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The influence of the process parameters of drag finishing on the surface topography of aluminium samples

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## ABSTRACT

Tribofinishing techniques are superfinishing processes that enable surface roughness improvement due to the mechanical action of abrasive media. A wide variety of kinematics can be employed and these abrasive media can have various trajectories and speeds when impacting the treated surface (normal, oblique, tangential, etc.). This work focuses on the drag finishing process, and in particular on the effect of spherical abrasive media impacting normally the surface of an aluminium part (6061T6). It investigates first the influence of the initial surface roughness and the diameter of spherical media when a lubricant is used. Secondly, it analyses the effect of a chemical accelerator surrounding abrasive media and the surface. An original experimental set-up was designed to observe the evolution of various surface roughness parameters and to identify local physical and chemical mechanisms. The results show that the final surface finishing greatly depends on the size of the abrasive media, and that a chemical additive can accelerate the material removal rate and improve the roughness when compared to a lubricant.

**Key words:** drag finishing, abrasive media, chemical accelerator, surface topography, oxide layer.

## 1 INTRODUCTION

Tribofinishing belongs to the family of superfinishing processes, which enable significant improvements in surface roughness due to the flow of abrasive media around a surface. It also enhances the functional performance of parts produced by conventional machining processes (turning, milling, etc.) [1]–[3], as it induces compressive residual stresses and high surface hardness. There are a wide variety of kinematics that can be employed to achieve tribofinishing [2]. The simplest and most cost effective kinematic is the mass finishing technique (also called vibratory finishing), consisting of a bowl containing loose abrasive media, a liquid compound solution and several workpieces moving freely. An oscillatory movement of the bowl induces a toroidal macroscopic movement of the abrasive media and workpieces. This relative movement between abrasive media and parts induces material removal and plastic deformation at a local scale [4]. Mass finishing processes are considered as suitable methods for replacing hand polishing techniques due to the simplicity of the equipment required, the wide range of processing conditions (abrasive particles, frequency, velocity, compound, etc.) and the option of finishing several workpieces at the same time [5].

The second most widely employed tribofinishing technique is the drag finishing process. A single workpiece is fixed to a spindle (several spindles can be used in parallel) and is dragged through a media and compound solution mixture. Each part rotates around its own spindle so as to obtain a homogeneous surface improvement. High speeds can be applied to the workpiece, increasing relative speeds between the media and the surface, as well as media pressures in the workpiece, making it a faster and more efficient process [4].

In contrast to conventional machining processes such as turning, milling and grinding, tribofinishing processes have received little attention in the scientific literature. Some authors have studied mass finishing, such as Hashimoto et al. [6]–[8], who described the movement of abrasive media and observed that mass finishing induces small magnitudes of movement between media and surfaces. Song et al. [9], Pandiyan et al. [10], Ciampini et al. [11]–[13] and Mohajerani and Spelt [14], [15] carried out experimental investigations to evaluate the influence of power imparted to vibratory bowl. Mediratta [16] stated that high frequency vibratory finishers can reach values of 40 Hz, and process time to roughness saturation is reduced by 40 % compared with machines of 25 Hz. Wong et al. [17] polished titanium parts with bowl frequency of 50 Hz and 75 Hz, and concluded that process time could be reduced up to 80 % with 75 Hz. This higher efficiency seems to be related to the increase of the impact forces of media [9] [17].

The size of the media also affects the impact forces. Song et al. [9] measured the impact forces with small (0.12 gr/piece) and large media (2.25 gr/piece) using a force dynamometer. As they predicted, the highest forces were obtained with the heaviest media [9]. However, the normal contact forces generated on a workpiece surface with ceramic spherical media of 7, 9 and 11 mm in diameter were also measured by Wang et al. [18], and no significant differences were found. This may be because the media diameters and weights were too similar. In the research carried out by Mohajerani and Spelt [15], media impacts that occur in vibratory finishing were simulated, and the maximum material removal with greater impact densities was correlated. In addition, the model of impact damage and material removal developed by Ritter [19], showed that higher forces lead to greater material removal. Thus, it can be said that the heavier the media, the higher the magnitude and the number of impacts, which will result in higher material plastic deformation and material removal. Uhlman et al. [20] studied the influence of media shape in the case of vibratory finishing, they had concluded that sharp edged media had a greater impact in roughness reduction.

In the case of drag finishing, some researchers have investigated the influence of media and their velocity. Barletta et al. [21] showed that the efficiency of drag finishing is correlated to the kinematic energy of media (mass and speed) and also to the impact forces. Kacaras et al. and Zanger et al. [22], [23] concluded that in stream finishing higher rotational speeds lead to higher impact forces and a faster surface improvement.

The abovementioned studies have focused on making a link between the macroscopic input parameters of the process (media size and geometry, relative movement, impact force) and the material removal rate + surface finish. However no works have been found in the literature which provide an in-depth investigation of the physical mechanisms explaining these phenomenological observations. There is thus a need to analyse in detail these local mechanisms, and it is particularly necessary to clarify how media interacts with the surface topography during tribofinishing.

Depending on the tribofinishing process employed, kinematic media (mass finishing, drag finishing, barrel finishing etc.), may have various trajectories when impacting the surface to be treated (normal, oblique, tangential, etc.). In addition, it is accepted in the literature that abrasive media may induce variations in surface topography through three main mechanisms: a pure plastic deformation of picks due to the impact (Figure 1a), a pure scratch (no chip) with a flow of the workmaterial on each side (Figure 1b), or a scratch with a chip (Figure 1c) [24], [25]. These three mechanisms are highly likely to occur simultaneously and successively as the orientation of the surface among the media flow vary during the process. It is of evidence that pure plastic deformation (Figure 1a) is more favourable when normal media impact occurs (high normal speed and small tangential speed)[25]. In contrast, the two scratching phenomena (Figure 1b,c) are more likely to occur when the media impacts the surface with a high tangential

trajectory (low normal speed). It is therefore important to determine which mechanism is predominant depending on the relative trajectory of the medias.

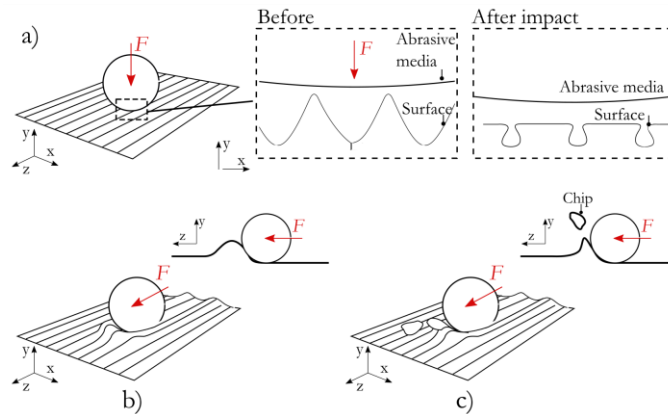


Figure 1. Main mechanisms during tribofinishing: a) pure plastic deformation, b) scratch with no chip, c) scratch with chip.

The aims of the present paper are twofold. Firstly, the work focuses on the effect of abrasive media with normal impact direction on the workpiece surface. In this context, a large amount of kinematic energy is transmitted to the surface which theoretically induces intensive plastic deformation. The first aim therefore, consists of analysing the surface modification mechanism. It can be modified by a pure plastic deformation (no material removal) or by chip generation (material removal) as well. To this end a purpose built experimental set-up was developed, to obtain a media flow perpendicular to the work material surface for a long duration. The evolution of the initial surface texture over the time was analysed. Tests were also carried out to investigate if a variation in size and geometry of media, as well as the initial surface roughness topography, influence the mechanisms when media impact the treated surface in a normal direction.

The second aim of the paper is linked to the interaction that may exist between the media and the liquid compound. In tribofinishing processes a wide variety of liquid compounds can be used, ranging from lubricants to active chemicals. Wang et al. [18] and Baghbanan et al. [26] reported that even pure water is sufficient to improve the surface finish. By observing the topography of impact craters, they concluded that a liquid preventing adhesion between the workmaterial and the media is required (lubrication effect). Malkorra et al. [27] showed that a lack of lubrication leads to debris incrustations in the valleys in rough surfaces. Then, the media impacts close the valleys due to plastic deformation, and the debris is retained inside. They demonstrated that lubrication and evacuation of the debris is fundamental to obtain good surface finishes.

Some end-users promote the application of active chemicals. Indeed, two industrial companies [28], [29] have patented the application of a chemical accelerator in combination with abrasive particles so as to decrease the processing time. However is not yet clear if a better surface finish or a higher material removal rate is obtained with a lubricant or with a chemical compound, and there is no scientific explanation of the synergy between the chemical accelerator, the workmaterial and the media. One reason for this is that the composition of many industrial chemical accelerators and media are not published for reasons of commercial in confidence. Thus it is unclear if the chemical accelerator is responsible for a dissolution of the work material, or if the chemical accelerator creates a new material on the surface that is more brittle and as a consequence is much easier to remove with abrasive media.

In the scientific literature, it is possible to report the work of Song et al. [9] who have tested different chemicals in vibratory finishing. They found that with some chemicals, roughness

decrease is accelerated. They also observed that the created oxide layer is weaker and rougher than the bulk material, thereby facilitating easier removal and obtaining smoother roughness in a shorter timeframe. In another industrial field (the microelectronics industry), the synergetic effect of chemical and mechanical actions is used to facilitate polishing by oxidizing the surface which weakens the material [30], [31]. However, the available scientific literature in the field of chemically accelerated tribofinishing of metallic parts is limited, and there is thus a need to investigate the synergetic effect between a chemical accelerator/media/workmaterial.

The present paper investigates the mechanisms of interaction between various media and initial surface profiles. In addition, an analysis of the influence of a chemical accelerator on the mechanisms of interactions is carried out. This work is applied in the context of an aluminium part.

## 2 EXPERIMENTAL PROCEDURE

### 2.1 Experimental set-up

An experimental set-up was designed to investigate the evolution of a tribofinished surface. In this set-up a cylindrical sample was dragged through a mixture of abrasive media + compound solution (Figure 2). A single rotation  $W$  around the  $y$ -axis of the bowl ensured the Frontal zone (or the treated zone) of the sample was tribofinished with a constant and normal flow of media. The kinematic of the set-up was inspired by a drag finishing machine, where the part has a rotation  $W$  around the bowl and a second rotation around its own axis to reach a uniform surface finishing. However, these both movements make complicate the study of media trajectories and their interaction with workpiece surface. In the actual configuration, the part cannot rotate around its own axis. The system employed was therefore the mechanical system patented by Grange et al. [32].

The experimental set-up enabled the analysis of the mechanisms occurring during tribofinishing in the frontal zone (Figure 2c), where normal media impact is likely to occur with intense plastic deformation as shown previously in (Figure 1a). In contrast, the lateral zone is more favourable to investigate scratching phenomena (Figure 1b,c), as the tangential velocity is high and the normal impact velocity is low. Preliminary investigations have demonstrated the efficiency of the set-up [33]. The present paper will focus on the study of the frontal zone.

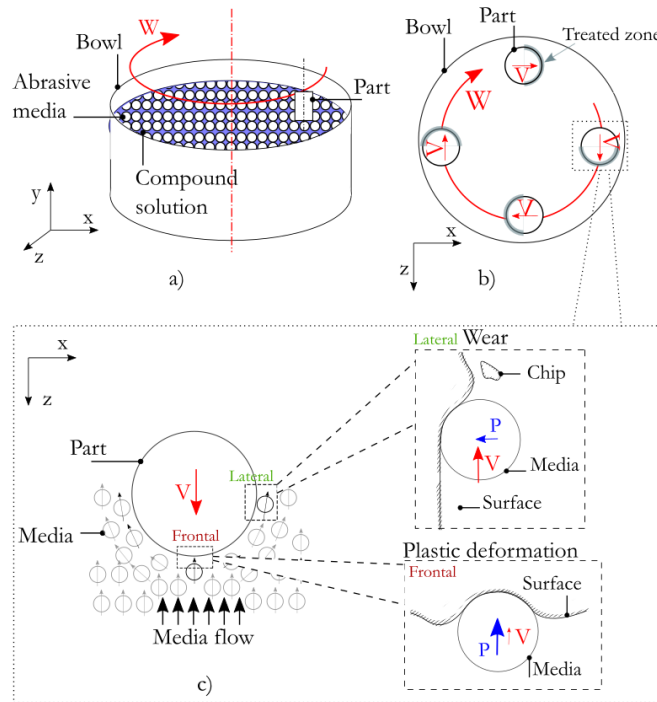


Figure 2. a) Experimental set-up in 3D, b) motion imparted to the part in 2D, c) media flow through the sample and wear and plastic deformation mechanisms in frontal and lateral zone. (P=contact pressure, V=part velocity=media sliding velocity).

## 2.2 Surface characterization

### 2.2.1 Surface topography

This study focuses solely on the evolution of the surface topography in the frontal zone.

The geometry of cylindrical samples is described in Figure 3. The initial surface roughness was prepared by various machining strategies that are presented in section 3. As the samples passed through the tribofinishing process, the evolution of the surface topography was analysed using a confocal microscope 'ALICONA Infinite Focus' at time intervals of  $t = 0, 5, 10, 20, 40, 80$  min. A 20x magnification, a vertical resolution of  $0.1 \mu\text{m}$  and a lateral resolution of  $2.5 \mu\text{m}$  were selected for the measurements. Rectangular surfaces ( $0.8 \times 5$  mm) were measured in the frontal zone as shown in Figure 3. Then 2D profiles were extracted along a 4 mm distance and filtered with a short-wavelength cut-off  $L_c = 800 \mu\text{m}$  Gaussian filter (ISO 4287). Various surface roughness parameters were quantified:

- Parameter  $Ra$ , describing the average height of the profile (Figure 4a)
- Parameter  $RSm$ , describing the distance between surface irregularities (Figure 4b)
- Parameter  $Rsk$ , indicating if the topography is characterized by both peaks and valleys ( $Rsk > 0$ , Figure 4c) or only by valleys ( $Rsk < 0$ , Figure 4d).

In addition to the analysis of 2D profiles, complementary 3D surface measurements were also taken with the same equipment before and after the tribofinishing tests ( $t=0$  min and  $t=80$  min) to evaluate the surface isotropy parameter  $Str$  (area of  $1.5 \times 1.5$  mm + short-wavelength cut-off  $L_c = 350 \mu\text{m}$ ). A parameter  $Str$  close to 0 indicates an homogeneous surface (Figure 4f), whereas a value close to 1 reveals the presence of a texture (Figure 4e).

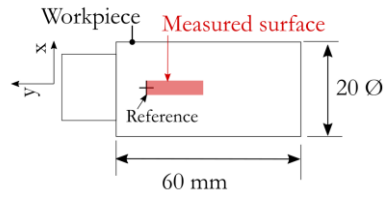


Figure 3. Sample dimensions.

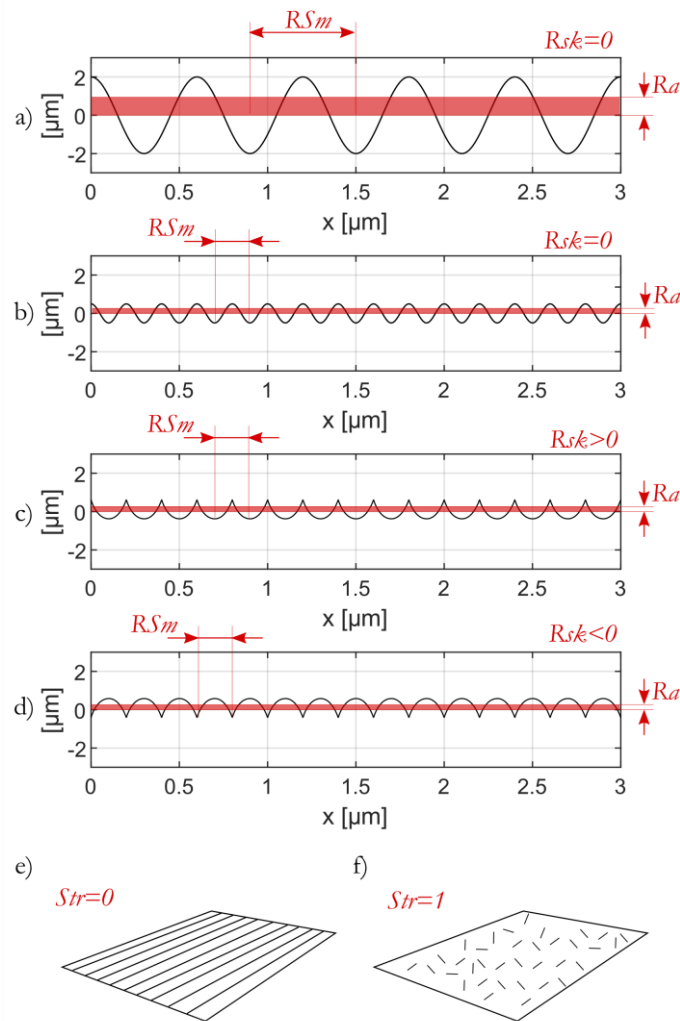


Figure 4. a) Rough surface, b) smooth surface, c) smooth surface characterized by peaks, d) smooth surface characterized by valleys, e) surface with a texture, and f) a homogenous surface.

### 2.2.2 Evolution of the average line of the profile

In addition to the evolution of surface parameters, it is important to verify the position of the average line of the profiles. When a plastic deformation is the dominant mechanism, the average line remains in the same position. However, if the average line of the profile is shifted significantly below the original profile, this reveals that an important removal of material occurred during the process. It is therefore crucial to compare the position of roughness profiles before and after each superfinishing step.

To obtain this comparison the evolution of the roughness profiles is superimposed on a common reference. In this study, each sample was scratched (micro-scratching) with a small indenter as shown in Figure 5. The scratch was much deeper than the original surface profile and its width

was narrower than the smallest media. This ensured that the valley of the scratch was not removed by the media, and thus could be used as a reference for each sample.

Figure 5 shows an example of superimposition of various profiles. Figure 5b highlights two profiles that only differ in their peak height. This reveals that the initial surface topography is not removed by tribofinishing. In contrast, Figure 3c shows that the entire original profile was removed, and the offset  $\Delta$  reveals that material removal occurred.

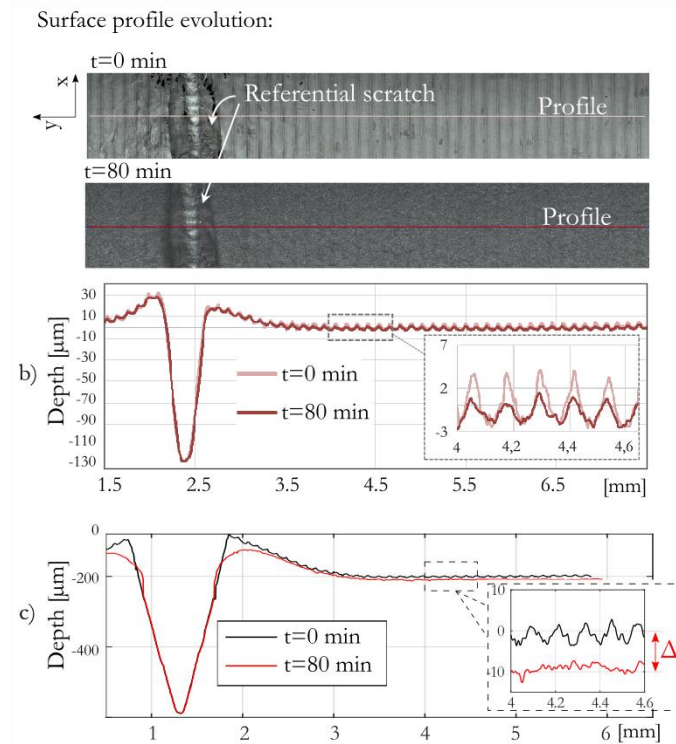


Figure 5. a) Measurements of the reference at  $t=0$  and  $t=80$  min, b) profile superposition showing that initial surface is not removed and c) when initial surface is totally removed.

### 3 DESIGN OF EXPERIMENTS

This section set out the experiments carried out in this paper. Sample fabrication and tribofinishing process parameters are explained.

The samples used in this study comprised of aluminium bars (6061T6), with varying initial surface roughnesses, obtained either by turning or belt finishing. The turned samples held an average value of  $Ra \sim 1.5 \mu\text{m}$  and  $RSm \sim 100 \mu\text{m}$ , whereas the belt finished samples were measured at  $Ra \sim 0.5 \mu\text{m}$  and  $RSm \sim 100 \mu\text{m}$ .

The turning conditions used to prepare the samples (hereinafter referred to as 'T'), were: insert CNMG 120408-PR Sandvik, cutting speed  $V_c=250$  m/min, feed  $f=0.25$  mm/rev, depth of cut  $a_p=4$  mm, lubrication = emulsion.

The belt finished samples (hereinafter referred to as 'BF') were prepared under the following conditions: belt grain size  $20 \mu\text{m}$ , normal pressure  $P=2$  bar, oscillation frequency  $f=10$  Hz, belt feed  $f_b=375$  mm/min, time  $t=1$  min, and no lubrication was used.

The experimental program was divided into six tests as set out in Table 1. Samples S1, S3 and S5 were prepared by turning, whereas samples S2 and S4 were prepared by belt finishing.

As regards the tribofinishing conditions, spherical media made of alumina ( $\text{Al}_2\text{O}_3$ ) abrasive grains were used. Two sizes of media were selected:  $\varnothing 5$  and  $\varnothing 1$  mm, and the macroscopic



impact velocity of the media on the frontal zone was 0.75 m/s. Samples S-1 and S-2 were tribofinished with  $\varnothing$  5mm media, whereas samples S-3 and S-4 were treated with  $\varnothing$  1mm media.

To determine if an active compound solution modifies the interaction mechanisms between the media and surface, two compound solutions were employed in the tests. These were a lubricant and a chemical accelerator, and were prepared as follows:

- a passive alkaline liquid (Pulibrill 6140 manufactured by ABC SwissTech) with pH=8 was used as a lubricant. This liquid was dissolved into a solution comprised of 5 % lubricant and 95 % water (hereinafter referred to as “Lub”). Samples S-1 to S-4 were tribofinished with this passive solution.
- a chemically active liquid (Pulibrill DP200 manufactured by ABC SwissTech), alkaline with pH > 11 was used as a lubricant. This liquid is designed to accelerate material removal in aluminium alloys and was dissolved into a solution comprised of 5 % lubricant and 95 % water (hereinafter referred to as “Acc “). Sample S-5 was tribofinished with this active solution.

In this study, only chemical action was studied by the immersion of S-6 into pure Pulibrill DP200 for 2 hours. For that purpose, a mirror polished sample (S-6) has been prepared. First the sample was cut with a diamond disc and set in an epoxy mounting resin (PHENOFREE manufactured by LAMPLAN). Then was polished with 240 nm, 600 nm and 1200 nm grinding SiC papers. The final polishing step was made with a silica suspension down to 1  $\mu$ m.

Table 1. Design of experiments.

N°	t[ $\mu$ min]	Manufacturing	$R_{a0}$ [ $\mu$ m]	Media $\varnothing$ [mm]	Additive
S-1 T- $\varnothing$ 5DF+lub.	80	T (Turning)	~1.5	5	Lubricant, Pulibrill 6140
S-2 BF- $\varnothing$ 5DF+lub.	80	BF (Belt finishing)	~0.5	5	Lubricant, Pulibrill 6140
S-3 T- $\varnothing$ 1DF+lub.	80	T	~1.5	1	Lubricant, Pulibrill 6140
S-4 BF- $\varnothing$ 1DF+lub.	80	BF	~0.5	1	Lubricant, Pulibrill 6140
S-5 T- $\varnothing$ 5DF+acc.	80	T	~1.5	5	Chemical accelerator, Pulibrill DP200
S-6	120	Mirror polished		-	Chemical accelerator, Pulibrill DP200

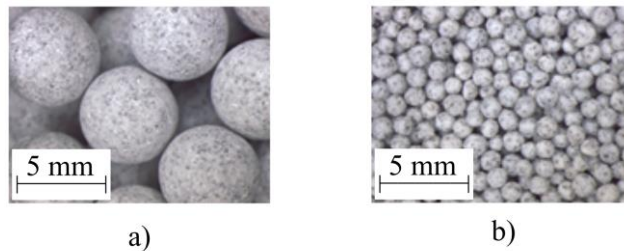


Figure 6. Spherical media a) Diameter = 5 mm and b) Diameter =1 mm. Commercial references of ABC SwissTech: MGA BALL 5 and MGA BALL 1.

## 4 RESULTS AND DISCUSSION

### 4.1 Influence of media size and initial surface roughness on tribofinishing mechanisms.

Aluminium samples (S-1, S-2, S-3, S-4) were subjected to a normal flow of spherical media for 80 minutes. The 3D surface topographies and the 2D profiles were analysed periodically ( $t = 0$ ,

5, 10, 20, 40, 80 min) so as to determine the influence of media size or initial surface roughness on tribofinishing mechanisms.

Figure 7 plots the evolution of the 3D surface topographies observed at the initial state (first column) and after 80 min of tribofinishing (second and third columns). Figure 9, Figure 10 and Figure 11 presents the evolution of surface parameters  $Ra$ ,  $RSm$  and  $Rsk$  over the time. The values of surface roughness parameters before and after the tribofinishing processes are set out in Table 2.

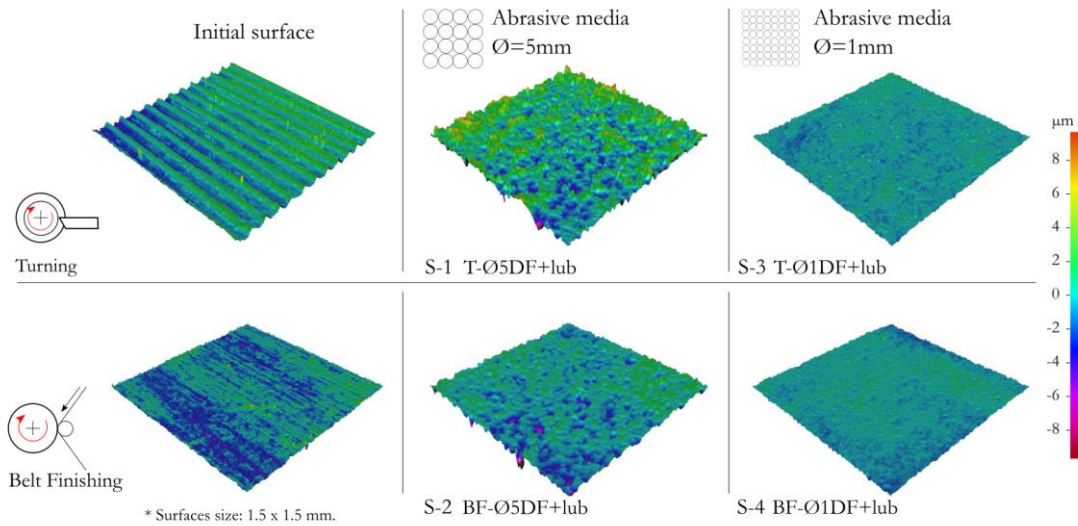


Figure 7. Surface topography of as-built turning and belt finished surfaces (first column) and drag finished surfaces after 80 min (second and third columns).

Table 2. Roughness and surface texture mean values for the samples before and after tribofinishing.

Sample	t=0 [min]				t=80 [min]			
	$Ra[\mu\text{m}]$	$RSm[\mu\text{m}]$	$Rsk[-]$	$Str[-]$	$Ra[\mu\text{m}]$	$RSm[\mu\text{m}]$	$Rsk[-]$	$Str[-]$
S-1 T-Ø5DF	1,50	113	-0,52	0,05	0,79	184	-1,33	0,89
S-2 BF-Ø5DF	0,31	127	-1,71	0,10	1,08	198	-1,24	0,95
S-3 T-Ø1DF	1,55	112	-0,06	0,05	0,63	85	-0,52	0,71
S-4 BF-Ø1DF	0,30	100	-1,54	0,03	0,52	119	-1,31	0,92

Figure 7 highlights that the initial surfaces obtained by turning or belt finishing were textured in the cutting direction, whereas the tribofinished samples (S-1 to S-4) showed a random distribution. This qualitative observation is confirmed when analysing the values of parameter  $Str$  in Figure 8. The initial surfaces recorded  $Str$  values of around 0.1, whereas  $Str$  increased until 0.8-0.9 after tribofinishing. The frontal zone is treated by normal impacts of media, which induces a random distribution of the surface texture.

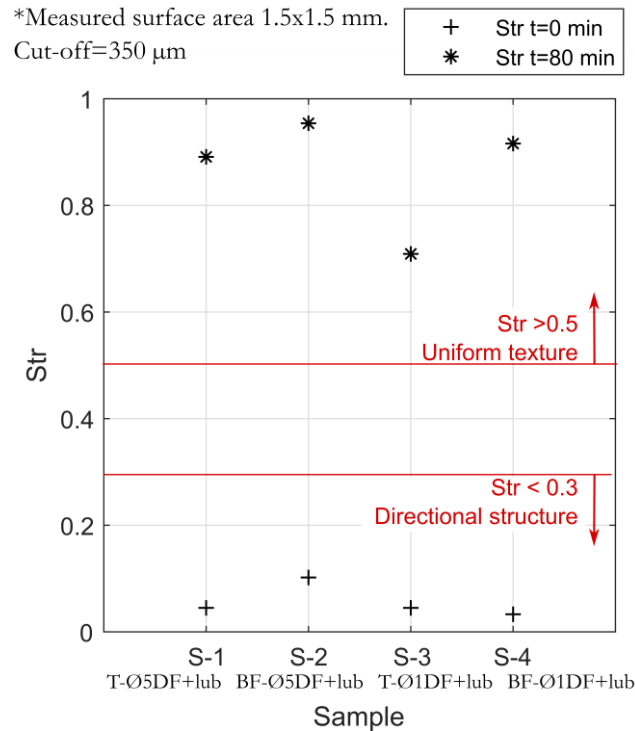


Figure 8. *Str* values before and after tribofinishing.

As regards the evolution of the parameters *Ra* and *RSm*, values reached a steady state at 80 min. This is in agreement with the common trend in abrasive processes, as reported by Hashimoto [34]. Moreover it would appear that, irrespective of the initial values ( $Ra_{turning} \sim 1.5 \mu\text{m}$  and  $Ra_{belt\ finishing} \sim 0.5 \mu\text{m}$ ), the final surface roughness *Ra* is directly correlated to the size of the media. The largest media ( $\varnothing 5\text{mm}$ ) led to a *Ra* of around 0.8 to 1  $\mu\text{m}$ , whereas the smallest media ( $\varnothing 1\text{mm}$ ) generated a *Ra* of approximately 0.5 to 0.6  $\mu\text{m}$ . This indicates that after a long duration (80 min), abrasive media are able to print their own signature on the surface. This trend was confirmed by the analysis of the periodicity *RSm*. Large media induced a high periodicity of around 200  $\mu\text{m}$ , and small media corresponded to a lower value, around 100  $\mu\text{m}$ . The final state was independent of the initial value. The correlation between the periodicity *RSm* and the size of media is also clearly observable on the 3D surface topographies presented in Figure 7. Surfaces generated by  $\varnothing 5\text{mm}$  media exhibited larger holes than those obtained by the  $\varnothing 1\text{mm}$  media. This can be explained by the momentum theorem of Yang et al. [3], which states that collisions of media happen in different intensities depending on the mass, and thus the impact force will be greater with a heavier media.

The analysis of Figure 10 shows that samples S-1 and S-2, which were tribofinished using a  $\varnothing 5\text{mm}$  media, presented a higher periodicity than their initial values, even though the parameter *Ra* was much smaller. This is due to the definition of *RSm* that considers the intersection of profiles with the average line and is explained in section 2.2.1.

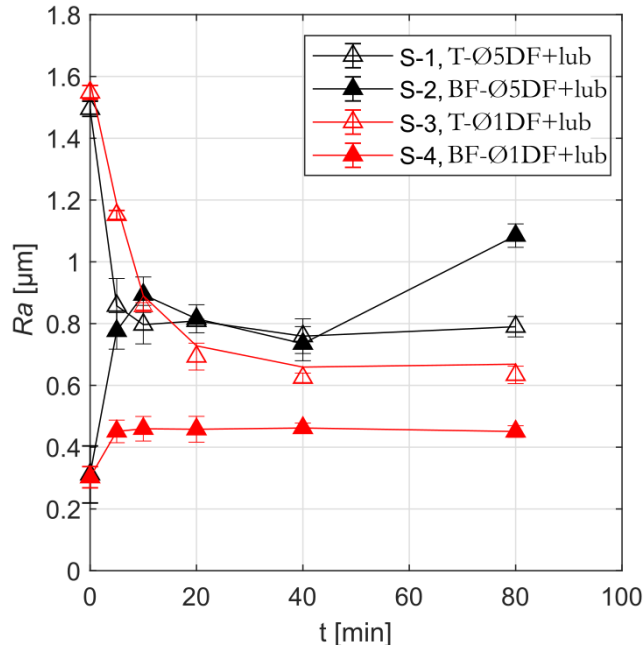


Figure 9. *Ra* parameter evolution from S-1 to S-4.

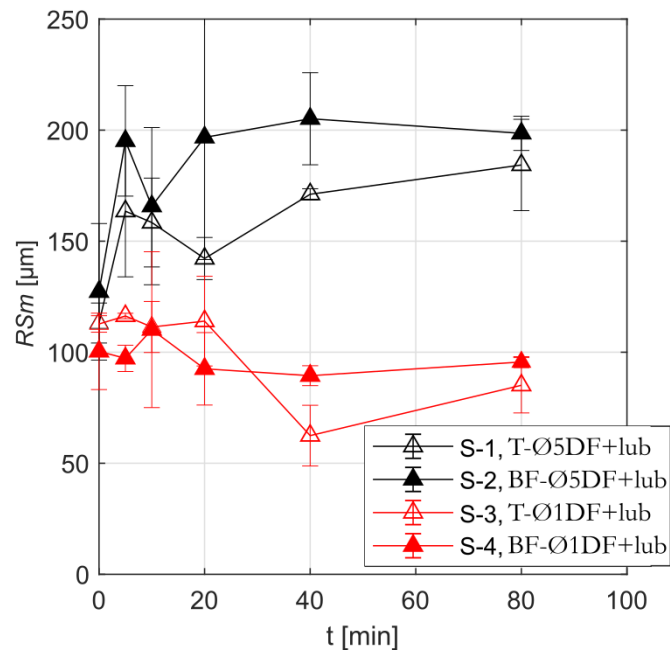


Figure 10. *RSm* parameter evolution from S-1 to S-4.

In addition, the analysis of the evolution of parameter *Rsk* (Figure 11) shows that the skewness of the profile is defined by the size of media. *Rsk* values reveal that the largest media (Ø 5mm) compressed the surface (in S-1 and S-3) creating surfaces composed entirely of valleys and plateau: *Rsk* ~-1.5. In the case of the smallest media (Ø 1mm) the *Rsk* values were around -0.5, due to its low compacting capacity and the limited contact surface with the sample.

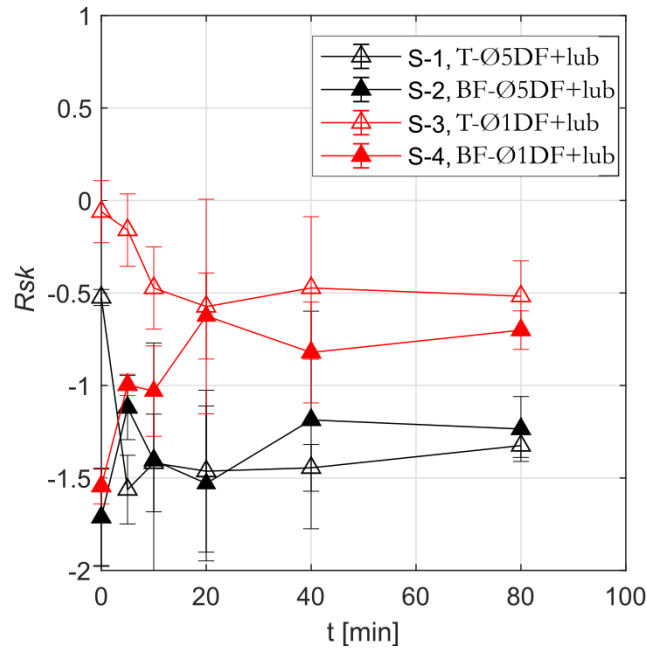


Figure 11.  $R_{sk}$  parameter evolution from S-1 to S-4.

The above analysis of surface parameters provides valuable information on the evolution of the various topographies, but does not explain the interaction mechanisms. From the results, it is evident that the normal impact of spherical media induced plastic deformation of the surface of the samples, but it is not clear if this plastic deformation is accompanied with a significant material removal. It is therefore critical to analyse the position of the average line of the roughness profile.

Figure 12 plots the offset  $\Delta$  induced by the tribofinishing process. This offset reveals the amount of material removed by tribofinishing. If  $\Delta$  is higher than the height of the material, it indicates that the initial surface profile has been fully removed. An analysis of the four samples S-1 to S-4, shows the four initial profiles were removed. It can therefore be concluded that in the frontal zone, a significant material removal occurs, even if the media have impacted the surface in a normal direction (perpendicular to the surface). Indeed, after impacting the surface, abrasive media flow to the right or left side of the frontal zone. This tangential movement occurs with a very low velocity, which seems to be sufficient to generate small chips and remove material.

In addition, a comparison of the four samples, clearly shows that small media lead to greater material removal ( $\Delta \sim 15 \mu\text{m}$ ) than large media ( $\Delta \sim 5/-10 \mu\text{m}$ ). This demonstrates that small media ( $\varnothing 1\text{mm}$ ) are more likely to remove material, whereas large media ( $\varnothing 5\text{mm}$ ) are more prone to plastically deform the surface. This is in contradiction with the work of Ritter [19], which stated that greater impact forces lead to greater material removal. The theory of Ritter is applicable when the surfaces is rough: peak removal happens faster with large media. In the contrary, small media abrades peaks by micro abrasion, which takes longer to remove them. When the surface has no more peaks, large media continue to deform plastically the surface, but has not capacity to abrade it. Whereas the small media, it continues abrading the surface. This can explain why more material removal happens ( $\Delta_{\varnothing 5} < \Delta_{\varnothing 1}$ ) with the small media.

The initial surface topography does not seem to significantly influence the offset value  $\Delta$ . This is in agreement with the analysis of the evolution of  $R_{sk}$  parameter. Tribofinishing with large media leads to smaller (more negative) values of  $R_{sk}$  due to the more intensive plastic deformation of roughness peaks.

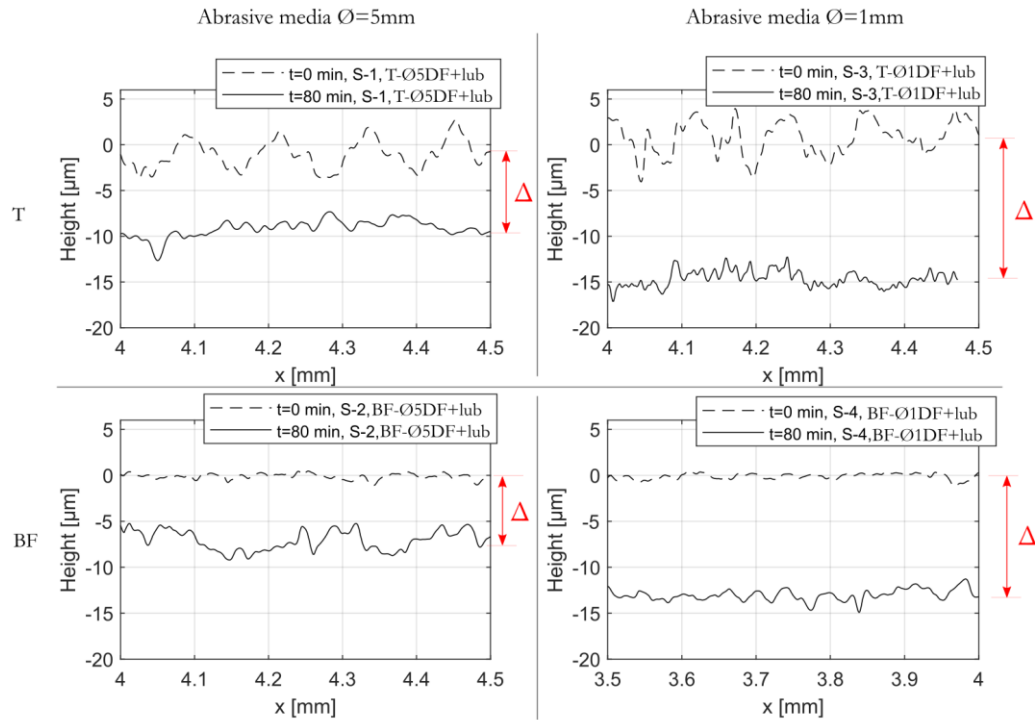


Figure 12. Surface profile evolution from S-1 to S-4.

## 4.2 Influence of chemical compounds on the interaction mechanisms

The second objective of this study was to analyse the extent to which a chemical accelerator may modify the mechanisms of interactions between the media and surface, when compared to a standard lubricant. To this end a tribofinishing test, named S-5, was conducted under the same conditions as S-1 (Turning + tribofinishing  $\varnothing$  5mm + Lubricant). The analysis of the 3D surface topography in Figure 13 reveals a clear difference. First, the final surface induced by the chemical accelerator appears to be smoother than the one obtained by the lubricant. Second, a flatter surface is visible in S-5, which is confirmed by the observation of roughness profiles in Figure 14. These qualitative observations are confirmed by the analysis of the evolution of parameter  $Ra$  over the time. The final average height of the profile was smaller ( $Ra \sim 0.6 \mu\text{m}$ ) using the active liquid than with the passive one ( $Ra \sim 0.8 \mu\text{m}$ ). The analysis of  $RSm$  (Figure 15) does not indicate any modification, which was as expected, given that periodicity is linked to the size of media as shown previously.

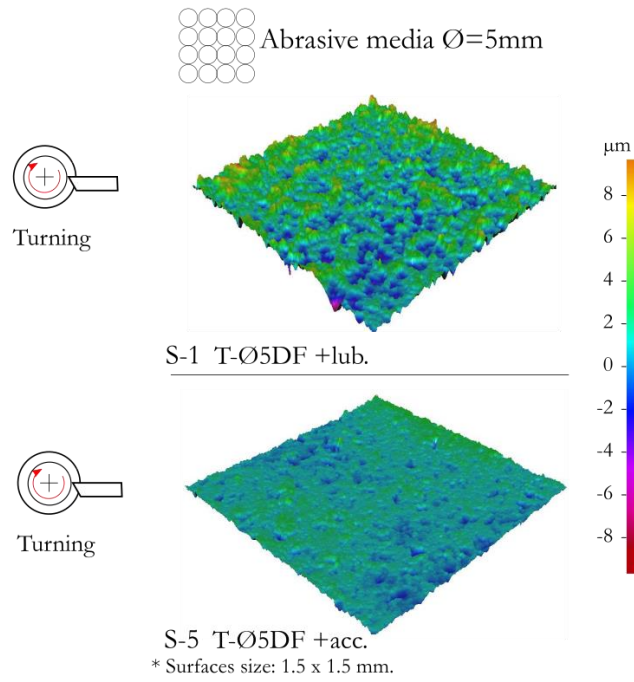


Figure 13. Surface textures for S-1 and S-5.

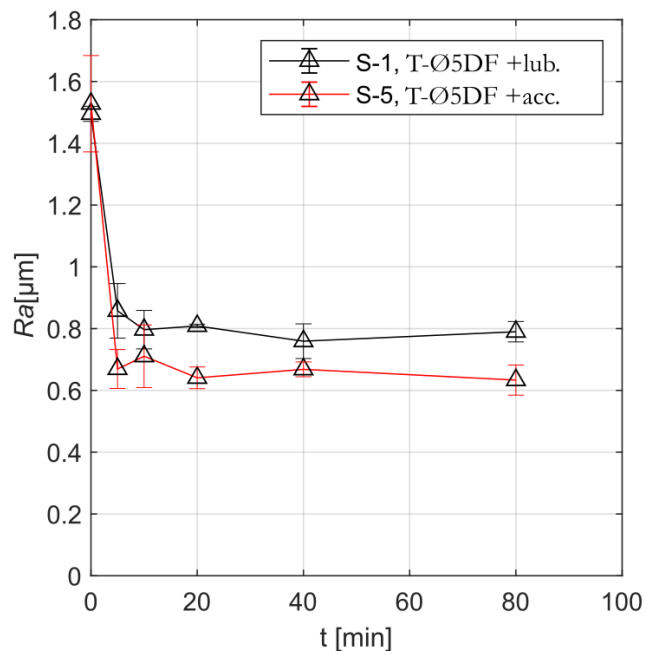


Figure 14.  $R_a$  parameter evolution for S-1 and S-5.

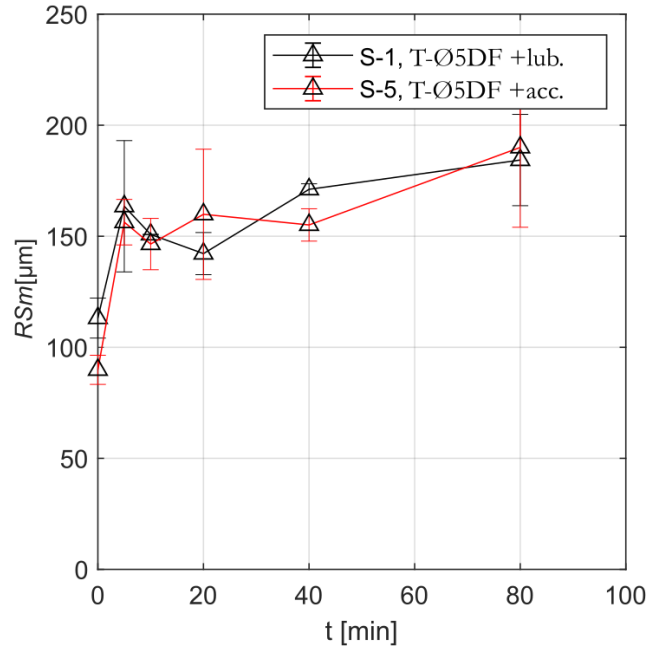


Figure 15. *Rsm* parameter evolution for S-1 and S-5.

Furthermore, the offset between the initial and final surfaces in Figure 16 shows that material removal in S-5 was greater than in S-1:  $\Delta_{S-5} > \Delta_{S-1}$ . This demonstrates that more material removal occurs when chemical accelerators are employed, and thus there is a clear benefit to using a chemical accelerator during tribofinishing operations in the frontal zone. However, it is still not clear the extent to which the chemical modifies the mechanism. As outlined in the introduction, two mechanisms may theoretically occur. First, it is possible that the chemical may dissolve the surface, which would shift down the entire surface profile (peaks and valleys). Second, the chemical may create an oxide layer (Figure 17b), which could be removed more easily than the bulk material when in contact with the media if its mechanical strength is weak (Figure 17c).

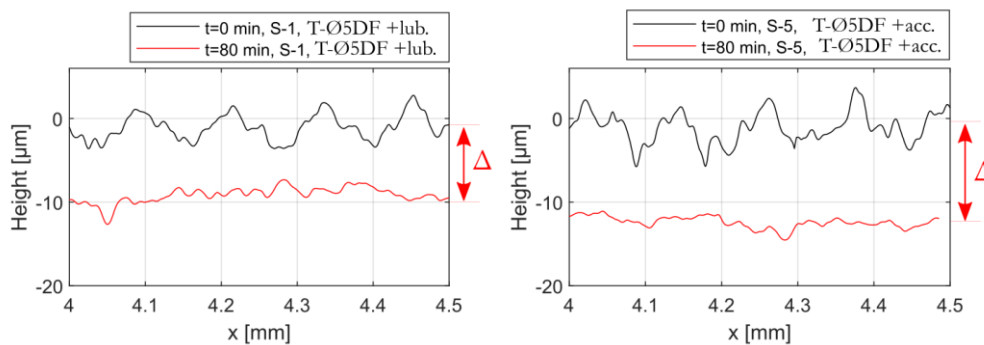


Figure 16. Surface profile evolutions for S-1 and S-5.



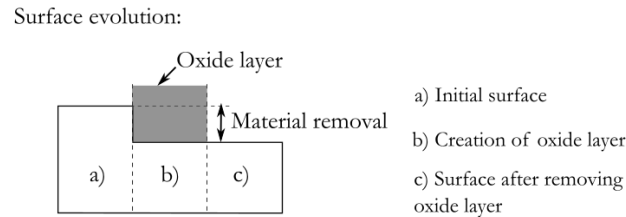


Figure 17. Theoretical mechanisms when using a chemical accelerator – a) initial surface, b) creation of an oxide layer, c) dissolution of the material.

So as to confirm which mechanism was responsible for the acceleration of the process, an additional test was performed. In this test an aluminium sample (Sample S-6) was plunged for 2 hours in a bath of pure chemical (Pulibrill DP200) so as to analyse the topography of the attacked surface (Figure 18a). Sample S-6 was mirror polished before the chemical attack, to facilitate the quantification of the material removal. Part of the surface was protected with an adhesive tape to create a reference marker (Masked surface in Figure 18a).

An oxide layer formed on the area that had been immersed in the liquid. Then, part of this oxide layer was cleaned back to the original material without scratching the surface. Finally, as presented in Figure 18, three surfaces were analysed: the reference polished surface (Figure 18-b1), the oxidised surface (Figure 18-b2) and the new surface after cleaning (Figure 18-b3). It can be clearly observed that the oxide layer, induced by the chemical, exhibits a larger volume than the original material, and the external surface is ~100-200  $\mu\text{m}$  higher than the original surface. Hence the density of the oxide layer is probably poor and it can be assumed that its mechanical properties are weaker than the original aluminium alloy. This supposition was also confirmed by the ease with which it was possible to remove the oxide layer with smooth cleaning.

Thus it would appear that the chemical accelerator induces a synergetic effect with abrasive media. The accelerator starts this action by reacting with the surface to generate an oxide layer (Figure 18b1). Then during tribofinishing operations, abrasive media can easily remove this weak layer, revealing a new fresh surface that can react again with the chemical. It should be noted that as the media have a large dimension compared to the distance between two roughness peaks, they interact preferentially on roughness peaks. This suggests that this oxide layer is more prone to be removed on peaks, and explains why S-5 (with chemical accelerator) appears flatter than S-1 (with lubricant).

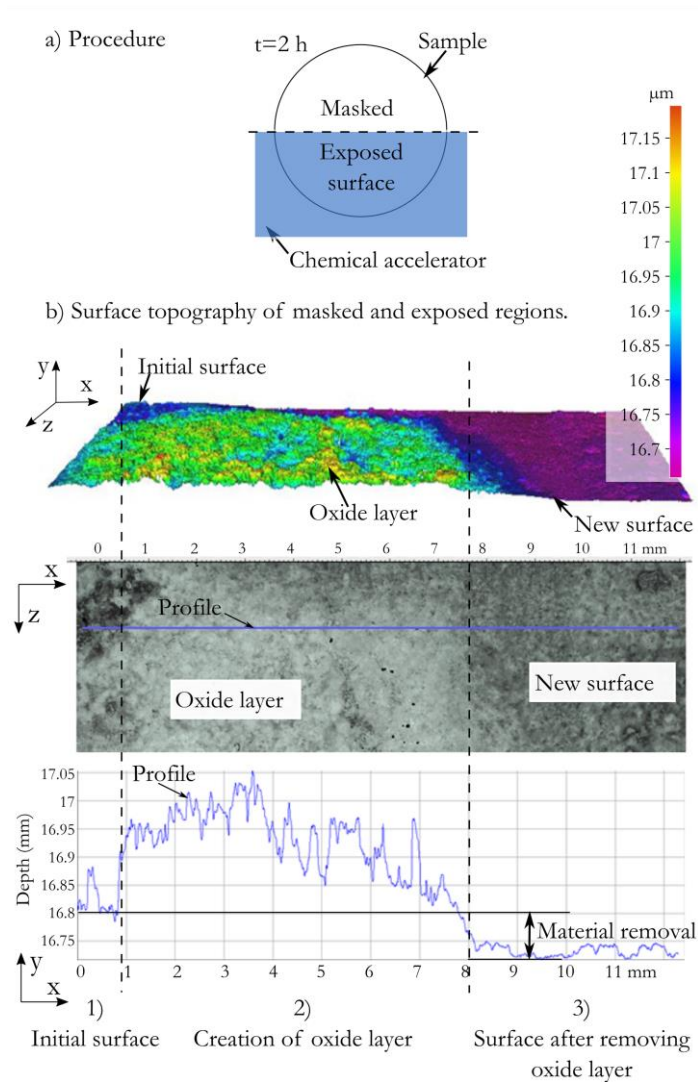


Figure 18. Aluminium surface layer height: original surface (masked), oxide layer on the exposed surface and new layer after oxide layer removal by hand. (S-6)

## 5 CONCLUSIONS

This work has investigated the drag finishing of a cylindrical part made of an aluminium alloy. It focused on the understanding of physical phenomena during an orthogonal impact of spherical media on a surface. The results reveal that that plastic deformation is the main mechanism of interaction irrespective of the initial surface topography. This mechanism is more dominant when using larger spherical media.

In addition, a significant amount of material is also removed as a result of local scratching after plastic deformation. This phenomenon is due to the flow of media across the surface after impact. The material removal rate becomes higher when using small media.

As far as surface roughness is concerned, it is confirmed that abrasive media lead to a surface topography corresponding to their signature. In particular, small media generate smoother surfaces with smaller periodicity, compared to large media. Irrespective of the size of spherical media, surfaces are randomly distributed as surfaces are sculptured by media impact.

Finally, the results show that the use of a chemical accelerator may induce an acceleration of the material removal rate, as well as a smoother surface compared to conventional lubricants. The chemical creates an oxide layer with weak mechanical properties. This layer is then continuously removed by the impact of the media on roughness peaks, which leads to a better surface roughness with smaller peaks.

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