Sliding contacts of 3D-printed direction control valves - tribological performance of suitable material pairs

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Abstract

Water hydraulics traditionally faces limitations, particularly concerning corrosion, lubrication challenges, and wear, as water lacks the natural lubricity of oil-based hydraulic fluids. However, with the precision and design flexibility provided by metal 3D printing, key components such as valves, or their parts, can be produced with complex internal geometries that both reduce component mass and improves flow. This enhancement has a direct impact on the efficiency and responsiveness of the hydraulic system, which is essential for proportional control applications.

In our study we have analysed materials suitable for spools in sliding contacts of Maraging steel 3D printed direction control valve housing. Tribological tests focused on identifying material pairs that exhibit low friction and wear in a water-based environment, which is crucial for extending the service life and reliability of water-hydraulic systems. For comparison reason, material pairs were also tested in hydraulic oil ISO VG46. Tested materials were nitride stainless steel, anodised aluminium and bronze. The durability tests on three valves with selected material pairs were also performed.

Based on tribological testing conducted in water, the lowest coefficient of friction was observed when a bronze pin slide over a 3D-printed steel plate. The minimal specific wear volume was achieved with a nitride steel pin. Additionally, anodisation was found to significantly enhance the wear resistance of aluminium. Durability tests of the valves indicated that the most suitable material combination involved a bronze spool. This study emphasizes the potential of water hydraulics in specific applications where sustainability and environmental considerations are critical.

Keywords: hydraulic valve, friction, wear, water, tribological tests, durability tests

1 Introduction

Hydraulic fluid power systems are vital in various engineering fields, including transportation, heavy industry and robotics. However, hydraulic oil leaks can cause significant environmental damage. Hose defects and leaking couplings are the most common causes of such accidents, accounting for 50 % of cases. On construction sites, 74 % of fluid leaks involve hydraulic oil, with 30 % of these spills exceeding 20 litres [1]. Contaminated soils or waters must be cleaned at considerable cost to restore them to their natural condition. Additionally, limited amount of mineral oils in the nature, underscores the need for sustainable alternatives and efficient resource management. Increased environmental awareness has led to an ecological transition, which aims to use both novel materials and environmentally acceptable lubricants to replace the traditional oil-based hydraulics.

1.1 Lubricants

Current EU and national emission regulations, based on United Nations memoranda, have already imposed restrictions on the use of certain key lubricants. Green lubricants are becoming mandatory in maritime and hydropower units, water-based hydraulics can be found in nuclear engineering, coal mines, steel foundries, desalination plants, firefighting, food/beverage production and plastics moulding. Green lubricants are also increasingly desirable in farming, forestry and mobile machinery, food processing and pharmaceutics [1], with high potential and concern on contamination or fire due to oil leakages. Growing concern about environmental issues has led to renewed interest in water hydraulics.

Water is non-toxic, environmentally friendly and readily available. Water-hydraulic systems are usually made of very high-quality materials and fabricated with precision machining, which for consequence has between 30 % and 400 % higher costs of water-based compared to the oil-based system [2]. Using water as a pressurized medium demands high corrosion resistance and presents potential issues such as cavitation, requiring the use of materials like stainless steel, bronze, or ceramics. Furthermore, the low viscosity of water necessitates the use of narrow clearances to prevent excessive leakage, components must be fabricated with high precision finishes. Water also does not provide adequate lubrication for commonly used stainless steel components. Consequently, the number of manufacturers and components suitable for water hydraulics remains limited [3–7]. The higher costs of water-hydraulic systems are a trade-off for their environmental, safety, and operational advantages. While upfront costs are steep, the benefits can outweigh these costs in specific applications where environmental sustainability and safety are paramount. Additional improvements can be achieved by improving valve construction and manifold design, potentially by using the advantages of 3D printing method.

1.2 Materials

Additive manufacturing (AM) has recently enabled the production of hydraulic valves and manifolds with intricate geometries that were often impossible using conventional manufacturing techniques such as CNC machining or casting. AM, a layer-by-layer assembly process based on 3D computer-aided design (CAD) data, offers significant design flexibility and allows for the realization of complex internal structures. The inherent advantages of AM include the elimination of design constraints associated with traditional methods which can contribute to optimized fluid flows and pressure drops. With this approach we can produce fully functional metal parts in a single process, without the need for extensive material removal. This results in products that are up to 70 % lighter than metal products made with traditional manufacturing methods. This process opens up new possibilities for design flexibility, production efficiency and waste reduction [8]. With AM capabilities, hydraulic systems can be designed with smoother, more efficient flow paths, resulting in improved performance, higher operational precision, increased pressure resistance, and enhanced reliability. In our recent work, we have shown that designing the component such as hydraulic proportional spool valve is complicated work but has many positive effects. We successfully reduced the mass of the final part by 63 % and increased the flow characteristic compared to conventionally manufactured counterpart [9].

Companies such as Aidro are already incorporating AM in production of hydraulic manifolds and valves production for diverse applications. John Deere has incorporated AM in manufacturing stainless steel valves for tractor fuel systems, achieving enhanced efficiency, smaller size, reduced material usage, and approximately 50 % cost savings compared to traditional manufacturing methods [10–14]. Also, USA based hydraulic components producer MOOG, has shown the 3D printed version of All-in-one hydraulic system with reservoir, pump, control components and actuator, showing another strong point of AM, which is consolidation of components into single unit. Beyond improvements in mass and flow characteristics, AM enables the integration of advanced functionalities such as embedded sensors or special designs such as a number of connected small on/off valves for digital flow control unit.

Incorporating new materials and manufacturing procedures consequently require the knowledge of mechanical and tribological properties of these materials. For hydraulic components, such as control valves, the tribological properties of incorporated materials pairs in combination with used lubricant are of special interest. By combining the advantages of the new surfaces, materials, and lubrication technologies for friction reduction and wear protection in various equipment worldwide, energy losses caused by friction and wear could potentially be reduced by 18 % in the short term (8 years), or as much as 40 % in the long term [15]. Although 3D metal printing seams very promising, it also brings challenges that require special knowledge to ensure the desired results of 3D printed metal. Achieving high surface quality, dimensional accuracy and appropriate mechanical properties are areas where much research has still to be done. In 3D metal printing, the porosity of the printed material itself is very important. It is known that the faster the printing, the greater the porosity of the material, which usually means poorer mechanical properties. However, high porosity when oil is present in contact can even be desired, since the oil retained in the porous holes can contribute to better tribological properties and lower friction [16].

In order to reduce the component mass, aluminium and as well as high-performance polymers are often used [17,18]. Due to aluminium low specific density, low weight, high thermal and electrical conductivity, and availability, aluminium and its alloys are the most widely used metals for reducing the total mass of the system and the energy consumed for their manufacture and operation [19]. However, due to their low hardness and higher possibility of successive abrasive wear, the use of these materials is often limited to applications with low friction and lower loads [20,21]. To increase the surface hardness of aluminium parts, various surface protection processes have been developed, such as conventional and hard anodising [21], micro-ring oxidation (plasma electrolytic oxidation) [20] or heat hardening with oxygen [22]. Conventional anodising typically produces aluminium oxides up to 25 μm thick layer, while hard anodising produces thicknesses between 25 and 150 μm thick layer [21] similar to HVOF [22], with surface hardness increased by a factor of 5 to 8 [19]. The anodising process and parameters can significantly affect the corrosion resistance of aluminium alloys [23]. Despite the widespread use of aluminium and its alloys in various industrial applications, tribological properties are most often investigated under dry conditions [19,21] or in hydraulic oil [24]. Another material known for excellent corrosion resistance and good sliding properties (even in aqueous environment) is bronze [25]. This alloy consisting mainly of cooper also has good strength and hardness even at elevated temperatures.

In this research, we have tested a 3D printed directional control valve body in combination with tree different materials for control spools: aluminium, bronze and for comparison reason standard stainless steel. These spools, and sliding contacts are essential for the operation of hydraulic systems. Basic tribological tests allowed us to study different material pairs and measure the coefficient of friction and wear, thereby determining the most suitable materials pairs for use in water hydraulics. Tribological tests were done in water and for comparison reason in standard hydraulic oil. In addition, we developed a measuring set-up for testing of hydraulic valves, for durability and reliability test under real operating conditions. Our research opens up new possibilities for the improvement of water hydraulic systems.

2 Methods

2.1 Tribological Tests

2.1.1 Materials – samples and lubricants

For the tribological tests (fig. 1.a) we prepared 3D printed discs (25 x 25 x 6 mm, fig. 1.c), made of maraging steel (MS1/1.2709) which represented valve body. The discs samples were polished in several steps using a RotoForce-3 automatic sample polishing and preparation device, to a final roughness of 0.1 µm. The pins samples (Φ 10 x 20 mm, with 12,5 mm radius, fig. 1.b), were prepared of three different materials: bronze (CuAl10Fe3Mn2/2.0936, fig. 1.b-1), a commercially available, standard hardened stainless steel (AISI 440-C/1.4125, fig. 1.b-2) and aluminium alloy (EN AW 6082/3.2315, fig. 1.b-3). The pin samples were also polished with the same procedure as MS1 discs, and after that aluminium samples were anodised by standard procedure (EN AW 6082 an, fig. 1.b-4). Pin samples represented valve spools. Materials microhardness was measured with standard Vickers hardness tester and an indentation force of 0.5 N. The main mechanical properties of used materials are represented in tab.1. Before each test, the samples, clamps and pins were cleaned in ethanol and dried in air.

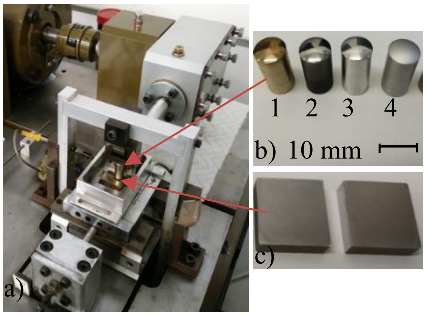

Figure 1. a) Tribological tests set-up;
b) pins: 1- Bronze; 2- AISI 440-C; 3-Al 6082; 4-Al 6082 an;
c) disc - 3D printed MS1.

First lubricant was commonly used ISO VG46 hydraulic oil. The second lubricant was demineralized water (W).

Table1. Material properties of prepared samples

Material	Density [kg/m^3]	Young modulus [GPa]	Ultimate tensile strength [MPa]	Hardness [HV]
pin				
Bronze	7,6	120	560-690	~261
AISI440-C	7,6	200	760-1960	~695
Al 6082	2,7	70	260	~132
Al 6082 an				~200
disc				
MS1	8-8,1	180	2080	~460

2.1.2 Experimental procedure

Tribological tests were performed on a Camern-Plint TE 77 high-frequency tribometer (fig.1a). During the test, the pin slides in a reciprocal mode on the 3D printed disk-like plate. The average sliding velocity was set to 0.05 m/s (frequency 10 Hz), with stroke length 2.4 mm, which represents the valve spool stroke in a CETOP 3 size 4/3-way slide valve. The tested 3D printed valves used in this research fall into this size class. The normal load was set to 65 N. Before each test, the tested samples were completely immersed in the selected lubricant. During the tests, the current value of the friction coefficient was automatically recorded. The tests were performed for 60 minutes based on our preliminary tests, which showed a stable value of the coefficient of friction and measurable wear. Each test was repeated three times in water and hydraulic oil, and the average values of the steady-state friction coefficient are used for the comparison analysis.

2.1.3 Wear evaluation

The wear volume of the pins was calculated from the dimensions of the wear tracks, which were measured using a 3D digital microscope with an additional nano-point confocal profilometer Hirox HRX-01 & NPS. We determined a 3D profile for each calotte and the dimensions of the wear calotte with Mountain Map software [17]. The digital microscope also made it possible to determine the shape and dimensions of the wear tracs and surface films on the steel discs.

2.2 Hydraulic durability tests

For the control spools, we used the same materials as for the pins during the durability test: aluminium alloy Al 6082, bronze and stainless still AISI 440-C (fig.2). Due to the problems with tolerances after the anodisation, we have only tested valves with standard aluminium alloy spools (Al 6082).

Figure 2. Prepared control valve spools: a) aluminium alloy Al 6082, b) bronze and c) hardened stainless steel AISI 440-C respectively.

The control valve body was produced with the EOS M290 metal 3D printer with the SLM (selective laser melting) method (fig.3). The Maraging tool steel X3NiCoMoTi (MS1) was used, with the properties of stainless steel due to its high nickel content. The printing of the valve with a final volume of 49 cm^3 took about 5 hours. The valve body was modelled and topologically optimised in few successive steps, the modelling process is explained in detail, in our previous studies [9].

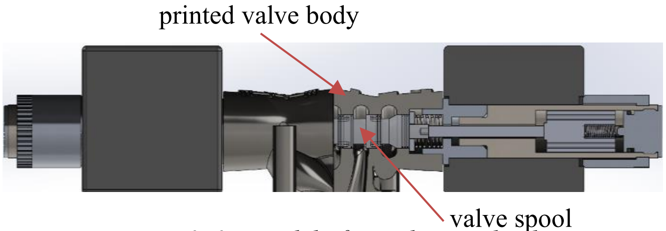

Figure 3. 3D model of tested control valve

2.2.1 Hydraulic test-bench

Figure 4 represents simplified hydraulic scheme of the test rig used for the durability test. An electric motor drives a high-pressure water pump in the main water tank. From the high-pressure pump water flows through a check valve, a flow meter and an adjustable flow valve with pressure compensation. After the pressure filter, the water continues its path into the hydraulic manifold (pos. 8), to which three 3D printed proportional hydraulic valves were attached (pos. 9.1, 9.2 and 9.3). From the P-line, water flows forward the A- or B-line of the individual valve (depending on the valve switching position). The water then continues its path to the orifices (pos. 10.1-10.6), which cause a load in the hydraulic system, simulating real working conditions. From here, the water travels forward into the common return T-line, and through a return filter back into the water tank.

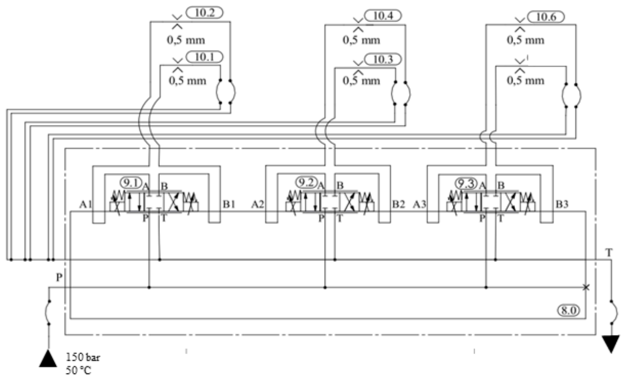

Figure 4. Simplified scheme of hydraulic test-bench

2.2.2 Experimental procedure

All connections to the hydraulic manifold and connections to the hydraulic pipes as well as rigid pipes were made of stainless steel.

The durability tests were performed for about 4 million switching cycles, with the pressure relief valve set at 150 bar. The water thermostat in the tank was set to 50 °C. The test bench operated in such a way that all three valves switch simultaneously.

For the measurement of internal leakage of the valves we installed new pipes on all A and B outputs from the hydraulic manifold, through which water flowed into the measuring cylinders. Test was performed for 90 seconds, while the amount of water that flowed into a specific measuring cylinder was measured. The internal leakage measurements were repeated 3 times for each valve. These tests were performed before the durability tests, and once a week for three following weeks, afterwards. The pressure of the relief valve was set to 50 bar during the internal leakage measurement. To be able to measure for a longer period of time. The water temperature in tank was set at 50 °C, with the cooling system operated when needed.

3 Results and discussion

3.1 Tribological testes

3.1.1 Coefficient of friction evolution

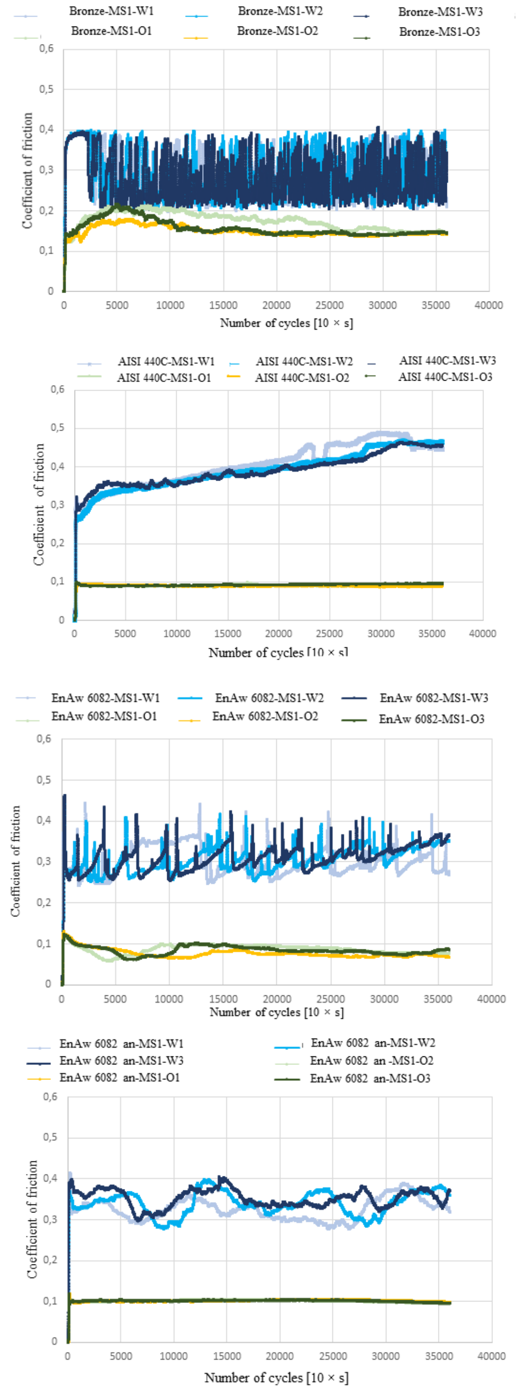

Figure 5. Coefficient of friction evolution during the tribological test of: a) bronze; b) AISI 440-C; a) EN AW Al 6068 d) EN AW Al 6068 an - Pin against MS1 in water and hydraulic oil

Figure 3 shows the evolution of measured coefficient of friction during individual tests of bronze, AISI 440-C, aluminium alloy Al 6082 and anodised aluminium alloy pin samples, respectively. When lubricated with ISO VG46 hydraulic oil, coefficient of friction reaches a stable value almost immediately for AISI 440-C and anodised aluminium, and relatively quickly, with in the first 5000 – 10000 cycles (500 - 100 s) for bronze and basic aluminium alloy respectively.

However, the coefficient of friction measured in the water doesn't show typical running in, it rather has unstable value around the relatively higher coefficient of friction compared to oil lubricated condition for all tested materials. Based on the results of measurements, the fluctuation observed in case of water lubricated conditions indicate, that water incorporates some instabilities into the sliding contact. Although, fluctuations do not disappear, there is a trend of normalization after about 200 s of running in time in case of aluminium alloy in water, also these instabilities are not as significant for anodised aluminium. In case of bronze the fluctuations are constant and persistent. In case of standard AISI 440-C these instabilities are not evident, although coefficient of friction is linearly increasing during the observed period of time (almost 50 %).

3.1.2 Coefficient of friction

Figure 6 represents average values of measured steady coefficient of friction for all tested samples in both water and hydraulic oil. Lower values of coefficient of friction were observed in hydraulic oil, for all tested samples compared to water lubricated conditions. However, the coefficient of friction increased in water, from about 1.75 times for bronze up to 4.5 times for AISI 440-C and aluminium alloys.

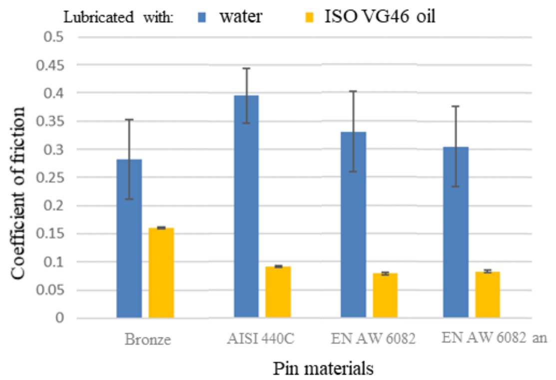

Figure 6. Coefficient of friction (average value ± sd) for all tested Pin-s against MS1 in water and hydraulic oil

In oil, EN AW 6082 showed lowest measured coefficient of fiction with comparable values to measured values for anodised aluminium and AISI 440-C, all around ~ 0.09. Under same lubricated conditions, bronze showed about 50 % higher values of coefficient of friction (~ 0.16).

When water was used as lubricant, the lowest value of coefficient of friction was measured for bronze, around ~ 0.28, followed by anodised aluminium (~ 0.33), standard aluminium EN AW 6082 (~ 0.33) and considerably higher values were measured for AISI 440-C (~ 0.39). In water both bronze and aluminium alloy give good response compared to standard stainless steel, and from that point of view could be potentially good materials for water hydraulics. When we account for fluctuations in measured values seen in for bronze, aluminium alloy is expected to enable smoother working conditions even in water. Additionally, process of anodising aluminium alloy, enabled considerable decrease of coefficient of friction.

3.1.2 Specific wear

Based on repeated measurements in water and hydraulic oil, fig. 7 represents average values of calculated specific wear from analyzed pictures of wear tracs, of all tested pin materials.

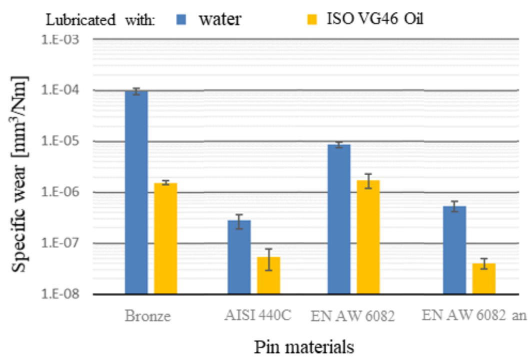

Figure 7. Specific wear (average value ± sd), for all tested Pin-s against MS1 in water and hydraulic oil

In hydraulic oil, we can see that both AISI 440-C and anodised aluminium showed lower specific wear (~ 5×10^{-8} mm^3/Nm), compared to EN AW 6082 and bronze with comparable and almost two orders higher specific wear (~ 1.5×10^{-6} mm^3/Nm).

As expected, specific wear was higher in water and again lowest measured was for AISI 440-C (~ 2.5×10^{-7} mm^3/Nm), fairly followed by anodised aluminium (~ 5×10^{-7} mm^3/Nm). The highest specific wear was measured for bronze (~ 1×10^{-4} mm^3/Nm). However, the increase of specific wear in water, for EN AW 6082 was not as significant, and stayed at the same order as calculated in oil (~ 8×10^{-6} mm^3/Nm).

Based on the results, we can conclude that the best results were accomplished by AISI 440-C and anodised aluminium. However, since water had the lowest impact on increase of specific wear of EN AW 6082 it can be considered as an interesting alternative, which can potentially be used for very different and demanding working conditions.

3.1.3 Surface analyses

After the tests, wear tracks of both pin and disc in sliding contact, were analyzed with digital microscope (fig.8). From the pictures it is clear, that the most significant wear and material removal area is evident in bronze, when lubricated with water (W). Also, for the bronze pin the stretches in the sliding direction are the most intensive, thick and prominent, suggesting abrasion as main wear mechanism.

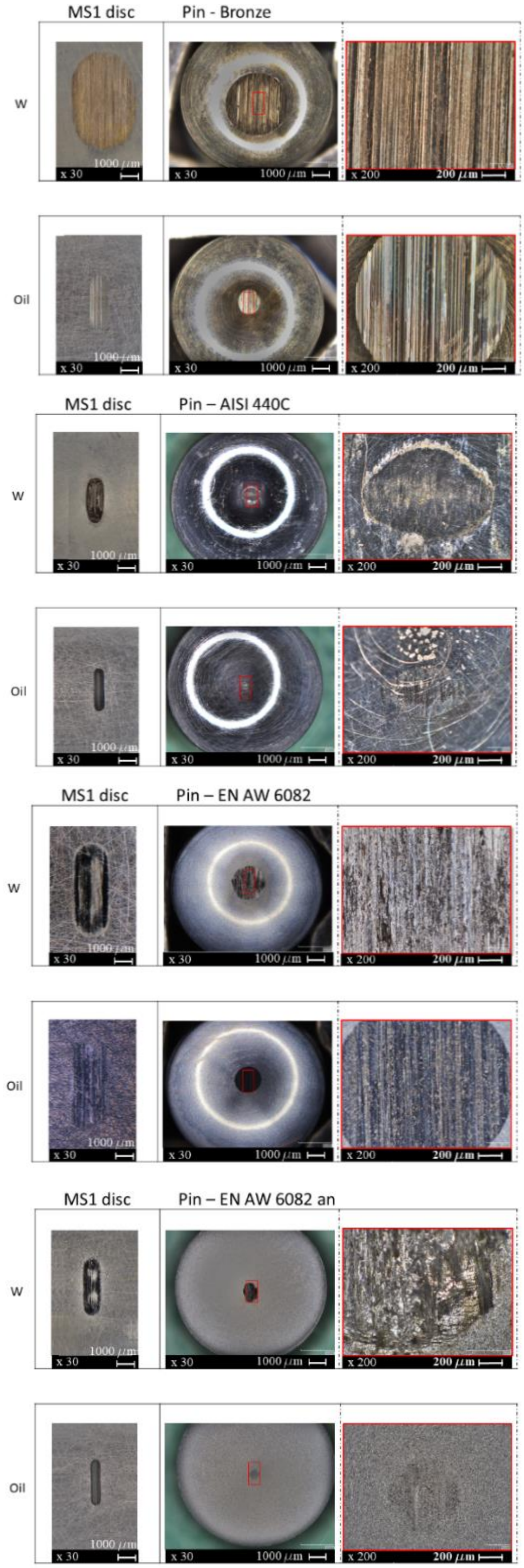

Figure 8. Digital microscope images of wear tracs on MS1 discs and all tested Pin-s after sliding in water(W) and ISO VG46 hydraulic oil (Oil)

For other tested materials, the difference between wear track on MS1 disc in water in oil is not as significant. But there is a trend in more prominent pin wear and material removal in water as compared to oil lubricated condition for AISI 440-C and anodised aluminium (EN AW 6082 an). Stretches in the sliding direction are also present in AISI 440-C and aluminium, but not as intensive. Anodised aluminium results suggest relatively small wear area, with area comparable to AISI 440-C, but different wear mechanism present. There were irregularities present, that probably present peeled anodised protective layer in water, thus suggesting adhesive wear.

3.2 Hydraulic durability tests

3.2.1 Internal leakage

The internal leakage was measured for each valve on lines A and B and averaged afterwards (Q_L). Figure 9 shows the internal leakage of all three valves, measured before the durability test, and after about 1, 2.7 and 4.2 million of cycles. Switching cycle represented the control spool movement from the zero position to the first working position, followed by switching from the zero to the second working position and returning the control spool back to the zero (middle) position.

As can be seen in fig. 9, the internal leakage increased by far the most on the valve with the control spool made of aluminium. If we compare the spools, we can see that in a valve with an aluminium spool, internal leakage increased 32 times more than in a steel one and about 220 times more compared to bronze spool. The leakage increased the least on the control spool made of bronze. After the end of the test, it increased by only 11 ml/min (~ 50 %). On the steel spool, the internal leakage increased by 172 ml/min (~ 8.5 times).

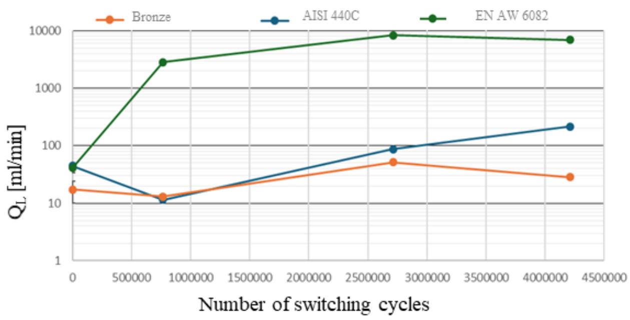

Figure 9. Measured internal leakage for all three tested control spool materials

During the durability test there was a problem probably due to the intense MS1 3D printed housings rusting. The rust caused the control spools to stuck in the valve. As a result, we had to regularly disassemble and clean the valves. Additionally, spools could potentially stuck due to different thermal expansions between the housing material and the control spool materials. This could also reduce the gap required for the spool to slide smoothly in the housing. This raises the question of how many switches some of the control spools actually made, because some got stuck much before others, and we could not precisely control the process.

3.2.2 Control valve spool surfaces

When the durability tests were stopped, for the leakage measurements, all control valve spools were inspected visually (fig.10).

a) Control valve spools after ~ 800.000 cycles

b) Control valve spools after ~ 2.7 million cycles

c) Control valve spools after ~ 4.2 million cycles

Figure 10. Control valve spools after durability tests in water

After about 800.000 cycles both bronze and AISI 440-C spools were stuck, with to the evident rust on valve housing. There were no evident damages on the spools. The spools and valve bodies were cleaned to remove rust particles and other impurities before measuring internal leakage. After about 2.5 million cycles, there was no severe damage evident on both bronze and AISI 440-C spools edges. But the aluminium spool after a number of cycles started deforming and even the washer on the left side of the spool could not be removed without using considerable force. After about 4.2 million switching cycles, we ended the durability test. The valves were stuck often during the test and needed to be cleaned regularly. In addition, the aluminium control spool was no longer switching because it had become so worn. After the last leakage measurement, all the control spools were analyzed with digital microscope. Special emphasizes was given to control edges to find the areas where the greatest wear (fig.11).

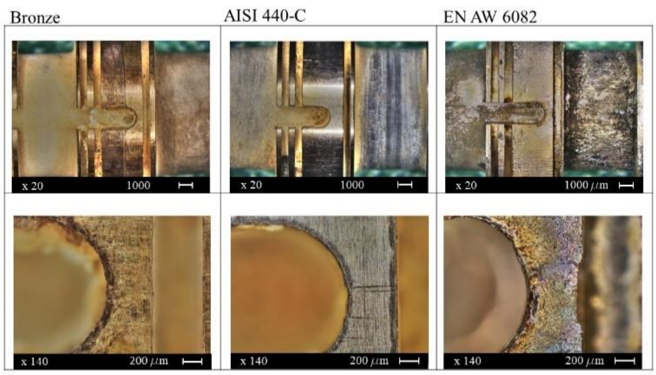

Figure 11: Wear of the control spool grooves on the P side of after durability test, top view

As seen also on the fig.11 the rust is present on all the spools. However, there is also evidence of damage of spool control edges, especially for the aluminium spool. This is why we further analyzed P and T port of the aluminium spool (fig.12)

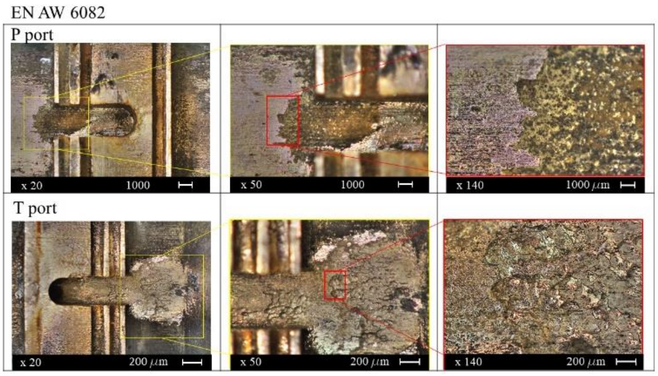

Figure 12. Aluminium control spool edges wear (P and T port)

Further deeper analyses are needed to accurately find the wear mechanism. However, we can see that erosion and cavitation were partially present here (fig,12), because aluminium peeling is visible on the spool surface, which is characteristic of material fatigue. Fatigue probably occurred due to continuous pressure shocks caused by water.

3.2.3 Control valve housing surface

Since dust was evident on MS1 3d printed housing of the valve, at the end of durability tests, the housing was cut in half, and analyzed with digital microspore. There was the most prominent evidence of intense rust on slide surfaces (fig.13a); edge intensive wear and erosion (fig.13b) and material abrasion and intense scratches, probably from rust impurities or worn particles (fig.13c).

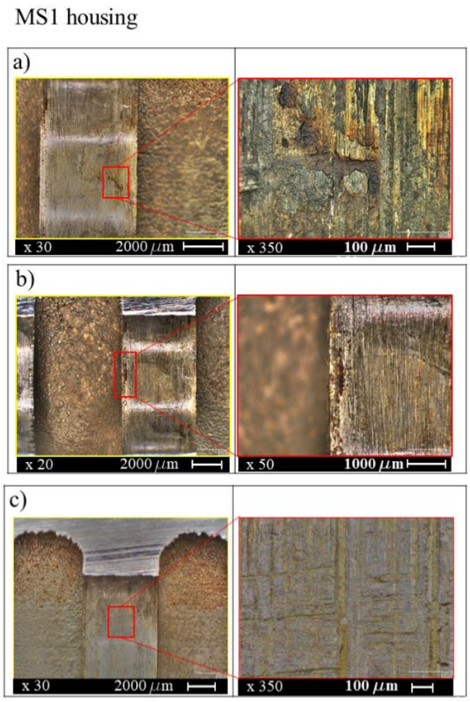

Figure 13. Wear of valve housing edges

4 Conclusions

As part of the research on effective components for water-hydraulics, in this study we have analyzed the potential of using 3D printed maraging steel (MS1) in combination with some materials typically used for traditional oil hydraulics. Based on tribological measurements in both hydraulic oil and water, we can conclude that water presents challenging lubrication conditions for all tested materials, with both the coefficient of friction and specific wear being therefore higher. The materials tested ranged from standard stainless steel, over corrosion resistant bronze down to lightweight and low-cost aluminium.

The highest specific wear was observed in bronze, the intense abrasive wear was observed especially in water and was also related to the unstable coefficient of friction during the experiments. However, these deep grooves in the material, which were probably filled with lubricant, allowed for smoother movement of the control valve spool, and a response closer to the valve with standard stainless-steel spool.

Aluminium was the material with the lowest microhardness compared to the other materials tested. However, the coefficient of friction was stable, and the specific wear was higher, but comparable to that observed in stainless-steel under the low-load conditions tested. The anodising process improved both the coefficient of friction and specific wear, bringing aluminium closer to the behaviour of stainless-steel under the conditions tested. The wear mechanism also included adhesions of material. In the traditionally used hydraulic oil, anodised aluminium also followed the stainless steel quite closely in tribological pair with the 3D printed steel.

Further tests and microscopic analyses would enable as to precisely analyse the effect of anodising on improving the tribological properties of aluminium alloys towards water-hydraulic components. In addition, the manufacturing process of such components should be precisely controlled, as we had problems with testing the anodised control spool with already prepared printed manifolds.

Leakage in spool-type valves is highly sensitive to clearance due to its cubic relationship to small gap, causing significant variation (up to 5-10 times) even within standard tolerances. Although this study did not specifically evaluate the tolerance limits of 3D printed parts, consistent post-processing—sandblasting, micro hardening, CNC machining, and fine grinding—was used to minimize housing variation. Given the tight tolerance requirements, especially for sliding surfaces, final machining plays a crucial role in performance. There are some experimental data on the influence of surface finishing of 3D printed parts, on friction and wear, which present a valuable direction for future studies of particular material and lubricant combination, as well as loading parameters.

Although, there are studies that confirm good corrosion resistance of miraging steel, within our research there were problems with intense rust of valve manifold. The results suggesting that special attention must be paid to the manufacturing and final thermal processing of miraging steel, before it is considered for use in water-lubricated conditions.

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