Development of a method for performance characterisation of PEMEC process considering electrolyte temperature in case of hybrid polishing of 316L steel

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Abstract. This work falls within the context of very rough parts (*Ra* > 10 µm) polishing using a new hybrid process called PEMEC, which combines a mechanical abrasion action (tribofinishing) and an anodic dissolution action (electrochemical polishing). The study of the performances of a polishing process requires the monitoring of the surface roughness, but also the monitoring of the dimensions and the shape of the parts. This paper proposes a new method for characterising polishing operations that enables all these criteria to be monitored in a single test. This method is applied to the study of the influence of the electrolyte temperature in the PEMEC process.

Introduction

The polishing of complex shaped very rough metallic parts (*Ra* > 10 µm) is an old subject in industry, often related to parts produced by casting, forging, etc. However, the functional simple shaped surfaces of these parts, such as plane or cylindrical, were usually calibrated using machining processes (turning, milling, grinding, etc.). The polishing of complex shaped very rough metal parts (*Ra* > 10 µm) is once again becoming a major research topic in the industry with the upgrowing development of additive manufacturing techniques, such as Laser Powder Bed Fusion (L-PBF). Additive manufacturing enables the design of new parts with complex functional surfaces. These complex surfaces are difficult to access and cannot be finished by conventional machining processes. In the case of L-PBF, the surfaces are very rough, and it is common to observe surfaces with *Ra* roughness values ranging from 10 - 30 µm depending on the area concerned [1]. Numerous recent research projects aimed to optimise conventional polishing processes on these rough and complex surfaces (chemical or electrochemical polishing, tribofinishing, laser polishing, water polishing, plasma electrolytic polishing, etc. [2-5]). Among these recent works, Malkorra et al. [5] have shown that it is possible to reduce the roughness from an *Ra* of 10 µm to 1 µm using the drag finishing process. However, to achieve this goal, very long treatment times are required. Then, conventional polishing processes tend to severely deteriorate the geometry of the parts (size, shape), especially the sharp edges. In order to solve this problem, new polishing processes have appeared with the objective of reducing surface roughness without deteriorating the shape of the parts. These processes are called "hybrid" processes because they combine the simultaneous and controlled action of several mechanisms (physical, chemical, optical, etc.) and/or energy sources/tools [6]. The main objective of hybrid processes is to increase the material removal during the polishing process through a synergistic effect between the mechanisms. For example, there are several hybrid processes daily used in industry that combine abrasion and chemical dissolution mechanisms [7-8]. In the scientific literature, there are also several processes that combine abrasion and anodic dissolution mechanisms [9-14]. Unfortunately, these hybrid processes have been designed to polish simple surfaces such as planes or cylinders and are not suitable for complex shapes.

Moreover, it can be stated that all the papers dealing with the polishing of rough and complex parts do not use any standardised method. Each paper develops a specific method for its own samples with respect to its application. It is therefore difficult to compare the performance between several processes. Additionally, the wide majority of the papers are focused on surface roughness. Only few papers have investigated the evolution of part's geometry (dimension, form, edges, …). The objective of this article is to propose a reference method for the characterisation of polishing processes on parts with complex geometries and very high initial roughness (Ra > 10 µm). The application case study of this new method concerns the investigation of the influence of electrolyte temperature in a new process called 'PEMEC'. This polishing process was recently proposed in [15]. This process combines an abrasive action (tribofinishing) with an anodic dissolution action (electrochemical polishing - ECP). Among the large variety of technical solutions in tribofinishing, the PEMEC process kinematic uses a drag-finishing machine kinematics that enables to polish complex surfaces thanks to its double rotation. The principle of this process is described in Fig .1

As a reminder, electrochemical polishing (ECP) is one of the most common electrochemical polishing processes used for metallic parts with complex shapes. This process involves the controlled dissolution of the surface to be polished. ECP commonly provides shiny surfaces. When electropolishing, current flows from the anode (the workpiece – Fig.1 A-D) to the cathode (the machine tank – Fig.1 A-D). The anode-cathode assembly is immersed in an electrolyte bath, the concentration and composition of which varies according to the metal being polished. The scientific community has conducted numerous studies on the sensitivity of the process parameters (temperature, electrolyte composition, agitation rate, distance between the electrodes, etc.) [3]. This process requires long treatment periods. Moreover, the concentration of the electric current lines on the sharp edges induces a modification of the geometry of the parts (Fig. 1D).

Drag-finishing is a mechanical polishing process that improves the surface roughness of parts with complex geometries. The parts are dragged through a mixture of a large number of abrasive particles (called abrasive media) immersed in a liquid. The interaction between the abrasive media and the surface to be polished induces 3 mechanisms: plastic deformation of the roughness peaks, scratches and finally it generates micro-chips. These mechanisms lead to an improvement of the surface finish. This process has been studied several times and it has been shown that the efficiency of the process depends on several parameters such as drag velocity, type of liquid and geometry, as well as size and composition of the abrasive media [5]. However, this process requires long polishing periods to achieve a low roughness. In addition, abrasives are particularly aggressive to sharp edges, which changes the geometry of the polished workpieces.

Rech et al. [15] have shown that there is a synergistic effect between abrasion and anodic dissolution during the PEMEC process. It becomes possible to reduce the roughness very quickly from a Sa value of 11 µm to 3 µm within 120 minutes on complex 316L stainless steel parts, without significantly modifying the shape of the parts and especially the sharp edges.

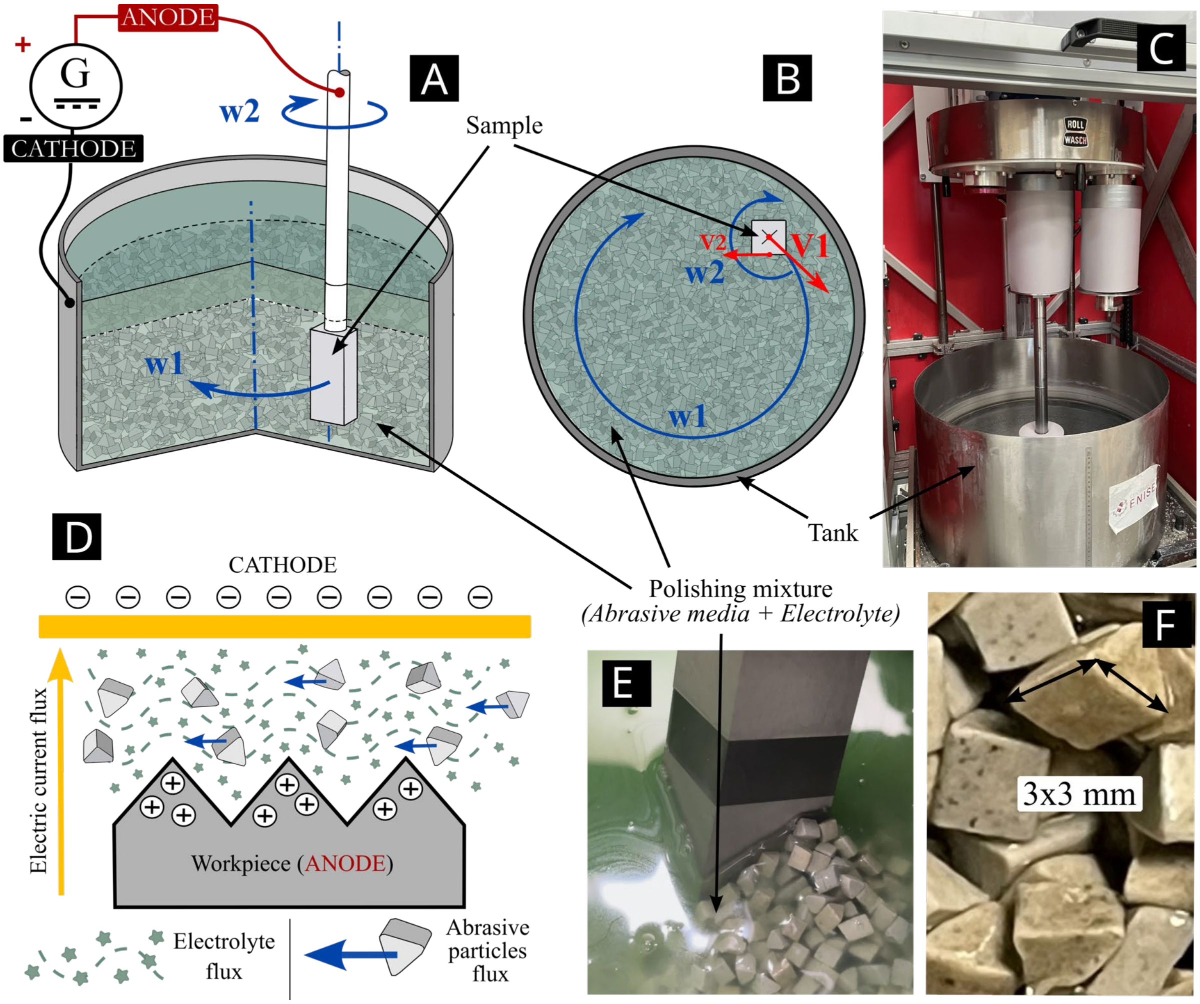

Fig. 1. PEMEC process principle: A) Schematic illustration; B) Schematic illustration; C) PEMEC machine; D) Schematic illustration of PEMEC principle; E) PEMEC polishing mixture (Abrasive media + Electrolyte); F) Elementary abrasive media used in PEMEC process.

Experimental Procedure

Definition of sample geometry.

The first step of the new method, to characterize polishing processes, is to define a new sample geometry with a calibrated geometry and roughness (Fig. 2). The part has rectangular parallelepipedal shape with two *'reference surfaces'* at its upper and lower ends. These *'reference surfaces'* are flat and smooth (Fig. 2A). During the polishing process, these surfaces will be protected and will not be affected by the polishing process (Fig. 2C). These '*reference surfaces'* enable the sample to be relocated in an absolute reference frame. Then there are two groups of so-called *'transition surfaces'* (Fig. 2C). *'Transition surfaces'* are also flat and smooth. They enable to investigate the evolution of the macro-geometry of the sample (flatness, orientation, dimension) and the evolution of edge sharpness. Both the *'reference surfaces'* and *'transition surfaces'* have been generated by grinding. Finally, in the centre of the sample, there is the so-called *'calibrated roughness area'* where a high roughness is generated with a determined shape (Fig. 2B). The analysis of the evolution of the topography in this zone enables the analysis of the polishing mechanisms (plastic deformation, abrasion, dissolution, ...). The principle of this analysis has already been introduced by Malkorra et al. [16].

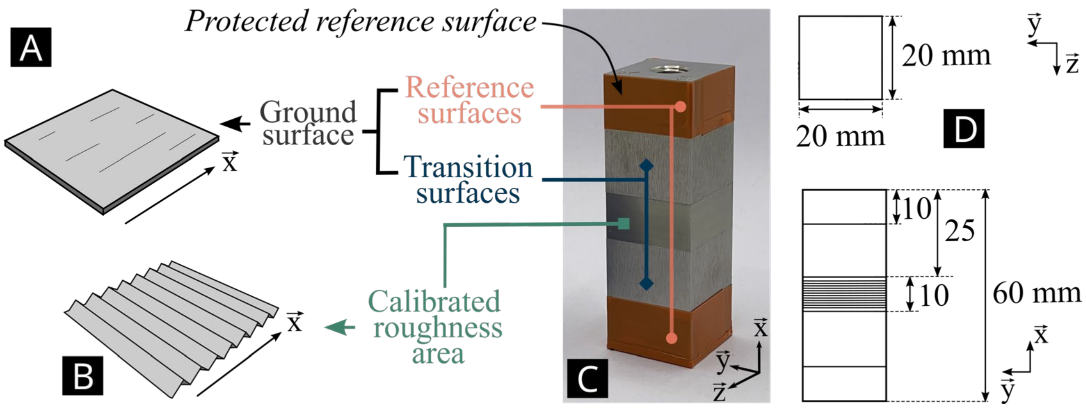

Fig. 2. A) Ground surface schematic; B) Calibrated roughness area schematic; C) Image of sample with protected reference surface; D) Sample dimensions.

Sample fabrication.

The samples were fabricated from austenitic 316L stainless steel. For logistical reasons, it was decided to use 316L stainless steel from laminated bars. After milling, *'reference surfaces'* and *'transition surfaces'* were both manufactured by fine grinding. Before polishing, the *'reference surfaces'* and *'transition surfaces'* cannot be distinguished from each other. The only difference between these two surfaces is that *'reference surface'* will be protected during the polishing process, and thus will not be modified. The edges around the transition surfaces are sharp (Fig. 3E). The so-called *'calibrated roughness area'* was machined by milling (Fig.3 A to D) with the aim of reproducing a microgeometry similar to those obtained after additive manufacturing processes. This step allowed to obtain a high roughness value ($Ra \simeq 12$ µm / $Rz \simeq 50$ µm). The results found when polishing this *'calibrated roughness area'* have the same trends as those obtained when polishing real parts produced by additive manufacturing [15].

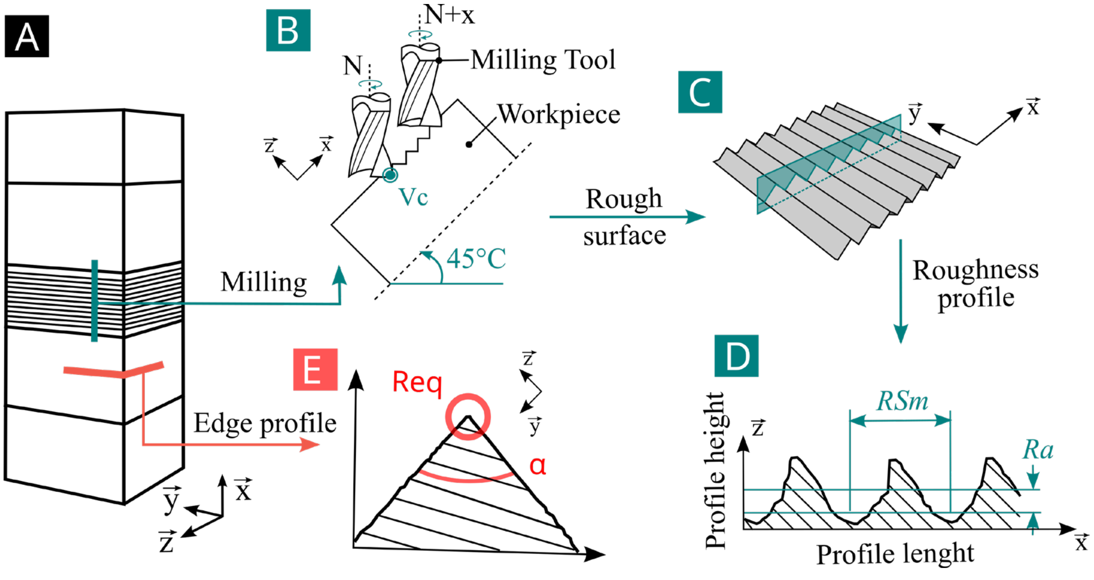

Fig. 3. A) Sample schematic; B) Calibrated roughness milling operation; C) Calibrated surface schematic; D) Periodical calibrated roughness profile; E) Edge profile.

Polishing tests.

The samples were polished by the PEMEC process for 75 minutes. The PEMEC machine is designed within a drag-finishing machine, that enables both polishing processes (abrasion + anodic dissolution) to be carried out. The main rotation (w1 in Fig. 1 A-B) induces a drag velocity V1 responsible for the abrasive mechanisms, while the second rotation (w2 in Fig. 1 A-B) leads to a homogeneous treatment around the workpiece. This kinematic induces a high sliding speed. This set-up has already been used in previous works [15]. During the polishing process, the workpiece is immersed and dragged in the polishing mixture (abrasive media + electrolyte). Table 3 shows the composition of the polishing mixture and the process parameters used. A DC power supply was installed between the tank (cathode) and the workpiece (anode).

Table 1 Polishing mixture composition and process parameters

		PEMEC process	
Drag velocity V_1 [m/s]		0.6	
Rotation speed, w_1 [rpm]		200	
V_2 [m/s]		0.69	
Sample rotation speed, w_2 [rpm]		655	
Temperatures		25 °C	62 °C
“Polishing mixture”	Abrasive particles	Pyramidal shape Al_2O_3 abrasive particles, size 3x3 mm	
	Electrolyte / Lubricant	Phosphoric acid H_3PO_4 (85 wt.%) and deionised water	
Voltage [V]		12	
Current density [A/dm²]		20	

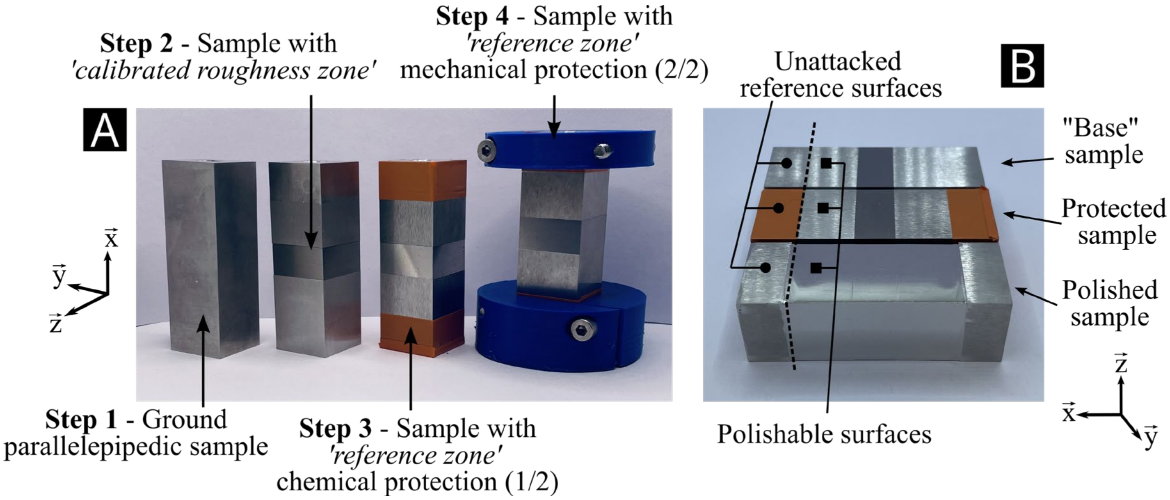

Fig. 4. A) Sample protection process; B) Protected reference surface principle.

The distance between the anode (workpiece) and the cathode (tank), and the drag speed are very influential parameters for the ECP mechanisms. The anode-cathode distance was set at around 30 mm, and this distance oscillates around this value due to the rotation of the workpiece (w2) and the geometry of the workpiece. It should be noted that the distance and drag speed used in this study are significantly higher than the values used in studies conducted by the scientific community on ECP. The temperature of the electrolyte is controlled before and during the treatment to ensure that the temperature is the same throughout the polishing process. In this study, two temperature levels were chosen: T°= 25 °C and 62 °C. The samples are mounted in the machine with a reference surface protection system (Fig. 4). The tests were interrupted every 15 minutes in order to characterise the topography evolution of the 4 calibrated roughness areas and the 8 transition surfaces and edges. This enables to obtain an average value, as well as to quantify the deviation.

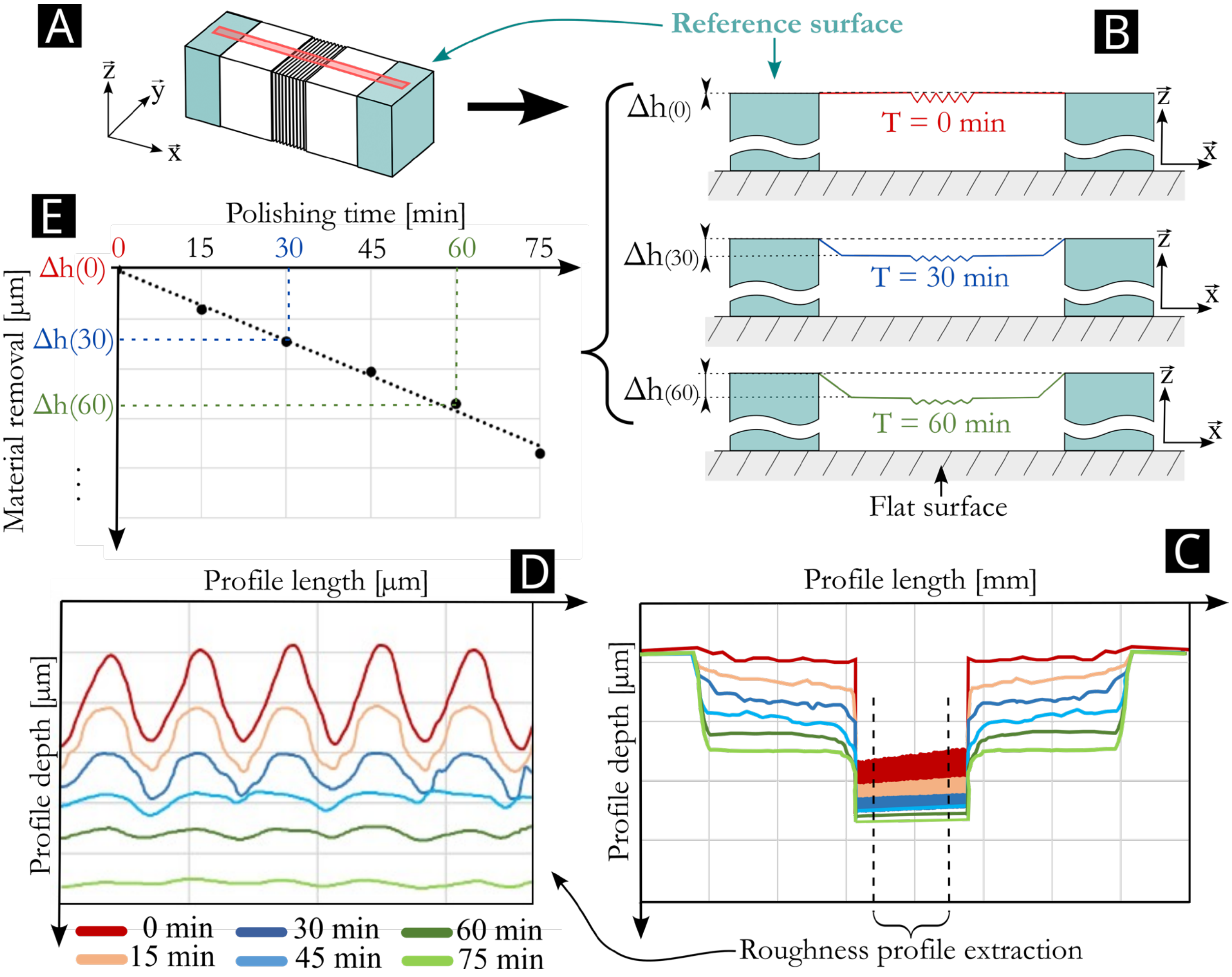

Fig. 5. A) Sample with highlighted reference surfaces schematics; B) Reference surface working principle; C) Profile overlay; D) Roughness profile extraction after profile overlay; E) Material removal evolution obtained.

Results and Discussions

The new method for characterising the performance of polishing processes was applied for two polishing conditions, corresponding to operating conditions, i.e. two different values for electrolyte temperatures. The results are presented in Figures 6, 7 and 8.

Fig. 6A shows the evolution of the amount of material removed (*Δh*) in the *'transition surfaces'* for both tested conditions. The process for obtaining figure 6 is explained in figures 5A, 5B and 5E. It appears that the material removal rate is much higher at high temperature. Thus, after 75 min, a value of *Δh* ~ 384 µm can be observed at 62 °C compared to 74 µm at 25 °C. If we analyse the evolution of material removal, we can observe that at 62 °C, the process removes nearly as much material after 15 min (*Δh* ~ 65 µm) as the process at 25 °C after 75 min (*Δh* ~ 74 µm). There is a ratio of around 4.5 on the material removal rate between the two different temperatures tested.

Fig. 6B shows the evolution of the *Ra* parameter in the *"calibrated roughness area"*. It can be observed that the roughness is improved much faster when using a high temperature. Thus, after

15 minutes only, *Ra* reaches a value of ~ 0.45 µm at 62 °C, compared to 8.22 µm at 25 °C. The PEMEC process at 25 °C only achieves a *Ra* < 1µm after 75 min.

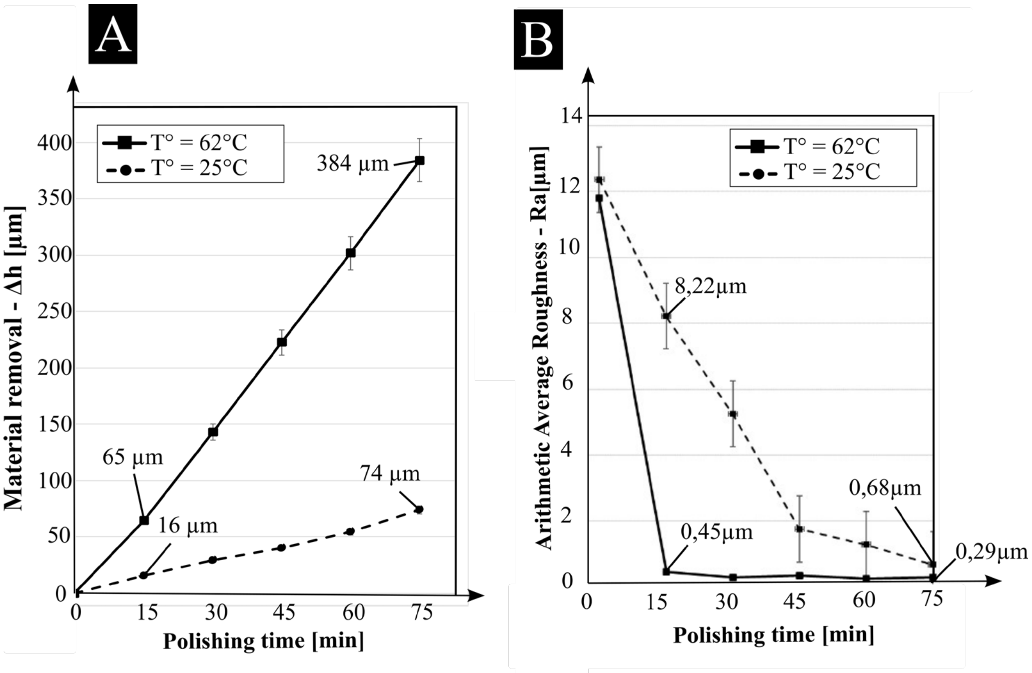

Fig. 6. A) Material removal, Δh[µm], over time; B) Arithmetic Average Roughness, Ra[µm], over time.

Fig. 7A and B show the evolution of the roughness profile, as well as their relative position compared to the reference surfaces. These figures were obtained by overlaying the different measured roughness profiles, using the *"reference surfaces"* as a reference (Fig.5 A-B). This overlay process is explained in Fig. 5 A to D. Fig. 7A and B illustrate clearly that the polishing process at 62 °C completely erases the initial roughness profile in less than 15 minutes. It can also be seen that the amount of material removed is greater than the initial height of the roughness profile. However, after a 15-minutes treatment, a slightly noticeable periodic surface remains from the initial roughness profile. The surface then becomes aperiodic from 30 minutes onwards.

In comparison, at 25 °C the profile remains periodic until 75 min. It can be observed that the valleys of the profiles are not much affected at the beginning of the treatment. This behaviour reveals the abrasion of the roughness peaks, which indicates that abrasion is probably the dominant mechanism. In sharp contrast, at 62 °C there is clearly a combination of homogeneous material dissolution and peak roughness abrasion (synergistic effect of the PEMEC process). These results confirm the findings of the literature regarding the importance of temperature control in electrochemical polishing [5].

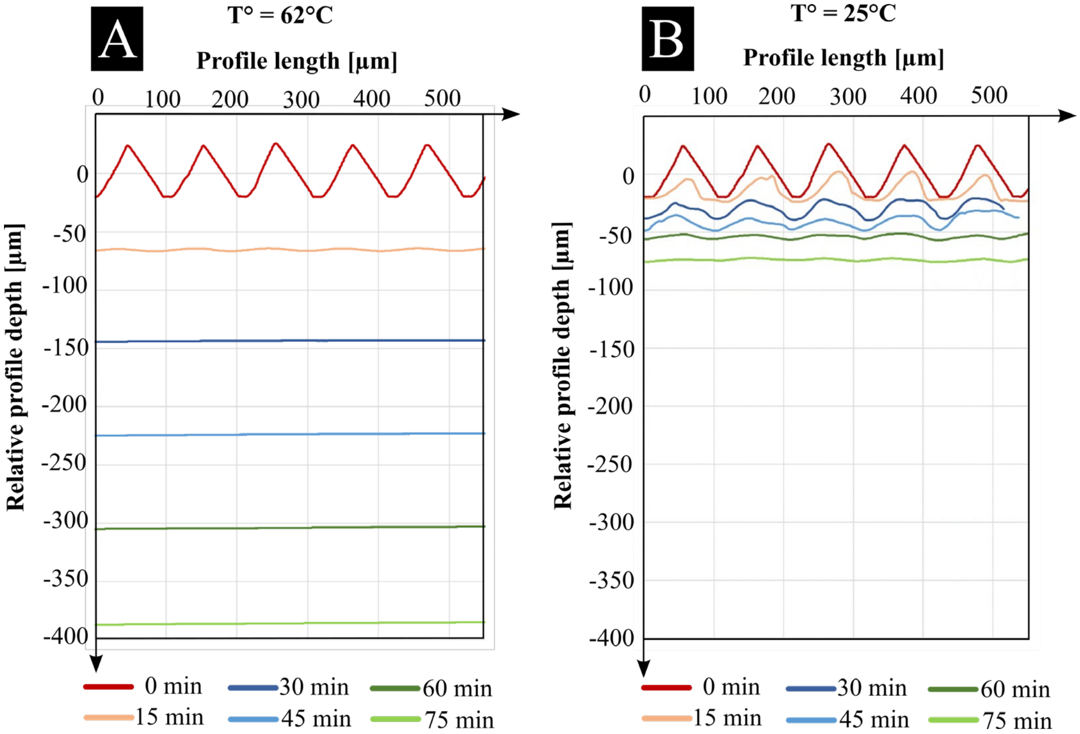

Fig. 7. A) Roughness profile evolution at 62 °C; B) Roughness profile evolution at 25 °C.

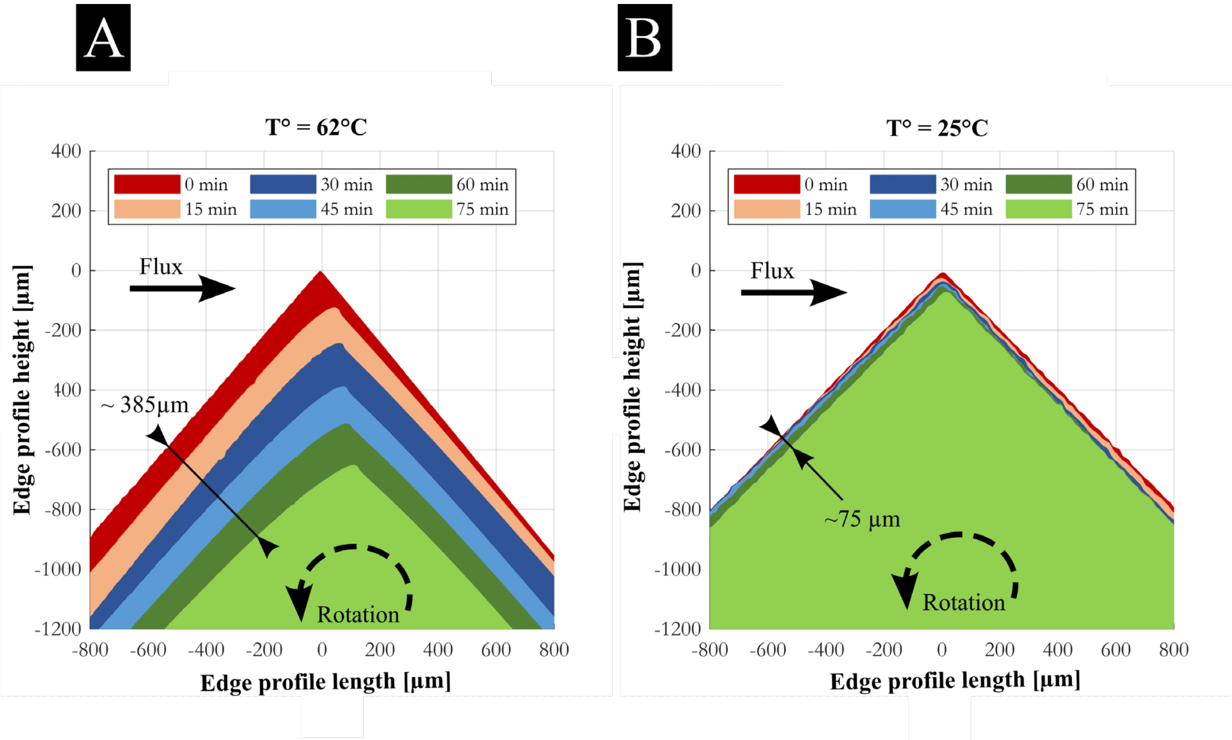

Fig. 8. A) Edge profile evolution at 62 °C; B) Edge profile evolution at 25 °C.

Fig. 8A and B show the evolution of the edge profile, were obtained by overlaying the different measured edge profiles. It is clear that at 25 °C the edges are only slightly affected by the process, while, at 62 °C the change in edge geometry is very rapid. This is in accordance with the previous results presented in Fig. 7 and 8. A large amount of material is removed. However, the edge sharpness remains quite sharp and not rounded (~ 1 mm) as is commonly seen in drag-finishing processes. A closer look at the profiles shows that the two sides are not symmetrical. On the left side, the shape is more affected by the polishing process than on the right side leaving non-flat surfaces near the edge, as well as a slightly curved edge. This is due to the direction of rotation of the sample in the machine. The w2 speed induces a greater abrasive media impact speed on left side. This asymmetry can be counterbalanced by regularly reversing the direction of rotation in the machine. So, it can be concluded that the PEMEC process enables to preserve edge sharpness thanks to the reduced polishing duration (some minutes).

Summary

This paper has presented a new method to characterise the performance of a polishing process on complex shaped samples with high roughness. This method was applied to the characterisation of the influence of electrolyte temperature in the PEMEC process, which combines an abrasive and an anodic dissolution action. This method has shown its ability to simultaneously quantify the multi-scale evolution of the samples: roughness parameters, roughness profiles, material removal and edge macro-geometry. This method allows to reveal the mechanisms of action of polishing processes.

In the case of the PEMEC process, it was shown that temperature is a key parameter for the efficiency of material removal. While the process is essentially dominated by the abrasive action at low temperature, the dissolving action plays a major role in synergy with the abrasion at higher temperature.

The perspective of this work will now focus on a generalised use of this methodology in order to study the sensitivity of the PEMEC process to all the mechanical parameters (shape and speed of the abrasive particles, ...) and the electrochemical parameters (voltage, electrolyte, ...) so as to identify the best synergistic conditions between the two mechanisms.

This geometry of samples has the potential to compare the efficiency of various polishing processes for complex and rough parts.

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