TECH FRONTIERS

Investment casting and 3D printing – Perfect combination for quality castings

Innovative, up-to-date technology, is providing the investment casting industry with unimaginable possibilities

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THE casting industry is one of the oldest existing sectors of our time. Castings have become indispensable, especially within aerospace and vehicle construction, the major customers of investment foundries. In the face of increased competition, more complex components and shorter and shorter product lifecycles, demands for parts and quicker product development times are increasing and must be met in order to compete in the market. Innovative, up-to-date technology, is providing the investment casting industry with unimaginable possibilities.

The desire for fast, yet economical, production of complex precision castings pushes production methods to their limits. The Voxeljet 3D printing technology allows quick, precise, and economical manufacturing of investment casting models, no matter if they are prototypes, separate components, or a small batch series. Speed and freedom of design possibilities lie at the heart of this technology. The use of large 3D printing systems is expanding the scope of application within many sectors. The automotive industry is one of the pioneers in digital production. It was not long before they realised the time and cost advantages of 3D printing. Nowadays quick layer manufacturing, which can be managed without elaborate tools, is well established in all areas of automotive production, including freedom of the resulting design construction. Meanwhile, the applications and broad technology range from components within the automotive industry and the aviation sector includes creative mechanical engineering from art to part.

THE INVESTMENT CASTING PROCESS

In the conventional investment casting process, a tool produces a wax pattern which can take up to several weeks, depending on how complex the component is. In the second step, these wax patterns are attached to wax clusters as a casting unit. Further a running system made of wax is required to complete the process. Next, a ceramic shell is dipped around the wax pattern, cured and dried, resulting in a final shell. Depending on the properties of the wax or the model, a certain minimum number of layers will be required so that the shell does not break when the model is burned out. In order to melt the wax, the coated model will usually be placed in an autoclave or flash fire furnace, which increases the pressure and temperature to liquefy the wax. Finally, the pattern within the cast ceramic shell is burned out resulting in a hollow cavity from which the molten metal can be poured. (**Figure1**)

As the part complexity of the components increases, the design modelling process becomes extremely consuming. The manufacturing of tools and models is a fundamental cost driver in the investment casting project and makes installing replacement sand prototypes largely uneconomical. (**Figure2**)

Aside from the high costs, the temporal aspects also play a crucial role. The conventional manufacturing processes of tools generally take 6-8 weeks of effort. By the time the finished casting is completely processed and sent to the customer, it can take up to10-12 weeks to be delivered. The investment casting can decidedly benefit from 3D printing as the initial parts, regardless of complexity and structure can be printed in a matter of working days (instead of weeks) and can quickly be integrated into the casting process.

Figure1: Complete process of investment casting

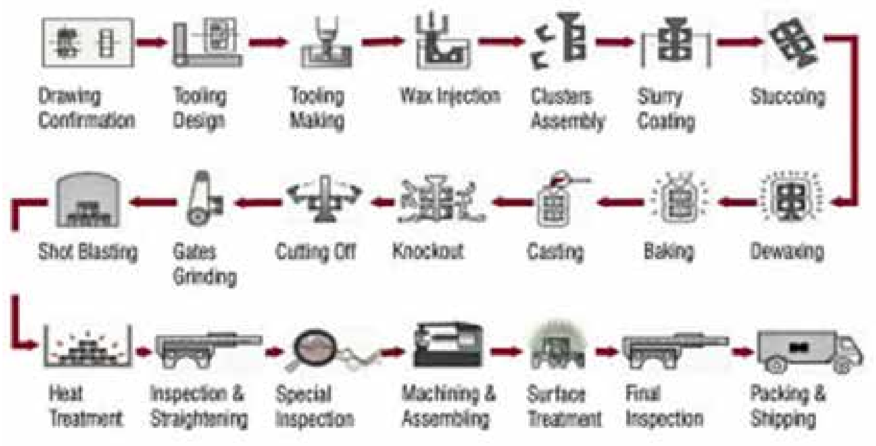
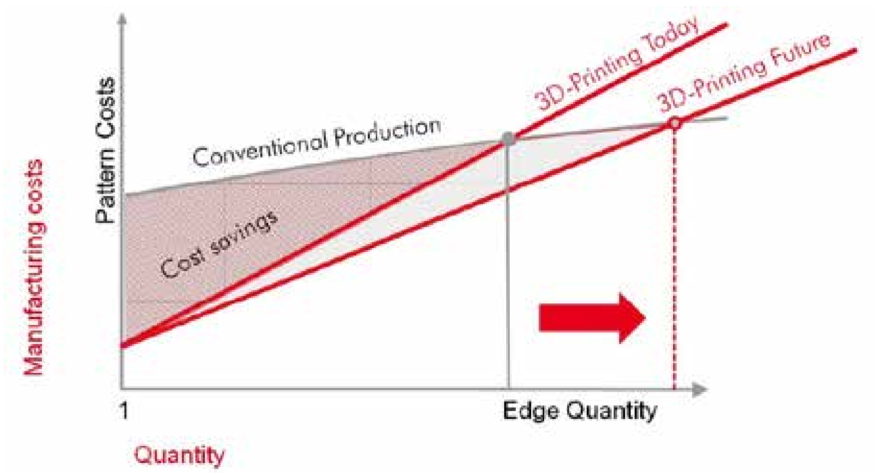


Figure2: Comparison among conventional, 3D printing-today and 3D printing-future costs

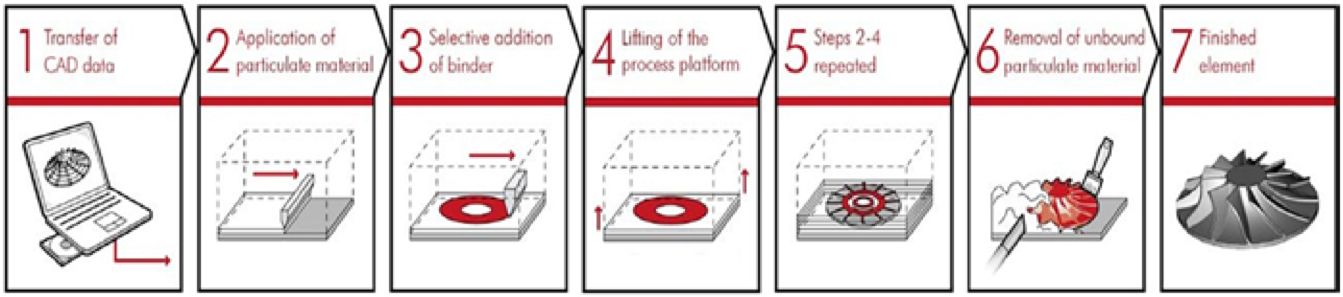


3D PRINTING OF INVESTMENT CASTING MODELS

Voxeljet's 3D printing process step by step

As a basis for 3D printing, only a CAD model will be needed. Once the building platform for the job box has been fully elevated, the recoater starts applying the appropriate particle material (PMMA plastic) on to a construction surface. The standard thickness of layers in plastic printing is 150 µm. Next, a high-definition print-head (600dpi) prints the surface as the design calls for. After each layer, the building platform descends by the respective layer thickness. The recoater applies another layer of the particle material, which, in turn, is bonded selectively with the previous layers. The process continues until the desired height of

Figure3: Seven steps of 3D printing process



the object is reached. After printing, the unprinted material is vacuumed off and recycled and the component is recovered, at which point almost 100% of the loose powder can be reused.

Finally, it is possible to refine the printed component, depending on its purpose. For smoother and dense investment casting model surfaces, the components are infiltrated with wax. Models that will not be further processed in a casting process, for example architectural models, are infiltrated with epoxy resin, which reinforces the strength of the component substantially.

IMPLEMENTATION IN LARGE FORMAT 30 PRINTING

For parts that exceed the platforms build envelope patterns are digitally split for optimisation of part assembly. Voxeljet propriety nesting software allows for better utilisation of the systems build envelope. Compared with widely available additive systems reproducing investment casting patterns, Voxeljet's VX 1000 offers the largest build volume in the market. (**Figures 4, 5, 6, 7**)

Figure4: Up to 780 stroke engines can be easily placed in a VXI000 job box

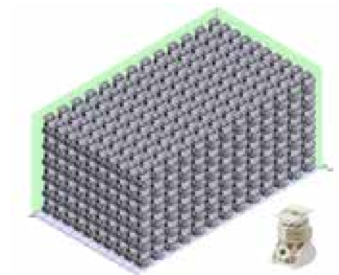
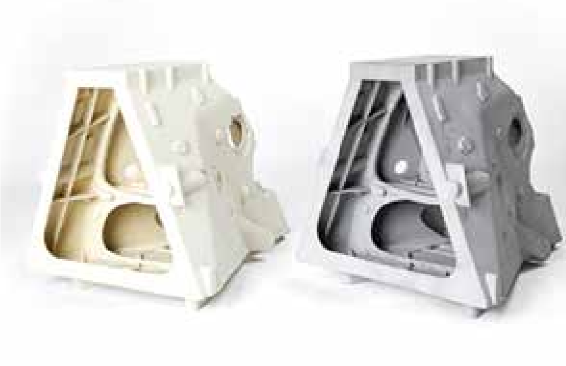


Figure5: (a) Formula 1 gear box housing – printed and cast as one piece; (b) Bronze sculpture assembly of a silverback gorilla

(a)



(b)

Figure6: Build volume (l): Build volume comparison of additive technologies for investment casting patterns

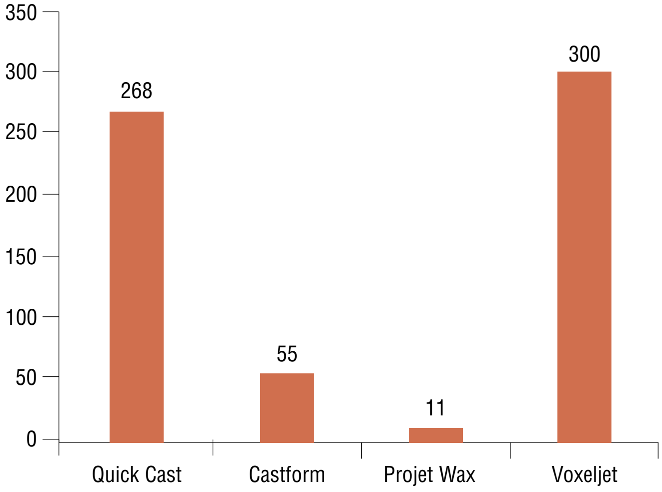
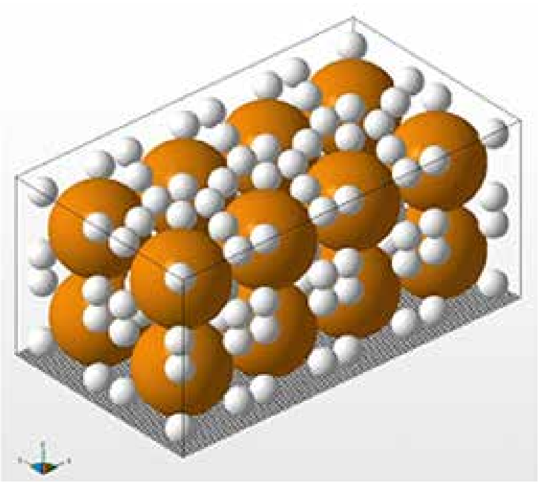


Figure7: 16 Basketballs and 168 Baseballs can be nested into the job



PRODUCTIVITY

The capability to print large patterns only makes sense if the additive system offers fast build rates. Binder Jetting boasts huge potential in terms of build speed, as Voxeljet employs advanced industrial print-head modules which offer large printing widths. Certain single module print-heads ranging up to 2500 individual jets, provide a print-head resolution up to 600 dpi. This width can be increased by aligning print-head modules next to each other, which yields remarkable build rates, more than twice as fast as other additive technologies. (**Figure8**)

Additionally, in powder-based 3D printing processes, the unbound powder works as a support for the patterns being printed. Consequently, after one layer of parts is completed, additional layers of parts can be printed on top of the prior layer. QuickCast and ProJet printers require printed supports to hold the patterns in position as they build. As a result, it is only possible to build single layer patterns, even if the height of the pattern is less than half the height of the build volume. (**Figure9**)

Figure8: Build rate comparison of additive technologies for investment casting

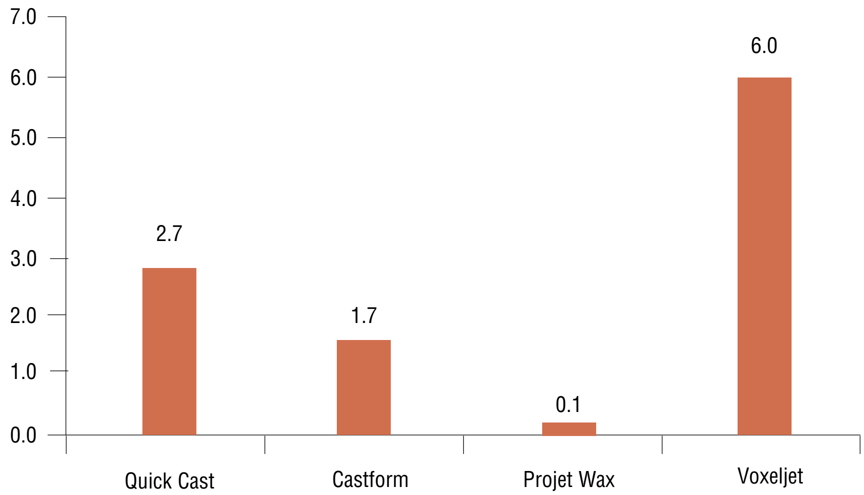


Figure9: Direct nesting comparison of additive technologies for investment casting

ECONOMICAL INVESTMENT CASTING PATTERNS

Taking a deeper look into profitability requires not only taking printer and printing rates into consideration, but also considering actual operating costs.

Voxeljet's powder-based process does not require supports in the build process. This feature, on the one hand, eliminates the need for printed (and lost) support structures, and on the other, almost100% of the unbound powder can be reused.

In order to determine material costs, a cost analysis needs to consider the price of PMMA powder, the binder used for printing, as well as the cleaner used to regularly clean the print-head during the build.

As the PMMA patterns consist of a density of 0.71/kg, one printed litre of solid material consists of approximately 700 gm of powder and 120 ml of binder, while 180 ml of cleaner is used during the build to purge the print-head. Therefore, the total material cost for a printed litre for a system customer is approximately €50.

Voxeljet's binder jetting is a relatively simple additive process, as the PMMA process works at ambient temperature where a gas atmosphere is not required.

Figure10: Print-head and building platform in VX I 000

Maintenance is regularly done during the printing process in the system's integrated print-head cleaning station to ensure consistent print-head quality as the print-head is the highest cost component. (**Figure10**)

The lifetime of a print-head also depends on the specific system user and the amount of time that the system is actually running. In general, the greater the print-head is used, the longer life will be sustained. In most applications, print-head lifetimes differ depending on the binder fluids used. All in all, combining the productivity (build rate), material, and maintenance costs, this technology enables its users to enjoy the lowest per piece cost.

EASY BURNOUT AND CASTABILITY

PMMA, which has many uses including being used as filler in conventional investment casting waxes, is processed in much the same way as wax patterns. Therefore, the investment caster can maintain his current process chain as normal without having to implement major changes in the casting preparation.

Even thin wall components, e.g. turbine blades or rotors, can be processed in the autoclave. (**Figure11**)

The components have a marginal density, as only 50% of the component volume consists of solid material. This high

Figure11: (a) PMMA printed rotor (left) and cast rotor (right); (b) Conventionally installed runner system before (left) and after (right) casting

(a) **(b)**

porous content, combined with the negative coefficient of thermal expansion, allows the model to shrink when burning out and ensures that there is practically no cracking to the ceramic shell. Furthermore, the consumed PMMA vaporises to virtually to nothing-residual ash content amounts to <0.0 wt%.

Conventional wax feeding systems can be attached easily to the PMMA components. Due to the optimised burnout condition, more and more investment foundries are convinced and finding advantages of integrated pre-printed runner systems. What is the advantage? The entire process is automated and accurately follows the CAD data sets. Complex geometries and difficult to manually install can be designed into the part file.

Casting simulation software can define the runner systems geometry for optimised casting. In order to guarantee optimal sprue and runner performance, casting simulation software will ensure higher processing safety conditions and process quality. Using 3D printing and the freedom that this allows, runner systems are created which ensure controlled metal flowability, free from turbulence, hot spots, and resulting alloy oxidations.

AVOIDING SHELL DAMAGE DURING BURNOUT

As mentioned, one of the curious properties of PMMA is that it features an apparent negative thermal expansion coefficient. The powder, however, is not 100% dense and as it heats up, it softens and allows the particles to move closer together.

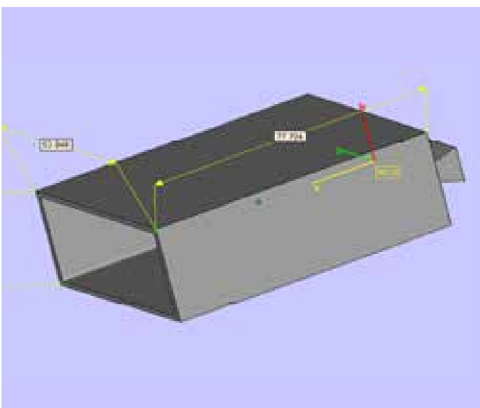
The objective of this study was to identify the necessary minimum shell thickness in order to find out which additive production process has the minimal probability of shell damage. In order to be able to compare the results, the same component was produced six times using the three different processes (**Figure12**). Six components were coated with different numbers of ceramic layers. In each component group, two prime coatings of zircon were applied. The backup layers were made of molten silicic. The number of shell layers ranged between 7 and 2. Each component group was identified numerically.The highest number of ceramic layers was ten, the lowest number was five. The coated components were simultaneously placed into an autoclave, so as to detach the model structures manufactured with additives from the ceramic. The results after burnout show that the shells with greater than six layers did not reveal any cracking. The stereo lithography shells revealed cracking to the shell when dipped with 5 or 6 1ayers, making the shell unusable.

The minimum number of layers needed for components printed with PMMA should be investigated. The PMMA model with four ceramic layer dips revealed no shell cracking. Only the model with three layers showed slight cracks, which, however, developed at the connection to the conventional sprue. These cracks could also have resulted during the expansion of the sprue. (**Figure13**)

The apparent negative CTE provides an advantage for PMMA in investment casting applications. The major cause of failure with printed patterns is thermal expansion during the dewaxing phase resulting in cracking the shell. It also allows for the use of fewer layers on the shell compared to other types of printed patterns.

Figure12: (a) CAD data of test pattern for study of shell cracking behaviour; (b) test results of shell cracking study, testing various additive technologies for investment casting

(a)



(b)

Coats	10	9	8	7	6	5
QuickCast	No Crack	No Crack	No Crack	No Crack	Fail	Fail
Projet Wax	No Crack	N/A	N/A	No Crack	No Crack	Minor Crack
Voxeljet	No Crack	No Crack	No Crack	No Crack	No Crack	No Crack

Conclusion

Voxeljet offers investment casting foundries the opportunity to process light and heavy metals ensuring a quality level that is comparable to series-production. The use of 3D printed models allows for fast manufacturing of complex components with complex design features, such as rotors, manifolds or turbochargers (**Figure14**). The Voxeljet process is applied to prototypes, small and medium production and projects that involve large, complex geometries. Therefore, the low operation cost allows for 3D printed patterns, whereby many casting companies are applying the technology for production. Recent advances have led to faster printing speeds therefore reducing overall costs. Nevertheless, 3D printing will never completely renounce conventional methods and processes in the investment casting industry. It does, however, create the opportunity to be able to create completely new components with unique features, especially with regard to enhanced functionality, longer service life and reduced weight.

A clear advantage is that product designers can move from art to part while optimising the functional component geometry. This results in enormous potential savings. The best example of this is the weight and resulting fuel savings for components in the aerospace industry.

Whether it is automotive, aerospace or fine art, every sector can benefit from Voxeljet's 3D technology. High quantities allow for lower cost with high- performance components. On top of that 3D printing in combination with simulation software is proving to be a very powerful tool combination.

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Figure13

Figure14