Project Acronym:	**FEMTOSURF**
Project Full Title:	Functional surface treatments using ultra-short pulse laser system
Grant Agreement:	825512
Project Duration:	1 January 2019 – 30 June 2022

D6.3 – Pilot testing in space application

Work Package:	WP6 – FemtoSurf piloting
Deliverables	D6.3
Lead Beneficiary:	Femtika
Due Date:	Month 41
Deliverable Status:	Final
Deliverable Type:	Report
Dissemination Level:	Public
File Name:	D6.3-Pilot testing in space application

FEMTOSURF Consortium

PHOTONICS
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PHOTONICS PUBLIC PRIVATE PARTNERSHIP

This project received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No. 825512. This project is funded by one of the call under the Photonics Public Private Partnership (PPP) (www.photonics21.org)

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Revision Control

Version	Status	Modifications made by
0.1	Initial Draft	Femtika
0.3	Final improvements	Femtika
1	Submission to the EC	Femtika

The main objective of the FemtoSurf project is to develop, test, and demonstrate industrial-grade solid-state 2-3 kW-level fs laser with parameters suitable for metal surface patterning applicable in industrial settings. FemtoSurf industrial-grade 2-3kW-level fs laser will be integrated into a propose-built optical chain enabling multi-beam processing (100+ simultaneous beams) with individually tailored spatial distributions in each laser spot, integrated into a fully automated processing setup for efficient patterning arbitrary shaped metal components with sizes exceeding several meters while retaining micrometer level precision and on-the-fly quality assessment (zero faulty parts delivered).

1 Introduction

The present document is a deliverable "D6.3 – Pilot testing in space applications" of the FemtoSurf project (Grant Agreement No.: 825512), funded by the European Union's Horizon 2020 Research and Innovation program (H2020).

The purpose of the DELIVERABLE is to provide a document that describes the development and testing process for space applications. In this document required information will be provided about the laser fabrication process, testing, and results for space applications. Specific tests such as salt mist test to verify corrosion resistance improvements, paint adhesion test to verify the increase in paint and adhesive film characteristics, and ball on disk test to verify low friction properties and evaluate its performance under load. Materials for fabrication were supported from, end-user AEREA to Femtika, for laser texturing. Prepared samples were sent to AEREA for testing.

The following document made use of the HORIZON 2020 FAIR DATA MANAGEMENT PLAN TEMPLATE and was written with reference to the Guidelines to FAIR (Findable, Accessible, Interoperable, and Reusable) data management in Horizon 2020.

2 Adhesion test

2.1 Samples fabrication for scratch test

For adhesion tests, multiple structures were fabricated on some aluminum 7075 samples and after fabrication cleaned in an ultrasonic batch for 10 minutes using isopropanol as a cleaning agent. From multiple structures were selected few with good wetting properties and specific patterns such as grooves and trenches, crossed lines, and dimples, SEM pictures of textures are shown in Figure 1.

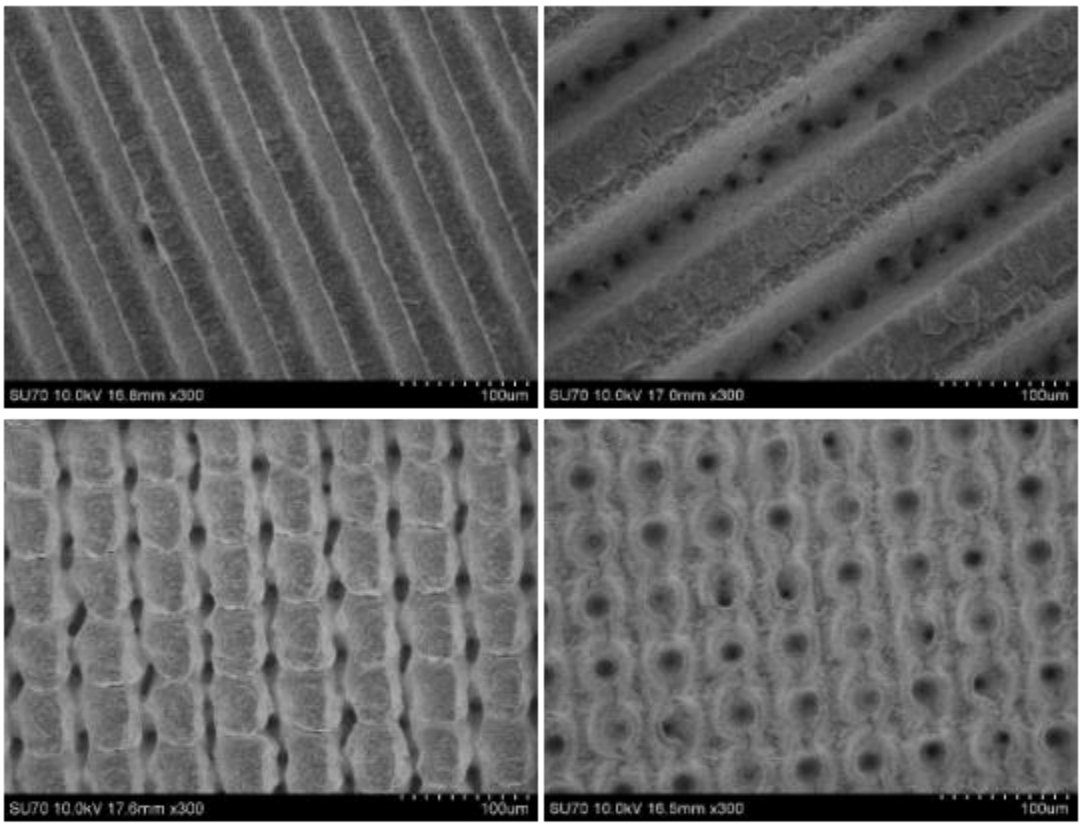

Figure 1. SEM pictures of textures. Above, at left are grooves, at right trenches, below, at left cross lines, at right dimples.

Each texture was replicated forth times on different aluminum samples, a total of 16 samples were made. Each sample was cleaned in an ultrasonic bath for 10 minutes using isopropanol as a cleaning agent and then sealed in vacuum bags (shown in Figure 2).

Samples were sent to AEREA for testing.

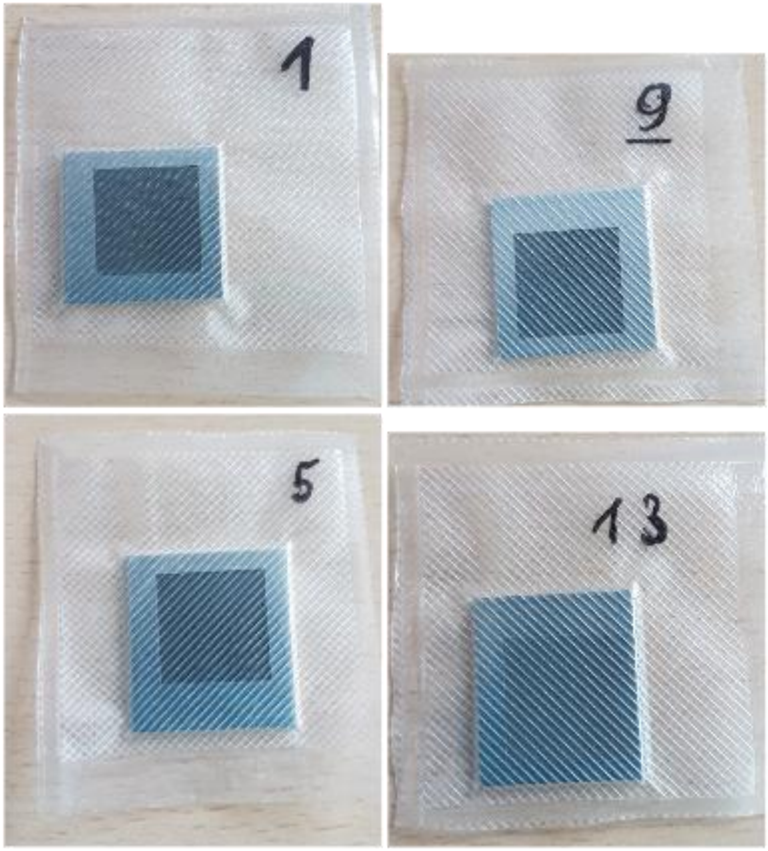

Figure 2. Sealed samples. 1 – groves, 9 – trenches, 5 – cross lines, 13 – dimples.

2.2 Scratch test and results

All samples were painted, and scratch tests were provided. The whole procedure was shown in Figure 3.

After painting samples, they were scratched, using a specific tool. Scratch was done in two directions, forming a crossed pattern. After the scratch adhesive tape was taped on the scratched area and then removed. After this, the left paint on the sample was analyzed and compared with the theoretical pattern of ISO standard, used to define paint adhesion to the surface. From all testing, it was found that dimple textures provide the best results compared with other patterns and match with ISO 1 / ASTM 4B standard, which indicates very good adhesion.

Similar tests were replicated and on larger samples (250×200 mm) showing similar results, very good adhesion.

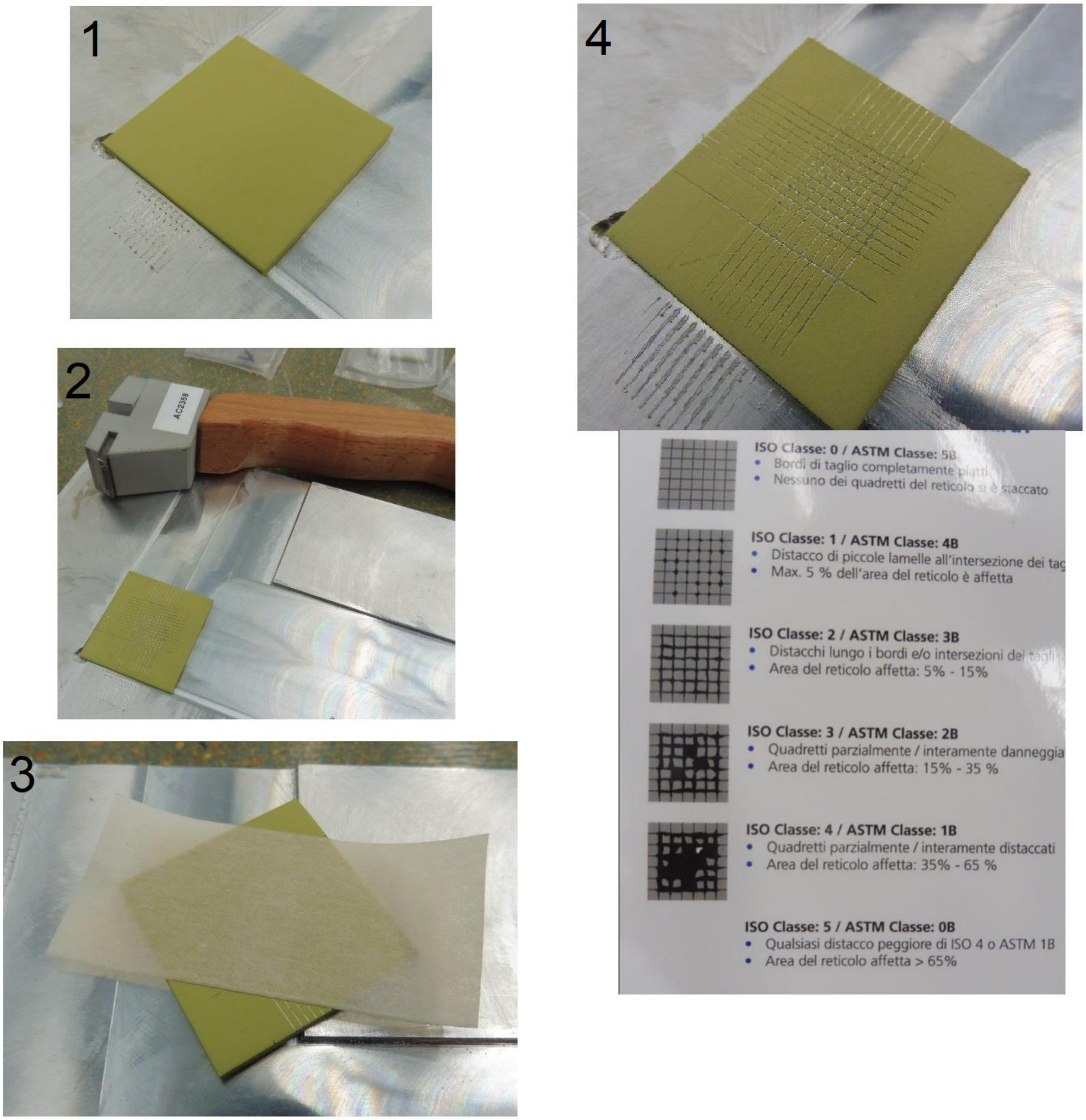

Figure 3. Scratch test.

After this test, it was decided to do a single lap shear test.

2.3 Samples fabrication for shear test

For the shear test, huge aluminum samples (Figure 4) were fabricated (Figure 5) and cleaned with isopropanol, and then sealed in a vacuum bag (Figure 6).

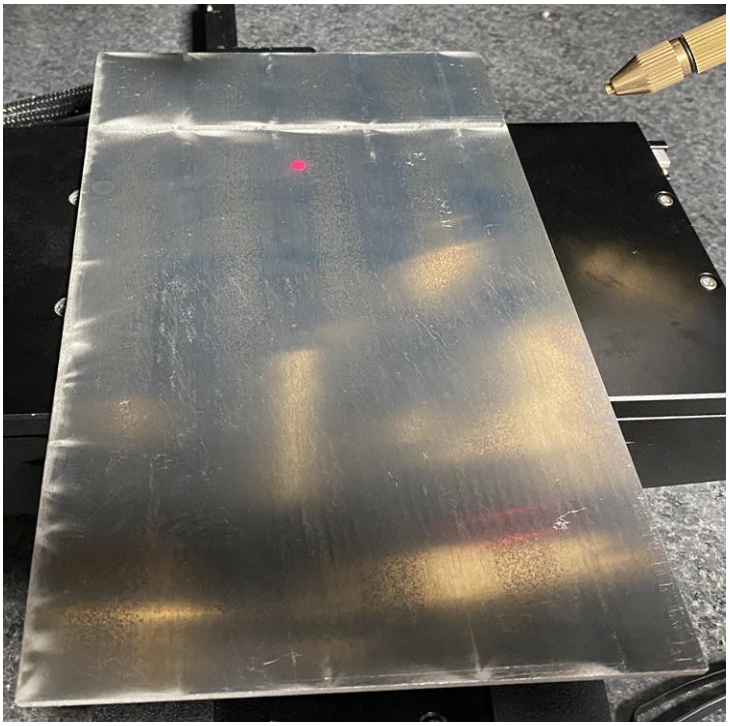

Figure 4. Sample before fabrication.

Figure 5. Sample after fabrication.

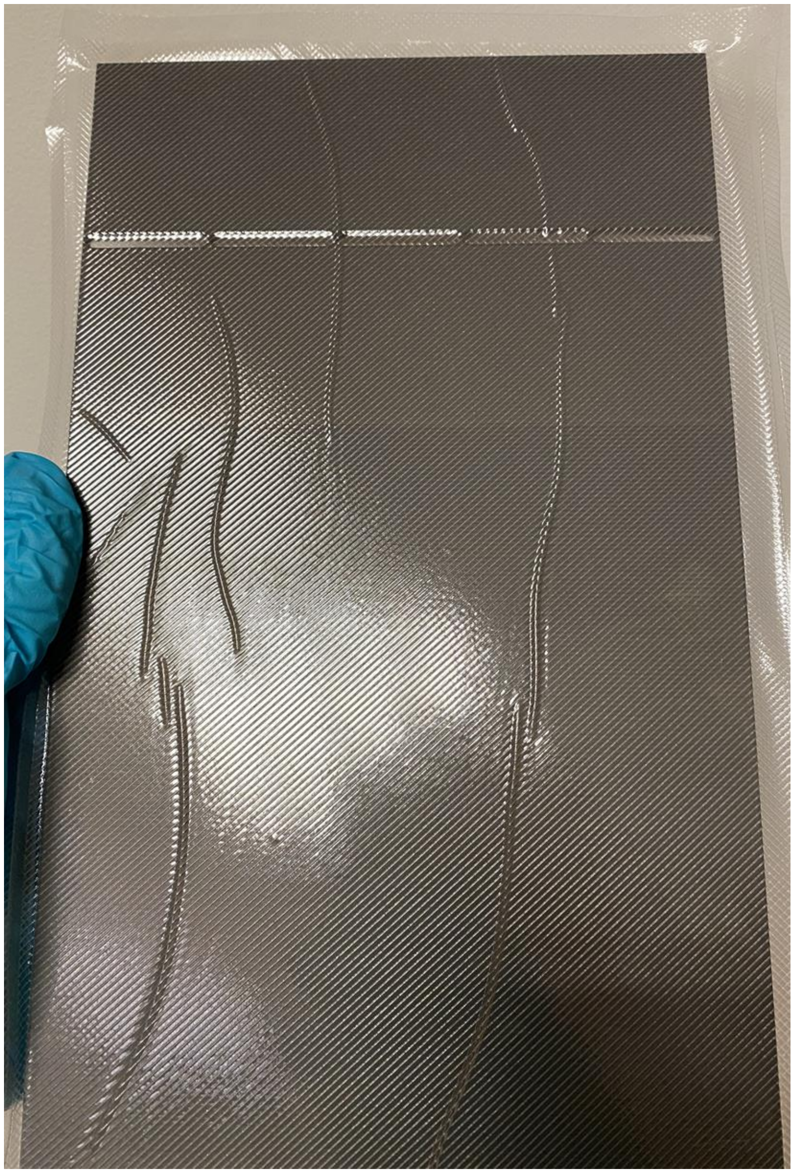

Figure 6. Sealed sample in a vacuum bag.

Prepared samples were sent to AEREA for a single lap shear test.

2.4 Shear test and results

Single lap shear tests were done following ASTM-D-1002 specification. Aluminum 7075 sheets fabricated with dimples pattern was combined with another fabricated sheet using adhesive and then pulled on each end of the sheet until bonded area breaks. Totally 6 tests were provided, prepared samples with the device are shown in Figure 14, and the process scheme is shown in Figure 7.

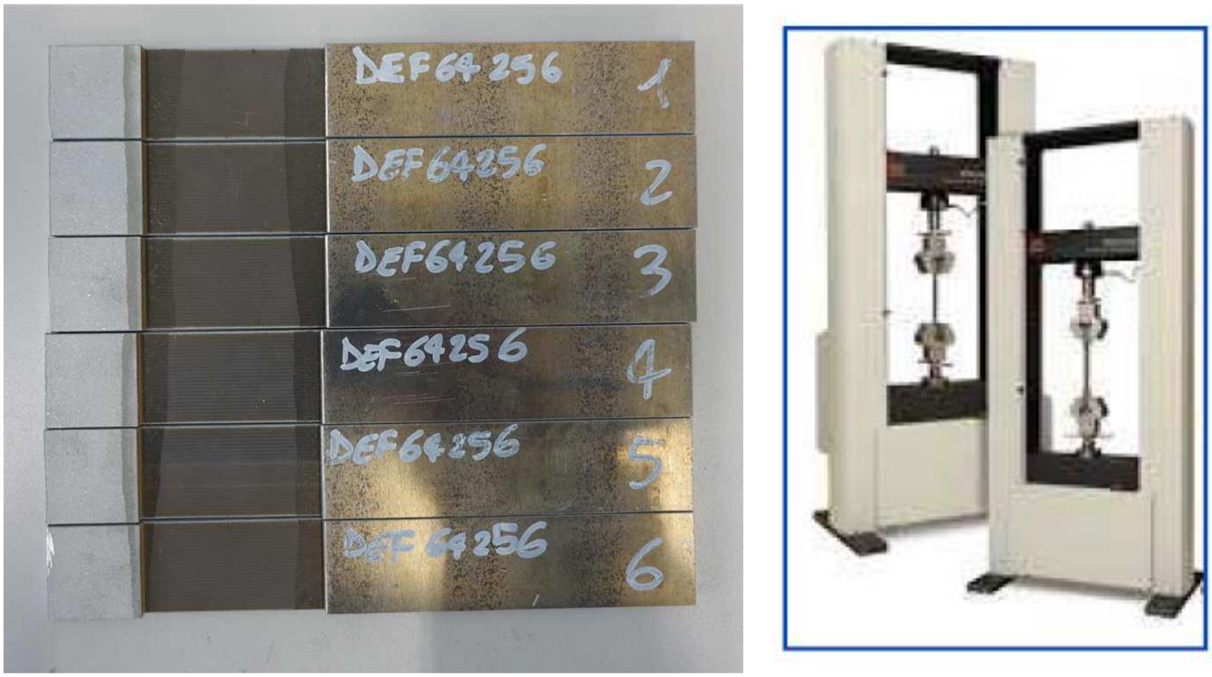

Figure 7. Prepared samples for shear test on left and device are shown on right.

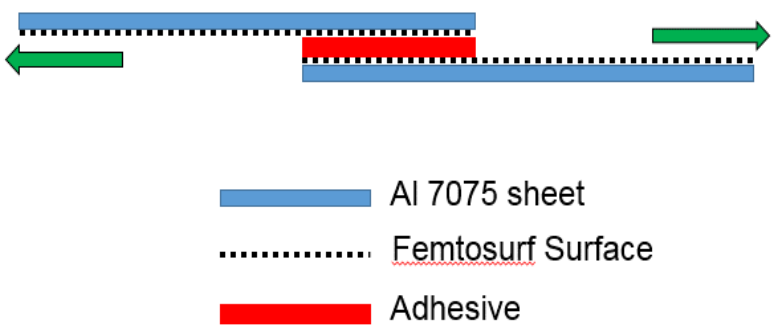

Figure 8. Principal scheme of process.

Single lap shear test testing information and the result are presented in Table 1, each test sample after bound loss is shown in Figure 7. A comparison of results with a standard sandblasts procedure result is shown in Figure 9.

Table 1. Information about single lap shear test.

Code	**DEF64256-SLS-DB-01**	**DEF64256-SLS-DB-02**	**DEF64256-SLS-DB-03**	**DEF64256-SLS-DB-04**	**DEF64256-SLS-DB-05**	**Average**	**Std. Dev.**	**COV %**
Width, mm	25.53	25.56	25.37	25.48	25.45	25.48	0.074	0.290
Overlap, mm	25.55	25.63	25.7	25.79	25.59	25.65	0.095	0.370
Thickness A1, mm	3.06	3.07	3.07	3.06	3.07	3.07	0.005	0.179
Thickness A2, mm	3.08	3.09	3.08	3.07	3.08	3.08	0.007	0.230
Total length, mm	174.41	174.44	174.47	174.52	174.61	174.5	0.110	0.063
Displacement, mm	0.447	0.422	0.43	0.429	0.455	0.437	0.014	3.160
τR, MPa	17.05	17.154	17.012	16.855	16.149	16.8	0.403	2.393
Peak load, kN	11.122	11.238	11.092	11.076	10.517	11.0	0.282	2.564

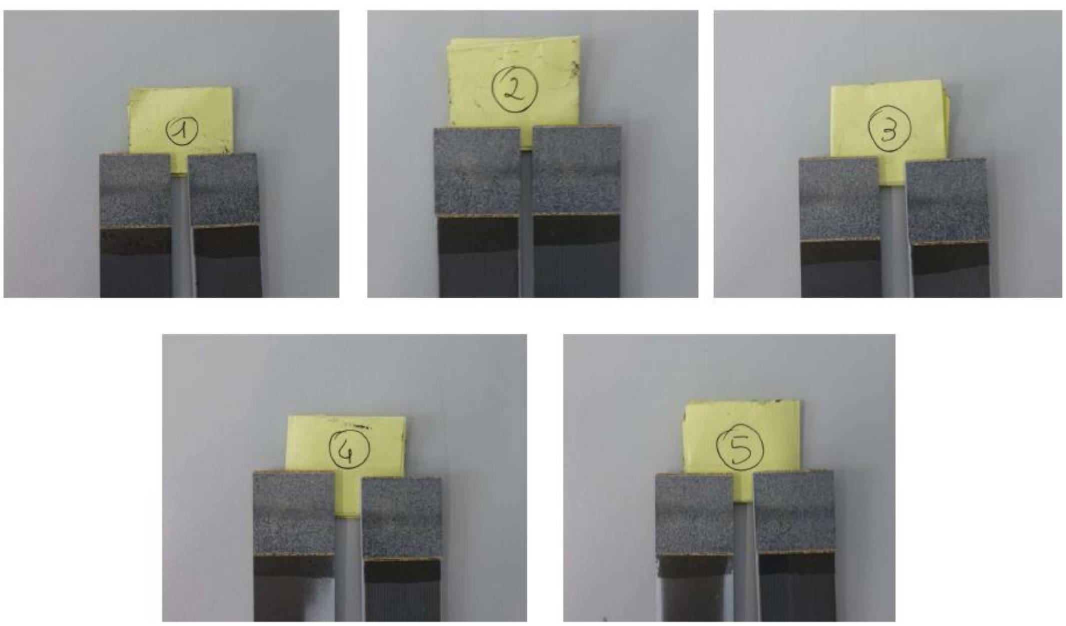

Figure 8. Samples after the test.

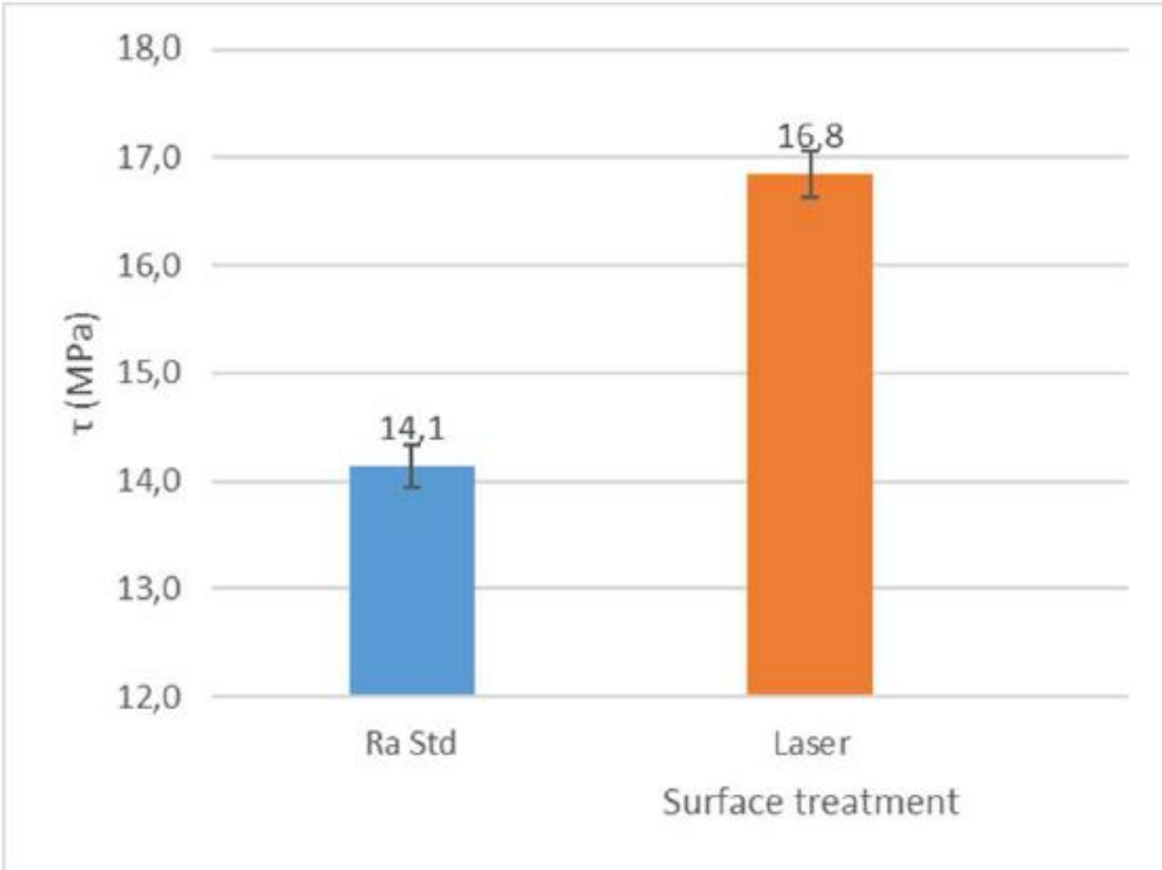

Figure 9. Shear test results comparison between standard sandblasting and laser treatment.

With femtosecond laser fabricated aluminum surface for samples, DEF64256 shows an increment of the mechanical properties of the bonded surfaces of the order of 20 % compared with sandblasting procedure, forming standard Ra from 4,8 to 5,2 µm.

Similar tests are planned that would test hybrid samples (carbon + aluminum alloy) and with the application of a specific primer (BR6700-01) before designing full-scale application on a real component.

3 Friction reduction test

3.1 Sample fabrication

For friction tests, disk shape metals were fabricated. Materials such as steels 17-4 PH H1025 and PH13-8Mo H1050 and titanium Ti6Al4V were provided by AEREA. On each material, the disk was fabricated specific structure, most of them were dimples of different depths and distances. On some of the disks were fabricated two types of structures forming inner and outer areas. After fabrication, each sample was cleaned for 10 minutes in an ultrasonic bath using isopropanol as a cleaning agent. Fabricated samples are shown in Figures 10, 11, and 12.

Figure 10. Fabricated 17-4 PH H1025 steel samples for the ball on disk test.

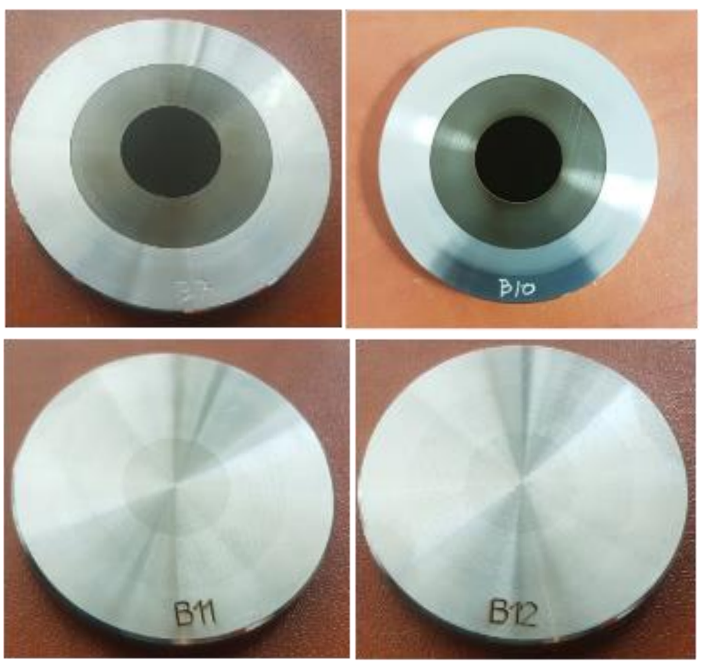

Figure 11. Fabricated PH13-8Mo H1050 steel samples for the ball on disk test.

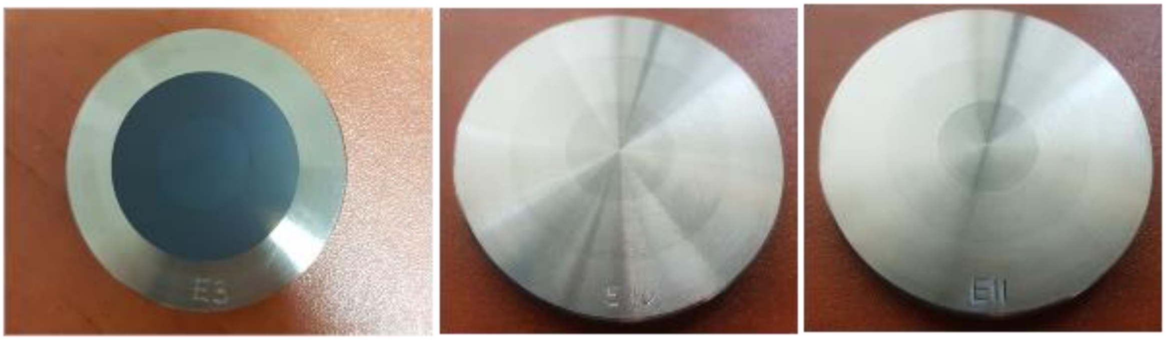

Figure 12. Fabricated Ti6Al4V titanium samples for the ball on disk test.

Each sample's inner (I) and outer (O) areas were observed with a profilometer to evaluate texture patterns. Profilometer pictures are shown in Figures 13, 14, and 15.

As it seems from profilometer pictures, most of the textures are dimples and their depth variate from about 10 to 40 µm.

Prepared samples were sent to Aerea for testing.

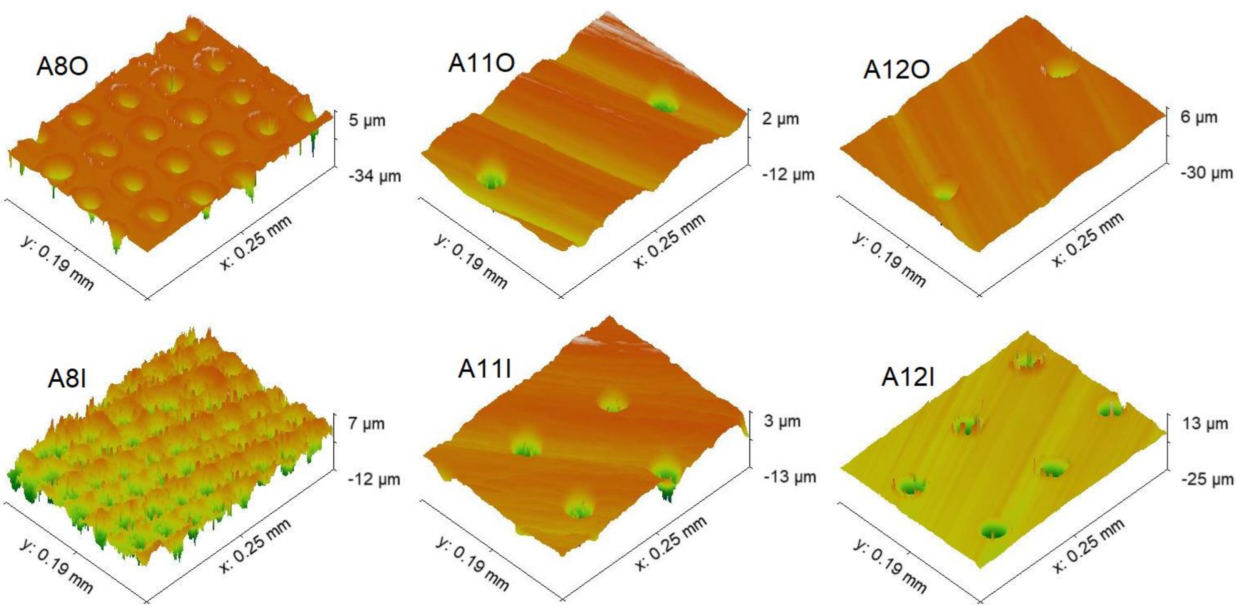

Figure 13. Profilometer pictures of 17-4 PH H1025 steel samples inner (I) and outer (O) areas.

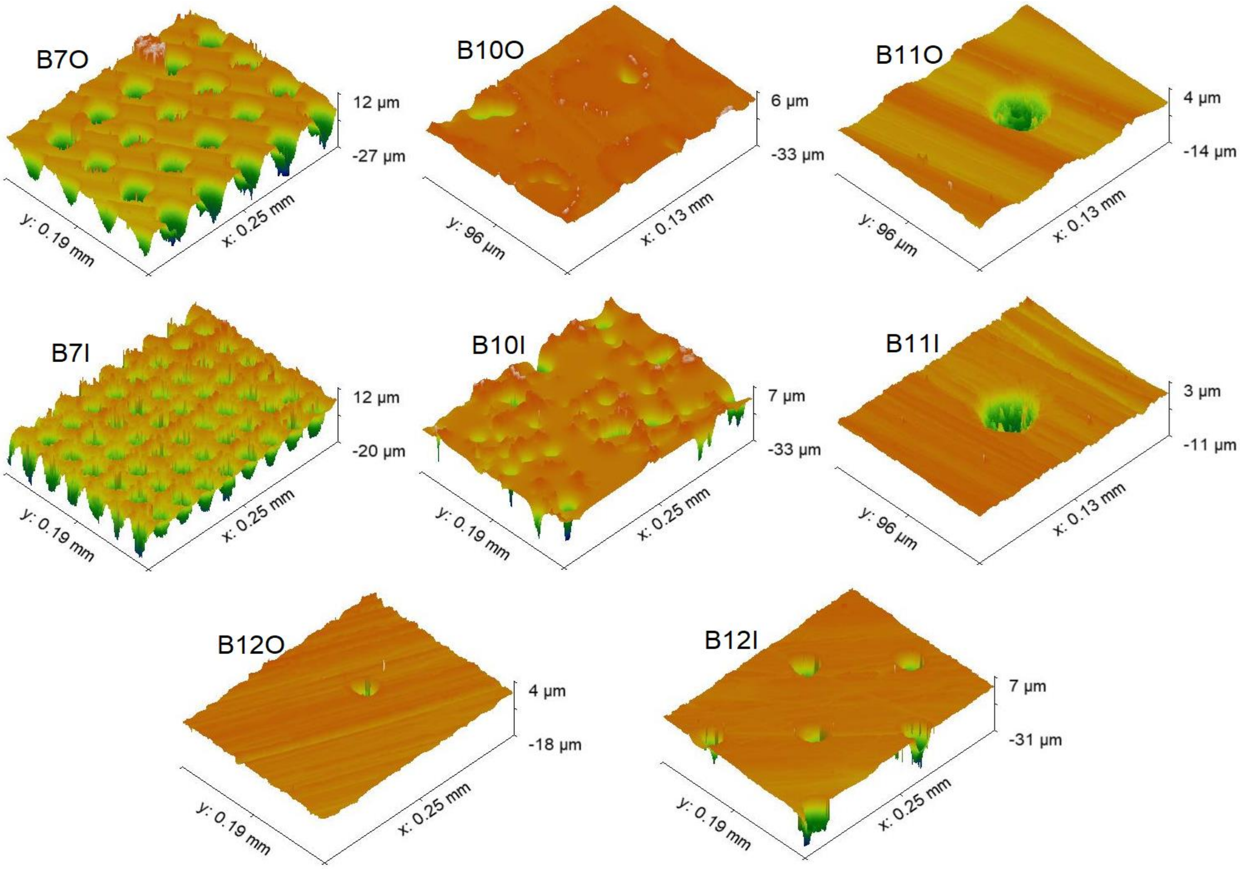

Figure 14. Profilometer pictures of PH13-8Mo H1050 steel samples inner (I) and outer (O) areas.

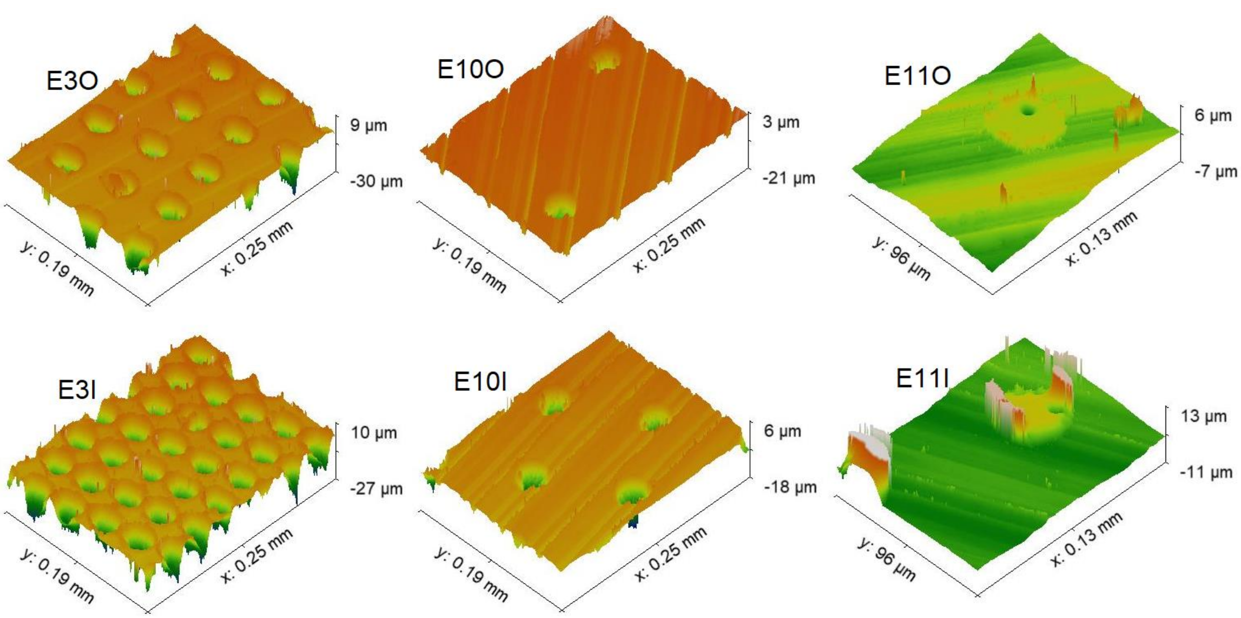

Figure 15. Profilometer pictures of Ti6Al4V titanium samples inner (I) and outer (O) areas.

3.2 Ball on disk test and results

To measure the friction of each sample textured area, ball on disk tests were performed, using a 6 mm diameter alumina ball, at 0,1 m/s, 0,2 m/s, and 0,3 m/s speed loaded with 0,5 and 1 N force. Each sample's inner (internal), outer (midge), and external regions were measured according to the model, which is shown in Figure 16, same as a ball on a disk device, and measurement results are presented in Table 2.

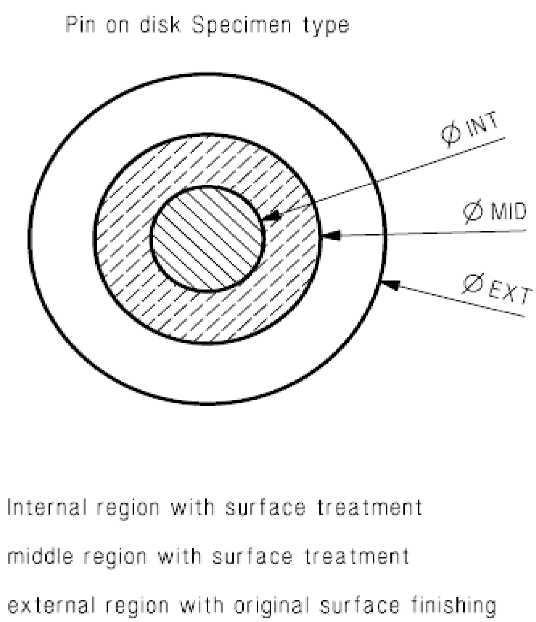

Figure 16. Measurement model on left and ball on disk device on right.

Table 2. Information about samples.

Disk ID	EXT, mm	Inner (MID), mm	Outer (INT), mm	Material
A8	56	40	20	17-4 PH H1025
A11	49	32	16	17-4 PH H1025
A12	49	32	16	17-4 PH H1025
B7	63	40	20	PH13-8Mo H1050
B10	63	40	20	PH13-8Mo H1050
B11	47	32	16	PH13-8Mo H1050
B12	47	32	16	PH13-8Mo H1050
E3	59	40	20	Ti6Al4V
E10	59	40	20	Ti6Al4V
E11	59	36	18	Ti6Al4V

At first friction of bare material was measured at 0,1 m/s with 0,5 and 1 N loads. Similar measurements were done at 0,5 N load with different speeds (0,1, 0,2 and 0,3 m/s). At different speeds and loads, measured friction coefficients were different, however, it was decided to use only 0,5 and 1 N load at 0,1 m/s results for comparison with textured areas. Measurement results were presented in Tables 3 and 4.

Table 3. Friction coefficient with 0,5 N load at 0,1 m/s.

Sample	Texture	Static friction coefficient	Final friction coefficient	Laps until coating removal
A	SUB	0.1710	0.6744	-
A8	INT	0.2551	0.8618	1000
	MID	0.2918	0.7813	1500
A11	INT	0.1762	0.8455	800
	MID	0.1912	0.8369	1900
A12	INT	0.0788	0.7626	700
	MID	0.2974	0.8432	800
B	SUB	0.2426	0.8660	-
B7	INT	0.3698	0.7563	500 (4000)
	MID	0.2350	0.8509	300
B10	INT	0.3438	0.5809	1000
	MID	0.2664	0.5857	2000
B11	INT	0.2896	0.8373	3000
	MID	0.3178	0.8148	3000
B12	INT	0.2728	0.9025	800
	MID	0.3067	0.9125	1000
E	SUB	0.3191	0.5454	-
E3	INT	-	-	-
	MID	0.2078	0.5409	150
E10	INT	0.3754	0.7167	50
	MID	0.3444	0.4975	50
E11	INT	0.3132	0.4909	50
	MID	0.3354	0.5951	50

Table 4. Friction coefficient with 1 N load at 0,1 m/s.

Sample	Texture	Static friction coefficient	Final friction coefficient	Laps until coating removal
A	SUB	0.2573	0.8604	-
A8	INT	0.1662	0.8378	1500
	MID	0.2600	0.7957	1000
A11	INT	0.1441	0.8660	400
	MID	0.1801	0.7964	400
A12	INT	0.1674	0.8521	600
	MID	-	-	-
B	SUB	0.1596	0.7937	-
B7	INT	-	-	-
	MID	-	-	-
B10	INT	-	-	-
	MID	-	-	-
B11	INT	0.3128	0.8649	1000
	MID	0.1953	0.8269	800
B12	INT	0.1258	0.8567	600
	MID	0.3868	0.8662	600
E	SUB	0.4987	0.6398	-
E3	INT	0.3232	0.6084	1000
	MID	0.2222	0.5907	150
E10	INT	0.2182	0.4876	50
	MID	0.3038	0.5907	50
E11	INT	0.2885	0.6238	20
	MID	0.3738	0.6893	50

As it seems that surfaces after several laps wear off and lose their lower friction properties, especially titanium samples, most textured areas wear off lower than after 200 laps, while textures on steel last much longer.

How friction coefficient changes overlap, at 0,1 m/s using 0,5 N load is shown in Figures 17 and 18.

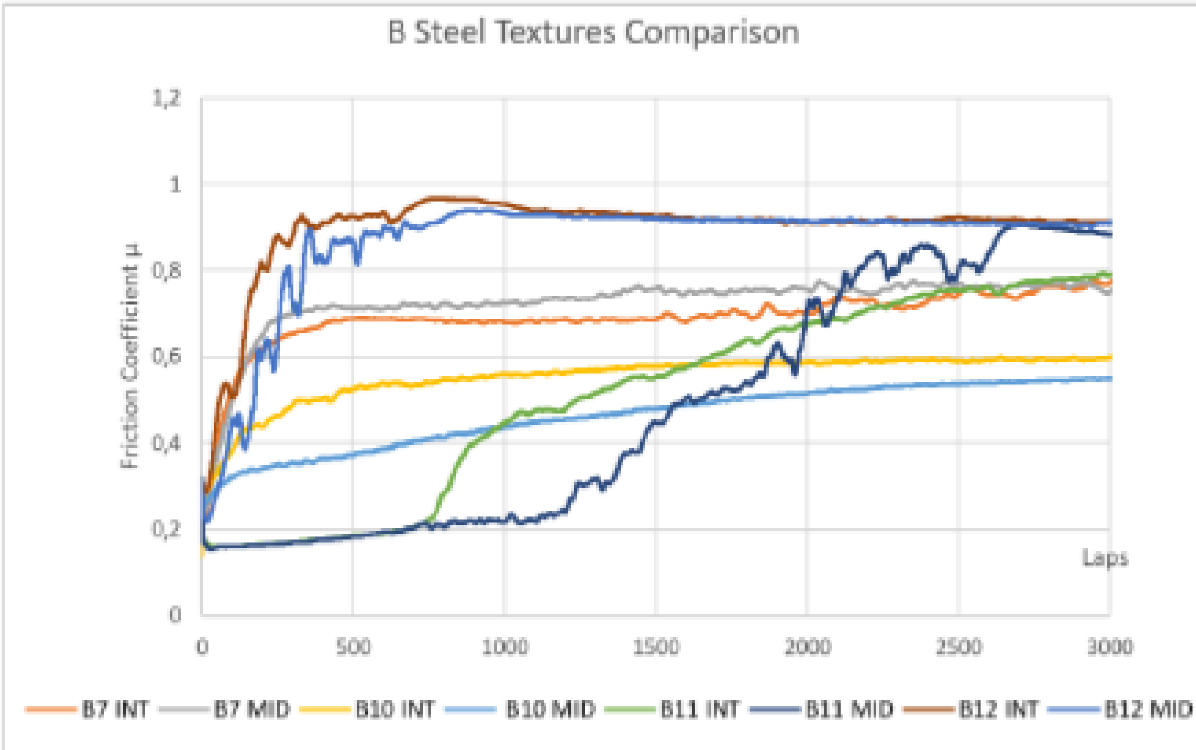

Figure 17. Friction coefficient changes overlap of PH13-8Mo H1050 steel samples inner (INT) and outer (MID) areas.

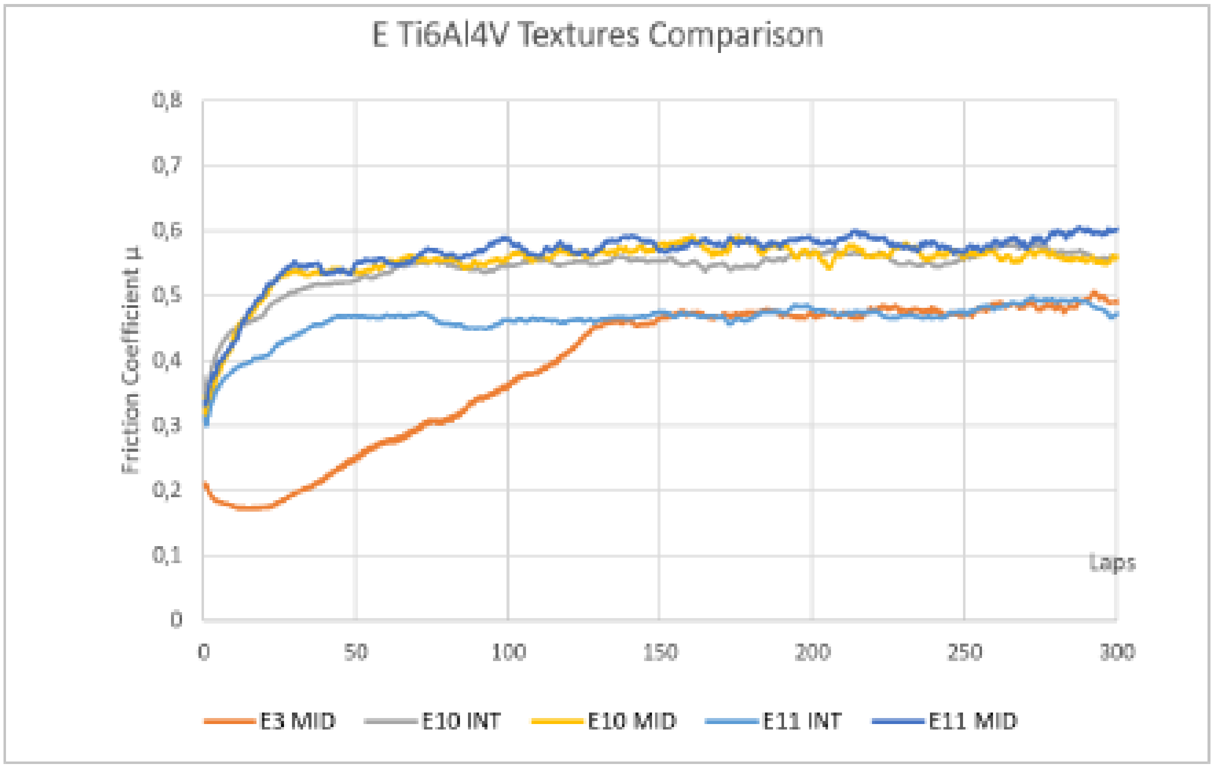

Figure 18. Friction coefficient changes overlaps of Ti6Al4V titanium samples inner (INT) and outer (MID) areas.

Even if the friction coefficient is lower at the beginning, however, it slowly rises. From all, A samples A11 outer (MID) area wears off slowest and provides lower friction coefficient for a longer time, also A8 outer (MID) area even if rises its final friction coefficient are lowest. From B samples B11 inner and outer areas, however, B10 outer (MID) area provides a lower friction coefficient over 3000 laps. And from E samples best results show the E3 outer (MID) area over 300 laps. However, from all results, it seems that over time textures patter wear off, and surfaces lose their friction properties.

By considering all results, some textured surface shows a lower friction coefficient than the regular surface, however, textured areas tend to wear off leading to increased friction.

4 Outlook

The current laser texturing solution for laser textured surfaces, for space application, was overviewed, specifically for corrosion-resistant, adhesion, and friction manipulation applications. We have analyzed literature about each application leading to texture pattern selection, which might exhibit the best results. After gaining positive results, there are possibilities to apply laser texturing for multiple industrial applications leading to the modernization of industry, reducing the exploitation cost of machines, and increasing longevity. However, for now, only adhesion testing shows applicable results compared with corrosion and friction reduction testing. Perhaps corrosion resistance might be improved by chemical treatment and friction reduction testing might provide positive results with lubricants.

5 Confidentiality

FemtoSurf partners must retain any data, documents, or other material as confidential during the implementation of the project. Further details on confidentiality can be found in Article 36 of the Grant Agreement along with the obligation to protect results in Article 27.

6 Conclusions

Corrosion testing shows some positive results on titanium and stainless-steel samples, however, aluminum samples exhibit increased corrosion.

For adhesion testing, the scratch test shows that dimples textures surface provides the best results compared with grooves, trenches, and crossed lines, and from testing it was confirmed that paint adhesion to the textured surface meets ISO 1 / ASTM 4B standard, which indicates very good adhesion. The further shear test shows an increment of the mechanical properties of the bonded surfaces of the order of 20 % compared with sandblasting procedure, forming standard Ra from 4,8 µm to 5,2 µm.

A friction test without lubrication on different textured materials shows that some textures provide a lower friction coefficient, compared with the bare surface of the same materials. However, over time textured area wears off leading to increased friction coefficient. The fastest wear is observed on titanium, while textures on both sheets of steel samples are maintained longer.