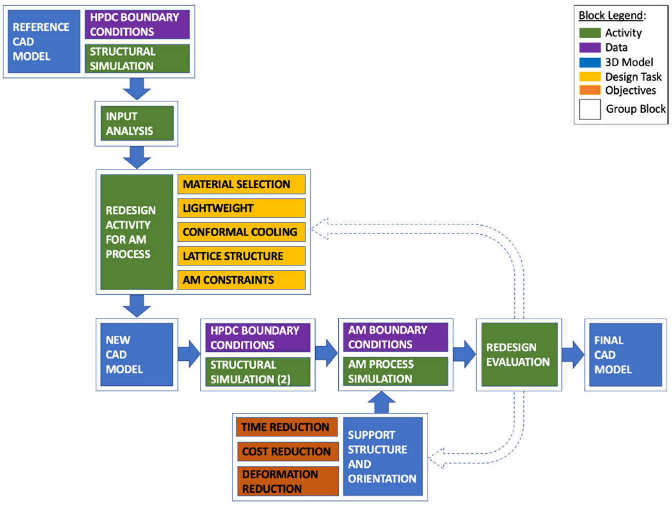


Fig. 1. The method to support the redesign of die inserts to be built by the AM process. Each block identifies a specific design phase and groups a set of different sub-blocks. Each sub-block is classified by activity, data, 3D model, and design task.

The first phase of the described workflow is the *input analysis* (Fig. 1). This phase interests the study of the reference model to be redesigned. In particular, the input data regards the geometry to be redesigned, the boundary conditions, and the structural simulations during operation. The structural behavior is analyzed by a FEM tool considering the operative conditions related to the HPDC process. The output of the structural simulations becomes an input for the next phase.

3.1. Redesign activity

The second phase, called *redesign activity for the AM process*, is focused on the product redesign. This phase considers a set of guidelines to redesign the part for the AM process. A group of five design activities has been here proposed to support the redesign elaboration:

- material selection
- lightweight
- conformal cooling
- lattice structure
- AM constraints

The first design activity, *Material selection*, is essential to analyze and select the right powder material applied in the AM study. SLM process requires powder, but sometimes the powder's thermo-mechanical properties could be different from the traditional raw material (e.g., billets, bars). The expected hardering of the material after 3D printing is another important aspect that must be analyzed. If the surfaces of die parts did not achieve the required hardering values, an additional hardering process must be considered with an increase in cost and time.

The second activity, called *lightweight*, aims to reduce the part's weight with a better material distribution. This step is also related to the activity of *conformal cooling* and *lattice structure*. The *conformal cooling* regards the redesign of the cooling channels for improving the thermal exchange. This activity is related to the *lightweight* one because the larger the cooling channels, the lighter the part. On the other hand, the activity called *lattice structure* is also related to *lightweight* because it studies the substitution of the filling geometry with a regular lattice. The lattice structure reduces the mass and limits the material deformation in 3D printing.

The final design activity, called *AM constraints*, regards a collection of geometrical checks. These controls regard hole diameters, minimum thicknesses, and overhang angle on vertical surfaces. Using these checks, the designer can evaluate whether the part can be printed.

3.2. Simulations

The output of the analyzed redesign activity is the *new CAD model* of the HPDC die insert. This model is the candidate solution to be printed. However, before confirming the final CAD model's geometry, it is necessary to investigate the model's validity by FEM simulations. In particular, two different levels of simulations have been analyzed: *structural simulation* and *AM process simulation.*

3.2.1. Structural simulations

This phase regards the structural analysis of the redesigned part under the boundary conditions related to HPDC. A FEM tool has been used to evaluate the structural behavior according to the simulation described in the first phase.

The output of this analysis allows the reference model and the redesigned one to be compared. The comparison is in terms of stress and deformation.

3.2.2. AM process simulations

The *AM process simulation* analyzes the 3D printing processes considering pre-heating, build, cooldown, thermal treatment, and supports removal. A commercial tool has been used to simulate these phases related to the AM process. These simulations require the previous definition of the printer's parameters and the part orientation and supports analysis.

The design of the supporting structures and the study of the part orientation are analyzed using a CAD tool with advanced features for additive design. This analysis is essential to evaluate the build time, cost, and part deformation after building. While a built part with many supports increases the 3D printing time and cost, a piece with small supports can show significant deformation.

Using the CAD tool, the designer can set the part orientation and analyze the surfaces with overhang angles to be supported. He/She can use a library of supports for modeling the supporting structures.

3.3. Redesign evaluation

The validation phase of the redesigned model considers the results of the two simulation phases. The *structural simulation* output evaluates if the redesigned die insert can be used in the related HPDC process. This evaluation is in terms of stress and deformation during the operation. The *AM process simulation* output is evaluated in terms of deformation, residual stress, and estimated built time.

The phase of the *redesign evaluation* considers all results to evaluate the effectiveness of the proposed solution. This double-check is necessary to validate the final geometry. The resulting 3D model has to compliance with AM and HPDC constraints. Negative feedback at this stage requires a further design activity. As reported in Fig. 1, two possible ways can be pursued.

4. Test case and results

As a test case, the paper describes the redesign of an insert used for the HPDC casting of aluminum gas burners. The reference insert (AS-IS model) is fabricated through the combination of milling, turning, electrical discharge machining and polishing operations. It has three cooling channels manufactured employing a drilling machine (Fig. 2). The insert material is a DIN ISO 1.2344 (AISI H13) steel tool. The redesigned model has been defined to be fabricated using the SLM process.

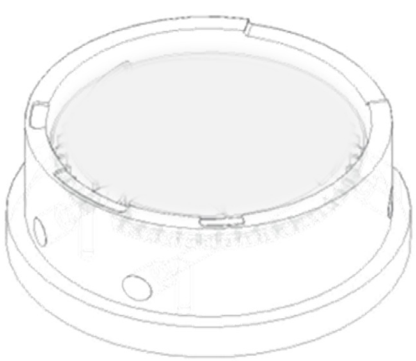


Fig. 2. The representation of the insert to be redesigned (AS-IS model). Geometrical details of the die surface have been obfuscated. The model shows the traditional cooling channels.

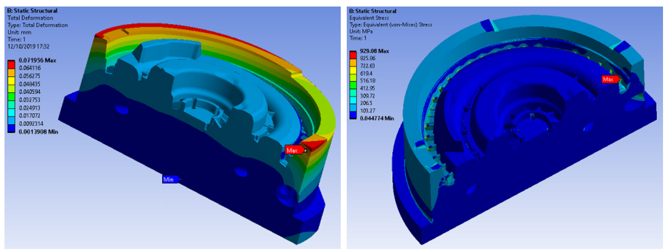
This die insert is an interchangeable fixed part on a holder plate. The coupling between the external cylindrical surface and the holder plate's hole is “H7/g6” in ISO Hole and Shaft tolerances (ISO 286–2). The general tolerances (geometrical and dimensional) required in the manufacturing of this die insert are “ISO 2768– fH”.

4.1. Structural Simulations of the reference die insert

This phase describes the result of the structural simulation related to the die insert's behavior during operation. The analyzed die insert is the reference model (the model before the redesign activity).

The simulations have been performed using a commercial FEM tool with a time-dependent solution. Pressure and temperature conditions have been reproduced during a cycle of about five seconds. In particular, 50 MPa is the maximum pressure, and 280°C is the average insert temperature considered in the boundary conditions (the aluminum alloy's casting temperature is 550° C).

Fig. 3a shows the maximum deformation, about 0.07 mm, achieved on the insert during the casting process (operation phase). On the other hand, Fig. 3b reports the maximum Von Mises stress-state reached on the insert. This value is about 929 MPa, which is under the yield limit.



a) b)

Fig. 3. Report of the structural simulation related to the AS-IS die insert during operation: max deformation 0.07 mm (a) and max stress 929 MPa (b).

4.2. Redesigned model

The first step of the redesign activity concerns the material selection for the SLM process. Since DIN 1.2344 is not widely used for SLM, different tool steel has been considered for this test case. Finally, Maraging steel (similar to DIN 1.2709) [28] has been selected as powder material. This steel is ultra-high-strength and is available in fine powder. It is harder than H13, with a minimum Yield Strength of 1450 MPa, and a minimum Tensile Strength of 1895 MPa (age hardened).

After the material selection, the redesign phase has been focused on the internal geometry. The main achievements have been the internal lattice section and the optimization of the cooling channels. The cooling channels have been changed in a cooling plenum, and the lattice structure is inside the cooling channel. This configuration also improves the heat exchange.

Fig. 4 describes the redesigned model. The redesigned model has a weight of 5.49 kg, which means a mass reduction of about 27 %. The internal lattice structure has a BCC geometry. The cell of the lattice structure presents surfaces with an overhang angle of 60°. This characteristic allows the lattice structure to be built without additional internal supports.

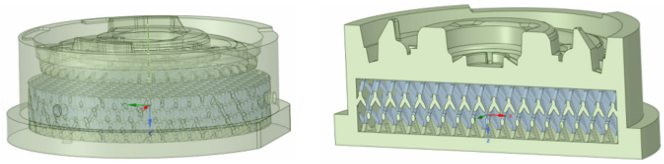
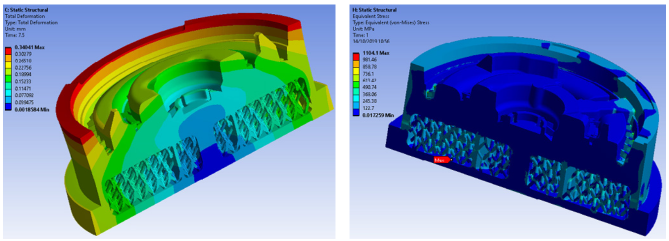


Fig. 4. The redesigned model analyzed for the die insert (TO-BE model). The internal lattice structure on the bottom has a BCC geometry. Four holes have been added in the die insert to remove the powder material inside the lattice structure.

4.3. Structural Simulations of the redesigned model

This second structural analysis regards the redesigned model's mechanical simulation under the operative conditions seen in section 4.1. Fig. 5a shows the maximum deformation, about 0.34 mm, achieved on the insert during the casting process. On the other hand, Fig. 5b reports the maximum Von Mises stress-state reached on the insert. This value is about 1104 MPa, which is under the yield limit. Even if the maximum deformation value and stress are higher than the previous model, the results can be accepted.



a) b)

Fig. 5. The structural simulation related to the TO-BE die insert during operation: max deformation 0.34 mm and max stress 1104 MPa.

4.4. AM Process Simulations of the redesigned model

This phase concerns the use of a simulation tool to analyze the behavior of the AM process. This virtual prototyping activity focuses on different sub-processes such as pre-processing, building, cooldown, and post-processing (heat treatment and supports removal). The AM process simulation considers structural simulation coupled with the thermal simulation to get a more realistic analysis of the 3D printing process.

Table 1 reports the main boundary conditions applied in the commercial software used for the AM process simulation.

Table 1. Boundary conditions for the AM process simulation.

Phase	**Boundary condition**
Pre-processing	Pre-heating temperature: 80°C
Building (processing)	Process type: Powder Bed Fusion
	Scan speed: 1400 mm/s
	Layer thickness: 0.05 mm
Cooldown	Room temperature: 22°C
	Combinate heat-exchange coefficient: 0.1 W/mK
Post-processing	Thermal treatment: max temperature of 486 °C [29]
	First cutoff: base plate and build part
	Second cutoff: build and supports

Fig. 6 and Fig. 7 describe the result of stress and deformation of the built part after the AM process. The maximum stress achieved after the post-processing phase is about 850 MPa (Fig. 6). This value is acceptable because below the material minimum Yield Strength. The total deformation reported in Fig. 7 (about 1.1 mm) is over the tolerance limits required for this part (±0.1 mm). For this reason, further finishing operations of the die upper and lateral surfaces must be considered (milling, turning, or electrical discharge machining).

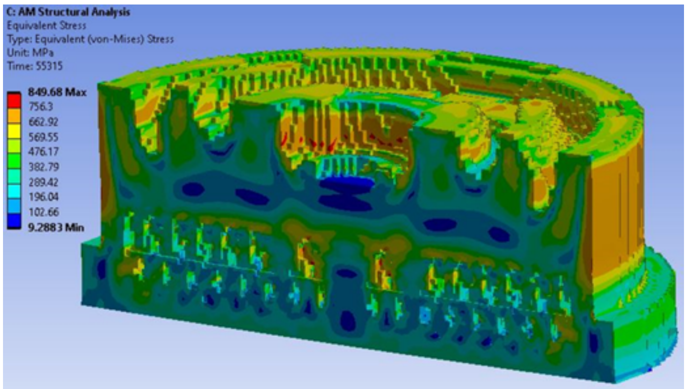


Fig. 6. Simulation report: the equivalent stress map on the redesigned insert (TO-BE model) after the post-processing phase. The maximum stress is about 850 MPa.

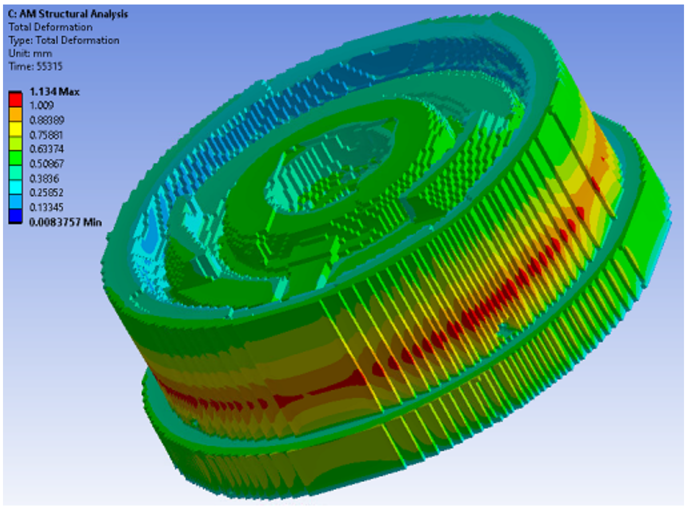


Fig. 7. Deformation map on the redesigned insert (TO-BE model) after the post-processing phase. The maximum deformation is about 1.1 mm.

5. Conclusions

The paper confirms that commercial DfAM tools can be used to redesign mechanical parts such as die inserts. However, the management of the complexity related to the overall design process requires different software tools. Therefore, expertise and methodological approach are necessary for this context. A design method used in this study has been described. This method helps the designer with simulation and advanced CAD tools. The use of simulation tools reduces the possible failures related to physical prototyping. Even if these tools support the design activity, the designer is still the main actor in this workflow. He/She defines the part orientation, supports type, the geometrical parameters of the lattice structure, etc.

A test case has been proposed to describe the redesign activity of a die insert for aluminum gas burners. The study shows the use of each DfAM tool inside the design workflow. The redesigned model achieves good results in structural simulations; however, the AM process simulations show an excessive deformation after the 3D printing. Therefore, further machining operations are necessary to achieve the required tolerances on the analyzed die insert.

The redesigned die insert shows a weight reduction of about 27%. This achievement is significant for different reasons. Firstly, the cost of the AM process is directly related to weight. Secondly, a fair weight distribution reduces the risk of excessive deformation in 3D printing. Moreover, in this case, using a cooling plenum with a lattice structure inside increases the thermal exchange with benefits on the takt time.

As future work, a cost analysis could be added to improve the decision phase and evaluate the impact of 3D printing.

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