Design and impact assessment of a die-casting insert made with Additive Manufacturing

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The challenges for the manufacturing sector, and in particular for the light alloy die-casting sector, are manifold. Being competitive in dynamic environments requires rapid product innovation and consequently, the rapid adaptation of production systems. A structured, integrated and easily reconfigurable system is required to create more responsive and agile production lines which integrate with robust supply chains that supply the necessary materials, tools, and resources to respond effectively to emergency situations such as pandemics. A good example is an additive manufacturing system that enables both the production of small batches and the ability to make rapid changes to dies and tools in response to individual customer demand or to replace damaged parts. A high-quality agile production system must guarantee the reliability and performance of the products it produces before they are sent to market. Lastly, an efficient and safe production line requires the rapid reconfiguration of processes in order to maintain extreme competitiveness with equivalent quality/functionality and work security.

In response to these challenges, this paper presents a summary of some of the significant results obtained in the metallurgical part of the Veneto region's AGILE project. Digitalizing the design phase transforms, systematizes, and virtualizes design, making it faster and more flexible and enabling it to become a company "asset" that can be improved as contexts and scenarios change, all of which strongly support competitiveness.

The solution described in this paper was introduced into one of the aluminium alloy high-pressure die-casting (HPDC) foundries of one of the project partners (Saen) and used various simulation tools to redesign both the HPDC process and a die to accommodate the insertion of an insert with conformal channels made with additive printing in H13 steel. The die-casting simulation optimized the shape of these channels and of the process parameters in order to maximize heat removal in the massive zone of the casting, thus reducing the risk of defects. At the same time, the simulation enabled the prediction of the thermo-mechanical behaviour of the insert, and of the entire mould, both of which are crucial for estimating the fatigue life of the insert itself.

SCOPE OF THE PROJECT
Agility in high-pressure die-casting (HPDC)

The foundry sector, and particularly the die-casting sector, has undergone an evolution over the last ten years that is gradually transforming it into Foundry4.0, and increasing numbers of the enabling technologies of Industry4.0 are being integrated into the design and management of production systems.

It is widely acknowledged that the heart of die-casting lies in the mould or die that, together with the press, represents the essential equipment necessary to mass-produce numerous light alloy castings. Notwithstanding the consolidated use of simulation in the design phase, and a marked increase in process control, the agility of the die-casting process is significantly affected by slow product-code changes, the inability to economically produce small-batch production runs, and the lack of intelligent tools to control production and final quality: all aspects that were made even more apparent by the pandemic.

There are four strategic approaches that can be taken to create a highly automated yet highly operator-dependent and mass-production-friendly process more agile:

- The virtualization of the design phase transforms, systematizes, and virtualizes design, making it faster and more flexible and enabling it to become a company "asset" that can be improved as contexts and scenarios change, all of which strongly support competitiveness;
- The implementation of advanced and high-speed manufacturing technologies, such as additive manufacturing (AM), that allow completely new components or totally reconceived equipment and/or parts to be produced quickly and easily;
- The rapid reconfiguration and optimization of the production process by rendering equipment and process parameters as flexible as possible;
- Intelligent quality management focused on zero defects but with increased attention to productivity, tool life, and time to market.

Broadly speaking, "agility" should increase the skills, boost the production, and enhance the market competitiveness of all the companies in the light-alloy foundry industry, Italy's leading production sector in Europe.

Design of an HPDC insert with conformal cooling channels

Issues of thermal fatigue and the consequent damage to the die, and deteriorated casting-surface quality, or alloy-to-mould bonding, which requires an interruption of the production cycle for maintenance, are more likely to occur in zones where it is more difficult to thermally control the mould.

The use of "plugs" and "inserts" to maximize mould life and productivity was introduced some time ago. These are components, frequently made of higher-quality materials that better resist thermal stresses, which are incorporated into the mould. Plugs and inserts are generally produced by machining from bar stock, but this approach limits the ability to implement and/or optimize internal cooling circuits.

The recent growth in interest in the use of Additive Manufacturing to create these inserts and/or plugs is therefore easily understandable, particularly considering that AM guarantees two options:

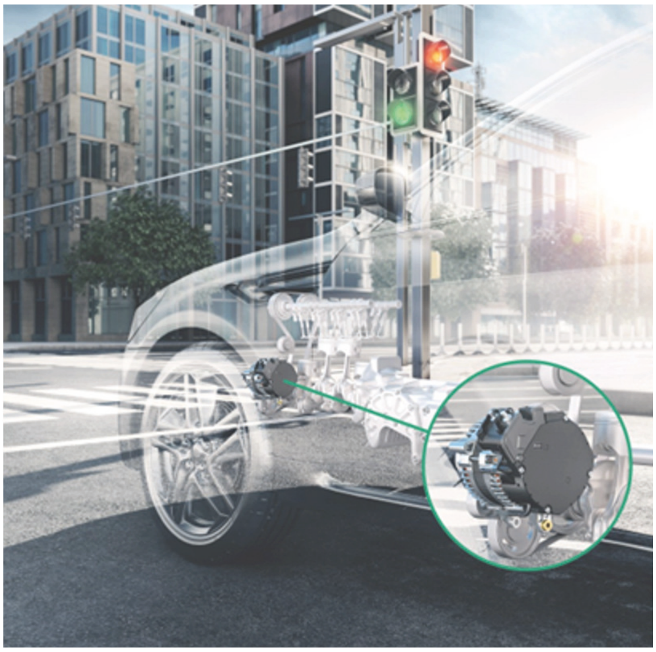

Fig. 1. Test case: SEG Automotive's Boost Recuperation Machine (BRM) system – one of the leading 48V machines on the market and already deployed in over one million vehicles on the road across the globe.

- the use of selected, high-performance materials where they are most needed while continuing to make the other parts of the mould with more conventional steels and materials;
- the creation and inclusion of "customized" cooling circuits to optimize the operation and duration of the entire mould, as well as to ensure the consistent quality of die-cast products.

The features of SEG Automotive's BRM system can be summarized as follows:

- It allows rapid, silent, immediate, and reliable engine start;
- It stores charge in a 48V battery from which it provides the electricity to power the car's 12V systems via a DC/DC converter;
- The kinetic energy created by braking is converted into electrical energy and stored in the battery;
- During acceleration, it provides additional torque to the thermal engine;
- At constant cruise speed, the BRM system maintains the vehicle's speed with the engine off in "free-wheel" mode and consuming zero fuel;
- Upon renewed acceleration, the system instantly starts the engine;
- Traditional start-stop functionality.

The cover/housing product development phase involved an initial numerical simulation that was conducted with MAGMASOFT, after which some die-cast prototypes were produced. These processes revealed some critical issues in the porous zones where the BRM attaches to the engine. To reduce the incidence of the problem, we studied an insert with specially designed thermoregulation channels to be inserted in the critical area. Thermal simulations were used to define these thermoregulation circuits (see Fig. 2). The small insert (30mm x 30mm x 60mm) was optimized by developing specific geometries for the thermoregulation channels that are impossible to achieve with traditional machining. AM technology, however, allowed us to create channels with extremely narrow diameters (2mm) and curved flow trajectories, "free" from any of the restrictions of traditional machining. This enabled us to significantly optimize the insert's conditioning effect in the critical area.

The plug's thermo-fluid dynamic function must maximize heat extraction from the casting as it solidifies during the die-casting production cycle and also consider the production rate of the system that determines the quantity and potency of the thermal shocks created, which can limit the fatigue strength of the casting.

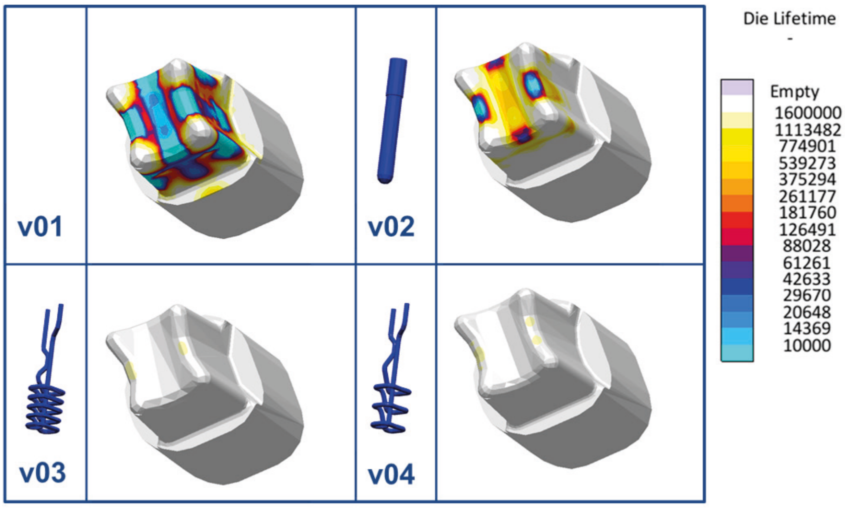

Fig. 2. Study of special thermoregulation system using MAGMASOFT.

To achieve the twofold objectives of reducing defects and increasing the life of the insert, we used MAGMA5 software simulations under steady-state thermal conditions to replicate those of actual production (Fig. 3) to support the design of the die.

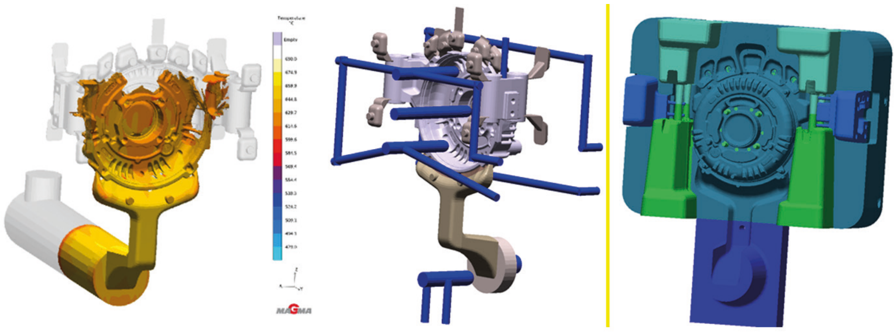

Fig. 3. Simulation of the thermal process.

The simulation of the die-casting process considered all the injection parameters and all phases of the production cycle, perfectly replicating real production. The plug, redesigned to be inserted into the mobile matrix, was studied in four potential configurations with increasingly complex and effective cooling (Fig. 2). The shapes with more or less compact spiral circuits (v03 and v04), take full advantage of the freedom offered by additive printing and provide significantly superior fluid-dynamic performance (Fig. 5) compared to the plugs without cooling (v01) or with only a simple central cooling fountain (v02) that were used as references for suitable correlation.

The comparison considers the water-cooling circuits of the block that operate at an initial temperature of 30°C and a flow rate of 25 litres/minute. This made it possible to identify the greater cooling efficiency achieved by the conformal cooling compared to traditional technology and drastically reduces the thermal shock to the block thereby guaranteeing greater production longevity.

The fluid dynamics analysis conducted on the circuit verified the superior performance in terms of temperature, speed, and heat exchange (HTC) (Fig. 4). Both the parameters used, and the geometric shape of the circuit guarantee remarkable stability and constancy throughout the flow circuit. Most importantly, the analysis verified that the thermal degradation between the inlet (30°C) and the outlet (30.1°C) is practically zero, indicating maximum efficiency. This result was ensured by the high flow velocity of the cooling fluid within the circuit and as expected, heat exchange (HTC) is particularly high throughout the circuit, ensuring the plug's remarkably effective temperature regulation.

A plug with conformal cooling circuits and large coils (Fig. 4), was finally selected for production using additive technology; this geometric shape also facilitates the production of the insert itself and powder removal after 3D printing. The chosen configuration was finally verified in detail by simulating the thermal conditions during cyclical repetition of the filling and solidification phases of casting. The analysis of the filling and solidification dynamics highlighted the potential formation of residual porosities from air entrapment and shrinkage, particularly in the massive lateral

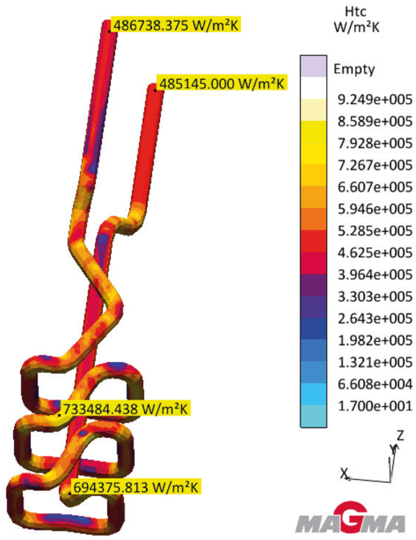

Fig. 4. Fluid dynamics study in terms of heat exchange.

parts of the component (Fig. 5). Fig. 5 shows the distribution of air envelopes (blue) and shrinkage porosities (red) in the right-hand area of the casting. A comparison of this analysis with an analysis of the actual quality using X-ray analysis and destructive testing highlighted the effective correspondence of the defects. This suggested that the shape of the casting should be modified to obtain a completely soundness casting.

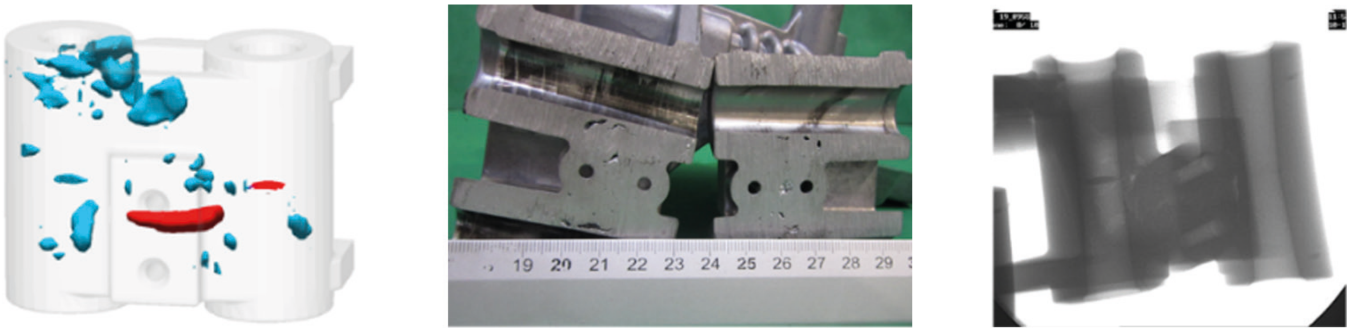

Fig. 5. Detail of predicted porosity defects due to shrinkage and air entrapment compared with X-ray analysis and destructive testing.

The thermal analysis of the plug also confirmed the minimal temperature difference (less than 60°C) before and after the lubrication phase, which guarantees a much longer thermal fatigue life (Fig. 6) than the current 150,000 cycles - an estimated increase of 120%. Lastly, the simulation also revealed a potential reduction in the cycle time thanks to the shorter solidification times of the massive area around the insert.

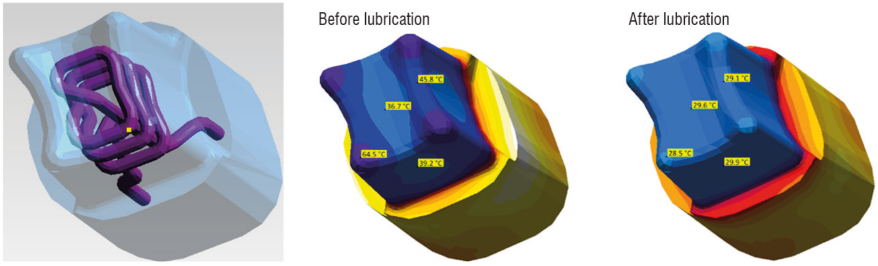

Fig. 6. Thermal analysis of the plug surface.

Simulation of the additive manufacturing process

The creation of dies or parts thereof using additive technology is nothing new; there are numerous applications for plastic injection moulds, and these have also emerged in die-casting and over the last ten years [1-5].

Additive printing of metal alloys is undoubtedly an agile and effective solution for quickly obtaining a plug of the desired shape for better heat removal thanks to the shaped circuits. Obviously each plug, like the one in the case in question, must be made with machines, powders, and process parameters that have been appropriately calibrated and configured to produce a plug of the required density, shape, and size.

The simulation of the AM process made it possible to calibrate the material model based on printing tests and simulation of ad-hoc samples, suited to applications in hot working equipment, and to study the orientation and the supports necessary for 3D printing in order to obtain a high-quality moulded insert at the first attempt. Like the simulation of the die-casting process, the simulation of the L-PBF 3D printing process also aims to numerically solve all the processes and metallurgical phenomena that occur during the laser sintering of the metal material deposited in powder form.

The targeted fusion determines the melt pool and the sequence of the deposited layers, while the path of the laser affects the size of the different melt pools that overlap and cool rapidly. A thermomechanical analysis follows the evolution from liquid to solid to predict the stresses and deformations generated at each layer and consequently within the final as-built state. The orientation and print layout, like all machine parameters, are inputs to the simulation which aims to virtually investigate the ideal setup required to obtain a complete and dimensionally correct part for the post-processing phase. The cross-section and layout of the shaped channels designed to maximize the fluid dynamic efficiency for cooling the plug must be self-supporting during printing to avoid the use of supports inside the channels and to ensure that any residual non-sintered powder can easily be removed.

Even though the insert in this study is compact and the ideal orientation for its printing is well known, all possible orientations were studied. These simulations provided useful results regarding the stability of the channels and the optimization of the printing parameters for the H13 material.

Calibrating the material model

Since the temperature-dependent thermo-mechanical properties of the H13 material were not available (because the temperature varies), it was decided to use an elastic-plastic material model with the same mechanical properties as this type of steel so that an inherent strain simulation could be performed. This method allows the powder bed additive process simulation to be performed as a purely mechanical (structural) simulation based on the base material's mechanical properties in as-built conditions, and on a calibrated material model of the intrinsic characteristic deformation (inherent strain) deriving from the nature of the process itself and from the setup used (hardware, process parameters, scanning strategy, etc.).

To determine the inherent strain value, most commercial software requires the user to print calibration specimens designed to distort significantly, such as a cantilever of the type shown in Fig. 8 which facilitate distortion measurements. The first activity therefore consisted of creating the material model containing the physical and mechanical properties of the alloy in its as-built condition, i.e. after printing.

These properties (listed below) were found in the literature and converted into true values

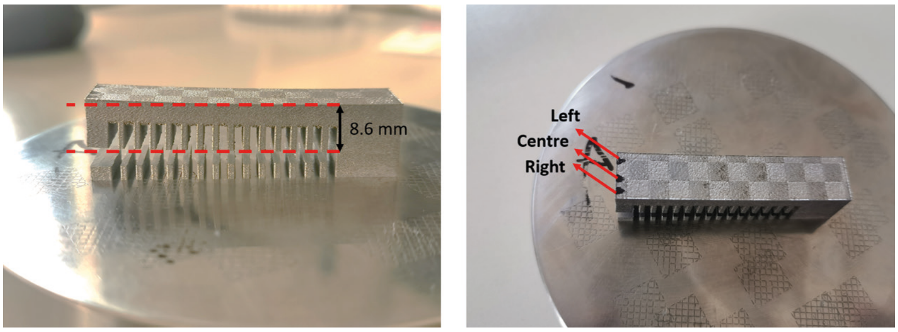

Fig. 7. Cantilever beam after being partially cut from platform (source: UNIPD_DII).

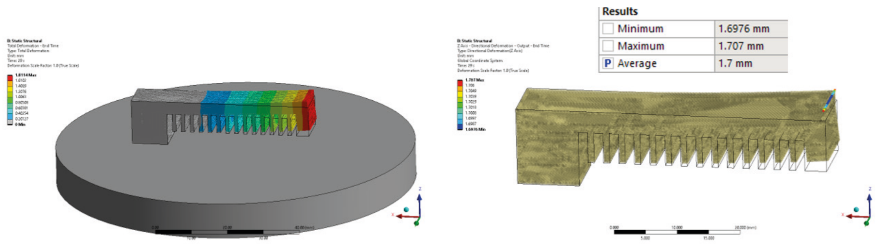

Fig. 8. Z-directional strain of the specimen and calibration of the SSF coefficient.

(true stress, true strain) to create the material model in Ansys Workbench:

- density, $\rho = 7800 \text{kg/m}^3$,
- elastic modulus, $E = 215\text{GPa}$,
- poisson's ratio, $\nu = 0.3$,
- yield strength $\sigma_y = 1512\text{MPa}$,
- tensile strength $\sigma_u = 1894\text{MPa}$,
- maximum elongation of 10% (0.1mm/mm).

The calibration procedure involves the creation of specimens (cantilever beams) using the standard scanning strategy that will then be used for the creation of the product. In order to improve the statistical analysis and limit the influence of manufacturing defects it was decided to make several specimens of which at least three were investigated. Once the specimens were made, they had to be partially cut from the platform while leaving intact the thicker section of the tack connecting them to the platform (Fig. 8). The measurement of the Z-dimension at the upper end of the bar tack is used for calibration by comparing it with the simulation values.

Calibration using the measured experimental results is achieved by repeating the simulations and adjusting the calibration factor (Strain Scaling Factor – SSF) to achieve convergence with an acceptable level of error between the measured and simulated distortions at a value of 1.7mm (Fig. 7). This procedure was performed using two products in the Ansys Additive suite, namely Ansys Workbench Additive with an optimal SSF of 0.41005, and Ansys Additive Print with a calibrated SSF of 0.434.

Print simulation of insert

Once the material model is calibrated, the additive process simulation verifies the quality of the virtual prototype using the already optimized printing parameters (Table 1).

The simulation was performed by discretizing the insert in tetrahedral finite elements with an intermediate node (quadratic formulation), which provides a good representation of the geometric features of the component and facilitates the next steps of post-processing and analysis of the results (distortions and residual deformations/tensions). The supports, on the other hand, are made homogenous using linear hexahedral finite elements. The actual amount of material contained in each one is considered by means of a knockdown factor for the mechanical properties. The discretization is obviously a layered mesh, in the sense that the geometry is subdivided into layers of finite elements, in this case all having the same thickness of 0.4mm. Considering that the actual component will be moulded in 20μm layers, this means that 20 layers of cast material are packed into one layer of finite elements.

The results of the preliminary simulations performed with Ansys Additive Print are shown below in terms of distortions, or rather, displacements (relative) to the simulated nominal (the blank), as well as other significant quantities depending on the magnitude. All results are in the as-built condition immediately after printing with the part still joined to the platform. Optical scanning and CT analysis of the as-built plug confirmed the predictions produced by the simulation with Ansys Additive suite.

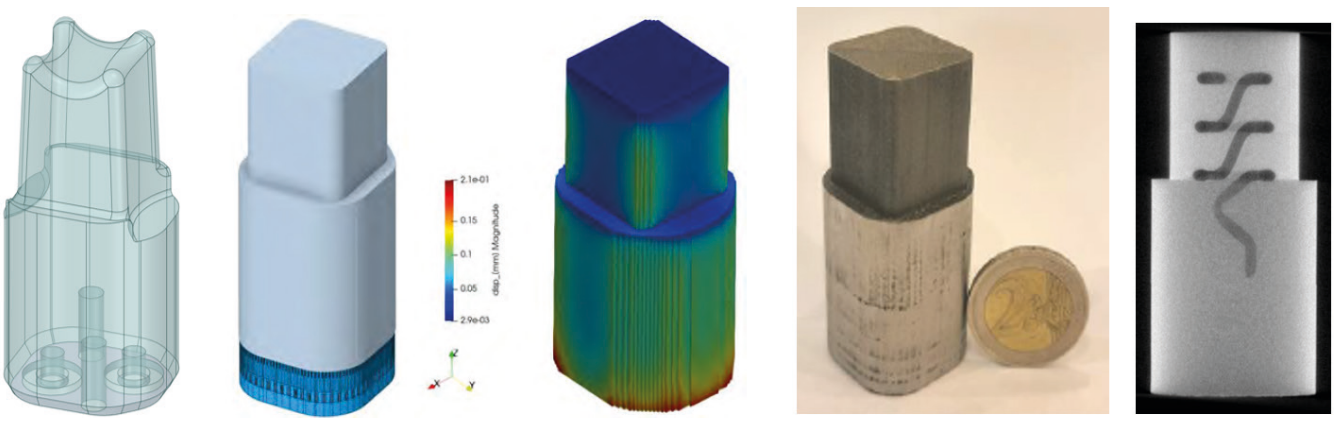

Fig. 9. Comparison of the blank of the insert and the print simulation (left). Insert manufactured using L-PBF parameters optimized by means of a preliminary experimental campaign and CT check of the moulded block (right).

3D-printing of the die insert

The steel powders for the H13 moulds were produced by Hogonas and supplied by MBN Nanomaterialia. The distribution of particles is shown in Table 1, following sieving after delivery, i.e. the dimensions of all the particles below 10%, 50% and 90% are indicated. The apparent density is 4.38g/cm^3, and the density measured with a pycnometer is 7.73g/cm^3.

	Delivered State	After Sieving
d10	33.3μm	29.6μm
d50	45.5μm	38.5μm
d90	62.0μm	50.0μm

Table 1. Distribution of H13 powder particles in the delivered state and after sieving

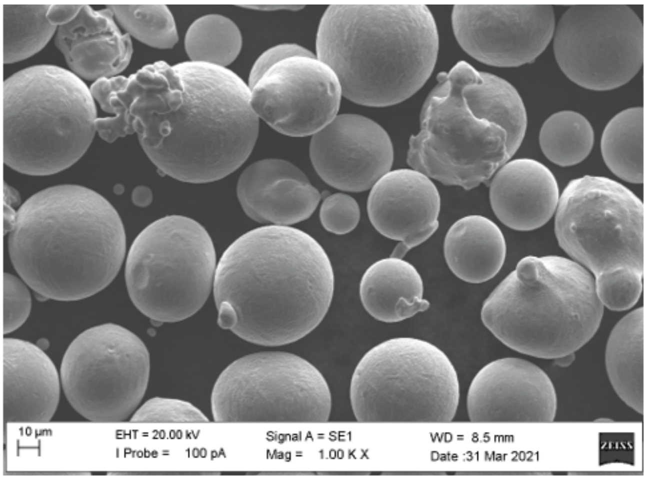

Fig. 10. SEM image of H13 powder after sieving.

Fig. 10 shows a scanning electron microscope (SEM) image of the powder particles after sieving: they have a rounded shape and sufficiently homogenous distribution to be suitable for the laser powder bed fusion (L-PBF) additive manufacturing process.

The L-PBF machine used to make the inserts is a Sisma MYSINT100 3D printer in the University of Padua's processing technologies and systems laboratory in the Department of Industrial Engineering (DII). This machine is equipped with a laser that has a 30μm spot diameter and a maximum power of 200W. Printing takes place in an argon-injected inert atmosphere to guarantee an oxygen content of less than 0.1%, thereby preventing oxidation of the powders.

An extensive experimental campaign (50 experiments) was conducted using a Design of Experiments (DoE) method to identify the optimal set of L-BPF process parameters. The layer thickness was kept constant at 0.02mm as was the laser spot at 30μm, while the laser power, scanning speed, and hatch spacing were varied as shown in Table 2. The output parameters chosen were surface roughness and density. Cubes with sides of 50mm were printed, an example of which is shown in Fig. 11.

The density of the printed samples was assessed according to Archimedes' method, favoured due to its simplicity, speed, and cost-

Laser power (W)	70->140
Scanning speed (mm/s)	300 -> 1000
Distance between tracks (mm)	0.05 -> 0.09

Table 2. L-PBF DoE plan

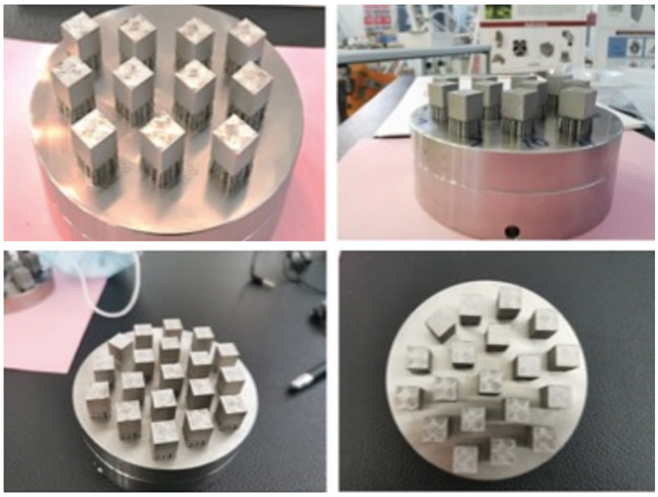

Fig. 11. Examples of samples printed using different L-PBF process parameters.

effectiveness, using a KERN ABT 1205DM scale with a measurement accuracy of 0.01μg. The surface roughness of the samples was measured using the Sensofar SNeox 3D optical profilometer. Given the high roughness of the samples, measurements were performed in focus variation mode using a 20x confocal lens. For each sample, a surface topography with an area of 3.68 x 3.2mm^2 was obtained for both the upper and lateral surfaces. Following the removal of the mould, the surface roughness (Sa) was assessed using ISO 4288.

A relative density of approximately 99.5% and minimal surface roughness on both evaluation surfaces was ensured by the following process parameters:

- laser power = 130W
- scanning speed = 600mm/s
- distance between traces = 0.08mm

These parameters were then used to produce the insert shown in Fig. 9. Following the 3D printing process, the heat treatment shown in Fig. 12 was used to obtain a comparable microstructure and hardness to that of conventionally manufactured H13 steel.

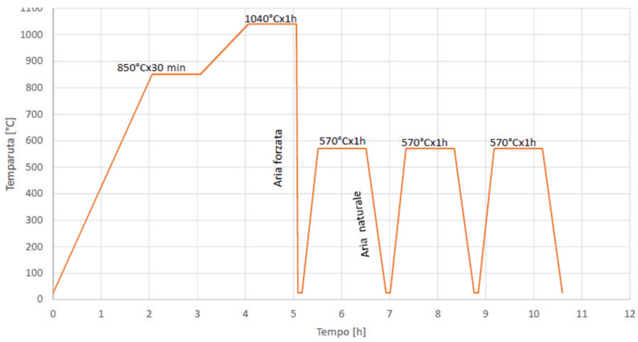

Fig. 12. Heat treatment after the L-PBF process.

This treatment achieved a hardness that was only 5% lower at room temperature than that of conventional H13, and this difference was also maintained at 300°C, thus demonstrating that an optimized L-PBF process combined with heat treatment is able to achieve characteristics similar to those of traditionally produced steel.

Implementation and testing of 3D-printed insert

Machining was performed with no problems and a surface finish comparable to traditionally manufactured and machined steel components was obtained (Fig. 13).

The machining and cutting parameters remained unchanged, enabling the final geometry to be produced promptly. No anomalous behaviour was detected at dimensional level either, as evidenced by the metrological checks performed.

Use of the plug during experimental foundry testing confirmed the efficiency of the thermoregulation system as well as the component's excellent thermal fatigue behaviour: no abnormal or early wear was found.

Analysis was conducted on the die-cast castings and on the pilot mould (a mould created for making die-cast prototypes), using CT scans and comparisons with the results obtained with traditional technologies for the former, and using thermal imaging cameras to monitor temperature trends in the plug area for the latter case.

In conclusion, additive manufacturing enables optimized and perfectly localized thermoregulation geometries to be designed, free of the limitations of traditional manufacturing technologies. This allows the best possible metallurgical results to be achieved for a predefined casting geometry that cannot be further optimized.

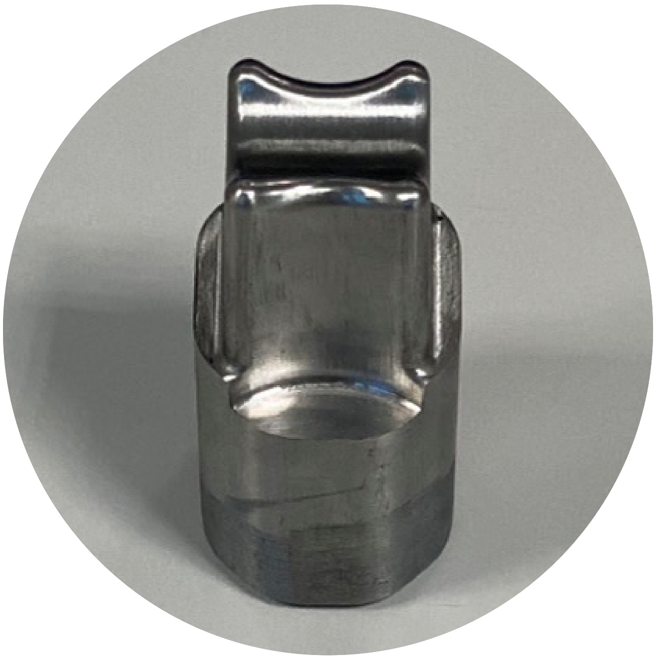

Fig. 13. Completed plug after machining.

Conclusions

The AGILE Project [6-7] emerged from discussions among a group of companies and research organizations based in the Veneto region in the post-pandemic-emergency period and aims to improve the region's industry's ability to convert their production systems in an "agile" manner using advanced solutions for product innovation.

The project falls under the Veneto region's "Smart Manufacturing" specialization strategy within the broader context of business competitiveness for Industry4.0 and represents an organized "industrial reaction" to the Covid-19 emergency characterized by flexibility, reconversion, and resilience.

More specifically, the project develops agile manufacturing solutions and tools to increase competitiveness and product innovation by targeting four areas of development:

- virtualization of the design phase,
- development and industrialization of advanced and high-speed production technologies,
- rapid reconfiguration and optimization of production lines, and
- intelligent quality management.

The AGILE Project focuses on specific, representative types of production lines in the Veneto region, and this paper describes the results achieved in High Pressure Die-Casting (HPDC).

Blending two technologies, die-casting, and additive manufacturing, made it simpler and easier to flexibly adjust and improve die performance and casting quality. The virtual design provided useful guidance for optimizing the shape of the thermoregulation circuits of the plug, which was then virtually inserted into the mould to predict its thermo-fluid-dynamic behaviour under thermal conditions typical of HPDC production. Likewise, the simulation of the 3D printing process ensured the highest quality of the 3D printed plugs from the very first print, after which they were machined and inserted into the die for the final test in production.

The MAGMA simulation software allowed the qualitative impact of different thermoregulation configurations on the die-casting process to be quickly compared, while the simulation of the AM technology with Ansys Additive suite enabled the designer to freely create the geometry that would yield the best results.

The technological development of 3D printing systems and the ability to use base powders made of the same materials as those used for traditional production of die-casting moulds provides the following benefits:

- Reduced die-casting costs in terms of materials and machining;
- Shorter lead times for manufacturing of components due to the use of AM;
- Consistent implementation of the best thermoregulation according to the customer's requirements and on the basis of numerical simulation findings;
- Decreased cycle times resulting in lower costs and increased competitiveness;

- Reduced scrap due to the improved casting quality;
- Lower energy consumption thanks to the reduced cycle times, fewer scrap castings and therefore less need to recycle them.

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References

[1] J. K. Pancholi, B. Padhiyar, V. Sutariya, and H. Pancholi, "Design and Analysis of Die Casting Die with Conformal Cooling Channel", *International Journal of Engineering Science and Computing,* March 2019

[2] L. Shu, Z. Zhang, Z. Ren, and T. Zhang, "Design and simulation of conformal cooling for a die-casting mold insert", *Journal of Physics:* Conference Series 1939 (2021)

[3] G. S. Phull, S. Kumar, R. S. Walia, "Conformal Cooling for Molds produced by Additive Manufacturing: a review", *International Journal of Mechanical Engineering and Technology* (IJMET) 9: 1, January 2018, pp. 1162–1172, Article ID: IJMET_09_01_124

[4] M. S. Shinde, and K. M. Ashtankar, "Additive manufacturing–assisted conformal cooling channels in mold manufacturing processes", *Advances in Mechanical Engineering* Vol. 9(5) 1–14, 2017

[5] P. Cicconi, M. Mandolini, F. Santucci, and M. Germani, "Designing die insert by additive approach: a test case", 31st CIRP Design Conference 2021 (CIRP Design 2021)

[6] N. Gramegna, and F. Bonollo, "Challenges and Benefits in AGILE manufacturing applied to metalworking production processes", 39° Convegno Nazionale AIM, September 2022, Padua, Italy

[7] Gramegna, N., Greggio, F., Bonollo, "Smart Factory Competitiveness Based on Real Time Monitoring and Quality Predictive Model Applied to Multi-stages Production Lines", in B. Lalic et al (eds) *Advances in Production Management Systems. Towards Smart and Digital Manufacturing,* APMS 2020. IFIP Advances in Information and Communication Technology, vol 592. Springer, Cham. doi.org/10.1007/978-3-030-57997-5_22