ISSN 1454 - 8003
Proceedings of 2019 International Conference on Hydraulics and Pneumatics - HERVEX
November 13-15, Băile Govora, Romania

RAPID PROTOTYPING AND ADDITIVE MANUFACTURING OF FLUID POWER COMPONENTS - SUITED FOR SPECIAL APPLICATION

Darko LOVREC[1]

[1]University of Maribor, Faculty of Mechanical Engineering, Slovenia, darko.lovrec@um.si

Abstract: *Additive Technology has already established itself as an important manufacturing technology to shorten the time from idea to product marketing, while reducing development costs and raising the quality of finished products. The prototypes thus created were considered to have a high geometric accuracy, and the mechanical properties of the materials from which they were made did not meet the requirements of the final product. Therefore, they were intended primarily for presentations of finished products, concept visualization, design and matching analyses, tool engraving and foundry moulding, and easier functional tests.*
The paper presents the possibilities of using Additive Technology in the field of Fluid Power and practical experiences: From simple parts of components, to high load valves of special shapes and requirements, and special cases in the field of Pneumatic Components. Each case presented illustrates the path of product development, and the limitations and specifics that dictated the use of layered technologies, right down to the end product effectively used in practice.

Keywords*: Fluid power, Additive Manufacturing, hydraulic valves, special components, accessories*

1. Introduction

Advances in materials and technologies, however, have led to the increasing use of these technologies to produce finished, functional products. That's why we are talking more and more about Rapid Manufacturing and not Rapid Prototyping. Essentially, rapid prototyping processes are ancillary procedures – the processes of adding materials that differ from each other, depending on how the material is added. The process is chosen according to the intended use of the end product, the product range being extremely wide: From housings, internal components of machines, bottles, tools..., to medical applications, e.g. surgical implants, hearing aids...
Fluid Power products represent a specific area, since the components are exposed to high internal pressure and to external mechanical stresses. The latter applies to hydraulic valve housings. However, in the field of Fluid Power technology, it is possible to apply modern technology to many other components, both hydraulic and pneumatic. Some examples of this will be discussed in more detail in the following Sections.

2. Rapid Manufacturing of hydraulic valves

The valve body, or valve housing, is usually the most basic part of the hydraulic valve, and, at the same time, the part that largely determines the characteristic and physical properties of the valve as a whole. In the classical valve housing manufacturing, there are two approaches. Manufacturing of housing from a raw, metal rod material, and manufacturing of a housing by using casting technolgy. Manufacturing of housing from metal rods is suitable for individual pieces or for smaller series, due to the costs associated with machining at machining centres and long technological processing times. Also, the designer, in this case, is relatively limited, since he has to adjust the construction more often in the direction of the possibility of the manufacturing process than in the direction of the best functionality of the component.
In the case of hydraulic valve housings made from metal rods, compared to the cast housing, the outer dimensions of the valve and, consequently, the weight of the valve, are larger, although both valves have comparable performance. Also, the internal shape of the channels is not optimal – Figure 1.

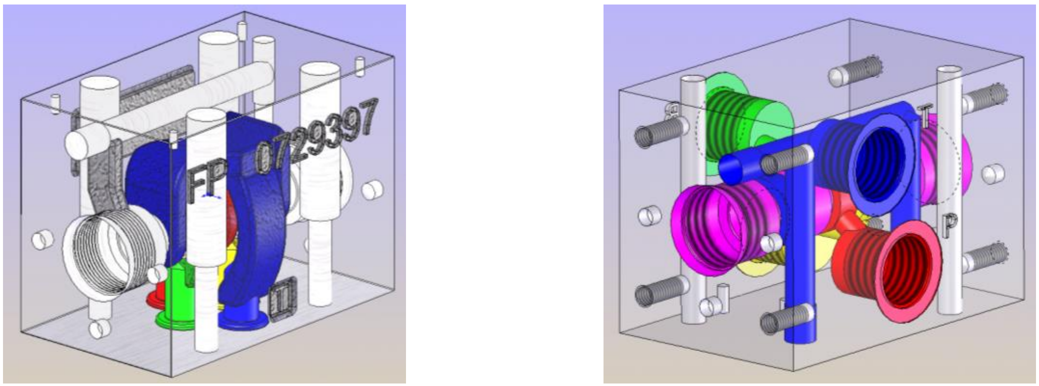


Fig. 1. Valve housing as a cast product (left) and as made from metal rods (right)

In view of its complex design and required mechanical properties, manufacturing of a valve housing by using rapid manufacturing, is very challenging. On the one hand, there is the rather complex internal geometry of the valve, and on the other hand, the product must be able to withstand all dynamic pressures and forces. There are two options for using the RM valve manufacturing method: Either to make only the casting core of the valve after the RP procedure and then cast it according to the classical procedure (saving the time and cost of prototype tooling, as well as the cost of subsequent corrections), or use the direct process, where the valve is literally "printed" using the appropriate material.

2.1 Rapid Manufacturing – RM of valve housings

The development of additive technology already enables the production of homogeneous materials that can withstand high pressure loads, which are characteristic for hydraulic components. Selective deposition of metal powders by means of a laser or an electron beam is available for the direct, rapid manufacture of valve housings. Regardless of the energy source, we get a product of full material density from original engineering materials.

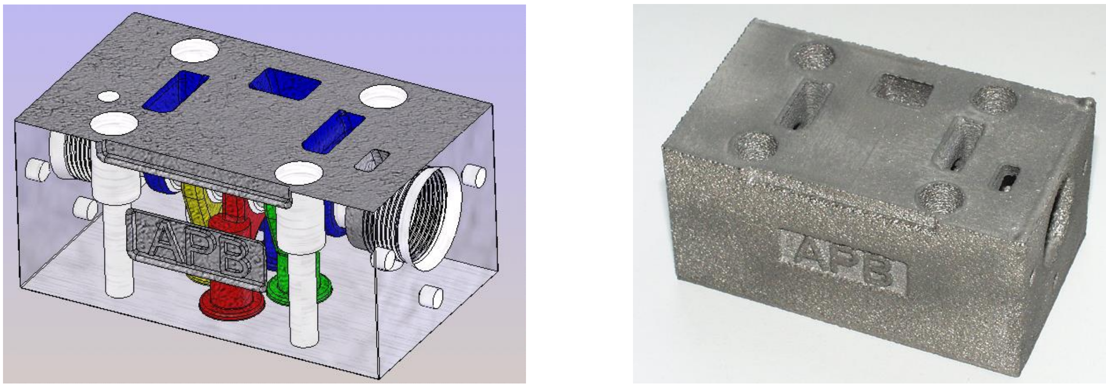


Fig. 2. Housing of a directional control valve size NG 6; CAD model (left) and finished product manufactured by the EBM process (right)

Materials include a variety of steels, from maraging tool steel, super alloy (e.g. inconel), to medical stainless (e.g. CoCr), and special metals such as titanium. The Selective Laser Melting (SLM) process allows for a rather high precision workmanship, making it possible to produce a valve in a final or near-final shape (near net shape) with all accessories such as threads and centring holes. Unfortunately, the process is quite lengthy and, therefore, disadvantageous in price. The Electron Beam Melting (EBM) Electron Beam Deposition Process has a significantly higher energy supply, making it significantly faster, and at least 5 times cheaper than the SLM process. Unfortunately, due to the huge energy input, the surface is quite rough, which makes it impossible to produce details such as threads – Figure 2.

2.2 Rapid tooling – RT for casting housings

In the field of Rapid Tooling, casting with a lost core and making sand moulds using layered technologies are available as representatives of indirect RT processes. A casting process with a lost core requires a casting model made of material with a relatively low melting point. The process is known in goldsmithing, where models are serially made from wax in rubber moulds.
For valve housings, this process is not appropriate, because it requires a tool to produce wax valve housings. Rapid Prototyping (RP) procedures using suitable materials are appropriate. For this purpose, there are a few printers which can produce models of synthetic wax, SLS – Selective Laser Sintering and stereolithography polystyrene with special photopolymers for this purpose. The model thus obtained is inserted into a special frame – coat, and filled with special reinforced plaster in a liquid state. When the plaster solidifies the resulting mould is heated appropriately so that the wax melts and drains from the mould. Liquid metal is then poured into the resulting mould. This gives a functional casting of the desired material. This is very advantageous, because the resulting model can be made of the same material as the castings will be made in series, making it easy to check the technological procedures and functions of the valve. The appearance of the molten core casting model is shown in Figure 3.
For this purpose, there are several printers making synthetic wax models, SLS – selective laser polystyrene sintering, and stereolithography with special photopolymers.

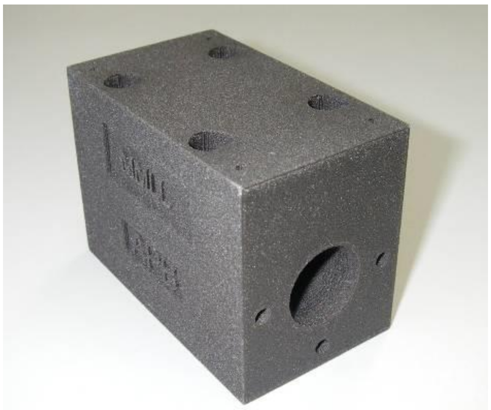


Fig. 3. Model for core casting made of polystyrene with the SLS process. The threads and other details are clearly visible

The production of sand moulds with layered technologies has evolved due to the requirements of the Foundry industry for the rapid production of complex moulds for small batches of products. There are some printers in this area that operate under the patented 3DP process. In this process, a layer of foundry sand is applied to the carrier tray, and the print head, as known from the ink-jet printers, injects a furon into the sand layer in the form of a single cross-section of an emerging foundry mould or core. The tray is then pulled down and repeated with the next layer – see Figure 4.
An alternative is the process of Selective Laser Sintering of foundry sand. The process is the same as sintering plastic or metal deposition, except in this case, the sintering powder has been pre-treated – mixed with furon. The laser thus "melts" or activates the furon, thereby causing the sand to adhere.

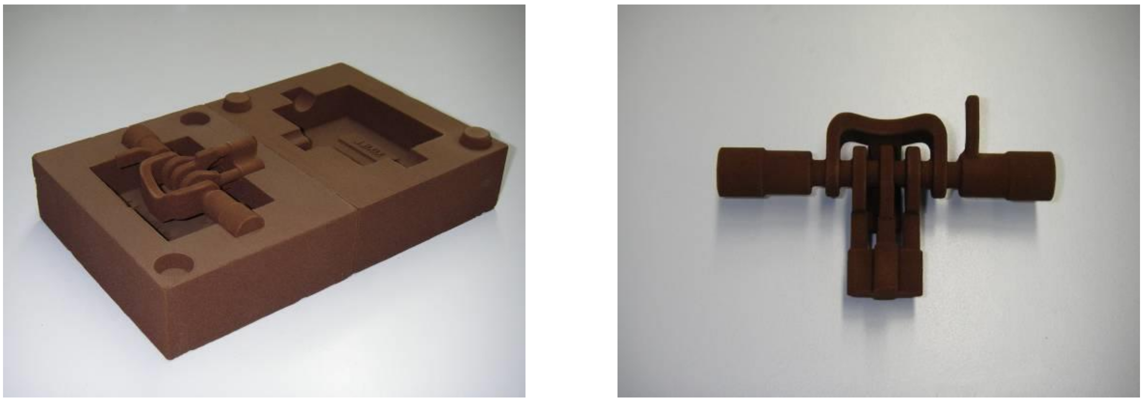


Fig. 4. Sand form and core made with Selective Laser Sintering

In both ways a relatively large series of cores and shapes can be obtained fairlyquickly and inexpensively, which is especially important in the production of prototype products. The moulds formed in this way are then used in exactly the same way as conventional ones, on moulding machines` manufactured moulds.

Manufacturing a valve for a known client is a fairly common process that has "inked" additive technologies. The usual procedure in these cases starts with reconciling the documentation between the buyer and the manufacturer, and then proceeds to produce some prototype products that the buyer tests, and orders the first batch of products if they meet his requirements. The problem is some prototype pieces that usually need to be made according to the casting process described above with the production of all casting tools. Price and time of manufacture of prototype products are, therefore, very large, and usually go at the expense of the manufacturer. Prototype pieces can be produced with the proper fast manufacturing process, and, in the case of small batches, the entire series of valves can be manufactured at relatively low cost and in a short time. In this case, each valve may have some specific design characteristics, but this does not affect the price or time of manufacture.
In addition to all the advantages of Rapid Manufacturing in the field of Hydraulic Components` Manufacturing, all other possibilities offered by Rapid Prototyping and products are not negligible. Rapid production of products in Hydraulics is also useful in the Marketing field, when the design and construction of a component is made, but it cannot be produced in a short time. In such a case, the addition of a non-functional physical model of the valve can be created quickly with the addition technology processes, which can then be presented to clients or used as an exhibit at a Trade show.

3. Compressor air consumption and RM technology

Also, in the field of Pneumatics, these technologies are very useful in the production of pneumatic components. As an example of the use of layered technology in the field of Pneumatics, two unconventional solutions will be presented which relate to savings in the consumption of compressed air.
Approximately 70 % of all manufacturers are using compressed air systems. These systems can power a variety of equipment, or can be used for cleaning, drying or cooling diverse products, using diverse blow-guns or blast nozzles. A significant reduction in compressed air consumption can be achieved by using energy-saving nozzles characterised by a very complex geometry that is based on CFD geometry optimization. However, such complex geometries cannot be produced by conventional manufacturing processes. The solution is to use RM technology.
Usability of RM technology will be shown on an example of an energy-saving blow off nozzle, which was produced with use of the Rapid Manufacturing process. Upgrading this approach represents the energy-saving cooling unit of plastic products with a much more complex geometry.

The designed nozzle-system was used for cooling purposes in plastic canister manufacturing. The previously used conventional cooling system presented the largest share of compressed air consumption in the company. The newly designed air-efficient cooling system, with increased capacity of the cooling air, allows enormous energy savings of compressed air – up to 50 %.

3.1 Energy-saving blow-nozzle

The most commonly used "pneumatic component" is the simple blow-nozzle. This small component is an integral part of any blow-gun, which is, without a doubt, one of the major consumers of compressed air. In order to achieve the highest efficiency of such a nozzle (minimum quantity of air at the inlet and maximum at the outlet), the inside of the nozzle must be designed appropriately to optimise the air-flow amplification principle, which allows air to accelerate, entraining the free surrounding air as it exits. Thus, on the basis of known physical processes, the nozzle-system is designed and optimised based on CFD simulation, and then produces using RP/RM (Rapid Prototyping / Manufacturing) manufacturing technology.
Energy-saving nozzles work on the “Venturi nozzles” principle with side inlets. The operating principle is based on the Bernoulli and Continuity equation. By reducing the cross-section, the speed increases, and if the speed is increased, the pressure is reduced all the way to the vacuum, so that the surrounding air is sucked through the side openings. We do not need to compress this additional air that is sucked from the ambient area. This means we are actually blowing more air out of the gun than we are providing to the gun – Figure 5. Example Type A shows the air consumption of a conventional blow-gun with classical nozzles, example Type B shows air consumption by using an energy-saving nozzle. Savings in compressed air consumption are approximately 40 %, in some cases, even more.

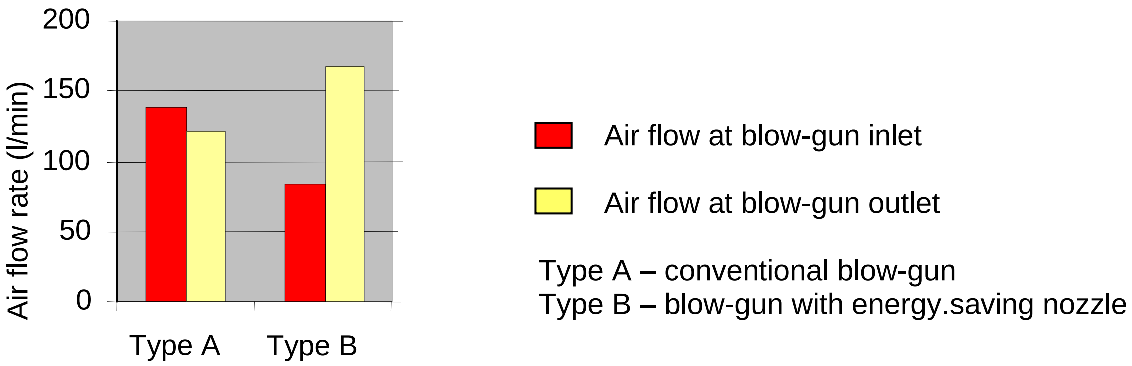


Fig. 5. Air consumption of different blow-guns types at an operating pressure of 4.5 bar

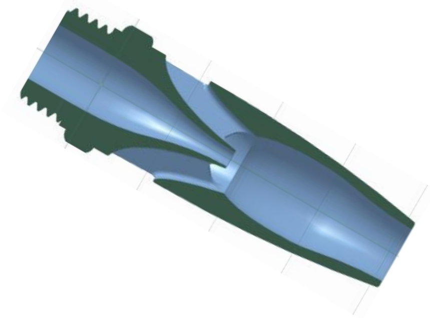
To achieve maximal efficiency of such a nozzle (the smallest amount of air entering and maximal leaving) the inside of the nozzle must be designed appropriately: Flow conditions must be optimised to ensure maximal suction effect. The optimal nozzle geometry, in terms of most effectively sucking the surrounding air, was designed based on a corresponding mathematical model and numerical simulations of air flow through the nozzle. Simulation was carried out in the program package ANSYS Workbench, based on the Finite Volume Method (FVM).
The mathematical background for a more complex two-phase homogeneous model is based on the current use of the following laws and equations:

- Mass continuity equation. The continuity equation results from the fundamental physical principle that mass is conserved.
- Momentum equation. The resulting force on the volume element is equal to the time increment of the momentum in the volume and the flux across the element surface.
- Conservation of turbulent kinetic energy and turbulent kinetic energy dissipation. The two-equation model for the turbulent kinetic energy k and the dissipation of turbulent kinetic energy ε

ISSN 1454 - 8003
Proceedings of 2019 International Conference on Hydraulics and Pneumatics - HERVEX
November 13-15, Băile Govora, Romania

or the *k*-ε model, is the most important two-equation turbulent model that is based on the turbulent viscosity principle.

More details of the equations can be found in the literature, for example [2] [3]. The equations represent the basis for carrying out numerical simulation of fluid flow. Numerical simulations in Computer Fluid Dynamics are divided into four phases: Design and meshing of the geometry – modelling the physics` phenomenon – numerical equation solving – processing of results.
The result of this approach is the optimal internal nozzle geometry, which enables extremely efficient use of compressed air. The internal geometry of the nozzle was optimised based on the simulations, and it is shown in Figure 6.



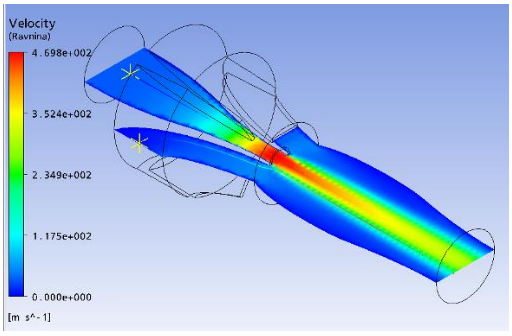


Fig. 6. Computer-based optimised nozzle geometry (left) and simulation result (right)

The external shape and internal geometry of the nozzle are, thus, determined. The problem that remained was the construction of such forms. It is usually where things come to standstill, as complex forms require the use of complex and expensive manufacturing procedures. But, if not, and we use simpler forms and construction, and, thus, lower the costs, the effect of nozzles is not optimal. Combine two good things: To maintain the complex geometry of the nozzles with low cost manufacture is possible using the Rapid Manufacturing technology.
For experimental verification of its effectiveness, the energy-saving nozzle was produced by the Rapid Prototyping method with SLS technology (Selective Laser Sintering). The material PA2200 with 30 micrometres` granulation was used, while the high power laser (CO_2 laser) sticks together fine particles of plastic, metal or ceramic powder into layers, that finally form a 3D object. The final product made from this material has sufficient strength, is thermally stable and has low weight. The effectiveness of the energy-saving nozzle is shown in Figure 6 – blow nozzle Type B.

3.2 Energy saving cooling block

Compressed air is also used on the plastic blow moulding machine. Blow moulding, also known as blow forming, is a manufacturing process by which hollow plastic parts are formed. In general, there are three main types of blow moulding: Injection blow moulding, stretch blow moulding and extrusion blow moulding. The blow moulding process begins with melting down the plastic and forming it into a parison or preform.
After the extrusion processes it is only necessary to remove the residues from the bottom of the plastic canister, or residue from the throat, and, in the case of canisters, the plastic rests under and above the handle. The cooling process is performed using compressed air via a simple cooling block with multiple nozzles, as shown in Figure 7. The cooling process causes a large consumption of compressor air – the cooling phase lasts cca 15 s, by consumption of compressed air in the amount of 48 m^3/h. Figure 7 shows the appearance of a discuses plastic canister as the end-product, with areas of hot plastic above and below the handle, which must be removed, showed in the infra red spectrum (as seen using a thermal camera). The Figure also shows the existing cooling block.

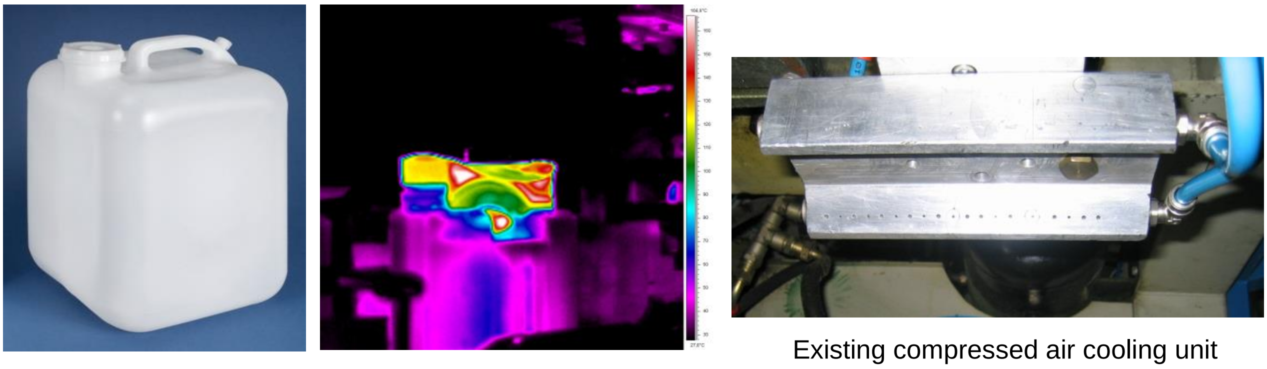


Fig. 7. Plastic canister, areas of hot plastic during the cooling process and existing cooling unit; temperature scale: 28 °C to 166 °C

A similar approach was used, as in the case of the energy-saving nozzle, to design an energy-saving cooling-block. Compared with the relatively simple geometry of the nozzle, the geometry of the cooling block is definitely more complicated and complex. The base idea in block design was to place a series of nozzles into line, with a single outlet joint to a common outlet manifold. A cross-section of the geometry at the nozzle location is shown in Figure 8.

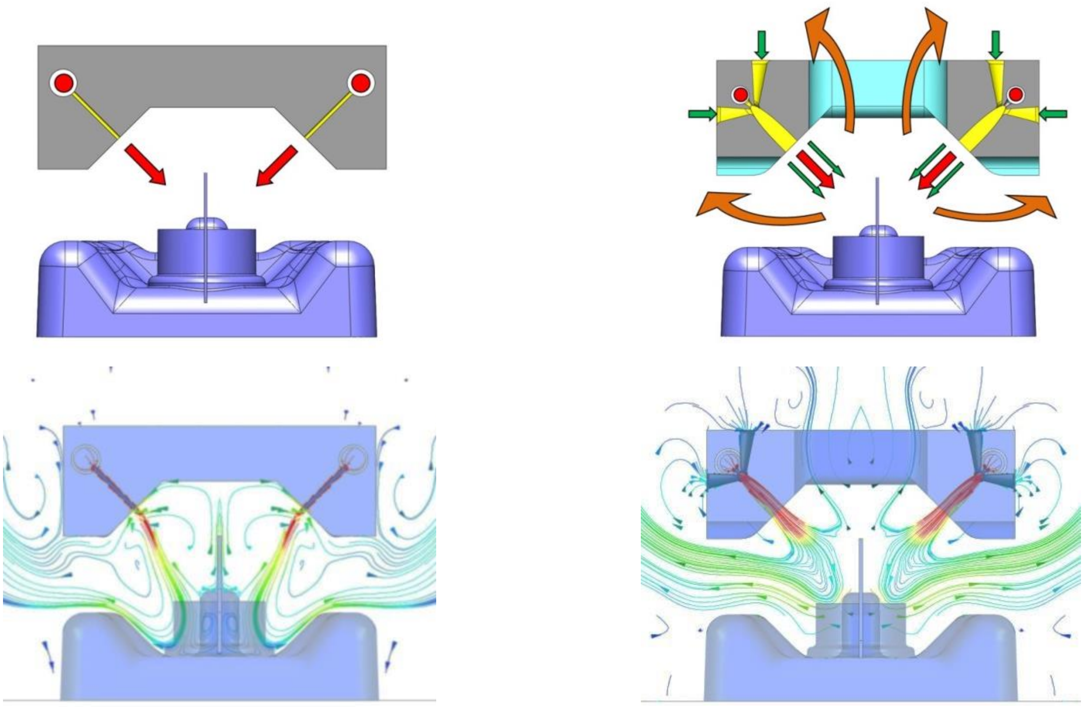
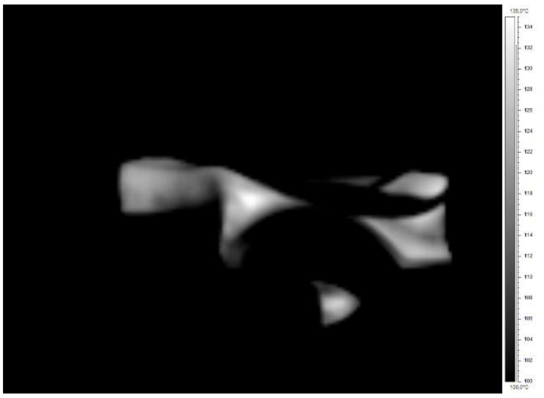


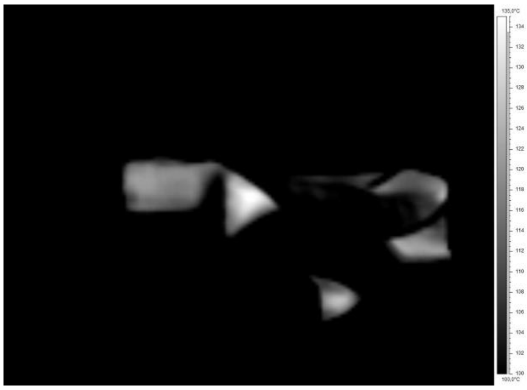
Fig. 8. Existing cooling block (left) and new optimised energy-saving design with additional openings to provide better warm air disposal (right) and, correspondingly, CFD flow stream lines

The results of air flow based on CFD simulations show 2D forward velocity streamlines starting from vertices on a cutting plane with a time limit of 0,01 s. A rainbow colour range is used, from blue 0.0 m/s to red 100 m/s. Air flow in the cooling phase is shown in Figure 8: Flow of fresh air from the cooling nozzles in place, sucking surrounding air through side inlets and disposal of warm air after cooling. Simulation results show 45 % increase of air mass flow at the outlet manifold compared to the existing block.
The existing cooling block, without optimization of nozzle geometry and without the possibility of sucking surrounding air, uses 48 m^3/h of compressed air, while the temperature of the cooled

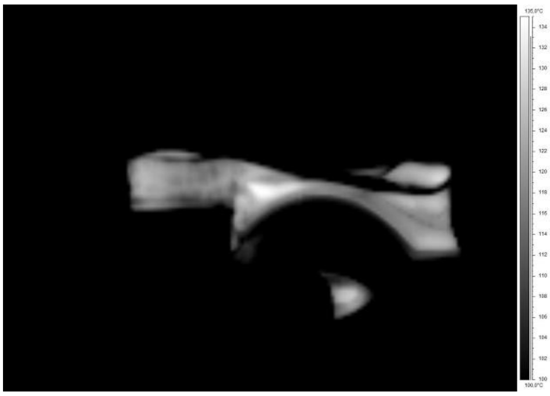
material ranged between 134 ^oC and 135 ^oC. At higher temperatures, which may arise due to lack of cooling efficiency, e.g. due to lower input quantities of compressed air, the plastic is not cooled sufficiently and may lead to bad material cut – an unusable product.
The key factor of the product quality is, therefore, a sufficiently low temperature of the plastic before cutting surpluses, with minimum consumption of compressed air, whether it is fully provided from a pneumatic network, or the amount provided from the network is smaller and an additional quantity is sucked from the block`s surroundings. Temperature conditions at the given measured flow rates of compressed air at the inlet of the cooling-block are shown in Figure 9. In all cases, the temperature fields were recorded at the end stage of cooling, immediately before cutting waste material.



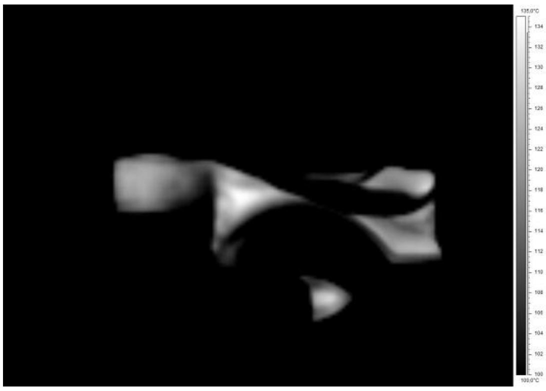
Existing cooling block; 48 m^3/h



Energy-saving cooling block; 48 m^3/h



Existing cooling block; 25 m^3/h



Energy-saving cooling block; 25 m^3/h

Fig. 9. Comparison of temperature fields of existing and new energy-saving cooling block (temperature scale: 100 ^oC to 140 ^oC)

From the comparison of thermal images of the temperature fields of waste materials, it is pretty clear that cooling with an energy-saving cooling block is much more effective than with the old one – Figure 9 above left and right.
In other words: A new cooling block allows equal effective cooling as the existing one with almost half of compressed air used – Figure 9, top left and bottom right. The remaining amount of air involved in the cooling was sucked “free” from the surroundings.
Despite the high performance achieved, there are many possibilities for further development of this system in the way of its higher efficiency, e.g. concentrated cooling at points with large amounts of material, cut-line aimed cooling instead of cooling the whole waste, production of light-weight unit in honeycomb-like design with possible significant material savings etc. The latter is only

achievable through the use of layer technologies, with the faster and cost-effective RP/RM manufacturing process: Higher efficiency at lower product price.

Conclusions

Rapid Manufacturing processes are still believed to be expensive, and, in some environments, they may even be a fashion fly or an unnecessary toy. This paper demonstrates that this is not the case, and that additional procedures are indeed an important tool for shortening both development and standby times. The reason for their relatively modest use in certain environments can be found primarily in poor knowledge of these technologies, limited experience in conventional manufacturing technologies, and the use of relatively expensive machines.

Some high-speed devices are actually expensive and often overpriced. This is due partly to the demand-driven market, and partly to the fact that the processes are still very young and, therefore, underdeveloped, necessitating continued investment in development and a correspondingly high price of products. However, some processes (particularly SLS and SLA) have already reached some maturity, which is reflected in the falling equipment prices.

However, this is not a reason for the low use of add-on technologies, as more companies could join forces and invest in this technology together. They are completely superfluous to competitively coloured fears – on the contrary! With this kind of cooperation, companies can only gain from the exchange of experience and their involvement in new problems.

It could even be said that add-on technologies are not just a new technological process, they are leading to a small industrial revolution. With the development of Rapid Manufacturing, not only the course of action changes, because the idea and knowledge, instead of technology, are at the forefront, but completely new solutions are enabled.

References

[1] Drstvenšek, Igor, Darko Lovrec, Vito Tič, Anton Burjek, and Luka Jelovčan. “Implementation of rapid manufacturing techniques for fluid power products.” *Ventil* 14, no. 5 (2008).

[2] Lovrec, Darko, and Vito Tič. *Energy saving cooling-unit for plastic moulding machine*. Strojniški vestnik, ISSN 0039-2480, feb. 2011, vol. 57, no. 2, pp. 83-90, ilustr., doi: 10.5545/sv-jme.2010.082, 2011.

[3] Lovrec, Darko, and Vito Tič. “Reduction in air consumption when air-blowing using an energy-saving nozzle.” Efficiency through fluid power: workshop proceedings, 7th International Fluid Power Conference (7th IFK), 22-24 March 2010, Aachen, Germany; 7. Internationales Fluidtechnisches Kolloquium (7. IFK), Vol. 4, pp. 303-316, 2010.