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Flow characteristics of an automotive compressor with an additively manufactured rotor disc

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Abstract This paper presents the results of experimental research regarding the determination of the flow characteristics of the compressor of an automotive turbocharger with a plastic rotor disc. The disc was manufactured using the 3D printing technology called the multijet printing, which allows complex geometries to be printed with high precision. Currently, in addition to speeding up the manufacturing processes and reducing their costs, 3D printing technologies are increasingly seen as standard tools that can be used in the design and optimization of machine parts. This article is a continuation of research on the possibility of applying additively manufactured elements in turbomachines. The experimental research was carried out at high rotational speeds (up to 110 000 rpm), using the automotive turbocharger with two different compressor rotors (*i.e.* one aluminum and one polymer). The first chapters of the paper discuss the preparation stage of the research (*i.e.* the manufacture of the rotor, the test rig). Then, the experimental research and the flow characteristics are described. The results obtained for the two types of discs were compared with each other and the area of application of the additively manufactured rotor was determined. The rotor functioned properly in the range of tested operating parameters and the results obtained showed that the technology and material applied could be used in the optimization studies of the blade systems of high-speed fluid-flow machines.

Keywords: Additive manufacturing; Material jetting; Compressor wheel; High-speed machines; Turbocompressor

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1 Introduction

3D printing technologies have seen significant development over the past decade. Their versatility has made them popular in many technological fields such as medicine [1–3] and widely understood engineering [4–8]. Studies carried out so far on the use of additive manufacturing (AM) technologies made it possible to determine their utility for the prototyping of machine components [9, 10] or even whole machines [11, 12]. One of the challenges of additive manufacturing concerns machines whose operating conditions do not always allow the use of 3D printed parts, especially plastic ones. Such a machine is, for example, an automotive turbocharger. It is one of the fastest turbomachines (including turbojet engines), which is characterised by extreme operating conditions such as very high temperatures or speeds ranging from 80 000 to 250 000 rpm. Turbochargers are mainly used in combustion engines to improve their power and efficiency. Due to the operating parameters, these machines are mainly supported on oil-fed slide bearings and do not require an additional cooling system. However, they are not resistant to long-term operation and generate friction losses. The development work carried out so far has shown the advantages of using rolling bearings in automotive turbochargers. Compared to a turbocharger equipped with slide bearings, the new ball bearings, by generating smaller friction losses, provide increased torque even at very low speeds [13]. Their application requires the use of body cooling systems (*e.g.* water body cooling system like in Garret's turbochargers) because exceeding the temperature of 150°C can lead to the rapid wear of the ball bearings or even their destruction. New automotive turbochargers are nowadays supported by adding electric engines that improve the torque and response time. The aforementioned works allow us to observe how important for the automotive industry is the development of turbochargers.

Additive manufacturing of plastic machine parts can save considerable time and money compared to conventional production methods. Its additional advantage is the possibility of manufacturing parts with very complex geometry without having to use more machines for this purpose, as well as parts with geometry impossible to obtain by traditional methods. One of the rapid prototyping methods used at the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences (IMP PAN) is the multijet printing (MJP) technology, which enables plastic parts to be printed with high accuracy using a polymer resin. It is an inkjet 3D printing process used for prints that require very precise production and complex shapes as well as series production.

The objective of the study was to determine the area of application of the selected AM technology for the experimental verification of the functioning of the designed machine parts. The use of 3D printing in this field of technology can significantly contribute to the development of high-speed machines in the design and optimization of rotor disc geometry. The used technology will also allow for experimental verification of difficult or impossible to manufacture (with conventional methods) geometries resulting from optimizations. In the study, the compressor of an automotive turbocharger was used. The analysis of the machine components manufactured using this method made it possible to assess their strength at high rotational speeds (over 120 000 rpm) [6]. The next step was to carry out the flow analysis of the compressor, which made it possible to determine the characteristics of the turbocharger at the boost pressure side. This side of the turbocharger was chosen due to the lower operating temperature. Conventional test stands for determining the characteristics of turbochargers use high-temperature exhaust gases as a source of energy, making it impossible to test turbochargers with plastic parts [14].

Due to the low heat distortion temperature of the material (lesser than 88°C), it was decided to use an air-powered test stand. In this paper, the operating characteristics of the commercial turbocharger compressor are compared with the results of the simulation. This article is a continuation of the study described in [6, 15, 16].

2 Manufacturing technology

Three different AM technologies are used in the IMP PAN. Based on criteria such as printing accuracy, printing time and cost of mass production, multijet printing technology, used in a printer produced by the company 3D Systems (model HD 3500 Max), has been selected. This technology makes it possible to obtain very high printing precision (the thickness of a single layer printed by the device is 16 μm with an accuracy of up to 1 μm). The producer offers a range of materials with different mechanical properties. The material sold under the trade name VisiJet M3 X in the form of a fluid polymer resin was chosen to manufacture the compressor wheel because it has the best properties. Studies on its mechanical properties have shown that the tensile strength is about 54 MPa [16].

The manufacturing process, which is based on multijet printing technology, is characterised by putting layers of material through printhead jets that are distributed over the entire printing platform. The MJP method is based on the inkjet approach to create 3D elements and photocure the printed photopolymer layers using ultraviolet light. However, this method should not be used at high ambient temperatures as it can cause errors during the printing process. Multijet printing is one of the most precise 3D printing technologies. This technology uses piezoelectric nozzles located in a printhead to deposit thin layers of photocurable resin and wax (support material). MJP is used to create parts with complex shapes (*i.e.* parts that have many details and complex geometries). The use of the support material (wax) is a huge advantage of this method because this material dissolves at a temperature of 60°C, without leaving any traces on the printed element. According to the producer, the selected building material plasticises at a low temperature (88°C).

3 Turbocharger and measurement equipment

As mentioned earlier, an automotive turbocharger was used in research. Such machines are used in combustion engines to improve their performance by pressure charging the engine. The construction of this machine is simple, which is another of its advantages. The turbocharger can be divided into three main parts responsible for its operation. The operating principle and cross-section of the turbocharger are shown in Fig. 1. The supply side – turbine side – is responsible for receiving energy from exhaust gases and converting it into torque. The compression side is responsible for converting torque to boost pressure *via* the compressor wheel. Both sides are embedded on a common shaft. The shaft is supported by two slide bearings lubricated with oil. The following factors had an impact on the choice of this machine: the nature of its operation (in terms of dynamics) as documented in the literature, its high rotational speed, its construction, the ease of assembly and disassembly of the components. Due to the low allowable operating temperature and the strength properties of the material, it was decided to perform the tests on the cold side (compression side) [17].

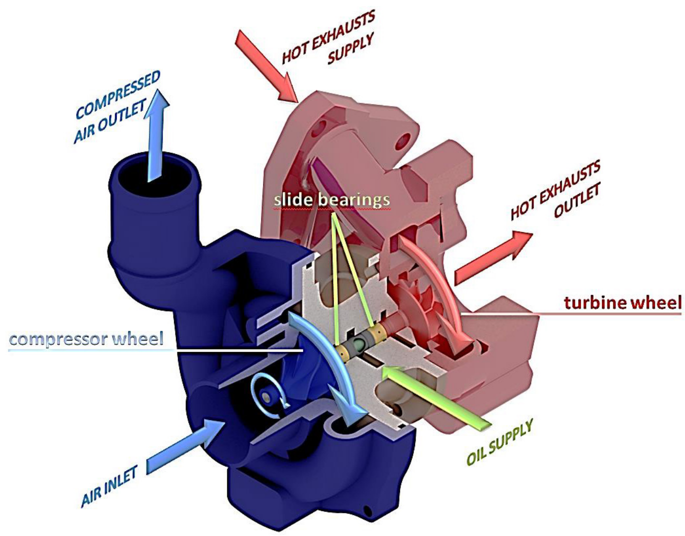

Figure 1: Cross-section of turbocharger: compressor, lubrication system, turbine.

The compressor wheel is the part of the turbocharger that has been manufactured using MJP technology. The 3D printer using ultraviolet (UV) curable polymeric resin manufactured the compressor wheel layer by layer until creating the whole part. After the manufacturing process, the supporting material (wax) was melted and the polymeric wheel was ready to use. The polymer wheel has the same dimensions as the aluminum wheel and they are as follows: diameter near the split blades – 42.5 mm, diameter near the supply of the compressor (*i.e.* near the non-split blades) – 30 mm. Using the surface roughness tester (Marsurf PA1 [18]) average roughness parameter, R_a, for polymer and aluminum disc was measured. The values were similar and were respectively: aluminum disc $R_a = 0.613$ µm; polymer disc $R_a = 0.568$ µm. During the measurements traversing length was set at 1.75 mm. Due to the similar values of R_a coefficients, a negligible influence of this difference on the value of the mass airflow generated by the tested discs was assumed. The chosen mechanical properties of compressor discs were presented in Table 1.

Table 1: Mechanical properties of polymer and aluminum discs.

Parameter	Polymer disc	Aluminum disc
Density	1210 kg/m^3	2700 kg/m^3
Heat distortion temperature	88°C	529°C
Elongation at break	8.3%	17%
Young’s modulus	2.168 GPa	68.9 GPa
Flexural strength	65 MPa	300 MPa
Tensile strength	54 MPa	276 MPa

The test stand, shown in Fig. 2 and described in [15], was prepared for testing the plastic compressor wheel (using MJP technology). During testing of this disc, the same temperature was set for the air supplied to the turbine as when testing the aluminum wheel. In this way, similar operating temperatures of the machine were obtained in both tests. The test stand with the measurement points is shown in Fig. 2. The stand was supplied with compressed air (1) using an industrial oil-free compressor, which made it possible to reach the operating pressure of up to 1 MPa with a flow rate of up to 250 kg/s. The temperature was controlled by an air heating system (2), designed in-house and composed of two air heaters connected in parallel (allowing a temperature between 30°C and 150°C to be reached). The measurements were carried out using a program created in the LabVIEW programming environment [19], coupled with the measurement system. The tests used six measurement points for each rotational speed. The measurement points corresponded to the throttle level at the compressor outlet (which was in the range of 0–60%). The air pressure at the compressor outlet was controlled using a throttle valve (7). The operating pressure of the oil in the lubrication system was dependent on the set rotational speed and was between 0.25 and 0.4 MPa. The following measuring transducers were used in the measurements:

Figure 2: Test stand with a measurement system for registering and determining flow characteristics of turbocharger compressor: 1 – air supply side, 2 – air pre-heated system, 3 and 6 – temperature and pressure sensors, 4 – turbocharger, 5 – speed sensor, 7 – throttle valve, 8 – flowmeter.

- K-type thermocouples with programmable transducers (TMD20 [20]), with an accuracy cold junction compensation ±1°C,
- laser rotational speed sensor (Optel Thevon [21]) enabling measurement in the range up to 1 million rpm,
- thermal flow meter (EE741 [22]) that allows mass airflow measurement with an accuracy of 1%,
- compression level was measured using pressure transducers (Peltron NPX type [23]) with an accuracy equal to 0.5%.

4 Results

4.1 Numerical results

The numerical calculations were based on the flow analysis performed for the compressor model described in [6]. Using this model, additional points have been calculated to plot the curves for high rotational speeds (up to 110 000 rpm). Figure 3 shows the operating parameters of the compressor obtained for different speeds.

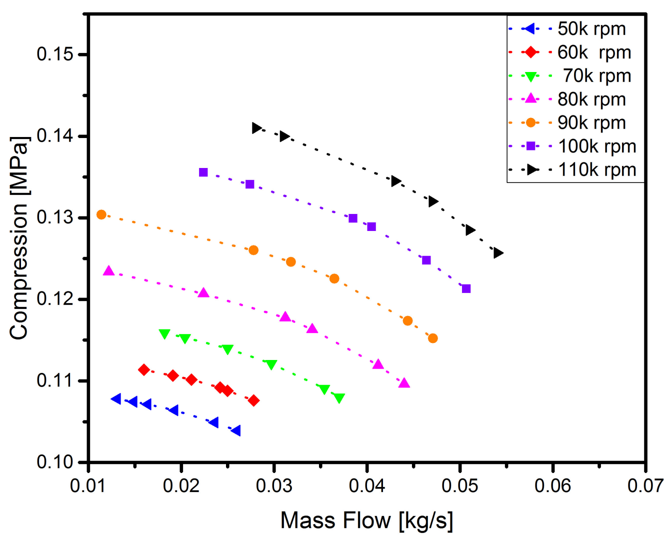

Figure 3: Simulation results: operating characteristics of compressor.

The results obtained from the flow analysis are typical for a radial compressor, as shown in Fig. 4. They are presented in the form of streamlines created in a relative reference frame (at a rotational speed of 200 000 rpm and a mass flow rate of 0.09 kg/s). A vortex is formed in the compressor volute. This vortex results from the momentum of the airflow at the outlet of the vaneless diffuser located upstream of the impeller.

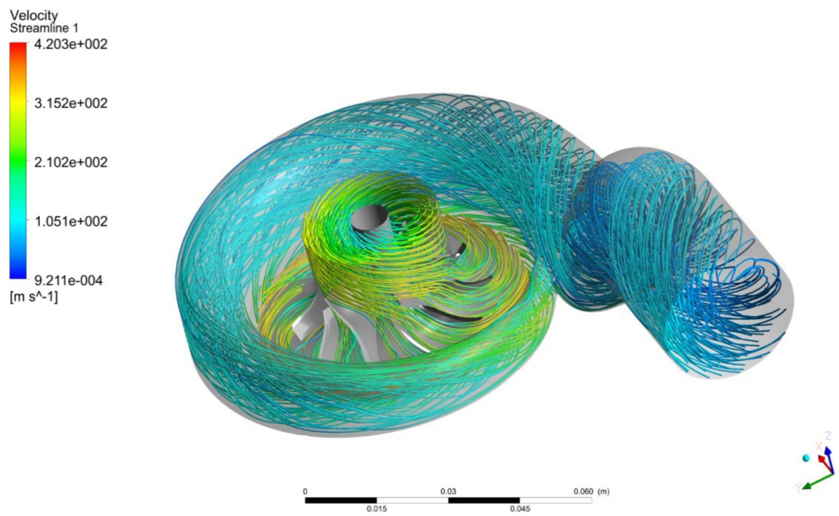

Figure 4: Streamlines in the computational domain of investigated compressor.

4.2 Experimental results

Preliminary experimental tests and strength analyses carried out previously [6] made it possible to determine the range of rotational speeds for which a plastic wheel can operate without risk of damage to the rotor which could occur as a result of its rupture. The range was between 50 000 and 120 000 rpm. Because at a speed of 120 000 rpm the operating temperature rises up to the heat distortion temperature of the material as a result of compression, it was decided to test the compressor only up to a speed of 110 000 rpm.

First, experimental tests were carried out using a conventional aluminum wheel in the selected speed range. Then, after mounting the polymer wheel, the characteristic curves were determined under similar operating conditions. The test consisted of collecting 6 points of the flow characteristic for each of the tested rotational speeds as a function of the boost pressure. Each of the points corresponded to the throttling level of the compressor outlet. The throttling levels were respectively: 0–0%, 1–10%, 2–20%, etc., up to 60% throttle. Each collected point of the characteristic was recorded after the working parameters were established. The duration of stabilization of working conditions was not constant and placed within the time range of 30–60 s. The obtained results are shown in Fig. 5.

The graph shows that the nature of the operation of the compressor with a polymer wheel is practically the same as that of the conventional compressor and the results obtained are very similar to the simulation results (Fig. 3). In contrast, the compressor with an aluminum wheel operates in the same manner only up to a speed of 70 000 rpm. For speeds above 70 000 rpm, and below 90 000 rpm the obtained results differ very slightly, which may indicate that the blades have started to adapt to the operating conditions. In the speed range between 100 000 rpm and 110 000 rpm, it is clear that as the speed increases, the compression does not increase, which confirms the hypothesis of the poor performance of the plastic blades of the compressor wheel since the stresses obtained are

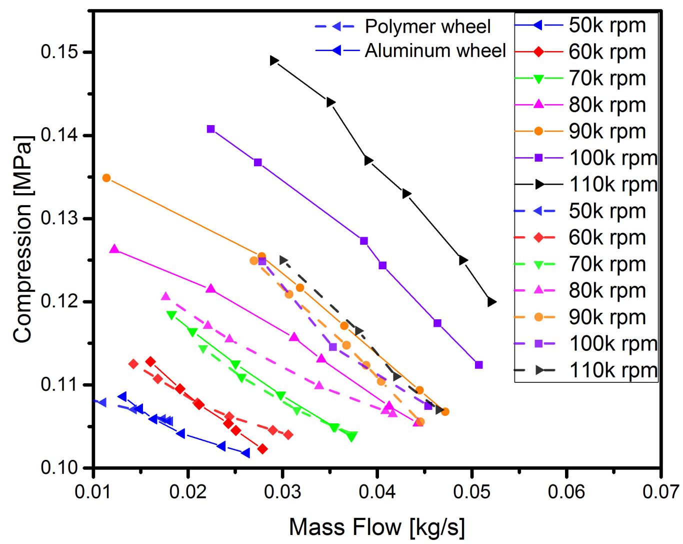

Figure 5: Comparison of experimental results obtained using polymer (dotted lines) and aluminum (solid lines) compressor wheels.

close to the allowable stress of the material used. In order to take a closer look at the operation of the compressor, it was decided to present the temperature results obtained at the compression side. These results are shown in Fig. 6.

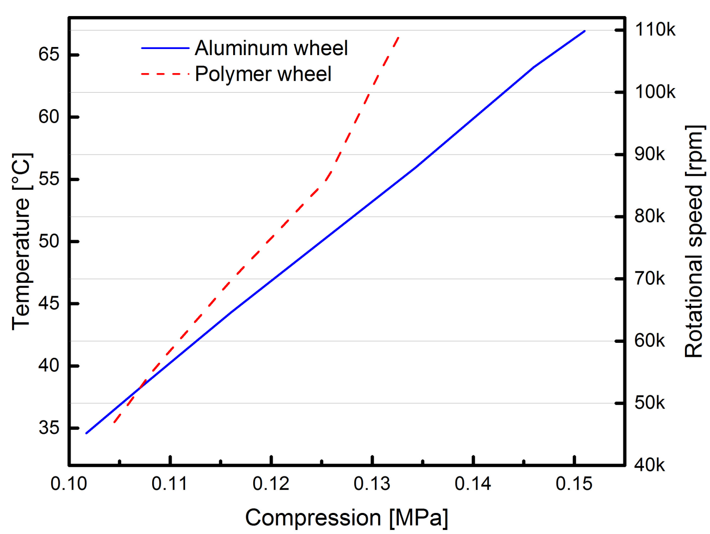

Figure 6: Temperature and rotational speed *vs.* compression.

The operating temperatures of both wheels have the same values at only one point in the graph (*i.e.* at the start of machine operation). Then, the temperature increases sharply for the polymer wheel up to a speed of 90 000 rpm, and beyond this speed, it increases even more sharply. The curve obtained for the aluminum wheel increases linearly but less sharply than that concerning the polymer wheel. This indicates that the polymer wheel has a lower efficiency, which can be observed in the flow characteristics, in particular by analyzing the curves obtained for the two highest rotational speeds. The main reason for the decrease in a mass airflow was the poor performance of the blades resulting from the mechanical properties of the polymeric disc. Both the working temperature and the stress values were close to the limit values.

5 Conclusions

The research presented in this paper was conducted in accordance with the adopted assumptions and made it possible to determine the flow characteristics of the compressor. This study is a continuation of research aimed at determining the area of application of additive manufacturing technology in high-speed machines. The obtained results made it possible to verify the numerical model on the basis of the experiment and to confirm the correct operation of the machine with a polymer wheel in a specified speed range (50 000–90 000 rpm). The presented results also made it possible to draw the following conclusions. The minor discrepancies between the results obtained from the flow analysis and the experiment stem from the fact that the blade clearance has not been taken into account in the numerical analysis. When using a polymer wheel, a faster increase in temperature was observed, indicating that its efficiency is lower. Nevertheless, this fact does not exclude the use of this material in further research on the design and optimization of blade systems of high-speed machines. The designed disc is not suitable for experiments where the rotational speed is higher than 90 000 rpm. Before continuing to use this disc, it is necessary to carry out strength optimization.

Future research will focus on flow and strength optimization using the manufacturing technology described herein. A dynamical destructive test will also be performed.

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