INTERNATIONAL CONFERENCE FLUID POWER 2021
CONFERENCE PROCEEDINGS
D. Lovrec & V. Tič (eds.)

University of Maribor Press

Development of metallic 3d-printed water hydraulic proportional directional control valve

JAN BARTOLJ, ANŽE ČELIK & FRANC MAJDIČ

Abstract New additive metal powder technologies are increasingly used for various prototypes. Different powder materials can be used for very complex shapes. Water hydraulics needs new technologies and new approaches to enable more frequent use by users. A new shape of housing for a water hydraulic proportional directional control valve was designed. FEM and CFD analyses of the valve housing were performed. Based on the results of the initial numerical analyses, topological optimization of the valve housing was performed. The prototype of the valve was fabricated from non-corrosive Inconel powder using 3D printing process. After machining, the valve was assembled and experimentally validated on the water hydraulic test rig. The new 3D-printed Inconel valve housing is more than 3 times lighter than similar housings of industrial valves.

Keywords: • additive technologies • metal 3D print • water hydraulics • numerical analyses • measurements •

CORRESPONDENCE ADDRESS: Jan Bartolj, University of Ljubljana, Faculty of Mechanical Engineering, Aškerčeva 6, 1000 Ljubljana, Slovenia, e-mail: jaan.baartolj99@gmail.com. Anže Čelik, Poclain Hydraulics d.o.o., Industrijska Ulica 2, 4226 Žiri, Slovenia, e-mail: anze.celik@poclain.com. Franc Majdič, University of Ljubljana, Faculty of Mechanical Engineering, Aškerčeva 6, 1000 Ljubljana, Slovenia, e-mail: franc.majdic@fs.uni-lj.si

DOI https://doi.org/10.18690/978-961-286-513-9.4 ISBN 978-961-286-513-9
Dostopno na: http://press.um.si.

1. Introduction

In everyday life, engineers are trying to maximize efficiency of energy transforming processes. The main goal is reducing volume of fossil fuels consumption, either directly (internal combustion engines of mobile machines) or indirectly (thermo-electrical power plants) [1], [2]. In mobile hydraulics engineers can achieve lower consumption of energy sources by reducing mass of final components.

Since a lot of unnecessary material is carried around in form of valve housings, we focused on them. We took an existing water hydraulics 4/3 proportional directional control valve housing [3] and optimized its outer and inner geometry.

2 Basics

As mentioned, we started with commercially available valve of nominal size (CETOP 6). We constructed the valve with potential mass production in mind, so we had to follow the trends of ISO 4401 [1] standard. By following those trends, the valve can replace any other valve of the same nominal size.

We also wanted to achieve that the final product would be able to survive the same pressure and other stress forms as commercially available valves. Final product had to be optimized to stand the pressure of 35 MPa at a flow of 50 l/min. We will satisfy both demands by using FEA and CFD analyses on the CAD model.

3 Development of valve housing

Since we chose metal 3D printing as a manufacturing process (MP), many limitations proposed by conventional MPs were avoided [5], [6]. That allowed us to design complex or organically shaped housing and greatly reduce mass of part.

We used SolidWorks program as software of choice for designing the CAD model. Because additive manufacturing can produce complex outer and especially complex inner geometry, we first constructed the inner chambers that were to be inverted outwards with purposive software function. At first inner chambers were made as basic cylinders, but after some consideration we made them toroidally shaped.

As we decided on the shape of inner chambers, the construction of connectional channels started (Figure 1). At first, the starting and ending shapes were projected on surfaces. Starting profiles were circles. Their locations and biggest possible radiuses are defined in ISO 4401 standard and were made accordingly.

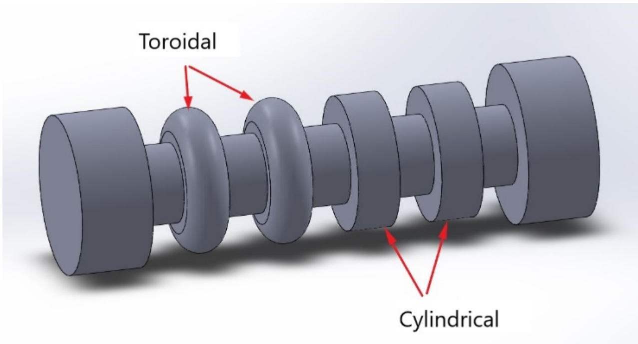

Figure 1: Difference between toroidal and cylindrical geometries (Φ 19 mm x 86 mm).

We projected the ending profiles on toroidal part of inner chambers. Contact surface was greatly increased because we used ellipse shape instead of circle. That will later reveal significantly smaller pressure drop because of smoother change between cavity shapes.

Next step was connecting the two profiles (Figure 2). Since they were not on the same surface neither were they orientated the same, we had to use three dimensional guide curves. This type of curves can be made in several different ways. Because we wanted small changes to be easily implemented to the curves throughout the whole design process, we used the projection technique. This means that each curve is made of two surface based curves, connecting same points stationed in 3D space. Two sketches, of surface based curves were then projected one to another. This gave us easy-to-correct guide curve. We made four guide curves for each of the profiles.

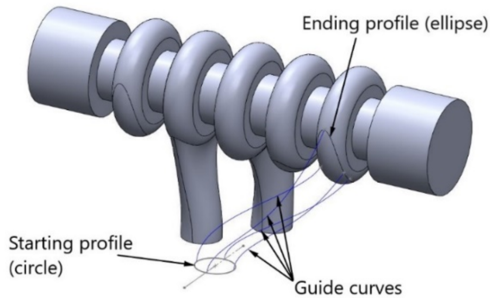

Figure 2: Profiles and guide curves (86 mm x 55 mm x 53 mm).

After finishing all internal cavities, the model was ready to be inverted. We completed this step with command Shell outward. The only needed parameter is wall thickness, which was decided to be 2.8 mm. When completed, we started adding guide holes for mounting bolts. Guide holes locations and bolt sizes are determined by standard. Bolts have to be M5 standard thread and since in hydraulics field are mostly used hexagon socket head cap screws (ISO 4762), we anticipated the usage of those.

We made base plate as adding bottom parallel sketch and extruding it upwards in to the model. Partial result of the design process is shown in Figure 3. This model is named Zeta. We made CAD model without any prior experiences in printing of hydraulic components. This was the first try to reduce mass of the valve housing body and make as smooth transitions between cavities as possible.

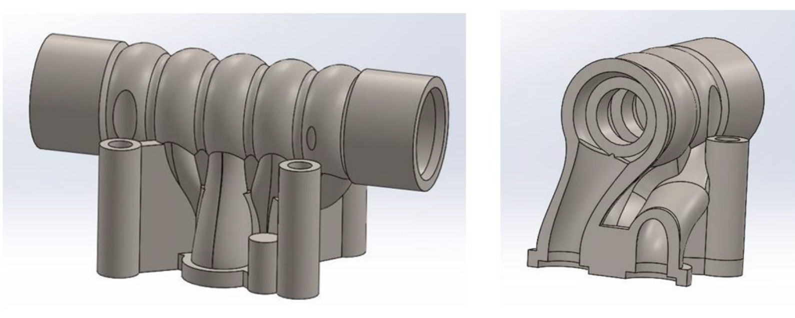

Figure 3: First valve geometry (86 mm x 47 mm x 43 mm).

4 FEA analysis

Since a lot of material was removed, compared to conventional valve housings, we used FEA analyses to confirm the strength of the part.

Analyses were made for different types of stresses. Firstly, we applied forces caused by operating pressure 35 MPa to all internal surfaces that are in contact with fluid. Secondly, we added forces that comes as result of tightening the magnet cores to control the spool valve. After that, the torque of tightening the mounting bolts had to be decided, so that we could applied forces to material. Finally, we defined supports – surfaces on the base plate that are fixed and prevent the structure from moving during the calculation.

Next step was meshing the model where we used second-order tetrahedral finite elements (Figure 4). Since the model has very complicated geometry, meshing was challenging. Some edges and surfaces needed to be removed or changed. After applying basic mesh, we tested to see if everything worked as it should. Once we were confident, we started decreasing size of finite elements and thus increasing their number. As a rule, the more elements, the better the result, and the longer the computation time. After numerous mesh manipulations (i.e. changing mesh size), we compared the results of displacement and stress analyses per elements number. When we saw that results were converging towards specific value, we stopped increasing the count of elements.

Since we were focused on metering edges of housing that are in contact with spool valve, we locally decreased the size of finite elements to prevent unnecessary increase of the calculating time.

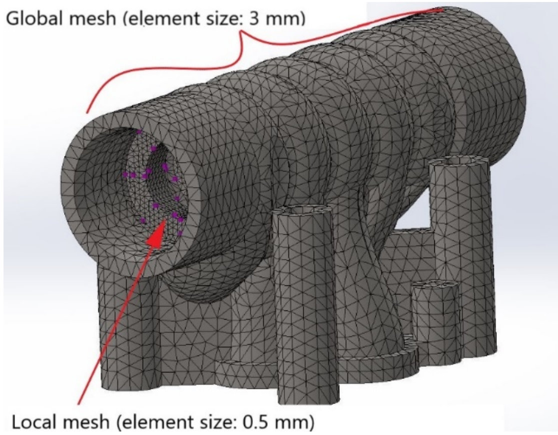

Figure 4: Meshing the CAD model (86 mm x 47 mm x 43 mm).

As a result of FEA analysis we focused on maximal stress through the whole model, maximal global displacement and maximal and minimal metering edges displacement (Figure 5). It was quite clear that stress and global displacement were not an issue for the material given. Major concern were displacements of metering edges. Displacement of metering edges for water hydraulic are expected to be less than 3 microns but were in our case more than four times that value. In aspect of metering edges displacement, we encountered two problems. First: values were much bigger than we wanted; second: in local cylindrical coordinate system we encountered negative displacements. Second problem has to be taken especially carefully. Positive displacements in cylindrical coordinate system mean that the observed radius is increasing its value. But negative values mean that specific radius is closer to the central axis of the coordinate system. So, if values are positive, we are talking about leakage between inner chambers of valve body; but if values are negative, there is the chance of spool collision/jamming.

Both problems are directly related to minimizing the housing body volume and mass. The solution was found adding supports to the most outer metering edges. Those supports connect the base plate with outer cylinders of metering edges in an arcade shape. Just adding those supports reduced the metering edges displacement values to ones that could be tolerated.

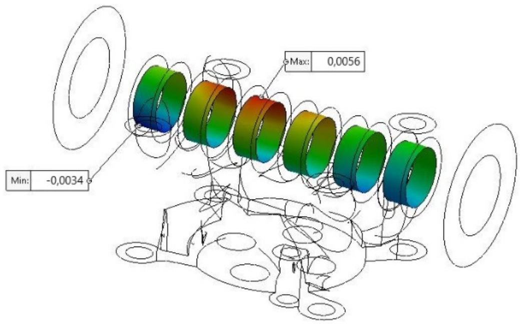

Figure 5: FEA analyses – displacement of the metering edges (86 mm x 47 mm x 43 mm).

5 CFD analysis

Analysing flow characteristics, we came to conclusion, that printed valve housing has significantly lower pressure drop. High flow (from 50 up to 80 l/min) simulations have shown up to 40 bar difference compared to conventional valve characteristics.

Starting parameters were: water temperature 50 °C, fully developed flow, flow rating from 10 to 80 l/min and spool valve offset position. Main points of research were pressure and velocity conditions when fluid was moving through housing.

Similarly to FEA we paid great attention to meshing internal cavities. We chose to make mesh denser locally. Mesh during calculation is shown in Figure 6.

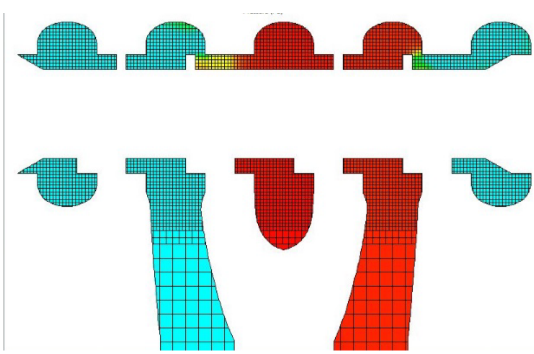

Figure 6: CFD analyses and mesh (86 mm x 47 mm).

When calculating, we focused on cut sections of specific channel. The most interesting was P channel that needed to be corrected. Since flow had a tendency to rotate the spool valve, the shape of channel had to be fixed according to partial results. Corrections to P channel are visible in Figure 7.

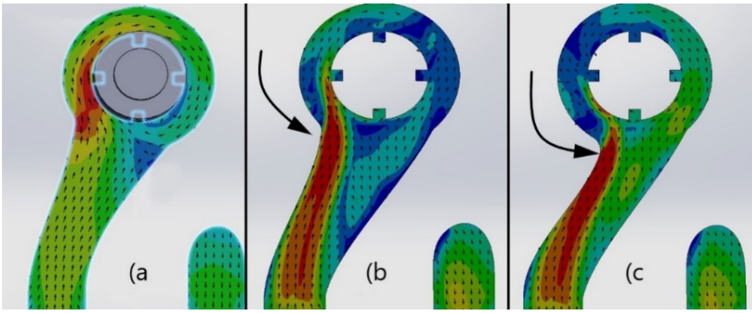

Figure 7: Reshaping the P channel geometry (47 mm x 43 mm).

As can be seen in Figure 7 most of velocity vectors have the same direction clockwise around the spool valve and thus trying to rotate it. If flow is divided in halves, then spool valve has less tendency to rotate.

6 Finished model

According to all the corrections from numerical analyses, we finished a model. Finally, we added small clamping appendixes at the top, and bottom, for final CNC machining. Pockets for O-ring seals were added on bottom end, which required some base plate to be made. Finished model Zeta is shown in Figure 8.

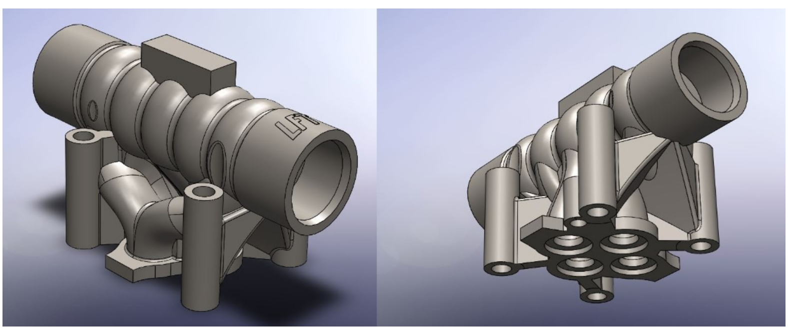

Figure 8: Finished CAD model of the valve housing (86 mm x 47 mm x 43 mm).

7 Valve printing

We printed the valve housing (Figure 9) on the EOS 3D printer with the MS1 [7] material. Maraging steel 1 or tool steel that has great content of nickel and is stainless because of that. This feature is necessary for water hydraulic. Material has yield strength 2010 MPa and ultimate tensile strength 2080 MPa. Material has a density 8.1 g/cm^3 and could after heat treatment achieve 50 -57 Rockwell hardness.

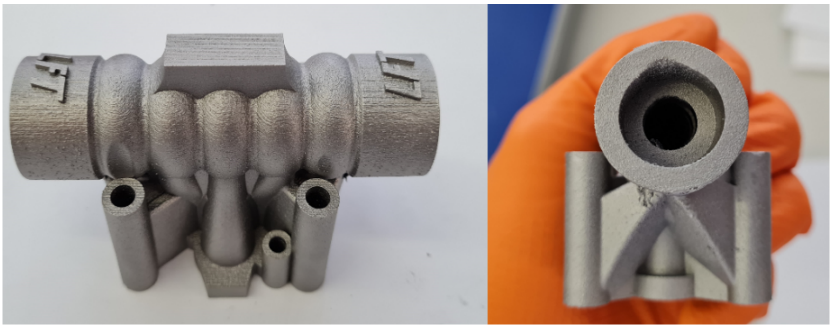

Figure 9: Printed model of the valve housing (86 mm x 47 mm x 43 mm).

After printing, we CNC machined the part to final dimensions. Finally, the hole was honed to exact dimension to accommodate the existing spool valve.

8 Valve testing

We wanted to test the valve to prove that the actual model has similar results to CAD model that was numerically tested. Internal leakage, and Δp-Q characteristics were tested. To ensure as static initial conditions as possible, we kept the water tank temperature at 50 °C using the secondary cooling system.

8.1 Internal leakage

Firstly, we tested the valve housing for internal leakage. We connected the pressure channel of the valve with the water conduit from pump, put the spool valve in centre position and applied 300 bars of pressure. In the period of 1 minute, we measured the leakage from A and B channels. We repeatedly made three tests and moved the spool valve and returned it to initial position between each repetition to simulate realistic scenario. The tests have shown that in a minute an average of 281 ml of water leaked on A channel and 236 ml on B channel.

8.2 Δ*p*-*Q* characteristic

Secondly, we experimentally defined the Δ*p*-*Q* characteristic of the valve (Figure 10). We repeatedly measured the pressure drop between inlet and outlet port of the valve for four different spool valve positions.

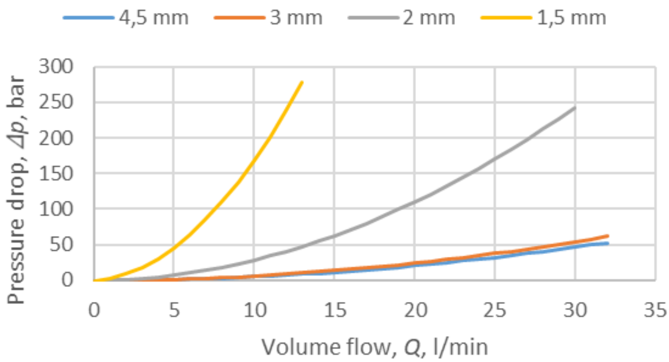

Figure 10: Measured Δ*p*-*Q* characteristic of the valve.

9 Topology optimization

Lastly, we took the internal cavity of the valve and used topology optimization tool to define outer geometry. We wanted to compare our geometry, to the one that we got from topology optimization, to see, where volume of material was unnecessary and could be taken off the initial model. Variating some parameters gave us various results, between which we had to choose from. We took the best result and started to parameterize it into a model, suiTable for printing. Optimized geometry, could not be directly used for further testing, since number of finite elements meshing the model, should be greatly increased. A model straight out of topology optimization is shown in Figure 11.

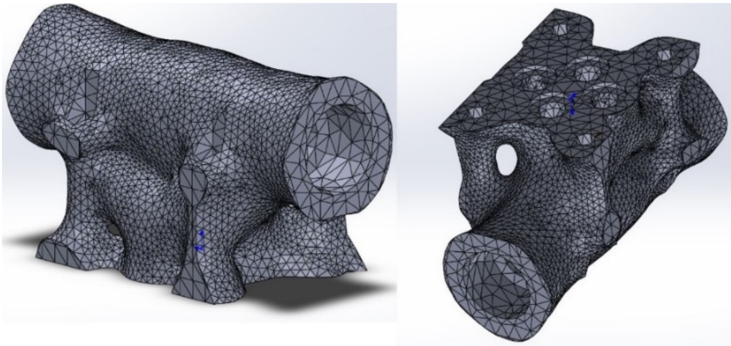

Figure 11: Topologically optimized outer geometry (86 mm x 50 mm x 45 mm).

Model is shaped based on FEA analyses and forces applied. Parameterized finished model is shown in Figure 12.

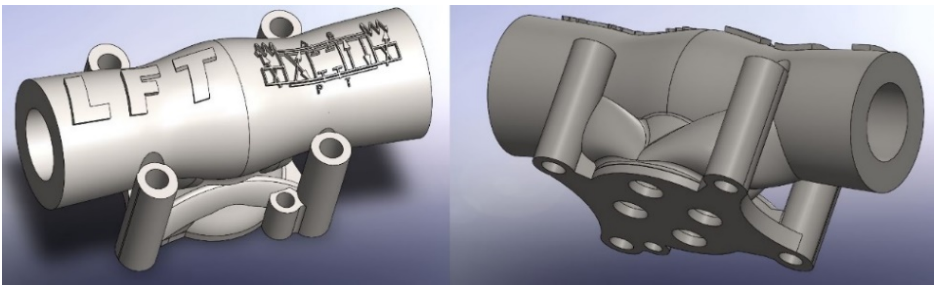

Figure 12: Parametrical finished model of the valve housing (86 mm x 44 mm x 41 mm).

10 Conclusion

3D printing of the parts is a relatively new manufacturing process. It was firstly used just for concept models and small series. In the era where humanity is tending towards a cleaner environment, reduction of mass and lower consumption of energents are crucial for continual development. Metal printing can achieve both of those criteria and can even surpass the competition by lowering the pressure drop because of its internal geometry possibilities.

References

[1] Majdič, F. (2010). Voda kot hidravlična kapljevina: doktorska disertacija. Ljubljana

[2] Majdič, F., Pezdirnik J., Kalin, M. (2011). Vodna hidravlika v Sloveniji in pogled v prihodnost. *Fluidna tehnika, Maribor*

[3] Šenica D. (2015). Proporcionalni potni ventil za vodno hidravliko. Diplomsko delo. Ljubljana

[4] ISO 4401:2005(E). *Hydraulic fluid power— Four-port directional control valves— Mounting surfaces*

[5] Vayre, B., Vignat, F., Villeneuve, F. (2012). Metallic additive manufacturing: State-of-the-art review and prospects, Mech. Ind. 13, 89–96. https://doi.org/10.1051/meca/2012003.

[6] Ngo, T.D., Kashani, A., Imbalzano, G., Nguyen, K.T.Q., Hui, D. (2018)- Additive manufacturing (3D printing): A review of materials, methods, applications and challenges, Compos. Part B Eng. 143, 172–196. https://doi.org/10.1016/j.compositesb.2018.02.012.

[7] EOS: Material data sheet EOS MaragingSteel MS1. Munchen, 2017