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The Effect of Additive Manufacturing on the Utility Properties of the Reducing Valve Rezistor

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The article is focused on the analysis of the additive technology (3D printing) applicability by using DMLS in the production of the reducing valve part, i.e. atmospheric resistor. Currently, the mentioned part is produced by EDM in combination with soldering from the Inconel 718 steel. The use of additive technologies brings the assumption of greater flexibility and economy of production, which is verified by a set of analyzes focused on the accuracy of production and the utility properties of the mentioned part. In addition to technological aspects, such as individual production processes, economic aspects are also compared. Individual comparisons are the basis for assessing whether replacing the conventional production approach with 3D printing is advantageous in this case. The results of this assessment can subsequently be used for future applications of the considered additive manufacturing approaches in the case of similar components.

Keywords: DMLS, Additive technology, Valve resistor, Inconel 718

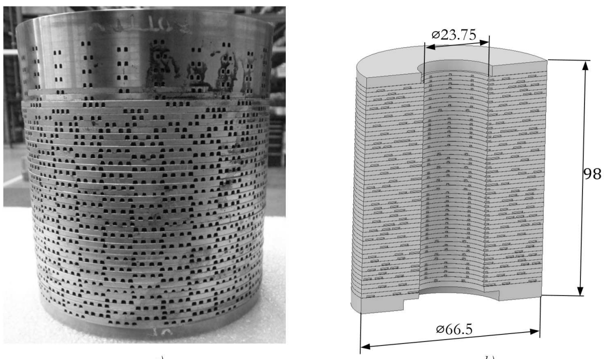
1 Introduction

Electrical power can currently be produced in a variety of ways. One of them is the use of thermal power plants. In order to make this method as efficient as possible, reduction valves are used before the medium entering a turbine. These valves are used to prepare ideal conditions for the medium, which enters the turbine space only when it reaches ideal pressure and temperature. Ideal conditions are characterized by high temperatures and pressures, the combination of which can create certain phenomena that can negatively affect the function of the valves. In order to avoid these phenomena, the production of the valves, including their internal components, must be adjusted accordingly. [1], [2]

To achieve optimal functionality of the mentioned devices, it is often worthwhile to combine different production technologies. Reducing valves and their components can be produced by conventional technologies, such as machining, casting, or forming. Today, it is possible to connect these technologies and thus obtain the best from each method, either with a view to the ideal functionality of the device or its most economical production. For this reason, the industry has recently become aware of additive technologies, which bring new possibilities to the issue of reducing valve production. Despite its short history, the printing of solid semi-finished products is a relatively widespread technology that is being used to an ever greater extent. [1], [2]

2 Analyzed Part

The solved component is a part of the reducing valve called the atmospheric resistor, which is shown in Fig. 1. The resistor serves to control and reduce the incoming pressure and temperature of the medium, i.e. steam, flowing through it. The ability to control and adjust the temperature and pressure of the medium has a fundamental influence from the point of view of safety, reliability and efficiency of the operating conditions of thermal power plants. [1]



a) b)

Fig. 1 *Atmospheric resistor a) manufactured part b) main dimensions* [1]

Ideal conditions in terms of temperature and steam pressure are achieved when the steam passes through the superheater. Valves controlling steam injection into superheaters are the final control element of the secondary circuit of thermal power plants. Therefore, these valves are the critical components responsible for the fine control of the steam temperature. The corresponding setting is ensured by throttling the flow through the reducing elements of the valve, i.e. by inserting a spindle into the atmospheric resistor, as can be seen in Fig. 2.

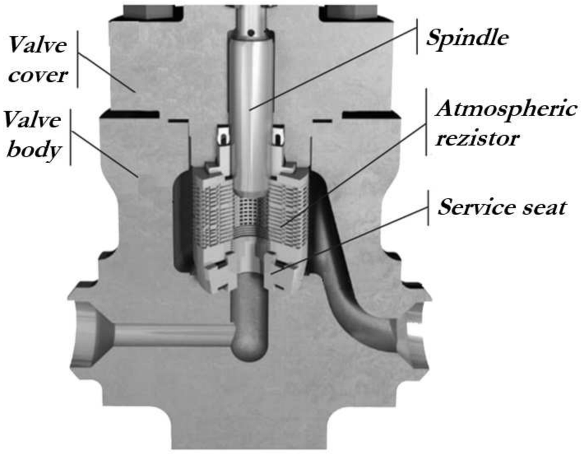


Fig. 2 *Reducing valve* [1], [3]

The resistor consists of a certain number of defined rings (Fig. 3) providing fine regulation of fluid pressure to prevent cavitation and other undesirable phenomena in this process. Each ring has pre-defined channels embossed on its surface. Each set of channels forming the labyrinth corresponds to one reduction phase of the atmospheric resistor. Currently, electric discharge machining (EDM) is used for production, which has replaced ring punching. During the completation of resistor using EDM, individual rings with hollow channels are placed on top of each other according to the shape of these channels. The combination method depends on the configuration of ring labyrinths, which are responsible for the regulation of the medium flow. [1]

A set of rings with the same channel configuration forms one reduction unit. Individual stages differ from each other in the degree of flow regulation. A standard atmospheric resistor consists of several control stages, see Fig. 4, where the stages are represented by the corresponding color. The red zone represents high media flow (low regulation) and the gray zone represents low flow (high degree of flow regulation).

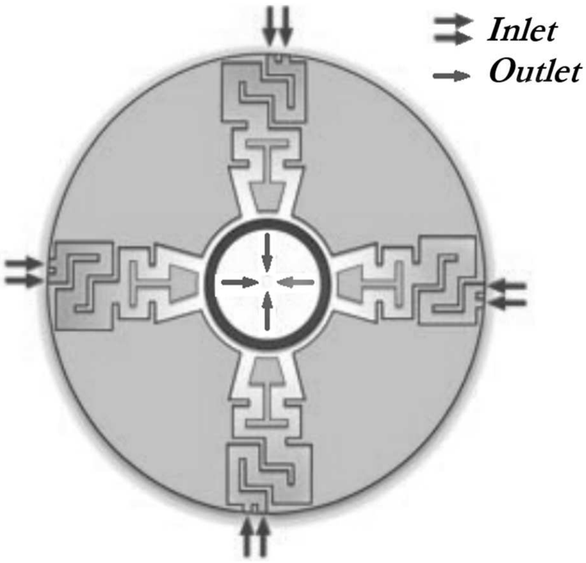


Fig. 3 *Rezistor ring* [1], [3]

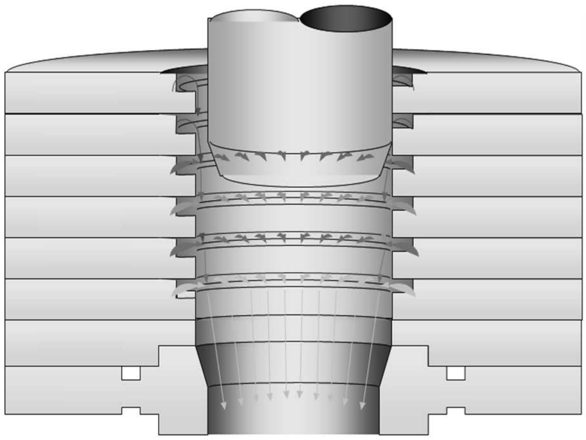


Fig. 4 *Atmospheric resistor composition* [1], [3]

The equipment must handle pressures and temperatures conforming to ANSI B16. In practical operating conditions, i.e. temperatures of approx. 260 °C and pressures of up to 420 bars. Depending on the temperature and pressure level, different materials are chosen for the production of resistors. In this case, the resistor is made of Inconel 718 steel, which meets above mentioned requirements. The basic mechanical and thermal properties are given in Tab. 1. Moreover, Tab. 2 shows the basic chemical composition. [1]

Tab. 1 *Mechanical properties of Inconel 718* [4], [5]

Yield stress	R_e	[MPa]	1 240
Ultimate strength	R_m	[MPa]	1 035
Young's modulus	E	[GPa]	193
Ductility	A_5	[%]	12
Specific heat capacity	C_p	$[J \cdot kg^{-1} \cdot °C^{-1}]$	435
Melting temperature	T_m	[°C]	1336

***Tab. 2** Chemical composition of Inconel 718 [4], [6]*

%C	%Cr	%Ni	%Nb	%Mo	%Ti	%Al
max. 0.08 088	17.00 – 21.00	50.00 – 55.00	4.75 – 5.50	2.80 – 3.30	0.65 – 1.15	0.20 – 0.80

%Co	%Mg	%Si	%Cu	%Ta	%B	%P	%S
max. 1.00	max. 0.35	max. 0.35	max. 0.30	max. 0.05	max. 0.06	max. 0.015	max. 0.015

3 Current State of Production

As it is already mentioned above, currently, the technology of EDM in combination with soldering is used for the production of atmospheric resistor rings. In addition to the eroding and soldering of individual rings, the resistor production process consists of several other sub-steps, including blasting, machining and coating. Each of the steps is necessary for the subsequent assembly of the resistor, especially to ensure the accuracy of the finished reducing element.

A workpiece for the production of EDM disks for the atmospheric resistor is a laser-cut ring-shaped sheet. The outer diameter of 66.5 mm is cut without subsequent processing, i.e. with a roughness of Ra = 3.2 μm. The inner diameters of 23.75 mm are cut with a tolerance of ± 0.1 mm, due to subsequent machining after the discs are joined together. The thickness of the sheet is chosen according to the height of the future channel, which is eroded to half the thickness.

Next comes the EDM process itself, see Fig. 5. The basis of this technology is an electrode with the desired shape of the future cavity (chanels). This electrode is then slowly sunk into the workpiece, where by the discharges, while maintaining the prescribed distance, the cavity is created according to the shape of the electrode. Due to the presence of a dielectric, the eroded particles are washed away from the surface of the workpiece.

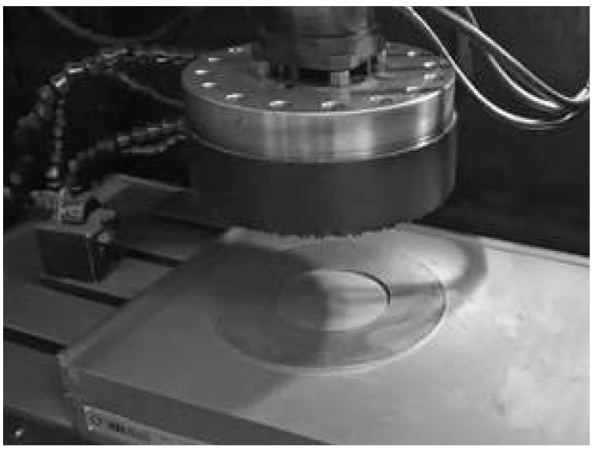


***Fig. 5** EDM process* [1]

The final machined part with already created regulation channels is shown in Fig. 6. In this case, the Gromax P46+E100A machine was used for EDM and the process was carried out under the following parameters:

- Depth of erosion: 0.5 × part thickness (± 0.05 mm),
- Electrode material: Cu,
- Cutting speed: v = 4 – 6 mm·min-1,
- Current intensity: I = 3 A,
- Voltage: U = 200 V.

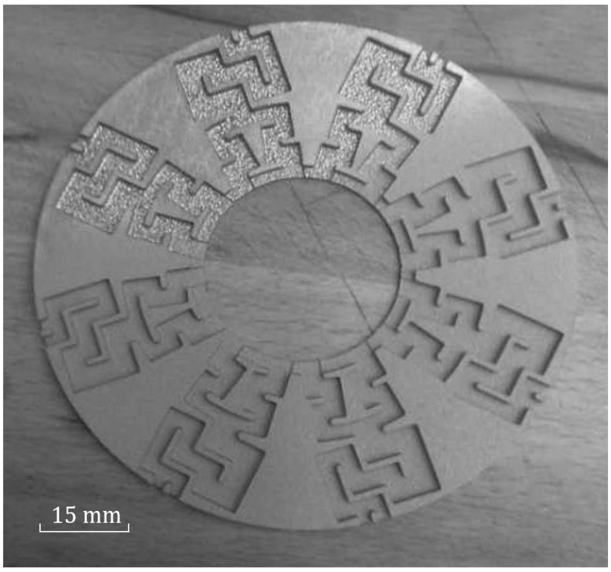


***Fig. 6** Eroded part* [1]

EDM process is followed by washing, during which discs are degreased and cleaned. The surface of the disk is further ground to reduce the roughness, thereby increasing the size of the contact surface between the individual disks. At the same time, the disc is adjusted to the required thickness, so that the required height of the resistor is reached after the subsequent assembly of all discs. This is followed by blasting by the SiC mixture. The blasting process is an essential step, during which impurities are removed and surface irregularities are further refined, which must precede the subsequent application of solder and the actual soldering of the parts. For this application, Nicrobraz EXP1307 Brazing alloy as the solder and Nicrobraz Cement 520 as a binder are used. Soldering was carried out in a vacuum furnace, see Fig. 7, where the set of disks is loaded with a weight in order to eliminate the increase in the height of the set, which could result in problems during the final assembly. The furnace is then set to the required course of temperatures and holding times at the given temperatures with respect to the soldered material.

Fig. 7 *Resistors before soldering* [1]

4 Production Innovation Using Additive Technology

The current production method is completely satisfactory, however, for standardized product lines. Due to the ever-higher demands on the accuracy of regulation, thanks to it is possible to react more quickly to changes in process parameters, this solution becomes unsatisfactory. For that reason, it was necessary to think about a new solution that would be able to meet these requirements. In addition, the innovative production method must have a minimal effect on the price or delivery time of the given components. Due to the demandingness and complexity of the internal structure of the resistor, especially the channel configuration, it appears to be an ideal use of additive manufacturing technology, i.e. DMLS method. DMLS (direct metal laser sintering) enables the production of parts from a wide range of materials with very complex shapes. In principle, DMLS is based on powder sintering under the action of a laser beam, see principle in Fig. 8. The sintered layer is typically 0.1 mm thick, depending on the accuracy that can be achieved. [1], [7], [8], [9]

The resistor design is more complicated from the point of view of CAD data preparation than in the case of using EDM method. This is due to manufacturing conditions and the nonlinear relationship between channel geometry and flow area. On the other hand, the basic assumptions for resistor design are similar, i.e. it is based on the determination of the number of sectors providing an optimal flow area. When using the DMLS method, the required number of stages, which differ from each other in the degree of regulation, is achieved by determining the height and maximizing the flat overlap. The width and the channel overhang are varied. Based on this, the maximum drain area that is achievable on the internal diameter of the resistor can be determined. During the design, several basic rules have to be observed in order to achieve the highest quality of printed channels:

- Minimum wall thickness: 0.8 mm,
- Minimum channel width: 0.5 mm (Fig. 9 – dimension "w"),
- Maximum overhang of the channel ceiling area: 0.5 mm (Fig. 9 – dimension "o"),
- Minimum side chamfer: 45°,
- Average process tolerance: ± 0.04 mm.

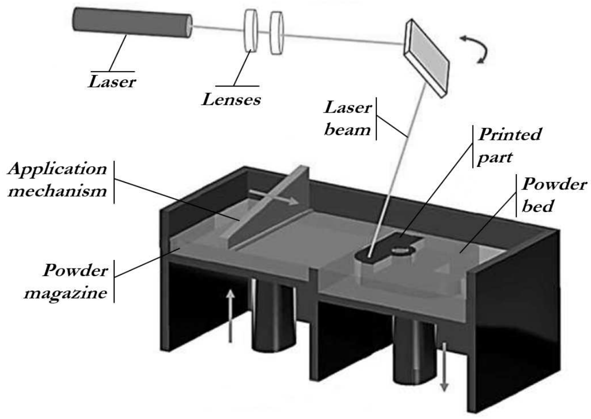


Fig. 8 *Schematic of DMLS method* [7]

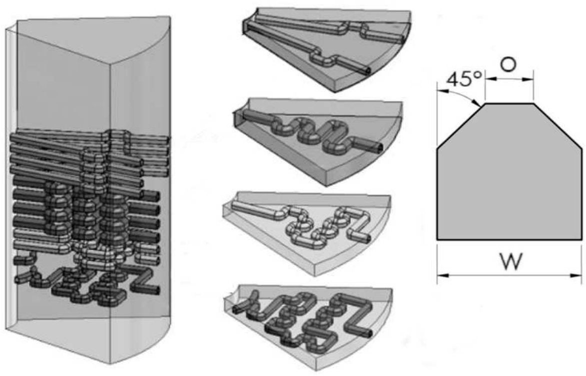


Fig. 9 *Innovative shape and cross-section of channels* [1]

The above mentioned conditions are defined in order to ensure adequate functionality of the resistor, or the feasibility of production from the point of view of technological processes during printing. One of the problematic parts of the design was the cross section of the channels. When using DMLS, it is not possible

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to print surfaces at an angle smaller than 45°. This is due to insufficient support of the underlying unbaked material. Therefore, it was necessary to modify the cross section compared to EDM. The solution was to design the cross section in the shape of a six sided polygon with corners in the upper part chamfered at an angle of 45° turning into a perpendicular surface, see Fig. 9. [7], [9]

Besides observing the shape regularities when designing the channel configuration, it is necessary to check the ability to regulate the given configurations. This would vary as a result of the change in the cross section of the channel compared to the initial solution. Therefore, the flow in different type of channels with a polygonal cross-section was verified by theoretical calculation with the support of numerical simulation using the finite volume method. The Solid-works flow simulation CFD software was used for the simulation, see Fig. 10. In the analysis, the inlet pressure was set as 0.138 MPa and the outlet pressure as 0.035 MPa for the fluid inside the channels (density 0.11 kg·m^{-3}). The output of the analysis is a simulation of the change in the flow rate of the medium in the channel with a partially throttled flow. It was possible to observed dangerous places from the simulation. According to calculated values, it can be concluded that the highest speed is logically reached when the medium leaving the channel. In these places, high stress occurs on the surface of the spindle. If safe values are exceeded, it can lead to cavitation and tearing of material from the surface of the spindle. The resulting values of all tested types do not exceed the prescribed permitted limit of approx. 10 m·s^{-1}. From this point of view, the proposal is sufficient. [10], [11], [12]

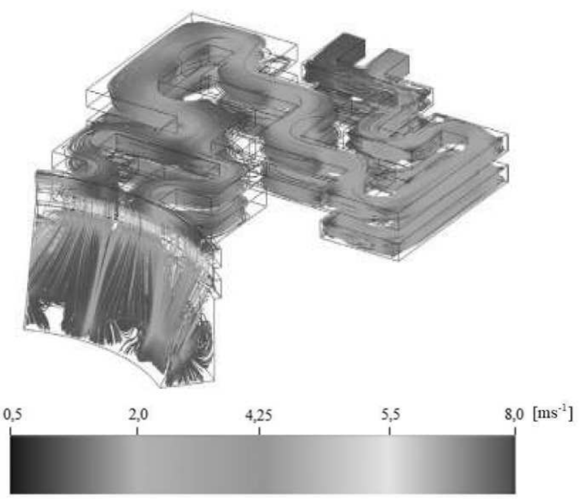


***Fig. 10** Flow rate simulation of the selected channel* [1]

An EOS M 290 printer was used for printing of the designed resistor. It was chosen because of the corresponding parameters for printing, which are determined by the size of the resistors. Furthermore, it was necessary to choose an appropriate alternative to the material Inconel 718 in powder form. The standardized EOS Nickel Alloy IN718 material was used for printing. The analyzed resistor was printed under the following parameters:

- Powder particle size: 20 – 50 µm,
- Laser power: 250 W,
- Print speed: 3.6 m·s^{-1},
- Scanning type: spiral,
- Printing time: 1 h 28 min.

The mentioned parameters were set with regard to creating the optimal roughness and structure of the material. The required roughness is not high. Therefore, it is possible to use faster printing. On the other hand, a low residual stress in the printed part is required, which limits the possibility of using high laser intensity. The spiral scanning method was used due to the presence of an internal hole that does not need to be scanned. Spiral scanning is characterized by high overheating in the middle of the part, which is eliminated in the case of atmospheric resistor printing. After printing and cooling, the part was cleaned of excess free powder. It was done using a fully automated device to remove residual material. Chanals were then cleaned with compressed air and ultrasonic waves. The resulting printed shape of the resistor (partially cut for clarity) is shown in Fig. 11.

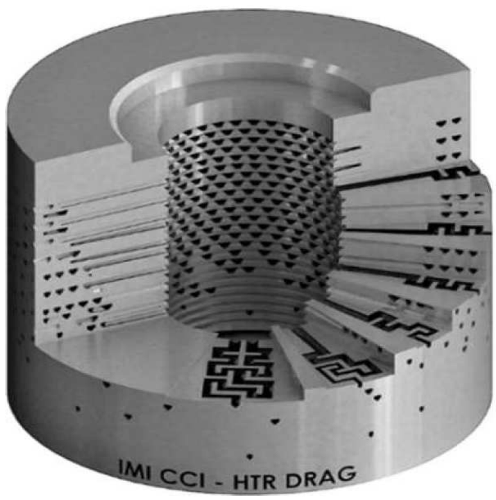


***Fig. 11** Printed resistor* [1]

5 Comparison of Current and Innovated Manufacturing

The following paragraphs are focused on the comparison of both approaches to the atmospheric resistor production process. The individual parts will touch on the maximum number of relevant and comparable properties, both individual production steps and the resulting properties of the part. The more important checks that have been carried out are mentioned below.

5.1 Mechanical properties

As part of the functionality classification of atmospheric resistors, the materials used for their production were subjected to a mechanical tensile test. Testing was carried out to verify the required values, prescribed for the appropriate functionality of the part. The tested specimens produced by the DMLS method were printed in two variants. 5 samples were printed vertically and then 5 horizontally. Firstly, rods with a diameter of 10 mm were printed from EOS NickelAlloy IN718. Subsequently, they were machined to correspond to the dimensions according to EN ISO 6892-1, see Fig. 12. Specimens of Inconel 718 for the resistors produced by the EDM were machined to the same dimensions. The tensile tests were performed in the mechanical properties testing laboratory of BUT FME using ZD40 hydraulic testing machine. [11]

Determined tensile test curves are summarized in Graph 1. Values of yield strength, ultimate stress and ductility for both production methods were determined by testing, see table 3. The test results of the individual tests were compared with the prescribed values. From the comparison, it is clear that not only EDM production, but also DMLS meets the required values of mechanical properties. In addition, EOS NickelAlloy IN718 specimens exceed the strength characteristics of the Inconel 718 material used for EDM production by more than 20 %. Furthermore, the Rockwell hardness values were determined with the help of the Rockwell HR-110MR device. Although, these are not specified in more detail in the product requirements, they provide another possibility to compare both materials. The comparison clearly shows the higher hardness of EOS NickelAlloy IN718 compared to Inconel 718, up to approx. 12 HRC, which favorably affects the service life and utility properties of the resistors. On the other hand, the machinability of the parts is thus reduced.

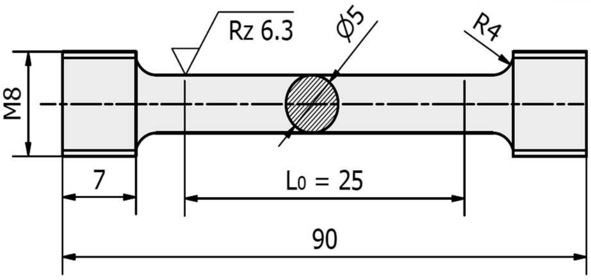
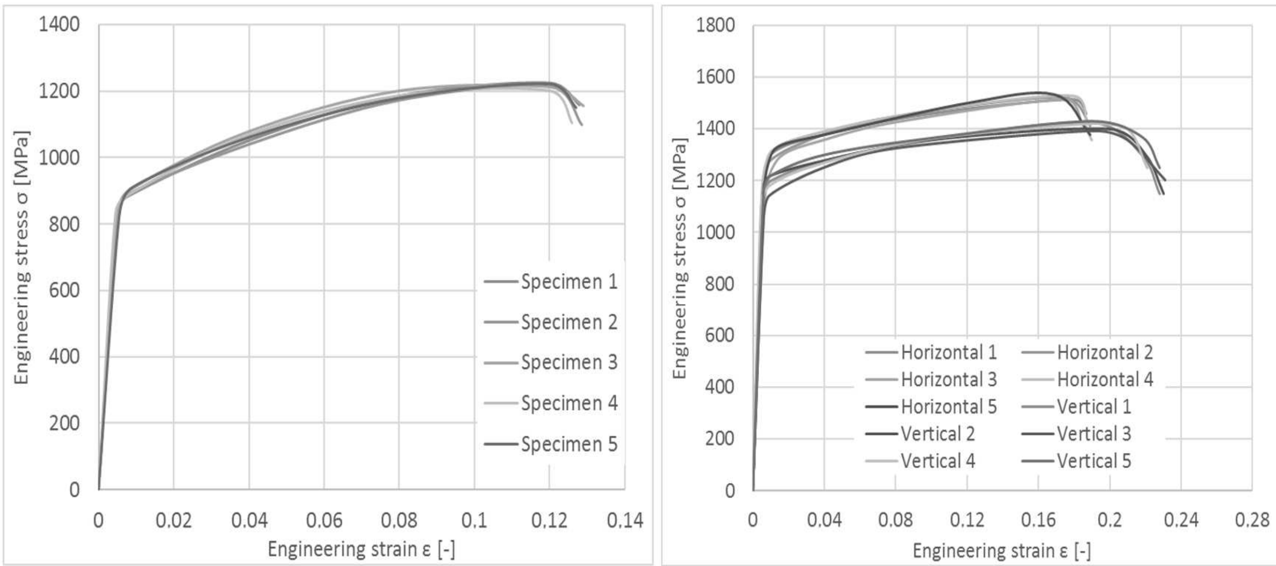


Fig. 12 *Tensile testing specimen* [13]



a) b)

Graph 1 *Engineering stress-strain curves a) Inconnel 718, b) EOS NickelAlloy IN718*

Tab. 3 *Tensile test values [1]*

			DMLS		EDM	Requirement
			Vertical	Vertical		
Yield stress	$R_{p0.2}$	[MPa]	1 198	1 298	883	≥ 725
Ultimate strength	R_m	[MPa]	1 425	1 513	1 224	≥ 1 055
Ductility	A_{25}	[%]	22.1	18.1	28.6	≥ 12
Hardness	HRC	[MPa]	48.2	48.2	36	-

5.2 Chemical composition

The internal composition of workpieces, depending on their applied use, is one of the most fundamental properties of the material defining its other properties as well. In the case of rezistors for the energy industry working with steam, the main properties are strength, resistance to fatigue and very good resistance to oxidation. The mentioned properties are mainly defined by the presence of Ni and Cr in combination with Mo. For the proper functionability and durability of resistors, a chemical composition is thus prescribed and must be checked. The parts produced by EDM and DMLS were thus subjected to an analysis of the internal composition of the material using Positive Material Identification (PMI) by spectrometer Innov-X Analyzer Alpha with an HP iPAQ control computer and they were subsequently compared with the required prescribed quantity, see tab. 4.

Tab. 4 *Chemical composition obtained from PMI [1]*

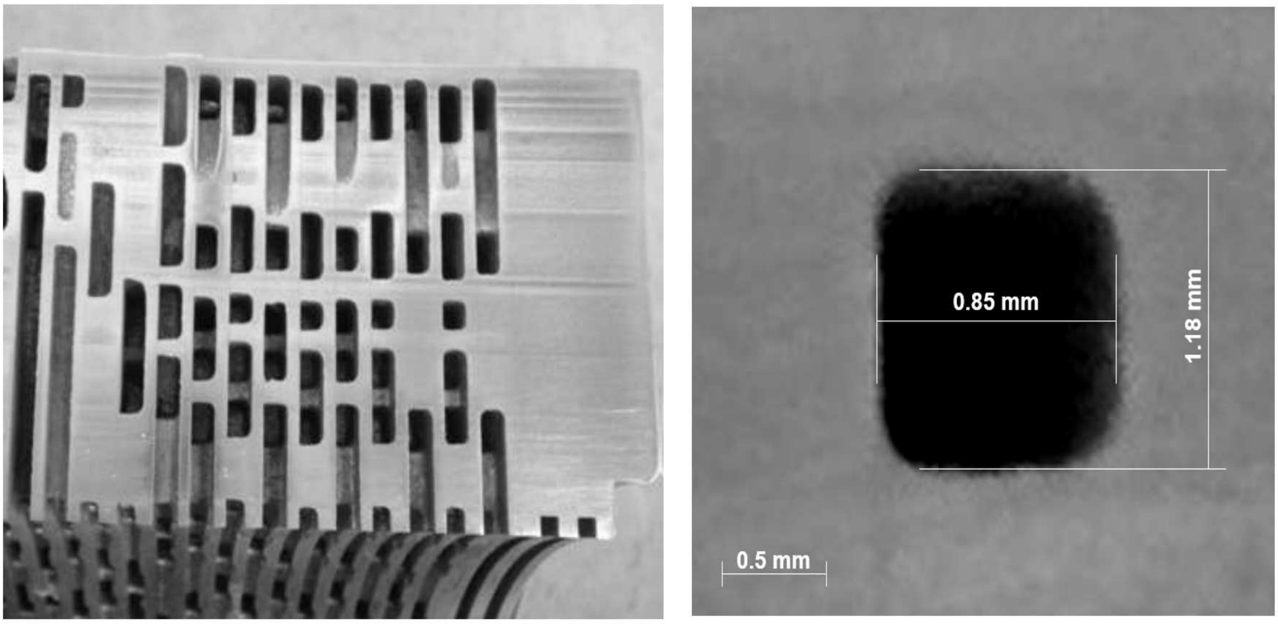
Element	DMLS [%]	EDM [%]	Requirement [%]
C	0.05	0.017	max. 0.08
Mg	0.03	0.002	max. 0.35
Si	< 0.01	0.06	max. 0.35
P	< 0.01	0.009	max. 0.015
S	< 0.005	< 0.001	max. 0.015
Cr	19.3	18.25	17.00 – 21.0
Ni	52.72	52.95	50.00 – 55.0
Mo	3.12	2.89	2.8 – 3.3
Nb	5.04	4.97	4.75 – 5.50
Ti	1.08	0.97	0.65 –1.15
Al	0.56	0.47	0.2 – 0.8
Co	< 0.01	0.347	max. 1.0
Ta	< 0.01	0.01	max. 0.05
B	< 0.003	0.004	max. 0.06
Cu	0.12	0.11	max. 0.3

The test results show that the chemical composition values correspond to the prescribed range. This is valid for both parts in all ranges of individual percentage representation of elements in the material. The assumption of the parts functionality is thus fulfilled from the point of view of the composition of the materials.

5.3 Cross Section Accuracy of Channels

The functionality of the atmospheric resistor is determined by its ability to achieve the required degree of reduction depending on the size of the flow throttling. In order to achieve adequate functionality, the manufactured part have to copy its digital original as ideally as possible. It was designed to meet the temperature and pressure drop corresponding to the given application and conditions. The most common deviation is failure to meet the required shape of the canal, especially in the cross-section. To compare the cross-sections of the resistors produced by both methods, the parts had to be cut and then ground. Cuts and cuts were made in areas that were comparable for both designs in terms of canal cross section. The measurement was carried out using Schut SSM-3E stereomicroscope.

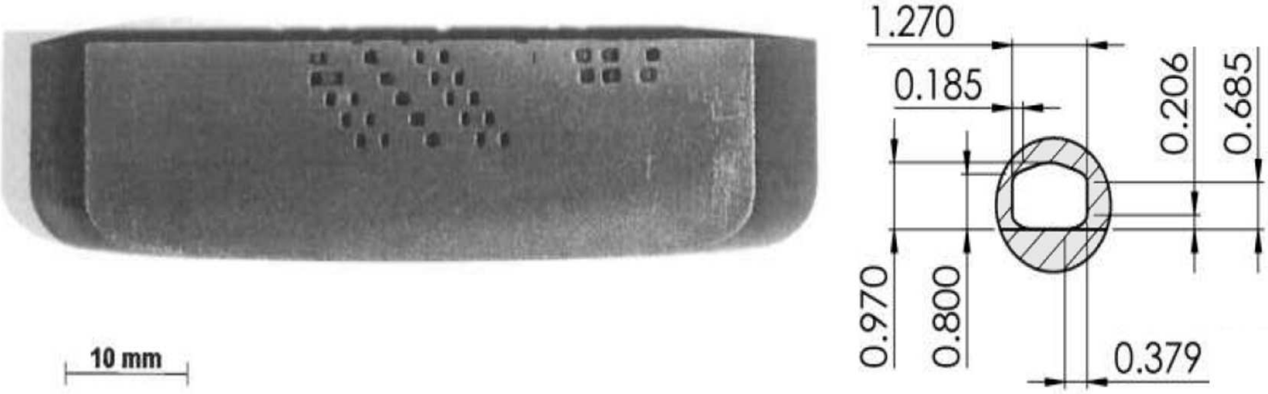
Cross section of the resistor made using EDM is shown in Fig. 13a. The proposed cross section of the channel is rectangular with dimensions of 1.2 × 0.9 mm. In thic sace, the production is already optimized, i.e. no significant deviation from the required shape and dimensions was obsedved during the inspection. The largest deviation from the 5 analyzed speciements was 5.6% (Fig. 13b), when measuring the height of the channel (0.85 mm compared to the prescribed dimension of 0.9 mm).



a) b)

Fig. 13 *Cross section of EDM resistor a) cut, b) channel detail* [1]

From the point of view of comparing and checking the manufactured channels, it is more important to focus on the production by DMLS. Unlike EDM resistor, its cross section is not rectangular, but polygonal for the reasons mentioned above. Fig. 14 shows a detail of channels design of the DMLS resistor channel and the cross section itself.



a) b)

Fig. 14 *Cross section of EDM resistor a) cut, b) dimensions of the analyzed channel* [1]

During comparing the cross section within the preliminary design and the subsequent implementation, a higher number of discrepancies compared to EDM was found. An incongruity of the cross section was discovered from the point of view of shape deviations, see Fig. 15, from which the collapse of the ceiling part of the cross section is visible. When using DMLS, this phenomenon is caused by the process of layering the powder layer by layer, where the bottom layer has only a limited bearing capacity if it is not melted.

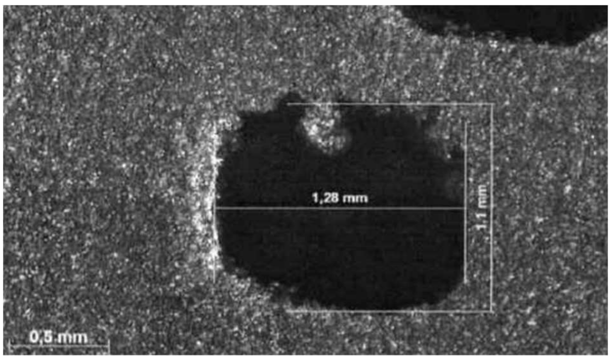


Fig. 15 *Detail of the channel with an overhang* [1]

Another parameter that was not fully respected was the dimensional uniformity, see Fig. 16. The photo shows two channels above each other rotated by 90°. The proposed dimensions of the channel compared to the real values from the sections did not match in several cases. Differences were found not only in terms of the dimensions of the sides, but also in the content of the cross section, which is more important in order to achieve an adequate flow of medium through the channel and to achieve the required regulation. The largest detected deviation from the required width was found, again during the analysis of 5 samples, to be 17.3 %. The maximum deviation from the designed height of the channel when comparing the actual height of the cut was even 25.8 % smaller.

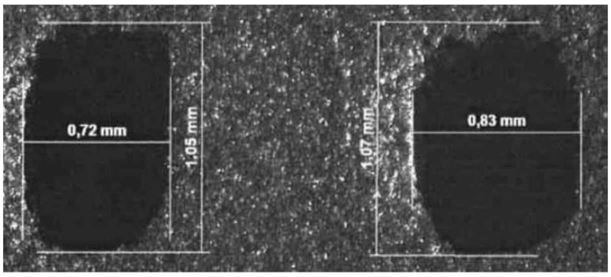


***Fig. 16** Detail of the cross cut of the DMLS resistor* [1]

From the individual analysis can be concluded that the DMLS resistor will be evaluated as non-conforming to a greater extent when subjected to the flow coefficient control than it will be with the EDM. Due to the burning of the ceiling in some parts of the cross section, it can also be assumed that the complete blockage of the channel at the DMLS resistor is also more likely. Therefore, the flow coefficient of the resistors was checked.

5.4 Flow Coefficient

One of the most important parameters that defines the utility properties of an atmospheric resistor is the flow coefficient "K_v". This coefficient conveys information about the amount of medium that flows through part per unit of time. In the case of reducing parts of the valve, the determination of this value is essential. The theoretical value of "K_v" is analytically determined with regard to requirements and the application in which the device will be used. The conditions for determining this value are given by the required values necessary to achieve the corresponding fluid flow at the valve outlet. This subsequently controls the steam cooling process, which is required to create ideal conditions for the medium passing through the circuit. The "K_v" value is given by:

$$K_v = q \cdot \sqrt{\frac{\rho}{\Delta p}}\ [m^3 \cdot h^{-1}] \qquad (1)$$

Where:
q…Volume flow rate [$m^3 \cdot h^{-1}$],
ϱ…Density [$kg \cdot m^{-3}$],
Δp…Pressure gradient [bar].

Volume flow rate of the reducing elements of the valve was tested at company IMI CCI Czech Republic s.r.o. using a drum measuring device. The device consists of a measuring drum, lid, pneumatic distribution and measuring and pressure apparatus. The measuring apparatus consists of several flowmeters, pressure sensors and a thermal anemometer. The measurement took place in several stages of closing the flow of the medium through the valve. Considering that only the reducing part of the valve is tested, the closure of the flow parts was done using an impermeable tape (Fig. 17). The part of the atmospheric resistor through which the medium should not flow in the given phase of flow throttling was always blinded with tape.

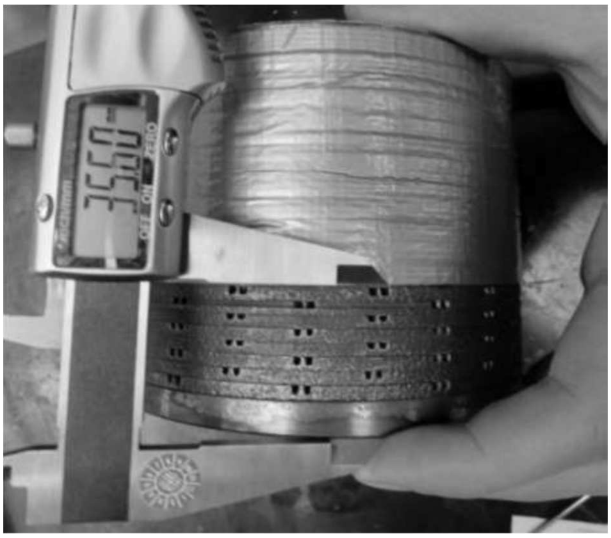


Fig. 17 Flow throttling simulation [1]

One of the prerequisites for the introduction of the innovative production of atmospheric resistors is the gain of an arbitrarily adjustable flow rate. During the production of the resistor using EDM, only parts with a standardized value of the flow coefficient can be created. In this case, the standardized flow coefficients are: 3.0, 4.6, 6.0, 7.8 and 9.9 $m^3 \cdot h^{-1}$. This is due to the limited combinability of individual reduction rings. These are designed in a limited number of configurations depending on the number of EDM electrodes produced. This restriction does not apply to the production of DMLS. The accuracy of the produced atmospheric resistor, as regards the values of the flow coefficient, is essential for the subsequent accuracy and the possibility of fine regulation of the output values of the medium. The difference between the designed "Kv" and the actual value must be between -10% and +20% for the resistor to be considered functional and suitable for use.

Tab. 4 *Detected values K_v in $m^3 \cdot h^{-1}$ [1]*

Standardized values	EDM 1	EDM 2	EDM 3	EDM 4	EDM 5	DMLS 1	DMLS 2	DMLS 3	DMLS 4	DMLS 5
3.0	3.21	3.24	2.95	3,05	3,10	3,76	3,05	3,38	2,94	2,55
4.6	4.82	4.76	4.55	5.23	5.32	4.65	4.88	4.35	4.53	4.18
6.0	6.62	6.60	5.66	6.28	7.86	6.30	8.91	6.80	6.40	6.26
7.8	7.84	7.78	7.70	7.72	7.82	7.51	7.47	7.98	7.82	6.53
9.9	9.11	9.72	9.96	10.59	10.59	9.99	10.20	9.87	10.40	9.56

To compare the conformity of the atmospheric resistors, 5 resistors produced by the EDM and 5 resistors produced by the DMLS were analyzed. The results obtained from the testing using the flow measurement device were compared with the required parameters, see tab. 4. The values show that EDM has on average a lower scrap rate compared to DMLS. It was found that 4 out of 5 resistors produced by EDM passed in accordance with the prescribed values. On the other hand, only 2 resistors out of 5 were declared identical by the DMLS. This may be due to the insufficient functionality of the production processes by the DMLS method, which has not been tested and optimized for as long as compared to EDM. The reason may be the differences in shape and size between the designed and real cross sections of the reduction channels. In the processes of producing resistors using 3D printing, it is therefore necessary to further optimize the approach to production or design, so that it is possible to achieve comparable values with the method of EDM.

6 Conclusion

The design and implementation of innovating the production of the atmospheric resistor was carried out, including the verification of the essential utility properties of the part. The new design using an innovative method iwas based on the original concept which resulted in easier controllability of achievable process parameters. At the same time, however, the concept had to be adapted to the parameters limiting production by an alternative method.

According to results of individual analyses, which dealt with the influence of production technology on partial aspects of the production process and the functionality of the analyzed resistor, several conclusions can be drawn. A comparison of the technological aspects of both production approaches pointed to the fulfillment of the required parameters from the point of view of chemical composition and mechanical properties. Comparison of accuracy of the internal resistors structure produced by DMLS, a high degree of deviations from the required channel cross sections compared to the proposed design was found. These facts have a definite effect on the up to three times higher rate of nonconformity of parts produced by the DMLS method, which was found when checking the prescribed flow rate.

Possible alternative is modification of the designed channel cross section, or a complete change of its shape. However, in order to evaluate whether it is appropriate to apply the mentioned approach, further analyzes are needed in the given issue. Nevertheless, from the point of view of production costs, production efficiency and possible material waste, it is clearly evident that the DMLS allows better outputs compared to EDM, i.e. lower production costs, a higher degree of flexibility and less waste during production. In addition, the process leading from the design to the final realization of a functional resistor can be significantly shortened when using the DMLS production method.

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