ANALYSIS AND COMPARISON OF MECHANICAL AND LASER TEXTURING

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Abstract: Many have been the efforts to improve the tribocharacteristics in surfaces under load, contact and relative movement. There are well-documented technologies such as heat treatments, new materials, improved lubricants, and more recently surface texturing which can be applied to surfaces by different methods such as micro-machining, laser or mechanical deformation in order to improve tribo characteristics. The objective of this work is to compare the tribological performance (Coefficient of friction (COF) and wear) at the laboratory level of mechanical texturing (MT) and surface laser texturing (LST); for this a statistical comparison between a determined mechanical texture (MT) and laser texture (LST) patterns are analysed in this project, as well as the development of a mechanic (not electric) (machine specifically designed and manufactured for this project) that can create the mechanical texturing (MT). The objective fi this research is to determine if mechanically texturizing in aluminium disc results in better wear and coefficient of friction (COF) reductions (tribo characteristics), compared to a laser textured pattern (LST) with the same characteristics. First a tuning process was developed at the tribotester in order to determine the best specifications of the laser texturing (LST) that could replicate, with a difference of at most 10%, the volume of a single micro-cavity. An Alicona surface analyser was used for the 3d measurements of the texturized patterns. A pin-on-disk (T-11 tribotester) with a load of 1.5 kg, 7 mm of turning radius on the disk, and 0.05 ml of PAO-IV lubricant applied at the beginning of the test were used in three tests of 7200 seconds each to determine the wear and COF of the 3 different textures: mechanical texturing (MT), laser texturing (LST), and no texturing. 3 replications were done for each of the textures. COF was found to be optimal at no texturing, due to aluminium oxide appearing in the test, which reduces the friction between surfaces, decreasing proportionally as the face-to-face contact area increases. Wear along the track was found to be best in the mechanical texturing, with a decrease of 34.7% compared to laser texturing (LST). Some conclusions and recommendations for the use of the mechanical texturing (MT) are also shown in this paper.

Key words: mechanical texture, laser texture, coefficient of friction.

1. INTRODUCTION

Energy consuming processes in the industry is a topic that has been investigated in the recent years. The losses caused by the great inefficiency these systems have, is a big area of opportunity for researchers to develop new technologies that can reduce the process costs in all type of industries. For example, from 15-25% of energy is lost by friction in paper mills [1], 40% of energy is lost in mining applications [2] and 28% of fuel energy in passenger cars [3]. Modifications in these areas of opportunity can reduce costs and enable us to have a more efficient use of the resources to which we have access to. With these problems, technologies like laser texturing [4], the application nanoparticles in lubricants [5], and other important technologies, have been achieved, which increase importantly the efficiency of certain processes in wear and friction reductions. However, as the world changes and effects by pollution in the global climate are more severe, the search for cheaper and more efficient innovations in processes is still a major issue that must be attended.

One option that has been used in the recent years is changing the surface finish in certain tools used in industry, more specifically, creating microcavities in the surface [6]. This microcavities have the function of reducing wear and the Coefficient of Friction (COF) by storing the lubricant utilized in a certain process in the microcavities, as well as to store residues that occur when surfaces rub each other, thus, increasing the time the surfaces remain lubricated, and subsequently decreasing energy losses in processes and incrementing the life of the tools utilized [7].

Laser texturing (LST) is known as the creation of micro-dimples in surface finishes which give a fast and great solution to decreasing COF and wear, increasing load capacity, and other applications [8]. This process is utilized in the industry in various applications like high-pressure engines [9], Rolling and Sliding contacts like the piston-ring systems, seals, roller bearings, and gears [10]. These applications have shown to decrease friction and wear, and thus increasing the life of the tools used, however, laser texturing has shown some imperfections when talking about surface finish, like the hat, which is a volcano-like deformation of the material around the micro-cavity created, and the lack of reliability in the constancy in the process. This lack of reliability refers to the different measurements of diameter and depth that occur when a laser is utilized to create micro-cavities. A great variability caused by the process creates an uncertainty about the confidence in the results obtained by using this method, and thus, this project was proposed.

Alternatives for laser texturing are a somewhat new topic which are yet not greatly discussed, because laser texturing is a fast and easily performed solution. However, the search for improvements should not stop, and thus Mechanical Texturing (MT) is analysed in this study in search for a cheaper and better alternative. This type of texturing (MT) can be created by resting a load on a surface, by impacting a point on a surface, and maybe by more advanced technics which are not discussed in this study.

Figure 1 shows a flow chart of the experiments and analysis in this study, in which the chronological steps of the different stages are shown in the centre. On the left the physical or methodological tools used in the central stages are shown, and in the right, the steps in each stage are shown, as to give a general idea of the results obtained in each stage.

The rest of the paper is composed as follows: Sections 2.1 and 2.2 define the procedures employed to design and create the first prototype of the machine and the testing of the creation of the mechanical texturing. Section 2.3 describes the tribological tests utilized to determine if the mechanical texturing works against no texture at all. Section 2.4 shows the final prototype achieved for the creation of the mechanical texturing, and the specifications utilized in the machine to create our mechanical texturing, as well as an overview of the pattern utilized for both textured disks (MT and LST).

Section 2.5 depicts the procedure used to find the correct pattern and laser specifications that would be used in the laser texturing, that could approach the most to our mechanical texturing. In Section 2.6 we provide an overview of the tribological test utilized, and the specifications, as well as the raw results obtained from the tests.

In Section 3, we analyse the results obtained from the tribological tests, and then, in Section 4, we show conclusions and state recommendations that could be used in future research.

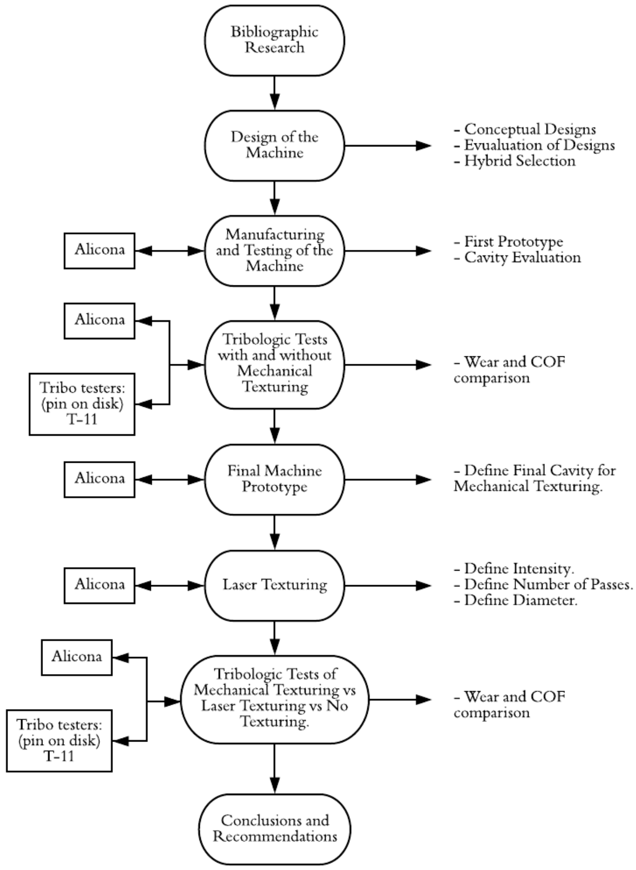

Fig. 1. Flow chart of experiments and analysis

2. METHODOLOGY

In order to compare the two different texturized disks studied in this project, first we need to obtain a device that can produce a mechanical texturing that can be replicated easily, as to reduce variation in the process, and compare with the best matching conditions. The process employed to develop this machine is shown in Section 2.1. In Section 2.2 the manufacturing process of the machine is described, the finished prototype is shown, and general characteristics of the micro-cavities created are defined. In Section 2.3 a single test to determine if the mechanical texturing is of use to the study, by decreasing wear and COF, was done. This step was done to check if the project had a significant value, as to continue with it, or if it didn't, to stop the study and show the results obtained until this point, as a comparison with a laser textured disk wouldn't be of any use. In Section 2.4, a new and final prototype was developed, in order to increase stiffness, and reduce variability in the process. In this Section, the specifications for the creation of the micro-cavities of the MT where defined. In Section 2.5, LST characteristics were varied between 3 factors, in order to define the pattern, intensity, and number of passes that the laser needed to have in order to be able to compare both textures with the best matching conditions. Section 2.6 depicts the raw results and the specifications of the tribological tests. Wear and COF are compared in the next section, “Results and Analysis”.

2.1 Design of the Machine

The design of the machine was the first step that we took in this project in creating the mechanic texturing. In order to analyse the type of machines that we could develop for this project, we first investigated if there was already an already developed model that could perform the mechanical texturing. We didn’t find a machine that was specifically for mechanical texturing, however, we got ideas from several marking machines used to write things in metal plates. We defined that the method used, should be an impact from a controlled distance to make the micro-cavities, and based on that concept, we developed 5 conceptual designs, which are shown in Figure 2. The shown designs were evaluated to select the winning design, in base of the next criteria:

-Stiffness: that the structure had no or minimal movements within its parts.

-Easy to manufacture: to ensure that the design is not complicated enough to soak up a lot of time in its making.

-Repeatability: to ensure that the physical phenomenon could be easily replicated the same way for each micro-cavity.

-Variable force: in order to change the impact force if necessary.

-2 degrees of freedom for the disk holder: in order to move the disk in x and y coordinates to create a matrix as the texturized pattern, or x and rotation on z axis, in order to create a circular pattern.

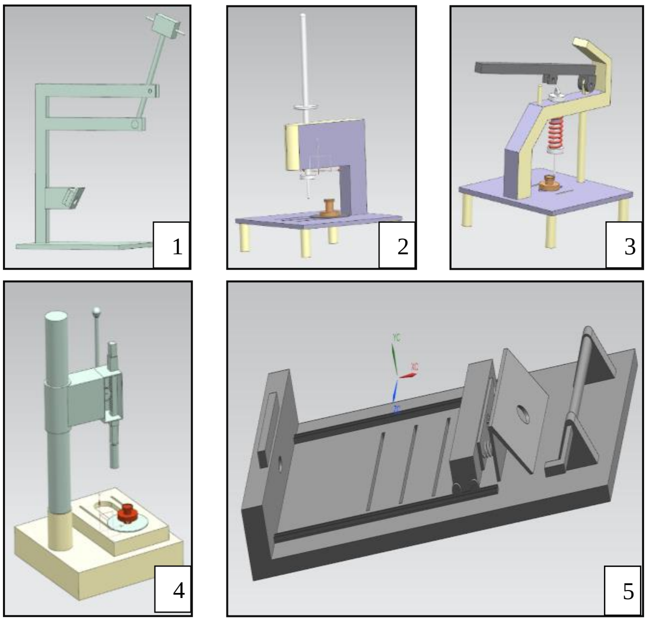

Fig. 2. Conceptual Designs: 1-Pendulum, 2-Hammer, 3-Spring, 4-Automatic Awl, 5-Impulse Car

Table 1 shows the evaluation done. The two best designs were chosen and re-evaluated to define the final prototype, from which in this case, a hybrid that contains elements from both designs was developed, thus resulting in a design that creates micro-cavities by impact from a determined distance, which can have weight changes. Later in this project (next Section), the impact was changed to resting the weight on the disk, because the impact created a far too deep micro-cavity, which exceeded the desired limits pre-defined by our research (from 20 to 30 μm of depth). Once the design was ready, we began the construction of the model, a step which will be described in the next Section.

Table 1. Evaluation of designs table

Design	Evaluation Score
Pendulum	29/40
Hammer	34/40
Spring	31/40
Automatic Awl	36/40
Impulse Car	25/40

2.2 Manufacturing and Testing of the Machine

The mechanism shown in Figure 3 is composed of a tempered steel shaft that passes through two linear bearings, with a cobalt point at the bottom end, which performs the mechanic texturing by impact on aluminium specimens. To change the location of the micro-cavities during the creation of the textures, we screwed the base of a little milling machine, to have one degree of freedom in the x-axis, and one in the y-axis with a precision of 50 μm.


Fig. 3. First prototype

The black weight on the top, is placed in a support created from an aluminium rod. In there we place the weights, which have a hole in the middle (The weights are the same from the Tribological Testing machines), and we just move the shaft along the z-axis, to perform the micro-cavities, which are created by a cobalt point.

The structured was made from a steel bar, which we cut in pieces and welded by ourselves, a process which generates imperfections in the unions, and which is probably not the best method for creating a machine which must have a lot of precision when used because of the nature of the application. But still, it's a good first prototype to determine if the mechanical texture can be achieved in the way we wanted to generate it.

Now that we have finished the prototype, we continue to verify if the characteristics of the mechanical texturing that we desire can be achieved by the machine, thus, we use the machine to create some micro-cavities. For this step, we use 1.5 kg on top of the shaft, and begin to create some micro-cavities by impact, however, as we analysed the results in the Alicona, which is a 3D optical surface analyser, we see that the microcavities are too big, as compared to the specifications we had researched before this project began (20-30 µm for depth and 130 µm for diameter of the micro-cavity), so we change the method of creating the cavities to simply resting the weight on the surface, The images of the micro-cavities created by this second method can be seen in Figures 4 and 5.

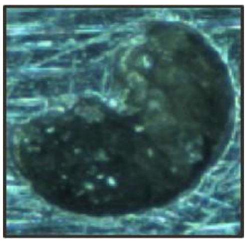

Fig. 4. Micro-cavity from first prototype example 1

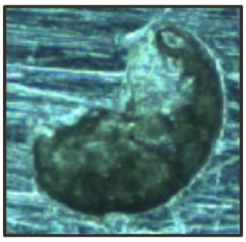

Fig. 5. Micro-cavity from first prototype example 2

The micro-cavities of the Figures 4 and 5 have the characteristics described in Table 2.

Table 2. Specifications from first prototype micro-cavities

Design	Evaluation Score
Pendulum	29/40
Hammer	34/40
Spring	31/40
Automatic Awl	36/40
Impulse Car	25/40

These characteristics comply partially with what we desired, so we moved forward with the project, and on to the next stage, however, the shape of the micro-cavity is somewhat strange (resembling a bean), which later was found to be because this first prototype utilized is not optimal, and has some variations, for example, the shaft is not fully perpendicular to the base. These problems are fixed later in this project, with the new prototype designed and manufactured.

2.3 Tribological Tests with and without Mechanical Texturing

Now that we have the prototype, and the desired features for our mechanical texturing, we proceed to the realization of the comparative tribological tests of the mechanical texturing vs no texturing, to validate that the mechanical texturing has a positive effect when talking about COF and wear reduction. The test used to compare the differences between them was the T-11 Tribo-tester, also known as "Pin on Disk" (Figure 6). This test measures COF and wear, in metal discs, by rotating the test specimen at determined values of velocity, radius distance, load, and time. The fixed values for this comparison are shown in the Table 3.

Table 3. Specifications for the Pin-on-disk tests

Distance (m)	Velocity (ms^{-1})
Load	5 kg
Time	7200 s
Radius distance	6 mm
Velocity	150 PRM
Lubricant	PAO-IV
Lubricant volume	1 drop (0.05 ml)
Pin material	Tempered Steel
Pin diameter	8 mm
Disk material	Aluminium

Fig. 6. T-11 Pin-on-disk tribotester

Now that we have all set, we continue to realize the tests and, analyse the results (The setting up of the machine, as well as the taring and the procedure is the

same for every test in this project and is not included in this paper).
Once the tests are done, we compare the results in order to verify the difference in COF and wear. The results are shown in the following graphs (Figure 7 is COF comparison, and Figure 8 is Wear comparison):

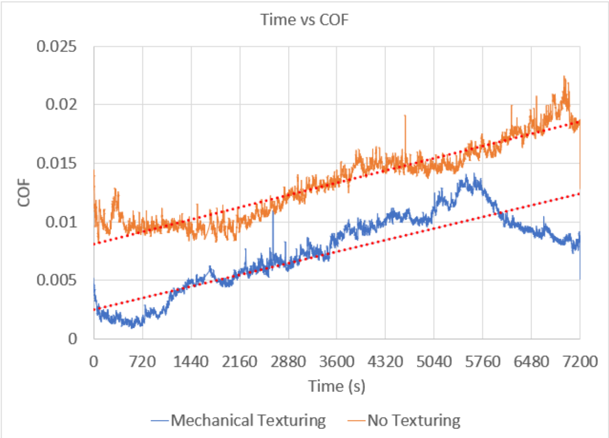

Fig. 7. COF obtained from the mechanical texturing samples and the un-textured ones

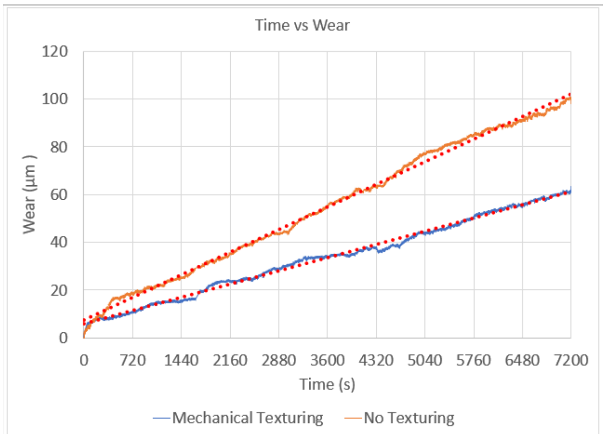

Fig. 8. Wear obtained from the mechanical texturing samples and the un-textured ones

From the Figure 7, we can see that the mechanical texturing appears to be better than no texturing by a big percentage, having almost parallel tendency lines, but no texturing being up by a value of almost 0.05, meaning that there is a big difference in between this two. In Figure 8, we can see that the MT is again better than the no texturing, by a value of almost 40 μm, and with a tendency line that has a lower slope, indicating that there is a big percentage difference. To continue the analysis, the numerical comparison is shown in the Table 4.

Table 4. Results of the first tribological test.

	MT	No Texturing	Improvement
Wear (μm)	81.9	116.6	29.76%
Wear (μm)	61.63	100.37	38.61%
Average COF	0.0075	0.0134	43.94%

In this table we can see that the improvement in wear and COF is considerably big, and that evidence exists to state that mechanical texturing is better than no texturing. Now that we have found out that the MT has a better performance, we continue to define the LST to be utilized to compare with MT, but first, we will create a better machine that has more stiffness, and that can better ensure that the shaft is perpendicular to the base, to certify that the weight is rested in a normal way, and that the force is applied at the specified point. We continue with this in the next Section.

2.4 Final Machine Prototype

Now that we made sure that MT works, and that the prototype made has the tools to make it in a good way, we will replicate the same prototype, but with materials that can ensure more stability, and thus, reducing variation within the different micro-cavities. We used aluminium bars to make the whole structure, because it's easier for machining, and as we will be using bolts and nuts for uniting the different pieces, we think aluminium is easier and faster for creating all the threads needed. We created a CAD model for the new prototype, to make that all the parts were correctly thought of, the measurements were correctly accounted for, and so we can have the blueprints if needed at a point in the project. An image of the blueprints without the bolt sockets is shown in Figure 9, and the final constructed model is shown in Figure 10.

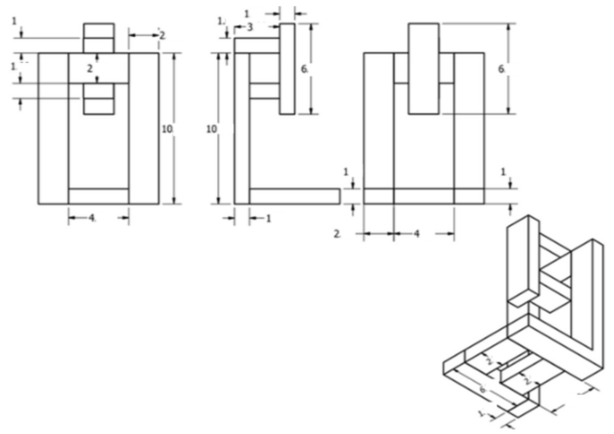

Fig. 9. Blueprints of the final prototype

Fig.10. Final prototype

The only change that was added to this model, is an extra lineal bearing, because we found out a problem in the first prototype, in which the shaft wasn't moving as frictionless as it should've, because the alignment was not done correctly, so to ensure that this problem didn't happen again, we added another lineal bearing.

Now that the final prototype has been finished, we continue to test the new micro-cavities that this machine can make, with the same weight as before. We found out some things that are important to state, which change the nature of our MT, these are discussed next. We found that the new structure created is more aligned, meaning that perpendicularity with the base was achieved. We found that the shape we had before, has changed to a half-moon (Figure 11), and analysing the cobalt point utilized, the half-moon appears the same as the new shape, meaning that in the first prototype there was probably some rotation along the z-axis, which cause the bean-like shape we presented earlier.

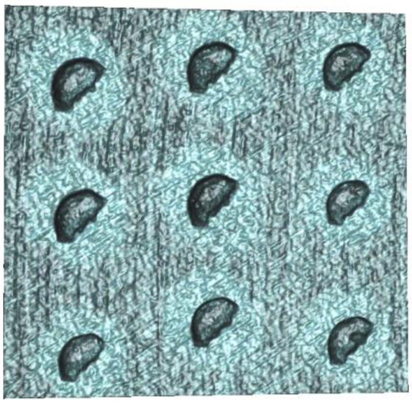

Fig. 11. Representation of the final MT achieved

We also found that the micro-cavities characteristics have also shifted a little, and that the depth of the micro-cavities have gotten very deep, and we decide to lower the weight utilized by the machine, and also, we take this opportunity to redefine the characteristic that would be used to compare the MT and the LST. We think the best measurement, that can be used to compare both textures, is the volume below surface, or the volume of space created in the measuring it from the surface, because it will define the amount of residues and lubricant it can store, so we measure the volume under the surface for the mechanical texturing based on the 40x40 matrix shown in Figure 12, in which 3 groups of 6 values were selected at random from 8 sections created around the centre of the matrix, and into the outsides, to make sure we obtain an approximate general average for the whole MT. This totals a total of 144 measurements for each of the MT disks, and so, we obtain an average volume value of 60,000 µm^3, for the whole disk with a standard deviation of 29,000 µm^3. As can be seen, the value of the standard deviation is very big compared to the mean, representing a 48% of the average value, however, this variation can be explained by the human factor, which can be reduced greatly by automatizing the process of MT.

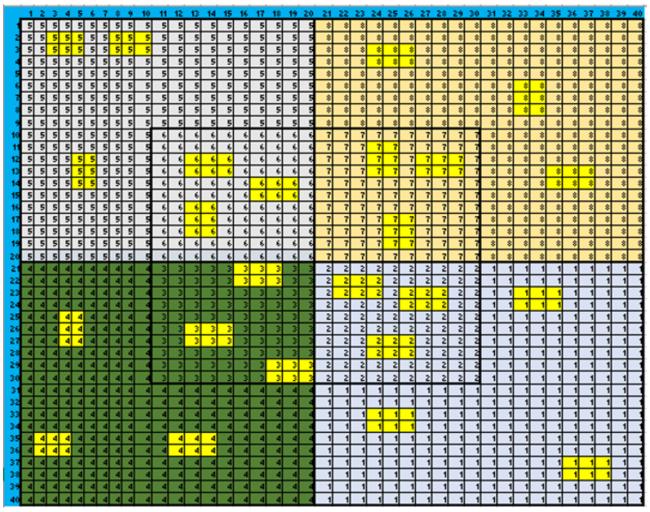

Fig. 12. 40x40 microcavities matrix

Now that we have this value, we continue to define the LST that will be used in this project, which will be selected as the set of characteristics which best approach the volume value of the MT. This procedure is described in the following section.

2.5 Laser Texturing

In this section, conditions required make the volume of the LST the most like the MT are investigated in the form of a tuning process, in which the characteristics of the laser will be changed, in order to find the set of specifications that will be used for the rest of the project. The process of tuning is kind of broad, and so, it is compressed into the following table (Table 5), for an easier analysis of it:

Table 5. Selected set of criteria used for making the LST

Intensities	-75% -85% -100% (selected)	
Number of passes	- 1 pass (selected) - 2 passes - 3 passes	
Laser Diameter (µm)	- 10 - 15 - 20 - 25 - 30 - 40 (selected)	- 45 - 50 - 55 - 60 - 65 - 70

The selection was done according to 2 criteria:

- The set of values which approximated better the MT volume.

- The values that showed the least variations.

The selected set of specifications give an average volume value of 57,000 μm³ and a standard deviation of 27,000 μm³. This value, as well as the one from the MT, is very big, representing a 47% of deviation from the average, however, this value cannot be explained by the human factor, as a machine is the one performing the micro-cavities. This great variation is due to the nature of the LST, which is a process which deforms greatly the surface it is applied on. The selected set of specifications give a 5% difference between the data, and so, we decide to use this laser texture as the one we will be analysing in what is left of this project.

2.6 Tribological Tests of Mechanical Texturing vs Laser Texturing vs No Texturing

The next and final step in the methodology of this project, is the tribological tests of MT vs LST vs no texturing, in which we will see the visual differences between the two of the surface finishes, using the no texturing surface finish as reference, specify the conditions used in the tribological tests, and display the general results to be analysed in the next section (Section 3: Results and Analysis). For the first step, we show the surface finishes of the three types of texture which are to be analysed. The next figures (Figures 13 and 14) show a visual comparison of the two main textures (MT and LST) compared in this project.

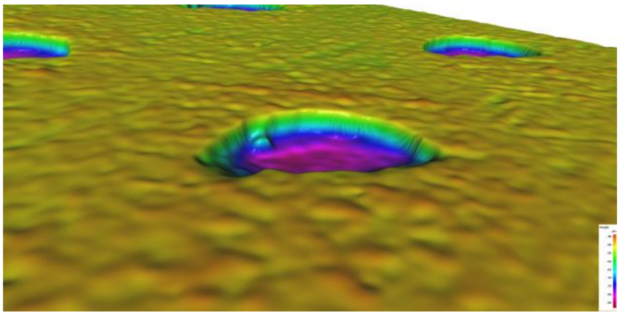

Fig. 13. Graphic representation of a micro-cavity in the achieved MT

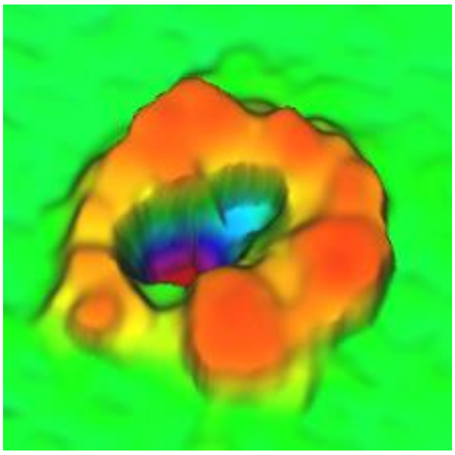

Fig. 14. Graphic representation of a micro-cavity in the achieved LST

As we can see in the MT disk, there appears to be no hat at all, we only see the micro-cavity that was created, with very defined edges and a well-distributed depth around the centre. In the LST however, there is only a portion of the micro-cavity that has a big depth, while the surroundings are barely affected, and, we can see that a big deformation of the material has appeared around the micro-cavity, a phenomenon usually referred to as the hat. This shows how the nature of the LST procedure creates imperfections in the surface finish that need to be removed by a very fine sandpaper, and very carefully, in order not to damage the surface finish. There is no need to present the no texturing image, as there is nothing to show except for the horizontality of the disk, which can be seen in the MT and LST disks. Now, we will continue to show the test specifications utilized in the pin on disk tribological test, these specifications are shown in Table 6.

Table 6. Specifications for the Pin-on-disk tests

Parameter	Value
Load	1.5 kg
Time	7200 s
Radius distance	7 mm
Velocity	150 PRM
Lubricant	PAO-IV
Lubricant volume	1 drop (0.05 ml)
Pin material	HARDOX 600
Pin diameter	4 mm
Disk material	Aluminium

Now that all is set, the tests are run, and the visual comparison of the results are shown in the Figure 15.

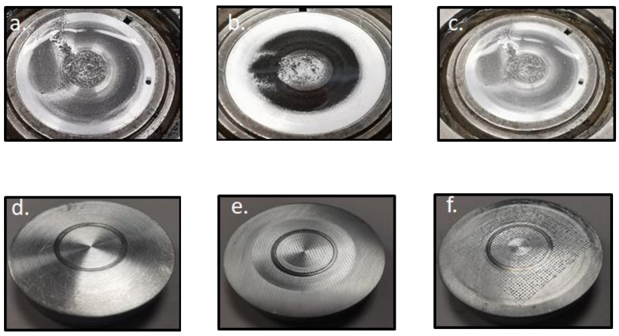

Fig. 15. No texturing, LST and MT aluminium disks are presented (a, b, and c, respectively), burr and excess lubricant can be seen. No texturing, LST and MT aluminium disks are presented (d, e, and f, respectively), after excess lubricant and burr were removed

We can see from these visual results that the lubricant never ran out, although it wasn't much. The burr concentrated in the middle of the disks, and the test where there is more burr created is in the no texturing disk. We can also observe something which seems important to denote, and it's that a black-like colour appeared in the wear tracks that were created when the test was ran. We believe this black rubbish, is actually aluminium oxide, and that this has been reducing the COFs in all of the test disks, however, if this is true, the most affected disks will be the ones that have a greater area of contact during the test, a phenomenon that would be the greatest in the no texturing disk. With no more to add, let's get to the analysis of the results obtained from these tests.

3. RESULTS

The next section shows the results obtained from the tribological tests utilized in this project. It is important to state that 3 tests were run for the MT disk, 4 were run for the LST disk, and 3 were run for the no texturing disk (each test had its own new test specimen). The first result shown is a visual comparison of the average COF of all of the tests (Figure 16).

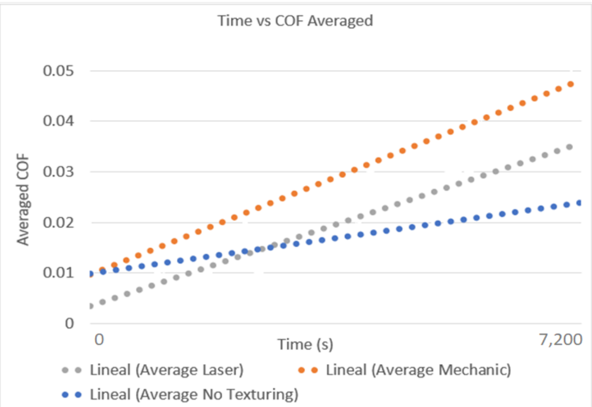

Fig. 16. Average COF

In this graph, we can see how the best COF is the one from the no texturing surface finish, as the best tendency line is this one. Just as was explained in the last section, this (we believe) is because of the aluminium oxides that are created in the wear track, because of reactions between materials utilized, temperature, and other factors that could affect this, thus reducing the COF the in the test. In the next graph (Figure 17), we can see the averaged wear from all of the tests utilized for each of the type of surface finish.

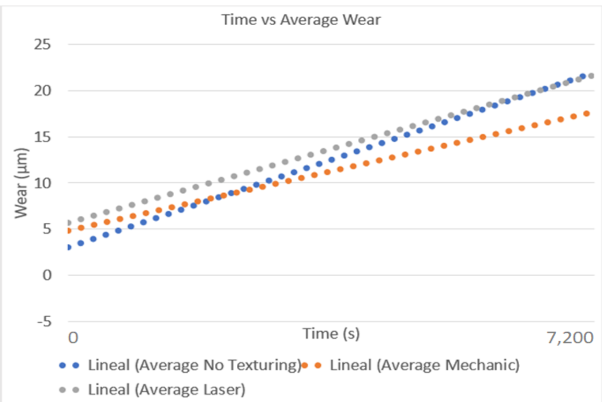

Fig. 17. Average wear

In this graph we can see how the best surface finish found out to resist wear the most, is the MT. This can be observed as the value at the end of the test is the lowest for the MT. Also, we can confirm this result by viewing the tendency line, which has the lowest slope in all three of them. In Figure 18, the average wear tracks comparison for the three types of surface finish is presented.

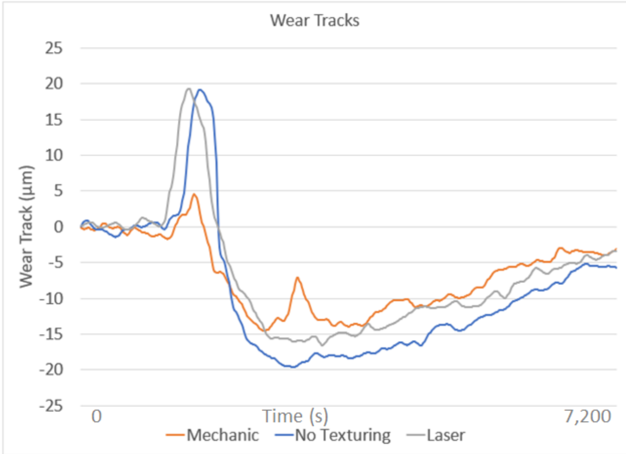

Fig. 18. Averages wear tracks

In this graph we can observe that the best surface finish is again the MT. These values are also shown in the next table (Table 7), where we can also see that the averaged values of the wear tracks obtained are the lowest for the MT, confirming that against wear, the best results are the ones obtained from the MT.

Table 7. Results for the average wear measured in the wear tracks

Surface Finish	Wear Average
MT	12.2 µm
LST	18.7 µm
No texturing	18.4 µm

Figure 19 shows the average wear and one standard deviation for each of the data.

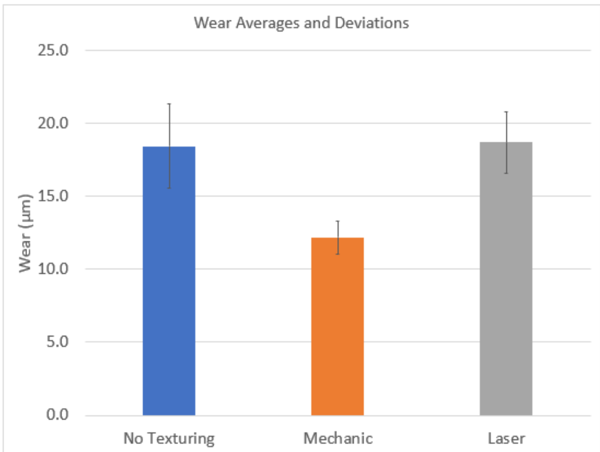

Fig. 19. Average wear

In this graph we can again confirm that the best surface finish is the MT. This, as we can see that the average wear is the lowest, and, that the standard deviation of the MT is also the lowest, and the intervals do not overlap, meaning that 68% of the data of MT is different than the ones from the LST and no texturing. As can be seen in Table 7, a numerical confirmation of these results has already been shown, resulting in an improvement in wear reduction of 34.7% as compared to LST. An extra step in this project, is the confirmation that the data utilized in these comparisons is reliable, and that these comparisons are statistically significant, we continue to employ a Dixxon test, in which we analyse the data in search for outliers that can demonstrate that the results are not comparable. We utilize this test with the wear averages for each of the type of tests used, with a confidence level of 95%, and we determined that the values are statistically comparable, thus reinforcing the statement that MT is significantly better than LST. A summary of this test is showed in the Table 8.

Table 8. Dixxon test results

Results	Qts	Qcv
MT	0.639	0.941
LST	0.4435	0.765
No texturing	0.467	0.642

4. CONCLUSIONS

As has already been shown in the Results and Analysis of this project, MT was shown to be 34.7% better than LST in wear. It's important to point out that these results are obtained for a certain set of specifications already explained in this project, and that changing the specifications of these, can change the results, and give way to new findings. MT may have been found to be better than LST in wear, but still, MT has its disadvantages when compared to LST, for example, LST can be applied in any surface, while MT is hard to apply in surfaces that aren't flat. Although the variability of MT and LST are practically the same, with a 1% difference, it is important to say that MT is no at its optimal level, because as every micro-cavity is made by people, the variability of the human factor plays a great role in this variation, and if the process of creation were to be automatized, this deviation would greatly decrease, thus making it more reliable than LST.

Another very important conclusion that needs to be explain, is the aluminium oxide proposal, in which we think that the aluminium oxide is greatly reducing the COF of the pin on disk test. This conjecture is based on the fact that the colour of the wear track appears to be oxidized. However, it is imperative that a chemical composition test is used to test this conjecture in order to check if this is what is really happening, and not something else.

Some specific conclusions that we developed from stages in this project are as follows:

- Stiffness in the machine is needed to create the mechanical texturing.
- It takes 1 hour and 30 minutes to create a MT test disc.
- Tip machining is difficult; texturized shape is hard to control.

Some recommendations have been developed, some for the use of this project as a tool for another investigation project or to tests the results obtained for veracity, as well as further research in the topic are as follows:

- Use mechanical texturing in flat surfaces.
- Automatize the process of mechanical texturing.
- Use another material instead of aluminium (I.E: Steel).
- Use EDAX (chemical decomposition) to analyse residues in search for oxides.
- Varying mechanical and laser texturing specifications, can result in new findings and optimal conditions discovery.

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