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3D-Printed Polymer and Ceramic Spools as Alternatives to Steel for Hydraulic Valves

Jan Bartolj[a)], Ana Trajkovski[a)], Mitjan Kalin[a)], Katharina Schmitz[b)], Franc Majdič[a)]

[a)] *Faculty of Mechanical Engineering, University of Ljubljana, Aškerčeva ulica 6, 1000 Ljubljana, Slovenija*

[b)] *Institute for Fluid Power Drives and Systems (IFAS), RWTH Aachen University, 52074 Aachen, Germany*

jan.bartolj@fs.uni-lj.si

Abstract.

In this work, the possibility of replacing steel spools in proportional hydraulic valves with additively manufactured alternatives was investigated. Four materials were selected: E-Rigid Form, HTM 140, Aceaddity ceramic resin, and SuperHDT. Spools were printed with the same geometry as conventional steel parts, without any optimization, to allow for a direct comparison. The main focus was on the manufacturing process itself and the dimensional accuracy that could be achieved. For this purpose, the spools were measured in 3D and evaluated with respect to circularity and cylindricity, as these parameters are critical for proper valve function. Besides this, hydraulic tests with tap water [1] were also carried out in order to observe flow behaviour, pressure losses, and leakage. The results show that polymer and ceramic resins make it possible to manufacture functional prototypes that are lighter and corrosion resistant, but that dimensional stability and reliability still remain the main limitations.

Keywords: Additive manufacturing, Hydraulic valve spools, Polymer and ceramic materials, Geometric tolerancing (GD&T), Dimensional accuracy

1. INTRODUCTION

Spools are a crucial components in the hydraulic valves, being a movable part that is guiding flow of the fluid through the geometry of the valve. Valves come in various shapes and sizes, and their design us usually based on functionality as well as years of testing, optimisation and engineering practice [2]. Spool valves and so spools can be divided in hydraulics into conventional, proportional and servo valves. Each of those have their unique design based on their operation. In this study we will focus on proportional spools for valves that allow for continuous operation and management of flow, having in theory indefinite possible states between closed and fully opened. Proportional spools have specially made control notches that are distinctive for this type of valves and that are working as nozzle, through which fluid us flowing and is being restricted, thus providing the ability for flow control.

Usually spools for hydraulic spool valves are of cylindrical shape because they need to fit into a hole that is drilled, grinded or honed by the rotating tool. Spools are conventionally made from steel, because this gives them excellent dimensional accuracy, wear resistance, long term reliability and manufacturability, because steel is very well-known engineering material.

However, manufacturing spools from steel also comes with some drawbacks. Machining spools and production of steel in general is highly energy intensive process. Also, if spools and other components were to be used in the water or wet environment, each component must be made of non-corrosive materials such as Stainless-steel or other alternatives. Third drawback is the weight of the steel spools since metals are in general denser compared to modern engineering polymers.

This all got us thinking if it is possible to create light and cheap spools that could withstand forces applied to them under hydraulic pressure and could also be manufactured with energy-less-intensive process thus having lesser impact on the environment.

Since there is a lot of different options to choose from in the engineering alternative materials we focused our direction into mainly polymers. We also wanted to be able to design and produce those vales by ourselves, so we used materials that could be Additively Manufactured (AM) on our 3D printers [3]. We have chosen four different engineering resins that have good thermal or other physical properties such as tensile strength or corrosion resistance. We have decided that this study was the first step towards better and optimized spools that could be used in hydraulics [4-7], but at this stage no geometry optimisation has been done.

Currently, polymers are used in hydraulics mainly for sealing applications and rarely as moving components, critical to the operation of the valves. So, study about feasibility in terms of material properties and dimensional accuracy of the AM manufactured spools, made from alternative materials, had to be made.

Since environmental awareness has been more and more important in recent times, we want to promote environmentally friendly or at least acceptable, hydraulic fluids [1]. In our case we will be using tap water as a hydraulic fluid, which will test our spools in tougher conditions, because water offers worse tribological protection and has tendency to corrode materials which will increase stress on materials. Water also has some positive effects that are combined with environmentally friendliness like non-flammability, availability in large quantities, …

Scope of this study is to manufacture spools originating from same geometry and create them using AM and alternative materials. We will be focusing on manufacturing feasibility, dimensional measurements and material evaluation while conducting the experiments. Goal is to determine whether the polymers are viable materials for spools in highly demanding environments like an inside of hydraulic valves [4].

2. MATERIALS AND METHODS

2.1. Spool Geometry and Design Constraints

As mentioned, we have used the same geometry that conventionally manufactured spool is based on. This is a geometry of quite standard CETOP 3 4/3 proportional directional spool, with outer nominal diameter of 12 mm. To allow the proportional flow control, there are control notches made, 3 per each chamber connection. Notches have width nominal dimension of 2.5 mm and have a depth 2.6 mm. Since this geometry of the spool is not adapted to the Additive Manufacturing (AM) we had to print the spools with a supporting structures that were removed after the printing process. Reference spool is made from Stainless-steel AISI 440-C, firstly turned to rough shape, surface heat treated and then fine grinded to the tolerance specified.

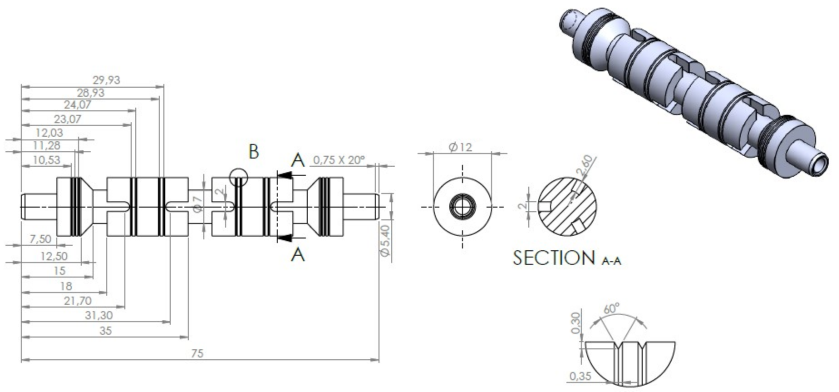

Figure 1: Detailed section from the manufacturing drawing of the spool for hydraulic proportional directional valves.

Usually, for practical application in water hydraulics it is mandatory for spools to achieve tight tolerances ranging from 0 to the negative value of 2 micrometres. This tolerance is crucial to ensure sufficient sealing between internal chambers of the valve by reducing the amount of leakage. Since we did not plan to do any postprocessing machining after 3D printing we did not expect to meet these criteria in full.

2.2. Used alternative materials

We have selected two polymer materials, one ceramic material and one hybrid/ceramic-reinforced resin. Another two polymer materials were from ETEC: High temperature mold material (HTM 140) with heat deflection temperature of 140 °C and Polyurethane-like resin named E-Rigid Form with very good tensile properties. Ceramic resin chosen was from Aceaddity and is named Ceramic Photopolymer 3D printing resin. According to manufacturer this resin contains 30 % ceramic particles. Lastly, we have chosen hybrid/ceramic-reinforced polymer resin SuperHDT that has excellent temperature resistance while still maintaining great load bearing ability. Most essential properties of each material can be found in the table below. In the results we will be presenting measured data with the short abbreviations of the names of each resin. Main advantages and material properties are shown in the Figure 2. Material properties are obtained from the manufacturers data and are dependant on the printing process.

Commercial name	E-Rigid Form	HTM 140	Ceramics 30 %	SuperHDT
Manufacturer	ETEC	ETEC	Aceaddity	3DMaterials
Material	Polyurethane-like polymeric resin	Polymeric resin	Polymeric resin, containing 30 % ceramic powder	Composite polymeric resin with nano-micro ceramic particles
Tensile strength [Mpa]	73	56	47.97 ± 10 %	39,5
Tensile modulus [Mpa]	3250	3350	819.52 ± 10 %	3
Elongation at break [%]	6	3,5	6.9 ± 10 %	<2
Temperature resistance [°C]	62.5	140	280	240
Essential properties	•Water resistance •High stiffness and dimensional accuracy. •Good for detailed geometries and tight tolerances. •Moderate resistance to water exposure; lower wear resistance compared to ceramics.	•Water resistance •Enhanced thermal stability. •Higher resistance to deformation under elevated temperature or prolonged stress. •Similar surface finish to E-Rigid Form, but slightly more brittle.	•Very high hardness and wear resistance. •Excellent corrosion resistance in water-based hydraulics. •Sintering shrinkage must be compensated in design. •Surface roughness and porosity depend heavily on post-processing.	•High density after sintering → improved mechanical strength. •Good dimensional stability and reduced brittleness. •Resistant to chemical attack and swelling in tap water. •Requires precise post-processing to meet hydraulic tolerances.

Figure 2: Alternative materials properties.

2.3. Additive Manufacturing process

Ceramics and SuperHDT were 3D printed using Stereolithography (SLA) process using desktop Anycubic Photon Mono M5 3D printer. SLA printing is a type of 3d printing process that uses photopolymeric resin and UV light to make printed parts. It has several crucial parameters, the most important being layer exposure time. This defines how long each layer is exposed to UV light from the illuminating display. Longer exposure time might make printed parts slightly larger, since more photopolymeric resin is hardening, but shorter times might create objects that are not fully hardened. Layer exposure time is mainly dependent on power of the light source and type of resin that is used for printing.

We used manufacturers recommendations to define parameters to manufacture and post-process the spools. Since recommended layer exposure time for SuperHDT was defined between 5.6 and 7 seconds for our printer, we have used both of these options. Similarly, when printing Ceramics, we used two different layer exposure times defined at 1.35 and 2 seconds.

HTM 140 and E-Rigid Form were manufactured by DLP process using Envisiontec (ETEC) D4K printer. Again, all manufacturers presets were used when defining printing and post-processing parameters. Post-processing in all cases was only cleaning the parts of any residual resin, supports removal and UV curing according to manufacturers specification. All spools that were compared during the research are shown on the Figure 3.

Figure 3: Spools made from alternative materials and standard spool made from AISI 440-C.

Additive manufacturing printers

ETEC D4K
The ETEC D4K is a professional DLP resin printer with a build volume of roughly 148 × 83 × 110 mm, prioritizing accuracy over size. It uses a 50 µm native XY voxel (with

enhanced modes down to ~25 µm) and typical 25–100 µm Z layers, enabling very consistent fine features. Recommended minimum wall thickness is ~0.5–1.0 mm, and dimensional accuracy is strong, with practical fit tolerances around ±0.05–0.15 mm for standard resins when well-calibrated.

Anycubic Photon Mono M5
The Anycubic Photon Mono M5 targets high detail at larger scale, offering a much bigger ~218 × 123 × 200 mm build volume. Its 12K LCD provides an ~19 µm XY pixel size, finer on paper than the D4K, with common 0.01–0.05 mm layers. Practical minimum wall thickness is ~0.5–1.0 mm, similar to DLP systems, while typical clearance fits require ~0.1–0.2 mm due to MSLA exposure and shrink effects.

2.4. Materials characterization

Dimensional properties

We have used different approaches to measuring the dimensional accuracy of 3D printed spools.

Firstly, we used Insize 3109-25A digital micrometre to measure the diameter of the spools. We took two representative spools of each material and took 6 measurements of the diameter per spool. After that, we have plotted all the results into a chart, where it is possible to compare the measured results for each resin.

Secondly measurements were performed on the Mahr MMQ 500 3D measuring machine. By using this, we wanted to measure the circularity and cylindricity. These two parameters are crucial for the geometry, so that spool fits properly into valve housing.

Cylindricity is a form of 3D geometric tolerance that controls how close the surface of the cylinders is to a perfect cylinder. Tolerance zone is the space between two coaxial cylinders within which the surface of a measured part must lie. It is basically a combination of circularity and straightness of the axis and taper.

Mass properties

After dimensional characterization we have also weighted the spools. We used laboratory Gram Lite EH scale to weight the spools and compare the results.

Tribological properties

For the tribological tests we prepared AM made steel discs made from Maraging Steel 1 (MS1) with a dimension of 25 X 25 X 6 mm representing the valve body. Steel discs were polished on automated preparation device RotoForce-3 to achieve surface roughness of 0.1 µm. Representing alternative materials, we made a pins with a dimensions of Φ 10 x 20 mm, with 12.5 mm radius on top.

Tribological tests were performed on a Camern-Plint TE 77 tribometer. In this test pin in sliding reciprocally on a printed disc with a frequency of 10 Hz. Stroke was 2.4 mm which is representative of a sliding distance inside valve housing. Normal load was 65 N. We used water as a lubricant. Testing period of each pin was 1 hour or 36 000 cycles. This was determined in accordance with the normal load to show some kind of wear on each pin. 3 repetitions were done per each material pair. After the tests we evaluated the wear and coefficient of friction and averaged the results. Coefficient of friction was calculated from the ratio of normal and tangential force, that was dynamically measured during testing. Specific wear was calculated using the following equation (1).

$$Specific\ wear = \frac{\pi * d_{mid}^4}{64 * R} \tag{1}$$

Secondly, we observed the wear that was the result of the normal force and reciprocating motion between each material pair. Since we were using pure tap water as a lubricant, we were able to observe the rust that was forming on our MS1 discs.

Hydraulic properties

Since geometry of the spools was the same in all cases we did not expect any differences (improvements) in hydraulic measurable parameters. Mainly we wanted to determine if these materials are suitable for use in hydraulic environment. We used self-developed water hydraulic test rig capable of 11 kW hydraulic power or 350 bar at 30 l/min. Pump used is axial piston pump with 3 pistons. Spools were tested in the AM made valve housing which is connected to the also AM made mounting plate. AM valve has been optimised in terms of complex internal geometry to impose as low as possible resistance to the fluid flow [8]. AM mounting plate has been optimised as well, but mainly in terms of transducer placement, because we can measure the pressure extremely closely to the valve itself, thus reducing the uncertainty in the measurement coming from other sources.

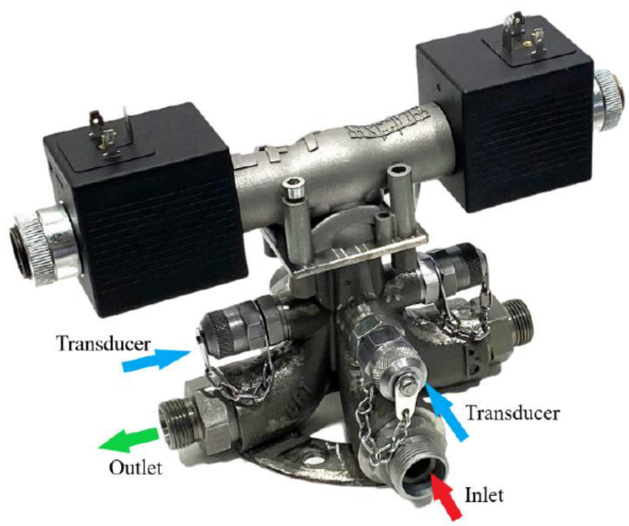

Figure 4: Valve in the testing assembly with magnets, mounting plate (AM) and hydraulic couplings.

Simple hydraulic scheme is shown on the Figure 5. As mentioned before, we have used 11 kW water hydraulic test rig. Each spool was tested separately to test its ability to withstand the load in form of hydraulic pressure. We were measuring hydraulic pressure on the input and at the output from the valve. Mainly we wanted to determine if alternative materials are suitable for usage in real hydraulic applications. So, leakage test was performed first, followed by pressure drop characteristics dependent on the volumetric flow. Lastly pressure was increased in the pressure chamber till the breakage point of the spool itself. Leakage test was performed with spool in the middle neutral position. After applying the hydraulic pressure, we have measured the amount of leaked fluid on the neighboring A and B channels. For the pressure drop test we have gradually applied volumetric flow, and measured the pressure drop between the pressure (P) and working (A) port. Spool opening was kept constant at predetermined displacements, spaced by 0,25 mm. Since internal structure of the valve is symmetrical, we have switched position of the spool to the other side, just to confirm that both values were comparable.

Hydraulic tests were performed only using Ceramics and SuperHDT spools. This was due to the unavailability of the E-Rigid Form and HTM-140 resins during the stage of printing actual spools for usage in hydraulic valve.

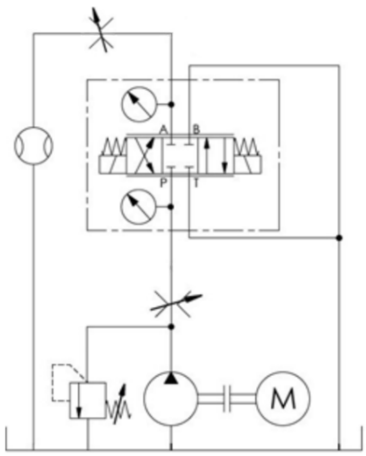

Figure 5: Simple hydraulic scheme for testing purposes.

3. RESULTS

3.1. Dimensional properties

Figure 6 is showing the measured results for each spool made from different materials. For the SuperHDT and Ceramics there are two sets of measurements, because these materials were printed at two different times of exposure per layer. It is evident that SuperHDT at both settings as well as E-Rigid Form and HTM 140 were printed with dimensions that were smaller than nominal dimension. Comparing these results to steel we can also see that distribution of measurement is quite large. Since steel spools were grinded to achieve the tolerance, the distribution of measurements is expectedly low. Largest distribution could be seen for the E-Rigid Form, but this is also the closest by the mean value to the nominal. HTM 140 was also relatively close comparing to the others, deviating from the nominal dimension by approximately 80 µm. It is interesting to note that both printed Ceramic spools were measured above the nominal dimension. We can also clearly see the increase in the dimension for the Ceramic spool where we used higher exposure time. Sam principle can be observed for longer time of the exposure at SuperHDT.

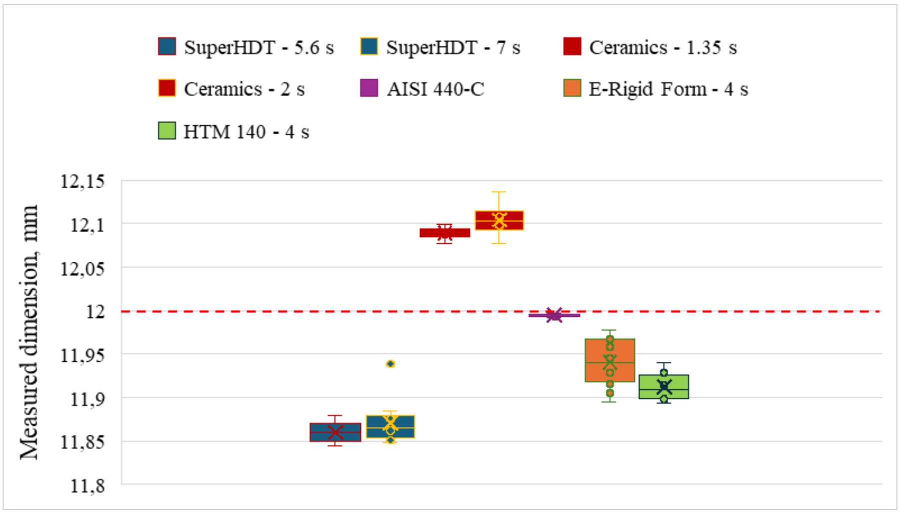

Figure 6: Measurements taken by micrometre plotted and compared according to 12 mm nominal dimension.

Cylindricity

In our case we measured each spool to determine the deviation from the perfect cylinder shape. Expected, from the previous circularity measurements, was that Ceramics printed at both exposures would perform the worst, which is actually the case here. Ceramics printed at 1.35 s exposure has a cylindricity 83.8 µm and printed at 2 s 112.3 µm. Again, we can see that elongation of exposure time made a result worse. HTM 140 resin preformed moderate with a cylindricity of 44.7 µm and E-Rigid Form 50.5 µm. Interestingly SuperHDT resin has a poor result at 5.6 s exposure time of 70.7 µm, but this result is greatly improved for increased exposure time at 7 s and was measured at 23.2 µm. Still the best performance was measured for the grinded Stainless-steel AISI 440-C spool at 2.4 µm.

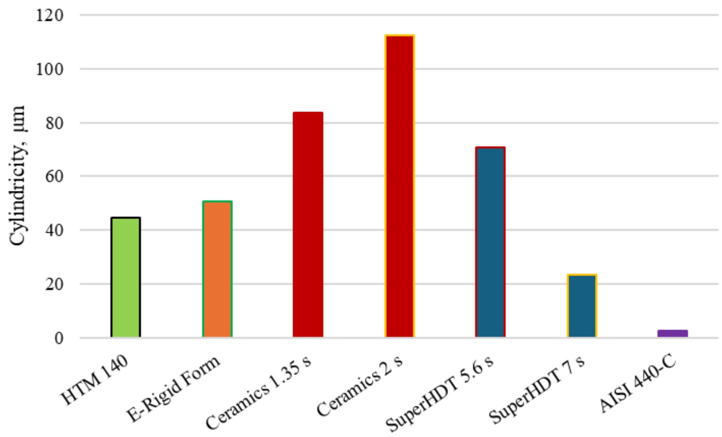

Figure 7: 3D measurement of cylindricity for each alternative material and standard AISI 440-C stainless steel.

3.2. Mass properties

Polymer spools weighted in at 6.21 g (E-Rigid Form) and 6.32 (HTM 140). Spool made from 30 % ceramics is weighing 7.01 g and partially ceramic spool (SuperHDT) 6.45 g. Our reference spool made from Stainless-steel has a measured weight of 44.82 g. In conclusion, all spools made of alternative materials are significantly lighter compared to the reference that is commonly used.

3.3. Tribological properties

Coefficient of friction

Firstly, we measured the coefficient of friction. This result is calculated based on the normal load and the measured value of tangential force needed to ensure reciprocating motion of the pin. Looking at the results of the measured coefficients of friction, we can observe how the values are changing per increasing cycle count. We can see the expected rising at the beginning where the load was applied and then all values star to converge towards certain values. Only E-Rigid Form is showing in this case that it would probably need more time and cycles to end the fluctuation in the results. No measurable differences between base and elongated exposure times were detected during testing for both Ceramics and SuperHDT, so we only included samples made with manufacturers recommended exposure times.

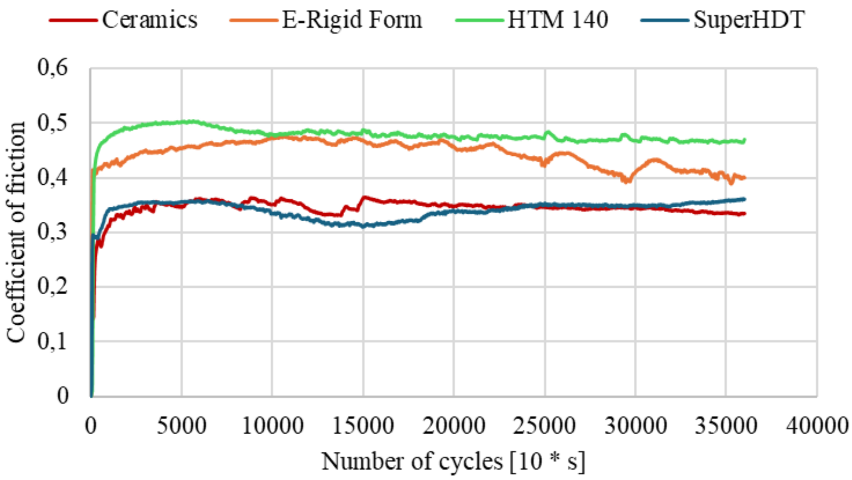

Figure 8: Coefficient of friction measured per 36000 cycles from the pin-on-disc tribological test.

Lowest averaged coefficient of the friction was achieved by the SuperHDT pin with a value of 0.342. Both polymeric pins did perform slightly worse with E-Rigid Form measuring 0.423 and HTM 140 measured 0.471. Here it is important to mention that only Ceramics had a noticeable sound when tribological test was performed. For comparison we have added the measured value of tribological pair AISI 440-C and MS1. It is very interesting that both ceramic and ceramic-powder-filled resin perform slightly better compared to steel-on-steel contact when lubricated with water.

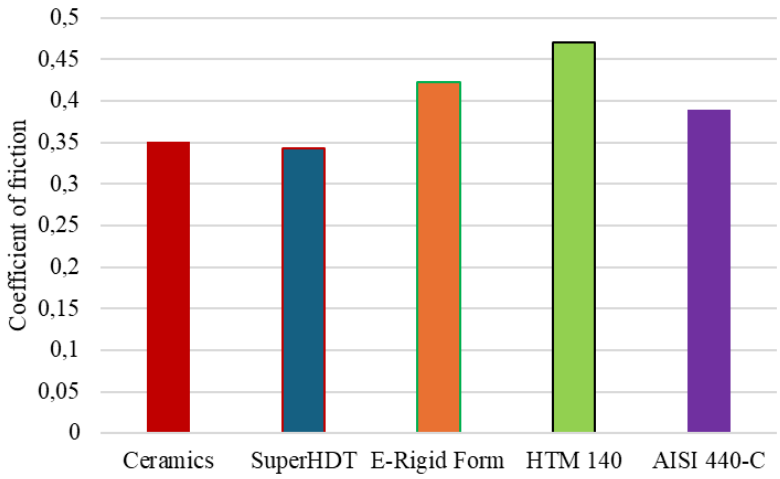

Figure 9: averaged value calculated of friction coefficient compared between alternative materials and standard AISI 440-C stainless steel.

Specific wear

It is evident that the smallest wear trace was left in the case of the Ceramics, because having the highest surface strength. Expectedly this also led to the smallest calculated specific wear of 0.223 mm^3/Nm. Impressively, HTM 140 also achieved quite low specific wear at 0.798 mm^3/Nm. Looking at the abrasion mark we can see that material was performing as a homogenous solid, without any material being compressed under the load force. Material degradation can be spotted in the case of E-Rigid Form. In the middle section of the pin abrasion mark it is evident that material did not withstand the load applied. Because of this, the highest Specific wear was calculated for this material at 1.986 mm^3/Nm. SuperHDT material had an abrasion circle on the pin with a diameter of approximately 4 mm with calculated specific wear 1.06 mm^3/Nm.

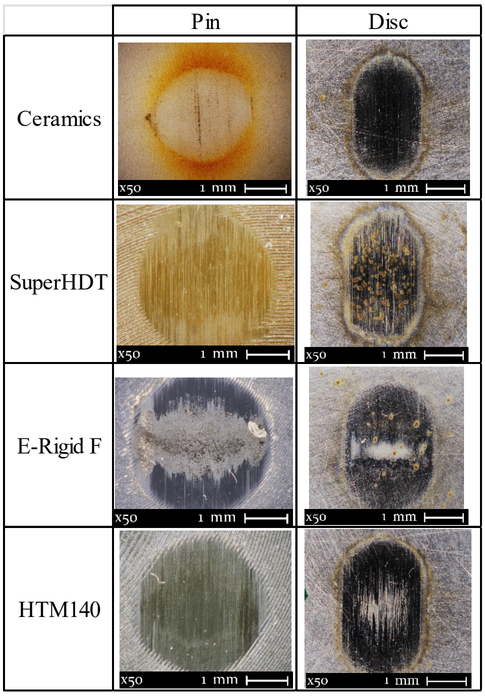

Figure 10: Digital microscope images of wear tracs on Pins from alternative materials and discs from MS1 steel.

Figure 11 is representing the measured specific wear values for each material.

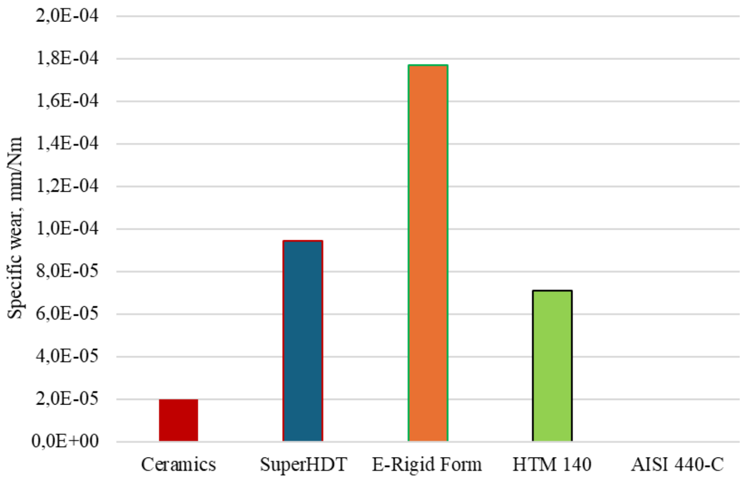

Figure 11: Specific wear for each material after tribological pin-on-disc test.

3.4. Hydraulic properties

Firstly, leakage of the hydraulic fluid was measured to determine the ability of the spools to sufficiently seal the internal chambers of the valve between themselves. Since circularity and cylindricity GD&T were not achieved, we did not expect the sealing and consequently to be sufficient and so that leakage to be quite high. This is confirmed on the Figure 12 where we can see that leakage measured was about 6 times higher in the case of two ceramic materials compared to AISI 440-C grinded spool. This was expected to have great consequences on the following results.

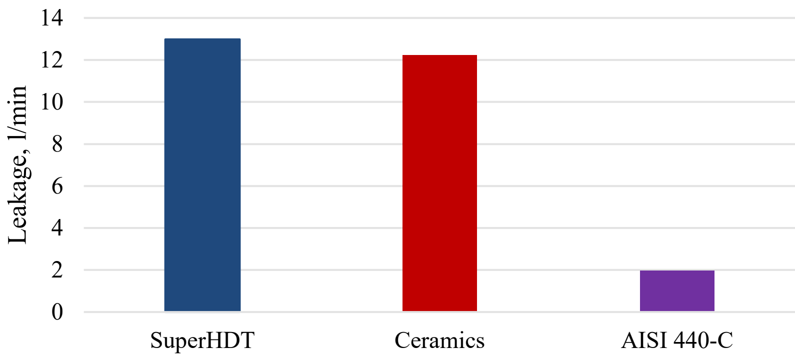

Figure 12: Measured leakage of hydraulic fluid between internal chambers of the valve.

Secondly, we measured the spool and valve characteristics during hydraulic operation. On the Figure 13, the results are shown for the 30 % valve opening. Effect of the internal leakage are quite obvious in this case. Since all measurements were supposed to show similar characteristics, due to leakage, the difference is quite noticeable. It is worth mentioning that results are shown at quite low pressure. This was done to prevent the spools from breaking under load prematurely. After determining the pressure drop per volumetric flow characteristics, we have used 15 % valve opening at high pressure to determine how high hydraulic pressure the spools could withstand. SuperHDT spool did brake at 8.5 MPa of pressure, while spool made out of 30 % ceramics did not break at 7.5 MPa but the leakage was so high that we could not increase hydraulic pressure any longer due to limitations of our hydraulic aggregate. But Ceramic spool did brake once 10 MPa of hydraulic pressure was applied as an impulse.

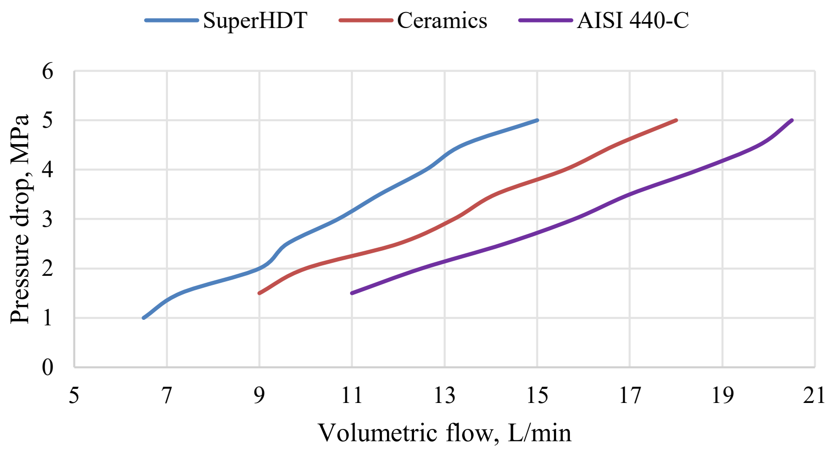

Figure 13: Measure performance of alternative spools compared to standard AISI 440-C steel spool.

Spools broken during actual hydraulic testing can be seen on the figure 14 below. Interesting, while also expected is, that both spools on the figure below did snap at the same location. This is obviously the weakest point of the spool geometry.

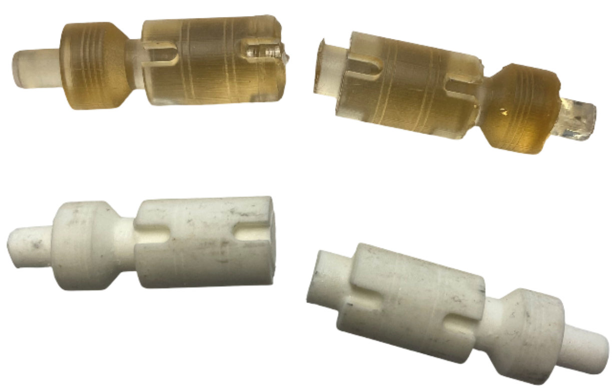

Figure 14: Spools from alternative materials, that were broken during actual hydraulic testing.

4. CONCLUSIONS

When comparing the additively manufactured spools with conventionally grinded steel spools, it is clear that the printed parts do not reach the dimensional tolerances required for efficient use in hydraulics. This was confirmed both by manual measurements and 3D evaluations, with circularity and cylindricity values outside the acceptable range. Some form of post-processing therefore appears unavoidable. On the other hand, the use of alternative materials results in spools that are about seven times lighter than steel, which can be advantageous in many applications. From a tribological point of view, the coefficient of friction is comparable, with ceramics and ceramic-filled resins even showing better performance than steel in certain cases. The weak point remains wear, which is significantly higher for all alternatives.

We have proven that simple spool geometry that was 3D printed could not withstand higher pressures that are usually applied to the hydraulic components. Both tested spools did brake at the pressures equal or less than 10 MPa. So, if there was an application of lower pressure hydraulics these spools might be feasible. For the lower pressure and power, we have proven that characteristics are relatively similar, but still the shape that is not reaching the defined GD&T tolerances, is mainly held back by the amount of leakage between the internal chambers of the valve.

For the further development, we are suggesting the improvement of manufacturing process in a way to create spools that are achieving or are at least closer to the tolerances that are required. Also, it would make sense to use materials that could withstand higher loads.

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Special thanks are also due to Poclain Hydraulics d.o.o. for conducting the 3D measurements of the manufactured spools, which were essential for determining the geometric specifications presented in this study.

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Biography

Jan Bartolj is a PhD student and researcher at the Faculty of Mechanical Engineering, University of Ljubljana, specializing in additive manufacturing and its applications in the hydraulic industry. His research focuses on the design, optimization, and numerical simulation of hydraulic components, with a strong emphasis on innovative 3D printing solutions. He has collaborated on multiple industrial and academic projects, authored several scientific publications, and was awarded the Golden Diploma by the Slovenian Fluid Power Society in 2023. Driven by the ambition to become a global leader in this field, he is dedicated to advancing the hydraulic industry through modern manufacturing technologies.