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Evaluating sliding properties of selective laser melted maraging steel against aluminium alloys in water and hydraulic oil

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Abstract.

Additive manufacturing (AM) of metals enables lightweight, customizable, and high-performance components, with maraging steel (MS1) being widely used for its strength and hardness. While much research exists on AM steels' microstructure and processing, limited studies address their tribological behavior, especially under lubrication. This study investigated the sliding performance of 3D-printed MS1 against aluminium alloys (EN AW 6082) for water hydraulics applications. Aluminium alloy, despite its low hardness, offers advantages in weight reduction and conductivity, and its performance can be improved by surface treatments such as anodization. Reciprocal sliding tests were conducted demineralized water, comparing untreated, conventionally anodized, and hard-anodized aluminium alloy compared to conventional oil lubricated conditions and hardened steel (AISI 440C). Results showed that in oil, sliding speed had little effect, and conventional anodization improved aluminium's wear resistance to nearly match steel. In water, however, sliding speed significantly influenced wear: at low speeds, anodized aluminium performed comparably to steel, but at higher speeds, severe wear occurred for aluminium, even after anodization. The findings suggest aluminium alloys can be potential counterparts to AM maraging steel in water-lubricated systems if sliding speed is carefully controlled.

Keywords. Maraging steel; aluminium alloy; anodization; wear; friction; water; hydraulic oil;

1. Introduction

Additive manufacturing (AM) of various materials offers unique advantages over conventional manufacturing processes, such as flexibility in geometric design, rapid component production, and product customisation, while reducing product mass through optimised design or cellular structures. In the last decade, AM has reached a technological level suitable for manufacturing high-performance components, and it is predicted that the market will be worth nearly $60 billion by 2030 [1]. Although plastics hold the largest share of the AM market, 3D metal printing enables the production of high-performance, lightweight, and customised metal parts, while eliminating most traditional tooling by allowing integrated cooling channels, lattice structures, and internal features not possible with conventional machining. This approach is highly attractive for the aerospace, defence, robotics, and automotive industries, and also supports efficient material use, rapid prototyping, and replacement of damaged parts. Among the different powder-bed-based approaches for metal printing, selective laser melting (SLM) and selective laser sintering (SLS) are the most common [2]. Extensive fundamental research has been conducted on the microstructure of 3D-printed steel, printing parameters, heat treatments, porosity, manufacturing technology, and post-treatments [2–4]. AM has also been successfully used in hydraulics for manufacturing valves, manifolds, and pump parts [5–8].

There are various metal-based components made from pure metals, alloys, or metal matrices, such as 316L stainless steel, titanium Ti-6Al-4V, aluminium Al 6061, ALSi10MG, Inconel, cobalt-chrome, or maraging steel [1, 2]. There is limited experimental data on the specific wear and friction properties of these materials. Tribological sliding tests are typically conducted under dry conditions, against different steels, carbide, or ceramic counterparts, at room or elevated temperatures. There are fewer studies on the behaviour of these 3D-printed steels under lubricated conditions. Stainless SLM steel 316L has been tested in hydraulic oil compared to brass or nitrided steel, where grinding and polishing [9] and brass counterpart [10] have been suggested for improved performance of SLM steel. Recently, the cavitation erosion resistance of AM materials was found to be lower than that of conventionally produced steel at the beginning of the test [11]. Maraging steel (MS1), also known as 18Ni-300 (1.2709) maraging steel, is a martensitic iron-nickel alloy with low carbon content that has been widely used due to its high yield strength, tensile strength, and hardness, especially in automotive, aerospace, and tooling applications, where high wear resistance is expected. However, most studies focus on microstructure, microhardness, tensile, and impact properties [3, 12–15]. Recently, conventionally and laser bed fusion fabricated MS1 were compared under different normal loads (5–35 N), sliding speeds (1–5 Hz), and temperatures (30–125 °C), but were tested under dry conditions [16] emphasising the importance of testing under specific real-time application conditions. Another study suggested comparable wear but superior corrosion resistance of additively manufactured MS1 components compared to conventional MS1 [17]. In particular, intercritical heat treatment was shown to enable better tribological properties of MS1 under dry conditions [14].

In our recent study, we analysed the tribological properties of 3D-printed maraging steel (MS1) in sliding contact with materials commonly used in hydraulics, particularly water hydraulics: nitrided steel AISI 440C, bronze, and aluminium alloy [18]. The aluminium alloy demonstrated results comparable to conventional nitrided steel and exhibited better wear performance than bronze under the tested conditions. Due to their low specific density, light weight, high thermal and electrical conductivity, and wide availability, aluminium and its alloys are among the most commonly used metals for reducing overall system weight and the energy required for production and operation [19]. However, their relatively low hardness and greater sensitivity to abrasive wear often limit their use to applications with low friction and lower loads. To improve surface hardness, treatments such as conventional or hard anodising, plasma electrolytic oxidation, and heat hardening are applied [20–23]. Hard anodising can produce oxide layers 25–150 μm thick, increasing surface hardness by

5–8 times [24]. The anodising process also affects corrosion resistance. Although aluminium alloys are widely used, their tribological behaviour is typically studied under dry or oil-lubricated conditions.

In this study, the aluminium alloy (EN AW 6082) was tested before and after both conventional and hard anodising in a reciprocal sliding test against 3D-printed maraging steel (MS1) in demineralised water at two different sliding speeds. For comparison, the same tests were also conducted in conventional hydraulic oil ISO VG 46, conventional HFC 46 lubricant, and with conventional nitrided AISI 440C steel. The results of the tribological tests were used to analyse the influence of the surface treatment of the aluminium alloy and the effect of sliding speed when sliding against MS1, to assess potential material pairs for efficient proportional valves designed for water hydraulics.

Common tribological test methods designed to reproduce simplified contact geometries and loading conditions in sliding interfaces include ball-on-disc (BoD), pin-on-disc (PoD), and cylinder-on-disc (CoD) configurations, often implemented in reciprocating sliding tests to simulate short-stroke motions. Standardized procedures such as ASTM G99 for pin-on-disc and ASTM G133 for linearly reciprocating tests (ISO 7148, ISO 6601-6605) are widely employed in both academic and industrial studies for comparative friction and wear analyses [25–27]. The ball-on-disc configuration provides a well-defined Hertzian point contact at relatively high local pressures, making it suitable for fundamental contact stress and lubricant behavior characterization, whereas the pin-on-disc test offers a more stable contact area and medium–low nominal pressures relevant to a broader range of engineering materials. Although a cylinder-on-disc or line contact test would more closely approximate the geometry, contact mechanics, and lubrication regime of a hydraulic valve spool within a valve body, there is no single fully standardized tribological test that exactly reproduces the quasi-line contact of spool/body interfaces. For this reason, we selected an established pin-on-disc setup, which ensures methodological rigor and comparability through well-defined standards, and provides effective material screening and ranking; this choice is complemented by consideration of reciprocating cylinder-on-disc testing when higher representativeness is required. A reciprocating pin-/cylinder-on-disc configuration therefore represents a practical compromise between the representativeness of the real valve contact and the experimental control necessary for reproducible and comparable tribological assessment of material pairs in proportional hydraulic valve spool–body contacts.

The simplified tribological test configuration provides an effective platform for preliminary material screening and is routinely employed within our research group for assessing novel materials, surface coatings, reinforcements, and finishing processes for hydraulic components [28, 29], as well as for evaluating new lubricant formulations [30]. Comparable methodologies have recently been applied to investigate the performance of various ceramic materials intended for water-lubricated axial piston pump friction pairs using ball-on-disc tests [31], and to examine the tribological behaviour of valve plate pairs through ring-on-block experiments [32]. Nevertheless, such laboratory-scale tests should be complemented by full-component experiments or simulations incorporating the selected material pairs to ensure realistic performance assessment. Extensive research on axial piston pumps has demonstrated the importance of validating numerical simulations with experimental data, particularly when integrating wear prediction, running-in behaviour, and friction analyses following innovative component redesign [33, 34]. This combined approach enables a comprehensive evaluation of overall component efficiency [35].

2. METHODOLOGY

2.1. Sample preparation

An EOS M290 3D metal printer using the SLM (selective laser melting) method was employed for sample preparation, with a laser beam speed of 1010 mm/s, power of 305 W, and a powder layer thickness of 50 µm. The material was in powder form with spherical grains ranging from 15 to 45 µm. As the material is melted in specific areas, the high temperature of the laser beam also locally hardens it. The final product exhibits anisotropic properties due to the layer-by-layer manufacturing process, which are eliminated by subsequent heat treatment. For the tribological tests (Figure 1.) 3D printed discs (25 x 25 x 6 mm), made of maraging steel (MS1/1.2709 also known as 18Ni-300) were used, representing a hydraulic valve body. The disc samples were polished in several steps using a RotoForce-3 automatic sample polishing and preparation device, achieving a final roughness of 0.1 µm.

The pin samples (Φ 10 × 20 mm, with a 12.5 mm radius) were prepared from two different materials: aluminium alloy (EN AW 6082/3.2315) and commercially available standard hardened stainless steel (AISI 440-C/1.4125). The pin samples were polished using the same procedure as the MS1 discs. After polishing, the aluminium samples were anodised using the standard procedure and underwent hard anodization. The pin samples represented hydraulic valve spools.

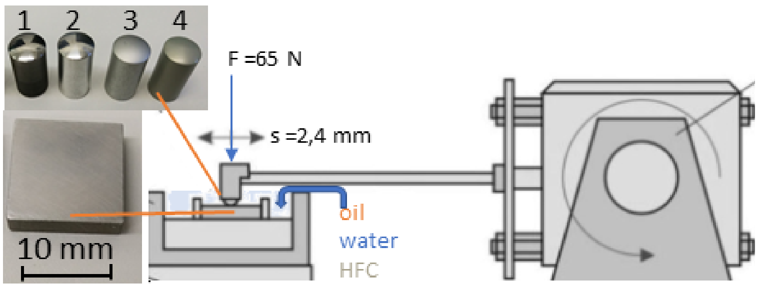

Figure 1. Experimental procedure: pins: 1- AISI 440-C; 2-Al 6082; 3-Al 6082 anodised; 4-Al 6082 hard anodised and disc - 3D printed MS1 at tribological tests set-up;

Materials microhardness was measured using a standard Vickers hardness tester, Leitz - Miniload 2, with an indentation force of 1.9 N (according to DIN 50133). However, with the measurement method employed, we were unable to measure the hardness of anodised aluminium samples successfully. Therefore, we assumed that the anodised samples had the hardness specified by the manufacturer. For soft anodised samples, this ranged from 200 to 250 HV. For hard anodised samples, it ranged from 500 to 600 HV. Before each test, the samples, clamps and pins were cleaned with ethanol and dried in air.

Table1. Mechanical properties of prepared samples

Material	Density [kg/m^3]	Young modulus [GPa]	Ultimate tensile strength [MPa]	Hardness [HV]
pin				
AISI 440-C	7.6	200	760-1960	~ 1330
Al 6082	2.7	70	260	~ 132
disc				
MS1	8-8.1	180	2080	~ 460

The first lubricant used was commonly available ISO VG46 hydraulic oil. The second lubricant was demineralised water (W). Additionally, commercially available HIDROL HFC 46 lubricant was tested. The selected HFC 46 is a water-glycol mixture (35–40% glycol content) with special additives that provide excellent corrosion protection. This lubricant contains no mineral oils, nitrites, PCBs, or phenols. The properties of the lubricants used were measured using an automatic viscometer, Anton Paar SVM 3001, and are presented in Table 2.

Table 2. Chemical properties od used lubricants

Lubricant	Density at 25°C [g/cm^3]	Density at 45°C [g/cm^3]	Kin. viscosity at 25°C [mm^2/s]	Kin. viscosity at 40°C [mm^2/s]
ISO VG46	0.86	0.84	100	41.4
Demin.water	0.997	0.99	0.89	0.66
Hidrol HFC 46	1.075	1.06	90	43

2.2. Experimental procedure

Tribological tests were conducted on a Cameron-Plint TE 77 high-frequency tribometer (Figure 1). During the test, the pin slides in a reciprocal mode on the 3D-printed disk-like plate. The average sliding velocity was set to two values: 0.05 m/s (corresponding to a frequency of 10 Hz) and 0.2 m/s (corresponding to a frequency of 40 Hz). The applied frequencies correspond to the dynamic opening and closing of the proportional spool valve. The maximum excitation frequency achievable with the tribometer was 40 Hz. The stroke length was 2.4 mm, representing the valve spool stroke in a CETOP 3 size 4/3-way slide valve. This value also represents the minimum stroke length available with the tribometer. The normal load was set to 65 N. Before each test, the pins and plate samples were fully immersed in the selected lubricant. During the tests, the current value of the friction coefficient was automatically recorded. The tests were conducted for 60 minutes, based on preliminary tests that showed a stable coefficient of friction and measurable wear. Each test (material and lubricant combination) was repeated three times, and the average values of the steady-state coefficient of friction were used for the comparative analysis.

2.3. Wear evaluation

After testing, the wear on the pins and wear tracks was analysed using a 3D digital microscope with a nano-point profilometer Hirox HRX-01 & NPS. The wear volume of the pins was calculated from the dimensions of the wear tracks. The 3D profile and dimensions of the wear calotte were determined with Mountain Map software [25]. The specific wear rate was determined by dividing the measured wear volume by the product of the normal load and sliding distance. The surface films on the printed plates were also characterised for shape and size.

3. RESULTS AND DISCUSSION

3.1. Evolution of coefficient of friction

Figure 2 shows the evolution of measured coefficient of friction during individual tests of pin samples againts MS1 printed disks, in water and hydraulic oil at two different sliding frequences.

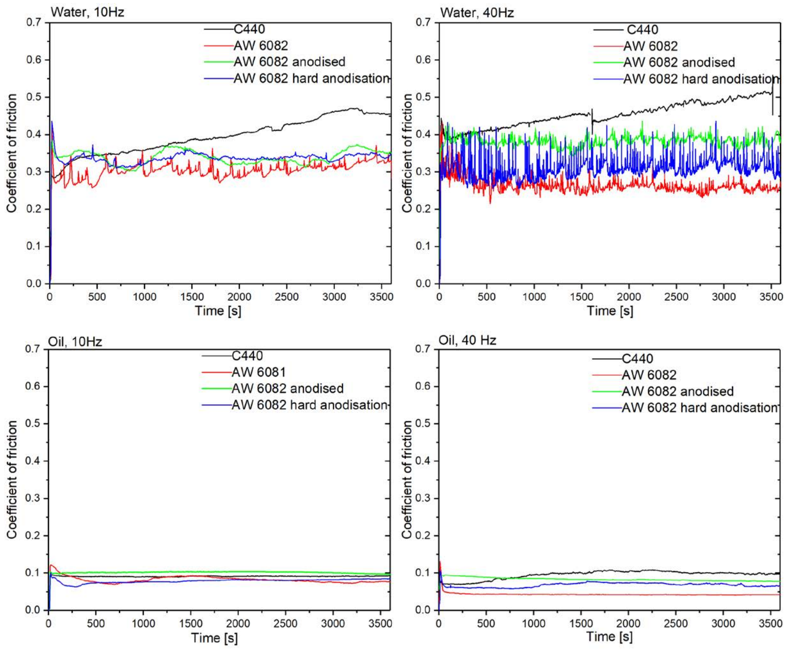

Figure 2. Evolution of the coefficient of friction during the reciprocal tests of of aluminium alloys pins against MS1 in water and hydraulic oil, at two different sliding speeds

The coefficient of friction measured in the water doesn't show typical running in, it rather has unusable value for all aluminium alloys. The fluctuations observed in case of water lubricated conditions indicate, that water incorporates some instabilities into the sliding contact. At lower frequency these instabilities are the most prominent for nature aluminium alloy, and tend to become smoothed after anodisation. At higher frequency these instabilities are simillar for nature alloy and standard anodisation, but more intense for hard anodized sample. 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 at both frequences (up to 34 %) and has higher value compared to tested all aluminium alloys. If we compare these results to the measurements in ISO VG46 hydraulic oil, the coefficient of friction reaches a stable value almost immediately for all aluminium alloys similarly to AISI 440-C, at both frequencies (with in the first 2500 cycles).

3.2. Coefficient of friction

Figure 3 represents average values of measured steady coefficient of friction for all tested samples in both water and hydraulic oil, at both frequences.

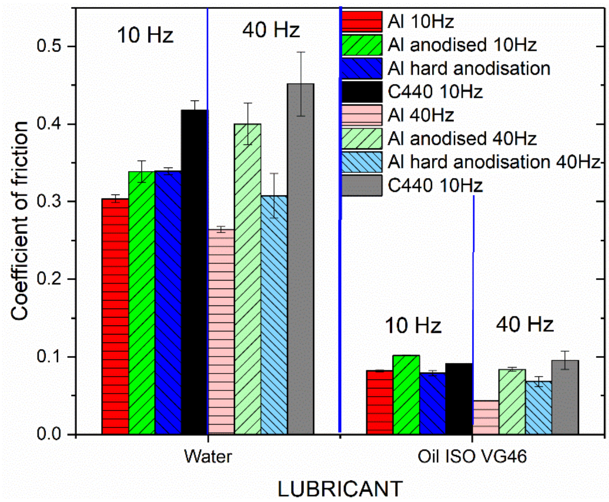

Figure 3. Average coefficient of friction during the reciprocal tests of aluminium alloys pins against MS1 in hydraulic oil and water at two different sliding speeds

When water was used as lubricant, at lower frequency, comperable values of coefficient of friction were measured for natrure aluminium alloy (around ~ 0.3), followed by anodised and hard anodised aluminium (~ 0.33), and considerably higher value was measured for AISI 440-C (~ 0.39). At higher frequency, nature and hard anodized aluminium alloy coefficient of friction even decresed (value around ~ 0.28 and 0.3 respectively). In water all aluminium alloys 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 aluminium alloys, anodisation it is expected to enable smoother working conditions even in water.

Lower values of coefficient of friction were observed in hydraulic oil, for all tested samples compared to water lubricated conditions. The coefficient of friction decreased in oil around 4.5 times for all aluminium alloys and AISI 440-C, at both frequences. However even in oil, nature aluminium alloy showed lowest measured coefficient of fiction with values comparable to measured values for both anodised aluminium and AISI 440-C, all around ~ 0.09. At higher frequency, slight decrese was observed for nature aluminium alloy.

3.3. Specific wear

Based on repeated measurements in water and hydraulic oil at two sliding frequences, Figure 4 represents average values of calculated specific wear from analyzed pictures of wear tracs, of all tested pin samples for each material.

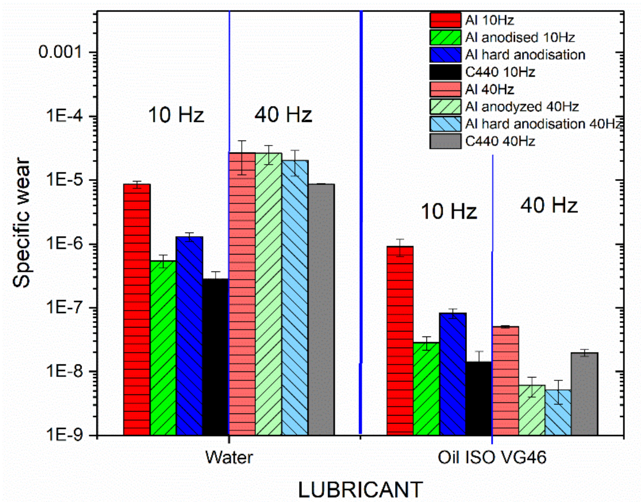

Figure 4. Average specific wear of aluminium alloys pins after sliding against MS1 in water and hydraulic oil, at two different sliding speeds

In water, the lowest measured specific wear was for AISI 440-C (~2.8×10^{-7} mm^3/Nm), fairly followed by anodised aluminium (~5.4×10^{-7} mm^3/Nm). Evidently anodization improved wear resistance of nature aluminium alloy (~ 8.6×10^{-8} mm^3/Nm), even comparted to hard anodization (~1.3×10^{-6} mm^3/Nm). However, at higher frequency difference between tested materials is lower. From all aluminium alloys (~2.3×10^{-5} mm^3/Nm) to AISI 440-C (~8.6×10^{-6} mm^3/Nm).

In hydraulic oil, we can see that both all aluminium alloys and AISI 440-C showed lower specific wear, compared to water lubricated conditions at both frequences. Smaller decrease was found at lower frequency (from 2 times for anodized aluminium up to 157 times for hard anodized aluminium alloy) compared to higher frequency (around 500 times for nature aluminium and AISI 440-C, up to around 4000 times for both anodized alloys). Again anodized aluminium alloy (~8.2×10^{-8} mm^3/Nm) fairly followed AISI 440-C (~1.4×10^{-8} mm^3/Nm) at lower frequency, with even better results at higher frequency (~6.1×10^{-9} mm^3/Nm and ~2×10^{-8} mm^3/Nm respectively).

Based on the measurements, we can conclude that the best results were accomplished by AISI 440-C followed by anodised aluminium, under harsh water lubricated conditions. In hydraulic oil, anodization improved aluminium properties to put it even in front of the AISI 440-C (for tested frequences and loads). Both anodization and hard anodization process improved tribological properties of nature aluminium alloy, however hard anodization did not significantly change properties compared to standard anodization, especially at lower frequences.

3.4. Comparison with HFC 46 as lubricant

The results of the same tribological tests in hidrol HFC 46, when nature aluminium and anodized aluminium alloy pins slide against MS1 at two different frequencies, are presented of Figure 5 and 6.

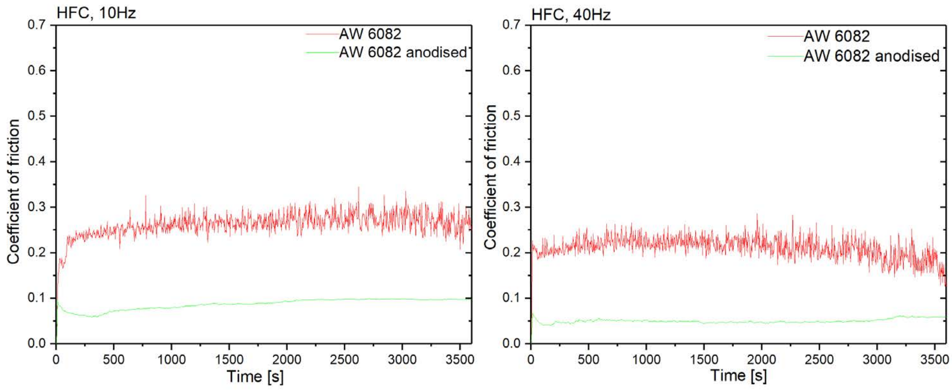

Figure 5. Evolution of the coefficient of friction during the reciprocal tests of aluminium alloys pins against MS1 at two different sliding speeds in HFC 46

From the results it is evident that anodization improves tribological properties of nature aluminium, and sliding frequency does not impact significantly measured properties (at sampled range 10 – 40 Hz). Measured coefficient of friction is smoother and more stable after anodization, at both frequencies (Figure 5), while average value of the coefficient of friction decreases 3.25 times at 10 Hz, up to 4.2 times at 40 Hz after anodization (Figure 6a). Specific wear also decreases after anodization, around 800 times at 10 Hz, up to 3000 times at higher frequency (Figure 6b). Specific wear of nature aluminium (~3.4×10^{-4} mm^3/Nm) is lower but not significantly affected by higher frequency (~2.4×10^{-4} mm^3/Nm).

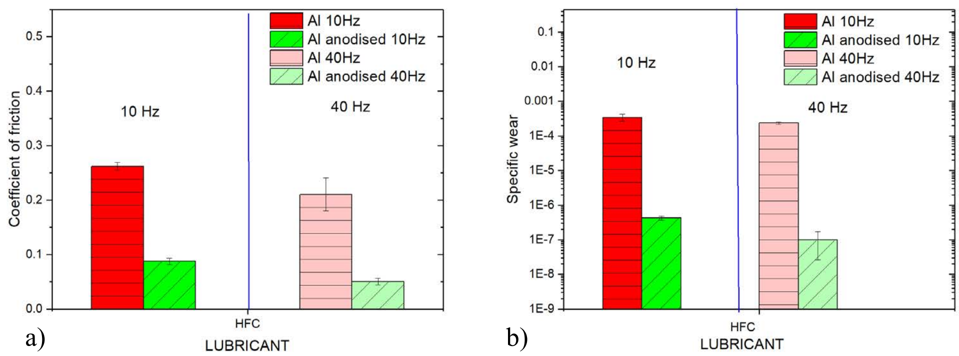

Figure 6. Average a) coefficient of friction b) specific wear of aluminium alloys pins after sliding against MS1 at two different sliding speeds in HFC 46

If we compare these results to the measurements in water and hydraulic oil, nature aluminium alloy responds similarly in water and HFC 46, with comparable values of coefficient of friction at both frequencies, and specific wear lower but comparable to the values in water. But after anodisation, measured coefficient of friction becomes comarable to the values measured in hydraulic oil, at both frequences. Also specific wear of anodised aluminum is one order (at 10 Hz) up to three orderes (at 40 Hz) lower compared to eater lubricated conditions, beeing closaer to the values measured in hydraulic oil ISO VG46.

3.5. Surface analyses

After the tests, wear tracks of both pin and disc in sliding contact, were analyzed with digital microscope (Figure 7 and Figure 8). From the pictures it is clear, that the most significant wear and material removal area is evident in water at higher sliding speed, for all materials. Also, for the nature aluminium pins the stretches in the sliding direction are the most intensive at both sliding speeds, thick and prominent, suggesting abrasion as main wear mechanism.

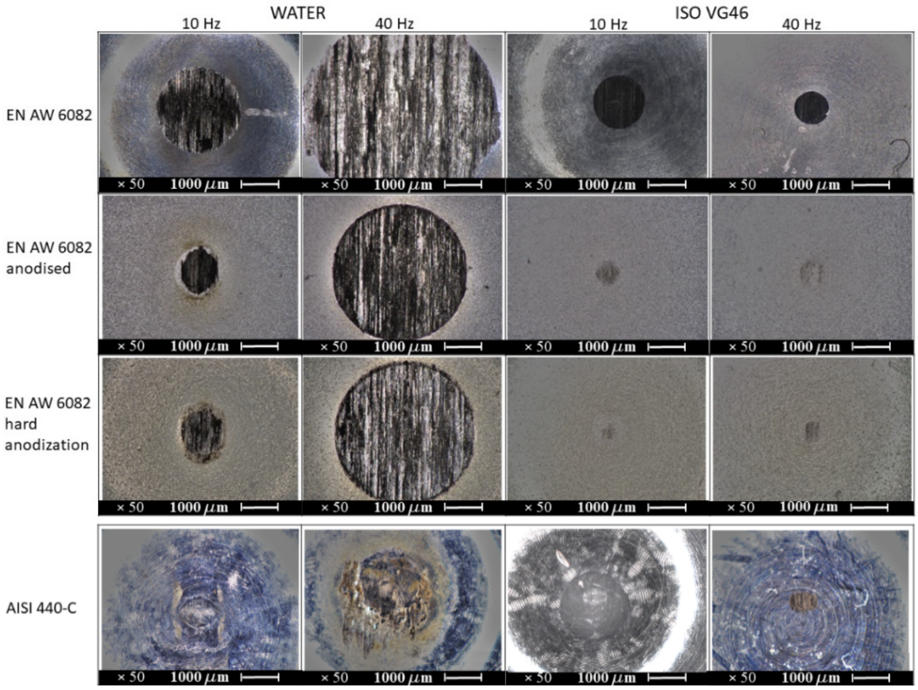

Figure 7. Digital micrographs of aluminium alloys pins after sliding against MS1 in water and hydraulic oil, at two different sliding speeds (magnification, ×50)

Aluminium alloy samples after both anodization and hard anodization suggest relatively smaller wear area, with area comparable to AISI 440-C, but different wear mechanism present. There were irregularities, that probably present peeled anodised protective layer in water, thus suggesting adhesive wear followed by two body abrasion. These adhesive debris and intensive delamination unevenly distributed over abrasive grooves were even more prominent at the four times higher sliding speed (increasing from 0.05 to 0.2 m/s). In case of AISI 440-C only some slight, rare unevenly distributed abrasive scratches were present.

The difference between nature and anodised aluminum is even more significant in hydraulic oil. Nature aluminum alloy shows stratches in sliding direction, less intense and thinner than in water, but comparable at both sliding speeds. In case of anodized and hard anodized aluminium in oil, only some irregular mocroploughings and pores are presents, even with smaller coverage area at higher sliding speed. These microplughings and microcracings are even less intense and with smaller coverage area in both anodized aluminium alloys comaperd to AISI 440-C.

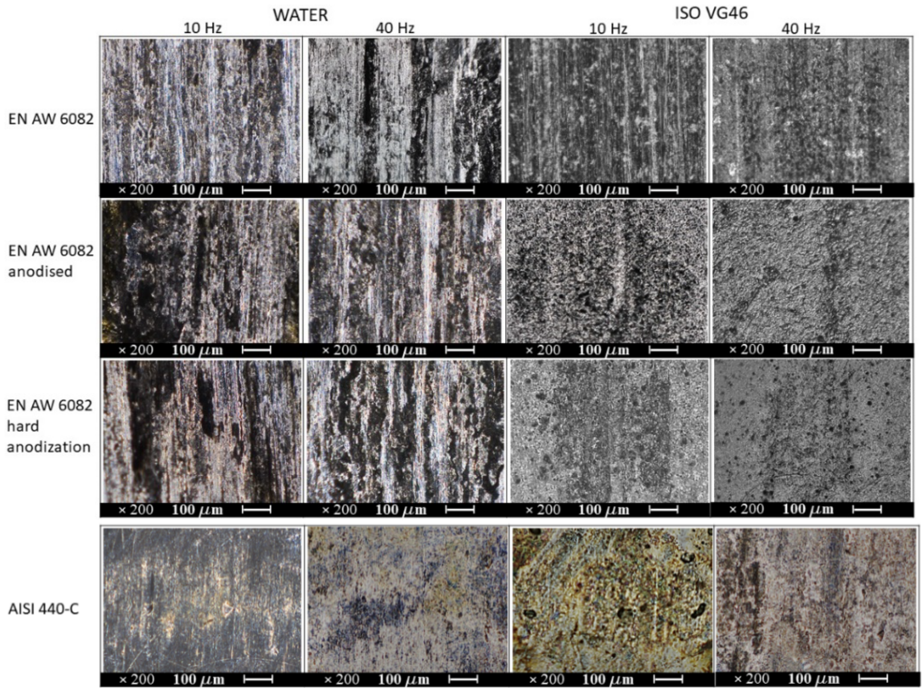

Figure 8. Digital micrographs of aluminium alloys pins after sliding against MS1 in water and hydraulic oil, at two different sliding speeds (magnification ×200)

The difference between nature and anodised aluminum is even more significant in HFC 46 (Figure 9), where the wear tracks of nature aluminum are comparable to the tracks seen in water at higher frequency. However, after anodisation wear track are comparable to the measurements in hydraulic oil, at both frequences. In case of nature aluminium alloy beside prominent intensive abrasive stratecs a lot of irregular embaded adhesive debris is pressent at both sliding speeds, with large wear area even compared to water lubricated conditions.

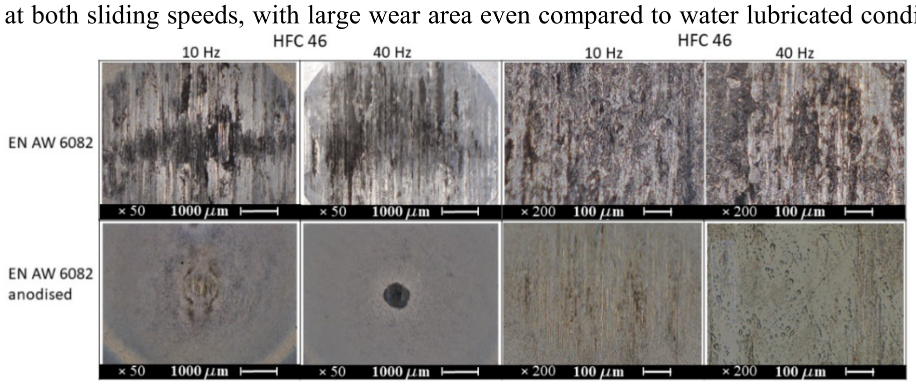

Figure 9. Digital micrographs of aluminium alloys pins after sliding against MS1 in HFC 46, at two different sliding speeds (magnification ×50 and ×200)

On contarry, in case of anodized aluminium alloy in HFC 46 relativelly small wear area was present at both slidin speeds, with some slight scratches at lower sliding speed and more microplugings and pores at higher sliding speed. However all observed material changes are comparable to the wear tracks seen in case of hydraulic oil (Figure 7 - 8).

After the tribological tests the surfaces of MS1 discs were also analysed (Figure 10 - 12). The anodization (both standard and hard) improved tribological properties, and decreased contact area compared to nature aluminium, the effect is even greater in oil at both sliding frequencies (Figure 10).

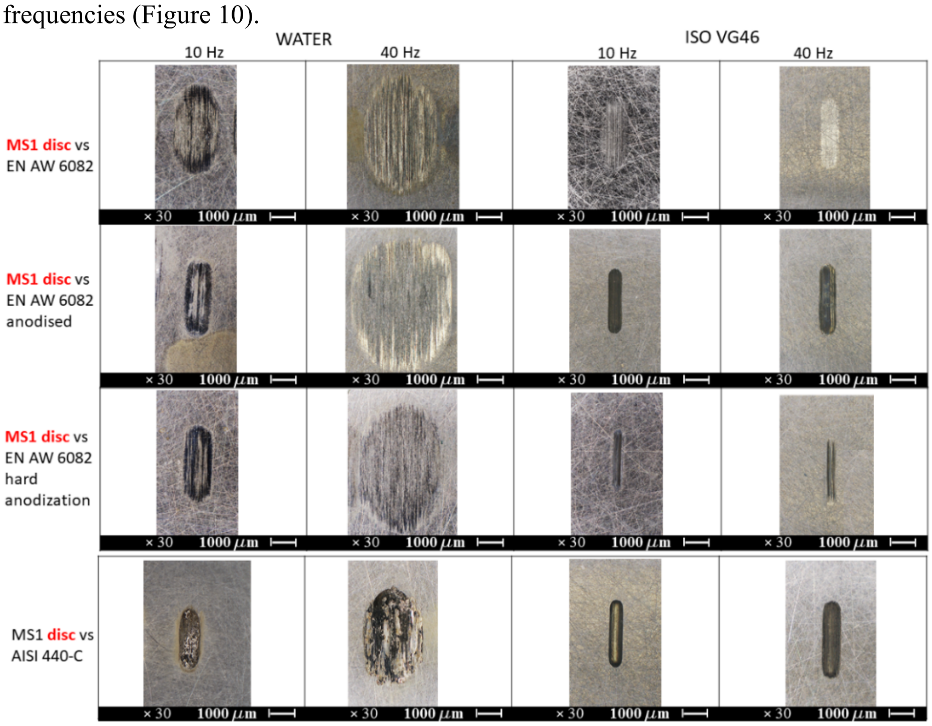

Figure 10. Digital micrographs of MS1 discs after sliding against aluminium alloys pins in water and hydraulic oil, at two different sliding speeds (magnification ×30)

The wear track widths at the lower sliding speed were generally comparable across most materials (~1070–1400 µm), with the exception of natural aluminium, with significantly wider track (~2300 µm) However, at higher sliding speed in water wear tracks become more prominent and intense for all tested materials *(~3500 µm)*. Under oil lubrication, the narrowest wear tracks were produced by hard-anodized aluminium pins at both sliding speeds (~350–450 µm). These were followed by C440 and conventionally anodized aluminium pins, which generated wear tracks of roughly 600–800 µm. In contrast, natural aluminium pins produced wider tracks, reaching ~1300 µm. The impact of higher sliding speed on MS1, is not significant in oil.

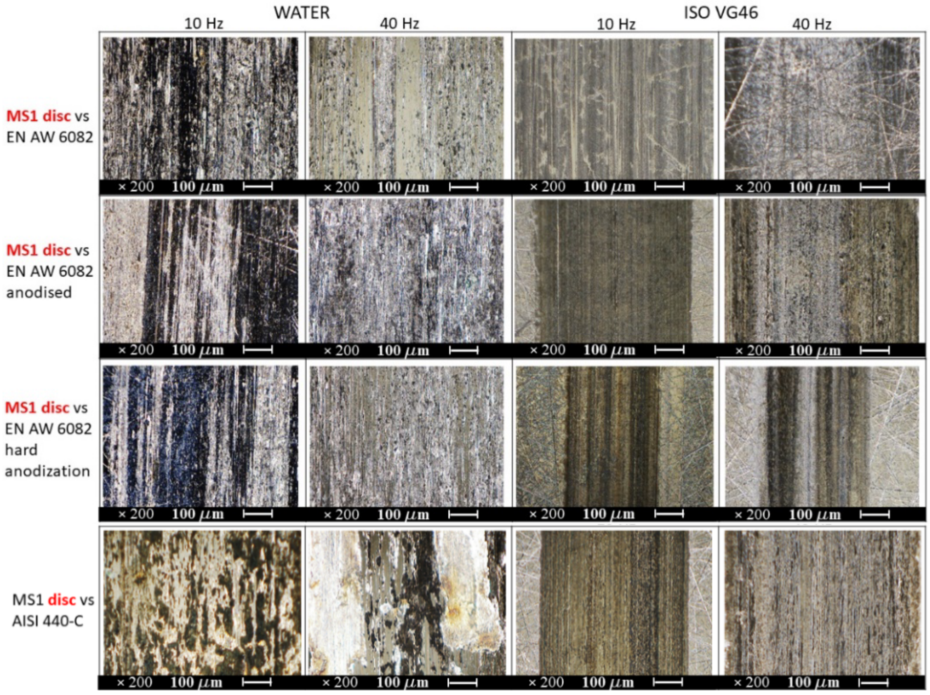

Figure 11. Digital micrographs of MS1 discs after sliding against aluminium alloys pins in water and hydraulic oil, at two different sliding speeds (magnification ×200)

At higher magnification (Figure 11) scratches and micro ploughing in sliding direction can be observed in all aluminium alloys in both water and hydraulic oil. Only the density and track width is much lower after anodization. In case of AISI 440C steel, intense delamination and adhesion is present especially at higher sliding speed. In case of HFC 46 (Figure 12), scratches are present in sliding direction, however the most significant difference is in the coverage area of the wear track between nature and anodized aluminium alloy.

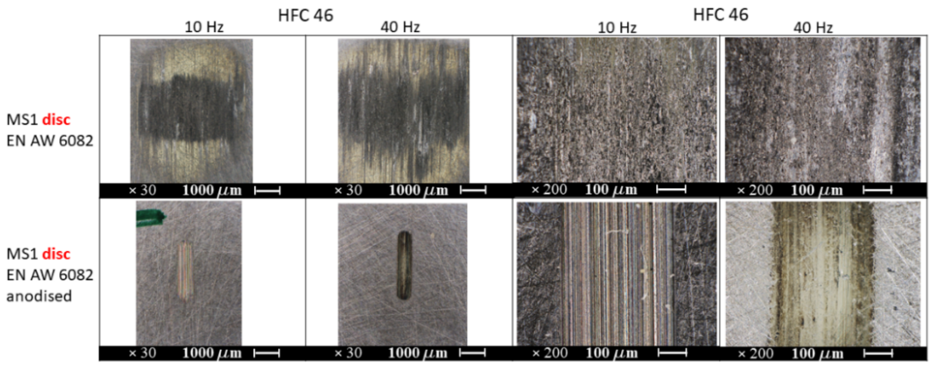

Figure 12. Digital micrographs of MS1 discs after sliding against aluminium alloys pins in HFC, at two different sliding speeds (magnification ×30, ×200)

4. CONCLUSIONS

In this study, the tribological properties of 3D-printed maraging steel were tested and analysed after sliding against three different versions of aluminium alloy AW 6082 at two different sliding speeds. The tests were conducted in water and compared to standard testing conditions in hydraulic oil ISO VG 46, as well as to sliding against the typical material used in hydraulic valves, nitride AISI 440C. A partial comparison was also made to the commercial water based lubricantHFC 46. The results of the tribological tests were used to analyse the influence of the surface treatment of the aluminium alloy and the effect of sliding speed when sliding against MS1, for potential material pairs in water hydraulics.

Sliding speed had no significant effect on the tribological performance of the tested materials in oil. Conventional anodization notably enhanced the surface properties of the aluminium alloy, achieving values comparable to those of AISI 440C steel. In contrast, under water lubrication, sliding speed emerged as a critical factor. At lower speeds, anodization substantially improved the specific wear resistance of the aluminium alloy, yielding results similar to those observed in steel. However, at higher sliding speeds, severe wear occurred on all aluminium specimens, although anodized samples still exhibited better performance than untreated ones.

The coefficient of friction in water was generally lower for the aluminium alloys compared to AISI 440C steel. While anodization did not significantly reduce the friction coefficient, it effectively stabilized the frictional response, producing smoother curves and more consistent sliding behaviour at both speeds.

Overall, the findings suggest that anodized aluminium alloys can be effectively employed in sliding contact with maraging steel, even under pure water lubrication, provided that the operational sliding speed is carefully controlled. Preliminary tests conducted in HFC 46 fluid further indicate that anodized aluminium in contact with MS1 steel demonstrates tribological performance comparable to that in hydraulic oil. This material pairing therefore holds promise for applications in standard hydraulic systems, offering a potential lightweight alternative to conventional steel components.

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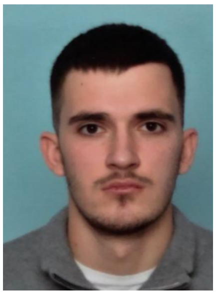

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