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(54) **SMOOTHING THE SURFACE FINISH OF ROUGH METAL ARTICLES**

GLÄTTUNG DER OBERFLÄCHENBESCHAFFENHEIT VON RAUEN METALLGEGENSTÄNDEN

LISSAGE DE FINI DE SURFACE D'ARTICLES MÉTALLIQUES BRUTS

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Description**Technical Field**

[0001] The invention relates to a process for smoothing the surface of a manufactured metallic workpiece.

Background

[0002] Standard engineering production methods usually provide articles with a wide range of surface roughness or surface finish. A technological drawback often encountered in manufactured parts is the reduction of their initial surface roughness to acceptable values required for a specific application. Standard engineering production methods will provide articles with a wide range of surface roughness or surface finish. Casting, Forming, Machining and Additive Manufacturing can produce rough surface finishes characterised by R_a -values above 2 μm (macro-finish).

[0003] However, a high surface roughness is usually undesirable as it often has a detrimental effect on wear and corrosion performance. High surface roughness is also usually undesirable for articles used in aerospace, medical and tooling industries due to increased wear and/or reduced corrosion resistance due to a large nominal area and encouragement of micro-crack propagation. A post-production operation, often called finishing, to reduce the initial surface roughness to a suitable value required for a specific application is often required in the manufacturing route of most engineering and medical components. Methods which reduce the surface roughness still further are sometimes also referred to as polishing.

[0004] Mechanical methods such as lapping, grinding and polishing can reduce the initial surface roughness of articles down to a micro-finish level (i.e. $0.01 < R_a < 2.00 \mu\text{m}$) (sometimes referred to as a micro-finish range).

[0005] Mechanical finishing methods (e.g. grinding, polishing) also have uniformity limitations when used in complex-shaped components. Uniformity may also be an issue for complex-shaped components, especially for metal articles made of materials traditionally difficult to polish such as titanium and its alloys and nickel superalloys.

[0006] Although mirror-like surfaces can be achieved on most metal articles by these mechanical methods, these processes tend to be labour-intensive and often leave the surface layer distorted, highly stressed and contaminated with grinding/polishing media.

[0007] Also, if the initial surface roughness is high, several grinding/polishing steps will be required in order to achieve a significant reduction in surface roughness, making these processes less economically viable in certain applications.

[0008] Electropolishing is a finishing technique suitable for finishing and polishing metallic components, especially materials such as nickel superalloys and titanium alloys which are difficult to polish by conventional methods. Electropolishing requires that the surface is clean and generally free of contaminants. Electropolishing produces a scratch-free surface and uniform finish on complex-shaped components. It is a commercially viable technique, as it can process several parts at once and polishing times are relatively short. This electrochemical treatment promotes levelling, shine and passivation of a metal surface that was originally dull and rough.

[0009] However electropolishing generally uses highly concentrated acids (e.g. sulphuric and phosphoric) with high viscosity in the electrolyte solution.

[0010] As electropolishing is driven by Faraday's Law, asperities (extruded features) on the surface will be selectively polished more severely. Although electropolishing provides selective smoothing of surface features and leads to an enhanced surface finish, the rate of material removal is considerably high (10-30 μm per minute, US patent application 2011/0120883A1). This has tolerance implications on high-precision metal components. Another disadvantage of electropolishing is that electrolytes normally used (i.e. highly concentrated acid solutions) are not environmentally friendly and can be difficult to dispose of. Due to the low voltages employed no plasma is generated.

[0011] A lesser-known process called electrolyte plasma polishing has also been suggested as a polishing technique on workpieces that already have a low level of roughness ($R_a < 1.6 \mu\text{m}$) or for cleaning oxides or removing coatings from a metal surface. Low surface roughness in the micro-finish range ($R_a < 0.2 \mu\text{m}$) can be achieved after this treatment.

[0012] Several patents related to the manufacture of equipment for performing electrolytic plasma polishing can be found in the literature (CN 102658506 A, CN 20257656 U, CN 102658506 A, CN 102828186 A, CN 202576569 U, RU 2,268,326 C1, RU 2,323,279 C1, RU 2324769 C2, US 8,882,974 B2).

[0013] US 6, 585,875 B1 discloses a plasma electrolytic process and apparatus for removing oxide scales from metal surfaces (steel and copper). Electrolytic plasma polishing processes for various ferrous and non-ferrous materials have been developed and documented in the literature. Plasma polishing conditions (temperature, voltage, electrolyte, etc.) have been established and tailored for specific materials. For instance, CN 103484928A discloses a plasma rust polishing process for iron and steel parts to remove surface oxide scales. After electrolytic plasma polishing the surface roughness (R_a -value) reduced from 1.67 μm (initial value) to 0.27 μm . Another electrolytic plasma process for polishing parts made of titanium or titanium alloys is disclosed in DE 10 207 632 A1. The polishing process aims at removing all types of surface residue such as rust, oxides, paints and varnishes using a mixture of ammonium chloride (NH_4Cl) and ammonium

fluoride (NH_4F) as the electrolyte. US application 2010/0200424 deals with plasma electrolytic processes for stainless steels 300 and 400 series), copper and titanium alloys for DC voltages not exceeding 80V. A method of multistage electrolytic plasma polishing of titanium and titanium alloys is disclosed in RU 2373306 C2. Polishing processes reported for these materials are claimed not to roughen the surface to R_a -values higher than 0.08-0.12 μm .

[0014] An electrolytic plasma treatment for metal surfaces comprising an aluminium or aluminium-containing alloy anode and a copper-plated steel cathode is documented in RU 2550393 C1. The aluminium or aluminium-containing alloy anode and the copper-plated cathode are immersed in an electrolytic solution to polish the aluminium or aluminium containing article (anode) to a specular gloss and simultaneously remove the copper layer from the steel cathode. RU2355829 C2 discloses a method for electrolytic plasma polishing of metal parts manufactured of chromium-bearing stainless steels and titanium or titanium alloy, mainly for the treatment of turbomachinery blades.

[0015] Another electrolytic plasma polishing process for titanium or titanium alloy articles is documented in CN 1534113 A. The electrolyte is a mixture of ammonium chloride and ammonium fluoride; DC voltage and temperature ranges for the polishing plasma process are 210V-420V and 60°C-98°C respectively. Although surface roughness is not quantified, a smooth finish (probably referring to a shiny surface in the micro-finish range) is reported to have been achieved.

[0016] US 8,444,914 B2 discloses a plasma polishing process for the manufacture of cobalt-chromium dental prostheses in order to obtain reproducible surface roughness without any additional finishing. The process involves DC voltages of 300-380V and current densities of 0.25-0.50 A/cm². However, the reduction in surface roughness after plasma polishing has not been quantified.

[0017] Thus, improved methods of finishing and/or polishing rough or very rough metallic workpieces would be desirable.

Summary of the Invention

[0018] The present inventors have discovered that electrolyte plasma polishing can be innovatively applied to workpieces with very rough surfaces and achieve excellent reduction in roughness in a more convenient manner.

[0019] The invention relates to a process for smoothing the surface of a manufactured metallic workpiece, the workpiece having a region having an initial roughness (R_a) of greater than 2.0 μm , the process involving (1) placing the metallic workpiece as the anode in an electrochemical cell, (2) arranging for the temperature of the electrolyte in the vicinity of the anode to be at least 50°C, (3) applying a voltage from 100V to 1000V across the electrochemical cell, thereby to generate a plasma membrane on the surface of the metallic workpiece which acts to remove material from the surface of the metallic workpiece, (4) maintaining the plasma membrane for a period effective to cause the roughness of the workpiece to be reduced.

[0020] Typically substantially all of the workpiece has an initial roughness (R_a) of greater than 2.0 μm . However it may be that only a part of the workpiece has this roughness value in need of treatment.

[0021] Unlike electropolishing, electrolytic plasma polishing is operated in a manner such that an electric arc discharge (i.e. electro-plasma) is established at the surface of the workpiece. Aqueous solutions of acids, salts or alkali at low concentrations (< 20 wt.%) are normally used, making the process environmentally friendly as electrolytes are usually non-toxic and easy to recycle or dispose of.

[0022] In the beginning of the process, high current density at the anode leads to intensive electrolyte evaporation (gas stream), enveloping the entire surface of the workpiece and leading to the formation of a plasma membrane. The typical material loss is around 2 μm per minute, which is 5 to 20 times lower than that achieved by electropolishing. It is therefore surprising that the present invention has been found to be effective on rough surfaces and does not need several treatment stages like similar polishing type treatments known in the art.

[0023] Preferably the rate of material removal is from 1 to 12 $\mu\text{m}/\text{min}$, more preferably from 2 to 10 $\mu\text{m}/\text{min}$.

[0024] The objective of the invention is to provide an electrolytic plasma treatment method to reduce the surface roughness of rough metal articles characterised by an initial R_a -value (or S_a -value) in the range of 2 μm to 100 μm and/or R_z -values (or S_z -values) between 2 and 150 μm , aiming at a resulting surface finish free of a heterogeneous texture and/or exhibiting a considerably lower surface roughness value after the electrolytic plasma treatment. Such an electrolytic plasma treatment may be of great interest for engineering manufacturing processes in which the resulting article has a very rough and uneven surface texture (such as 3-D printed components, coarsely blasted surfaces, very rough sintered parts).

[0025] The invention is concerned with improving the surface finish of very rough articles (exhibiting R_a -values above 2 μm , i.e. articles in the macro-finish range) produced by engineering production methods such as flame cutting, snagging, coarse blasting, shaping and 3D-printing (additive manufacturing). The present invention is particularly suitable for additive manufacturing as this produces a rough finish and the present invention can cope with the wide range of geometries producible by this manufacturing method.

[0026] However the initial roughness (R_a) of the workpiece is generally also less than 400 μm , more preferably less than 300 μm , most preferably less than 200 μm .

[0027] A list of suitable manufacturing techniques and the roughness levels they typically produce is as follows:

• Sand casting	Ra = 10-50um
• Investment casting	Ra = 2-10um
• Additive Manufacturing	Ra = 10-50um
• Metal Cutting (sawing, shaping, drilling, milling, turning)	Ra = 2-25um
• Hot rolling	Ra = 12-25um
• Forging	Ra = 3-12um
• Flame cutting	Ra = 12-25um

[0028] The electrolytic plasma treatment aims at a resulting surface finish free of a heterogeneous texture and/or exhibiting a considerably lower surface roughness value compared to its initial surface roughness value.

[0029] Suitable metrology methods to quantify surface roughness include surface stylus profilometry (from which R_a and R_z parameters are derived from a profile (line)) and 3D-optical surface profilometry (from which S_a and S_z parameters are derived from a surface area).

[0030] In the invention the rough metal part to be treated/polished (workpiece) is anodically polarised and placed in an electrolytic bath with a metal cathode. The process is operated in a manner such that an electro-plasma (i.e. electric arc discharge) is established at the surface of the workpiece.

[0031] Suitable rough metal articles to be treated in this invention may be made of any metal including stainless steels, carbon steels, tool steels, titanium and titanium alloys, magnesium alloys, nickel-chrome and its alloys, nickel superalloys, cobalt-chromium alloys, cobalt-chromium-molybdenum alloys, copper and copper alloys (including bronze), brass and its alloys and cast-iron. Other materials may include aluminium, vanadium, chromium, manganese, cobalt, nickel, copper, niobium, molybdenum, silver, hafnium, tungsten, platinum and gold.

[0032] The process is suitable for application to one or more workpieces immersed in the electrolyte at the same time.

[0033] The cathode surface is desirably 2 to 20 times greater than that of the anode surface area (i.e. workpiece surface area), preferably 5 to 10 times greater. A suitable metal cathode is the electrolytic tank in which the at least one anode workpiece (i.e. rough parts to be treated) is immersed in the electrolytic solution. Suitable metal materials for the cathode include stainless steel, lead, copper or any other metal which exhibits good conductivity and corrosion resistance.

[0034] A suitable DC or pulsed power supply (voltage or current controlled) should be used to polarise both electrodes (i.e. cathode and anode workpieces). The process is carried out at current densities of 0.01 A/cm² to 1.00 A/cm², preferably 0.1 A/cm² to 0.5 A/cm².

[0035] Preferably the voltage applied across the electrochemical cell is from 150 to 700V, more preferably from 200 to 400V.

[0036] Suitable chemicals (solutes) to be used in the electrolytic plasma treatment process are aqueous solutions of salts (e.g. ammonium sulphate ((NH₄)₂SO₄), sodium bicarbonate (NaHCO₃), sodium nitrate (NaNO₃), sodium carbonate (Na₂CO₃)), chlorides (e.g. ammonium chloride (NH₄Cl), sodium chloride (NaCl), potassium chloride (KCl)), fluorides (e.g. ammonium fluoride (NH₄F), sodium fluoride (NaF), potassium fluoride (KF)), acids (e.g. phosphoric acid (H₃PO₄), sulphuric acid (H₂SO₄)), alkalis (e.g. sodium hydroxide (NaOH), potassium hydroxide (KOH)) or a mixture of these.

[0037] Solution concentrations in the electrolyte may vary from 1% to 25% (i.e. 1 g to 25 g of chemicals in 100 ml of water), preferably from 2% to 10%. Solution concentration depends on type of metal article to be treated (e.g. stainless steel, carbon steel, nickel superalloys, titanium or titanium alloys, cobalt-chromium alloys) and electrolytic treatment time.

[0038] Treatment times may vary from 1 to 120 minutes, preferably 1 to 30 minutes. The longer the treatment time, the higher the solution concentration should be to avoid rusting of treated parts. Phosphoric acid may be added up to 10% to remove stains.

[0039] The electrolyte solution pH during the process is preferably between 2.0 to 14.0, more preferably 3.0 to 12.0, more preferably from 4.0 to 8.0, more preferably from 5.0 to 7.0. The electrolyte (solution) temperature should be maintained from 50°C to 100°C, preferably 60°C to 90°C.

[0040] The lowest treatment temperature threshold is related to the minimum electrical conductivity of the electrolyte, which is also dependent on solution concentration. The electrical conductivity of the electrolytic solution should be no less than 0.1 S.

[0041] In order to maintain the treatment temperature range, cooling methods are normally required. In a small scale (laboratory or development scale), a water/ice water bath in which a beaker containing electrodes and electrolytic solution is immersed should suffice for this purpose.

[0042] In a large scale (i.e. commercial process), re-circulating of the electrolytic solution and cooling of it by means of a suitable cooling unit should be more adequate. In addition to this filters should be used to collect metal/metal oxide debris from the electrolytic solution.

[0043] The invention will now be illustrated, by reference to the following figures, in which:

Figures 1a to d are photomicrographs showing the surface appearance of AISI 316 coupons: (a) initial surface texture (blasted surface) before the electrolytic plasma treatment; (b) after electrolytic plasma treatment for 5 minutes; (c) after electrolytic plasma treatment for 10 minutes and (d) after electrolytic plasma treatment for 15 minutes.

Figure 2a and b show material removal data for electrolytic plasma treatment of AISI 316 stainless steel. (a) Mass loss versus electrolytic plasma treatment (EPT) time and (b) Thickness loss versus electrolytic plasma treatment (EPT) time. Electrolytic solution: 2.5% $(\text{NH}_4)_2\text{SO}_4$ aqueous solution.

Figures 3a and b show 3D-roughness parameters obtained by 3D surface profilometry on coarsely blasted AISI 316 steel coupons before and after various electrolytic plasma treatment times. (a) S_a and S_q ; (b) S_z .

Figures 4a to d show 3D surface images and line profiles of AISI 316 steel coupons: (a) before electrolytic plasma treatments (i.e. initial blasted surface); (b) after electrolytic plasma treatment for 5 minutes; (c) after electrolytic plasma treatment for 10 minutes and (d) after electrolytic plasma treatment for 15 minutes.

Figure 5 is a photomicrograph showing the surface appearance of a 3D-printed 15-5 PH steel component. Region (a): initial surface texture of 3D-printed surface. Region (b): after electrolytic plasma treatment (EPT) for 15 minutes.

Figures 6a and b are charts showing 3D-roughness parameters obtained by 3D surface profilometry on 3D-printed 15-5 PH steel component before and after electrolytic plasma treatment (EPT) for 15 minutes. (a) S_a and S_q ; (b) S_z .

Figures 7a and b are 3D surface images and line profiles of 3D-printed 15-5 PH steel component before (a) and after (b) electrolytic plasma treatment (EPT) for 15 minutes.

Examples

[0044] The following examples will demonstrate how the electrolytic plasma treatment used in this invention can significantly improve the surface finish of very rough article surfaces (possessing initial surface roughness values of S_a and $S_z \geq 2 \mu\text{m}$ (i.e. in the macro-finish range)) by significantly reducing the initial S_a - and S_z -values.

Example 1: Electrolytic plasma treatment on coarsely blasted AISI 316 stainless steel samples

[0045] AISI 316 stainless steel samples (3.0 cm $\times$ 2.5 cm $\times$ 0.2 cm) were coarsely blasted with 120-150 grit pink alumina to achieve initial average S_a - and S_z -values of $2.4 \pm 0.1 \mu\text{m}$ and $52 \pm 5 \mu\text{m}$ respectively.

[0046] The electrolytic plasma treatment set-up consisted of a 2 litre glass beaker in which a cathode made of an AISI 316 stainless steel sheet (37 cm $\times$ 10.5 cm $\times$ 0.1 cm) was rolled and wrapped around the inner wall of the beaker. The effective surface area of the cathode was 388.5 cm². The 1.5 litre electrolytic solution used to plasma treat the coupons was an aqueous solution of 2.5% $(\text{NH}_4)_2\text{SO}_4$ (37.5 g of $(\text{NH}_4)_2\text{SO}_4$ in 1500 ml of water). The beaker arrangement was placed inside a water bath at a temperature of $18 \pm 1^\circ\text{C}$. The water bath volume was 17490 cm³. The solution temperature was monitored until it reached a value of $T = 60 \pm 1^\circ\text{C}$ before the electrolytic plasma treatment commenced. The solution pH at this temperature was 6.5.

[0047] An Advanced Energy MDX II 30 kW DC power supply was used in the voltage controlled mode. The AISI 316 coupon was the anode workpiece. The voltage was set to a value of 250V in the power supply, which was then switched on. The 'energised' anode workpiece (AISI 316 steel coupon) was fully immersed in the electrolytic solution and treated for a specific time. The resulting voltage and current during the electrolytic plasma treatment were 160-250 V DC and 25-40 A respectively. Oscillations in voltage and current occurred due to micro-discharges that take place during the process (a plasma envelope formed around the coupon). This current range corresponded to a current density of $\sim 0.1 \text{ A/cm}^2$.

[0048] AISI 316 steel coupons were electrolytically plasma treated for 5 minutes, 10 minutes and 15 minutes in the 2.5% $(\text{NH}_4)_2\text{SO}_4$ aqueous solution. Samples were weighed before and after each electrolytic plasma treatment to estimate volume loss (obtained by dividing mass loss by the density of the AISI 316 steel, 7.99 g/cm³). Thickness loss was also determined by dividing the volume loss by the total nominal surface area of the coupons (17.2 cm²). Finally the material removal rate was estimated from the gradient of the plot between volume loss or thickness loss and electrolytic plasma treatment time. Surface roughness parameters (S_a , S_q and S_z) were measured before and after electrolytic plasma treatments using a Zometics ZeScope 3D surface profiler. The sampled area was 449 $\mu\text{m} \times 335 \mu\text{m}$ for all 3D-surface roughness measurements.

[0049] Photomicrographs showing the initial surface texture of the coarsely blasted AISI 316 steel surface and after electrolytic plasma treatments for 5, 10 and 15 minutes are shown in Fig.1. The dull and rough appearance of the blasted surface (Fig. 1a) progressively improves to a silver and shiny appearance from left to right after a total electrolytic plasma treatment of 15 minutes (Fig. 1d). Material removal data for the AISI 316 stainless steel for electrolytic plasma treatments in a 2.5% $(\text{NH}_4)_2\text{SO}_4$ aqueous solution are illustrated in Fig.2. Under the experimental conditions herein reported, a small material removal rate of 3.2 $\mu\text{m}/\text{minute}$ resulted, suggesting that such electrolytic plasma treatments have great potential to be applied to high-precision parts where small tolerances must be retained.

[0050] 3D-surface roughness data for the coarsely blasted AISI 316 stainless steel is depicted in Fig.3. Initial S_a - and S_z -values (higher than 2 μm and 50 μm respectively) were significantly reduced after an electrolytic plasma treatment (EPT) for 15 minutes. Three and five-fold reductions in S_a - and S_z -values were accomplished after a 15 minute-treatment. Moreover, 3D images and line profiles of these samples are shown in Fig.4. A systematic reduction in profile peaks occurs as the electrolytic plasma treatment duration increases. After a 15 minute-treatment (Fig.4d) the resulting surface texture is considerably more even and smooth compared to that of the untreated surface which was very rough and uneven (Fig.4a).

Example 2: Electrolytic plasma treatment on 3D-printed 15-5 PH steel component

[0051] A 15-5PH component manufactured by 3D-printing was also trialled in this invention. The post-manufacturing surface roughness of this component was very high, characterised by $S_a = 6.5 \pm 1.7 \mu\text{m}$ and $S_z = 57.1 \pm 8.3 \mu\text{m}$ (very rough surface). High standard deviations in both S_a - and S_z -values reflect the uneven character of the component surface texture.

[0052] A similar experimental set-up to the one described in Example 1 was used. A 1.5 litre aqueous solution of 2.5% $(\text{NH}_4)_2\text{SO}_4$ (37.5 g of $(\text{NH}_4)_2\text{SO}_4$ in 1500 ml of water) was used to plasma treat the 3D-printed component. The beaker arrangement was placed inside a water bath at a temperature of $20 \pm 1^\circ\text{C}$ (water bath volume was also 17490 cm^3). The solution temperature was monitored until it reached a value of $T = 62 \pm 1^\circ\text{C}$ before the electrolytic plasma treatment commenced. The solution pH at this temperature was 6.5. An Advanced Energy MDX II 30 kW power supply was used in the voltage controlled mode. The 3D-printed 15-5 PH steel component was the anode workpiece. The voltage was set to a value of 230V in the power supply. The power supply was switched on to energise the 3D-printed 15-5 PH steel component (anode workpiece). Then the bottom one-third of the component was immersed in the electrolytic solution and treated for 15 minutes. The remaining top two-thirds of the component were kept out of the electrolytic solution (i.e. left untreated). The resulting voltage and current during the electrolytic plasma treatment were 170-230 V DC and 25-35 A respectively. These conditions led to the formation of a plasma envelope around the immersed part of the component and micro-discharges (arcing) were present. Surface roughness parameters (S_a , S_q and S_z) were measured before and after electrolytic plasma treatments using a Zometrics ZeScope 3D surface profiler. The sampled area was $449 \mu\text{m} \times 335 \mu\text{m}$ for all 3D-surface roughness measurements.

[0053] Fig.5 depicts a photomicrograph of the 3D-printed component showing electrolytically plasma treated (Region a) and untreated (Region b) areas. The treated area (Region a) exhibits a shiny appearance compared to the rather dull and matt untreated area (Region b). This finding was confirmed by 3D surface profilometry measurements (Fig.6). A considerable reduction in S_a and S_z was achieved after electrolytic plasma treatment (EPT) for 15 minutes (S_a lowered from $6.5 \pm 1.7 \mu\text{m}$ down to $1.7 \pm 0.1 \mu\text{m}$ and S_z lowered from $57.1 \pm 8.3 \mu\text{m}$ down to $14.5 \pm 0.4 \mu\text{m}$, resulting in a significant smoother and shinier surface. 3D images and line profiles (Fig.7) corroborate the benefit of the electrolytic plasma treatment on the very rough 3D-printed component. A much more even profile characterised by a considerable reduction in surface roughness resulted after the 15 minute electrolytic plasma treatment (Fig.7b) compared to the untreated 3D-printed component part (Fig.7a).

Claims

1. A process for smoothing the surface of a manufactured metallic workpiece, the workpiece having a region having an initial roughness (R_a) of greater than 2.0 μm , the process involving (1) placing the metallic workpiece as the anode in an electrochemical cell, (2) arranging for the temperature of the electrolyte in the vicinity of the anode to be at least 50°C , (3) applying a voltage from 100V to 1000V across the electrochemical cell, thereby to generate a plasma membrane on the surface of the metallic workpiece which acts to remove material from the surface of the metallic workpiece, (4) maintaining the plasma membrane for a period effective to cause the roughness of the workpiece to be reduced.
2. A process according to claim 1 wherein the initial roughness (R_a) of the workpiece is greater than 4.0 μm , more preferably greater than 10.0 μm , most preferably greater than 20.0 μm .

3. A process according to claim 1 or claim 2, wherein the cathode surface area is 2 to 20 times greater than that of the anode surface area (i.e. workpiece surface area), preferably 5 to 10 times greater.
- 5 4. A process according to claim 1 or claim 2 wherein the initial roughness (Ra) of the workpiece is less than 400 μm , more preferably less than 300 μm , most preferably less than 200 μm .
5. A process according to any one of the preceding claims, wherein the temperature of the electrolyte in the vicinity of the anode is from 50 to 100°C, more preferably from 60 to 90°C.
- 10 6. A process according to any one of the preceding claims wherein the voltage applied across the electrochemical cell is from 150 to 700V, more preferably from 200 to 400V.
7. A process according to any one of the preceding claims, carried out with a current density at the anode of 0.01 A/cm² to 1.00 A/cm², preferably 0.1 A/cm² to 0.5 A/cm².
- 15 8. A process according to any one of the preceding claims wherein the rate of material removal is from 1 to 12 $\mu\text{m}/\text{min}$, more preferably from 2 to 10 $\mu\text{m}/\text{min}$.
9. A process according to any one of the preceding claims wherein the plasma membrane is maintained for from 1 to 120 minutes, preferably 1 to 30 minutes.
- 20 10. A process according to any one of the preceding claims wherein the pH of the electrolyte is from 3.0 to 12.0, more preferably from 4.0 to 8.0, more preferably from 5.0 to 7.0.
- 25 11. A process according to any one of the preceding claims, wherein the electrolyte solution concentration is from 1% to 25wt/vol% (i.e. 1 g to 25 g of chemicals in 100 ml of water), preferably from 2% to 10 wt/vol%.
- 30 12. A process according to any one of the preceding claims, wherein the workpiece has an initial roughness as a result of being manufactured by any one of the following methods: sand casting, investment casting, additive manufacturing, metal cutting, such as metal sawing, metal shaping, metal drilling, metal milling or metal turning, hot rolling, forging, flame cutting, preferably additive manufacturing. rolling, forging, flame cutting, preferably additive manufacturing.

Patentansprüche

- 35 1. Verfahren zum Glätten der Oberfläche eines hergestellten metallischen Werkstücks, wobei das Werkstück einen Bereich mit einer Anfangsrauheit (Ra) von mehr als 2,0 μm aufweist, wobei das Verfahren beinhaltet: (1) Platzieren des metallischen Werkstücks als Anode in einer elektrochemischen Zelle, (2) Einstellen, dass die Temperatur des Elektrolyten in der Nähe der Anode wenigstens 50 °C beträgt, (3) Anlegen einer Spannung von 100 V bis 1000 V an die elektrochemische Zelle, um dadurch eine Plasmamembran auf der Oberfläche des metallischen Werkstücks zu erzeugen, die dazu dient, Material von der Oberfläche des metallischen Werkstücks abzutragen, (4) Aufrechterhalten der Plasmamembran über einen Zeitraum, der ausreicht zu bewirken, dass die Rauheit des Werkstücks verringert wird.
- 40 2. Verfahren gemäß Anspruch 1, wobei die Anfangsrauheit (Ra) des Werkstücks größer als 4,0 μm , vorzugsweise größer als 10,0 μm und μm stärksten bevorzugt größer als 20,0 μm ist.
3. Verfahren gemäß Anspruch 1 oder Anspruch 2, wobei die Oberfläche der Kathode 2- bis 20-mal größer ist als die Oberfläche der Anode (d.h. die Oberfläche des Werkstücks), vorzugsweise 5- bis 10-mal größer.
- 50 4. Verfahren gemäß Anspruch 1 oder Anspruch 2 wobei die Anfangsrauheit (Ra) des Werkstücks kleiner als 400 μm , vorzugsweise kleiner als 300 μm und am stärksten bevorzugt kleiner als 200 μm ist.
5. Verfahren gemäß einem der vorstehenden Ansprüche, wobei die Temperatur des Elektrolyten in der Nähe der Anode 50 bis 100 °C, vorzugsweise 60 bis 90 °C beträgt.
- 55 6. Verfahren gemäß einem der vorstehenden Ansprüche, wobei die Spannung, die an die elektrochemische Zelle angelegt wird, zwischen 150 und 700 V, vorzugsweise zwischen 200 und 400 V liegt.

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7. Verfahren gemäß einem der vorstehenden Ansprüche, durchgeführt mit einer Stromdichte an der Anode von 0,01 A/cm² bis 1,00 A/cm², vorzugsweise 0,1 A/cm² bis 0,5 A/cm².
- 5 8. Verfahren gemäß einem der vorstehenden Ansprüche, wobei die Geschwindigkeit des Materialabtrags 1 bis 12 pm/Min., vorzugsweise 2 bis 10 pm/Min. beträgt.
9. Verfahren gemäß einem der vorstehenden Ansprüche, wobei die Plasmamembran für 1 bis 120 Minuten, vorzugsweise 1 bis 30 Minuten, aufrechterhalten wird.
- 10 10. Verfahren gemäß einem der vorstehenden Ansprüche, wobei der pH-Wert des Elektrolyten zwischen 3,0 und 12,0, vorzugsweise zwischen 4,0 und 8,0, noch stärker bevorzugt zwischen 5,0 und 7,0 liegt.
11. Verfahren gemäß einem der vorstehenden Ansprüche, wobei die Konzentration der Elektrolytlösung 1 % bis 25 Gew./Vol.-% (d. h. 1 g bis 25 g Chemikalien in 100 ml Wasser), vorzugsweise 2 % bis 10 Gew./Vol.-% beträgt.
- 15 12. Verfahren gemäß einem der vorstehenden Ansprüche, wobei das Werkstück eine anfängliche Rauheit aufweist, die aus der Herstellung nach einem der folgenden Verfahren resultiert: Sandguss, Feinguss, additive Fertigung, Metallzerspanung, etwa Sägen, Umformen, Bohren, Fräsen oder Drehen von Metall, Warmwalzen, Schmieden, Brennschneiden, vorzugsweise additive Fertigung.
- 20

Revendications

- 25 1. Procédé pour le lissage de la surface d'une pièce à usiner métallique fabriquée, la pièce à usiner présentant une zone possédant une rugosité initiale (Ra) supérieure à 2,0 µm, le procédé impliquant (1) le placement de la pièce à usiner métallique en tant que l'anode dans une cellule électrochimique, (2) l'ajustement de la température de l'électrolyte à proximité de l'anode pour être d'au moins 50 °C, (3) l'application d'une tension de 100 V à 1 000 V à travers la cellule électrochimique, pour ainsi générer une membrane plasmique sur la surface de la pièce à usiner métallique qui agit pour éliminer de la matière à partir de la surface de la pièce à usiner métallique, (4) le maintien de la membrane plasmique pendant une durée efficace pour causer la réduction de la rugosité de la pièce à usiner.
- 30 2. Procédé selon la revendication 1, la rugosité initiale (Ra) de la pièce à usiner étant supérieure à 4,0 µm, plus préférentiellement supérieure à 10,0 µm, le plus préférentiellement supérieure à 20,0 µm.
- 35 3. Procédé selon la revendication 1 ou la revendication 2, la superficie de la cathode étant 2 à 20 fois plus grande que la superficie de l'anode (c'est-à-dire la superficie de la pièce à usiner), préférentiellement 5 à 10 fois plus grande.
- 40 4. Procédé selon la revendication 1 ou la revendication 2, la rugosité initiale (Ra) de la pièce à usiner étant inférieure à 400 µm, plus préférentiellement inférieure à 300 µm, le plus préférentiellement inférieure à 200 µm.
5. Procédé selon l'une quelconque des revendications précédentes, la température de l'électrolyte à proximité de l'anode étant de 50 à 100 °C, plus préférentiellement de 60 à 90 °C.
- 45 6. Procédé selon l'une quelconque des revendications précédentes, la tension appliquée à travers la cellule électrochimique étant de 150 à 700 V, plus préférentiellement de 200 à 400 V.
7. Procédé selon l'une quelconque des revendications précédentes, mis en œuvre avec une densité de courant au niveau de l'anode de 0,01 A/cm² à 1,00 A/cm², préférentiellement de 0,1 A/cm² à 0,5 A/cm².
- 50 8. Procédé selon l'une quelconque des revendications précédentes, la vitesse d'élimination de matières étant de 1 à 12 µm/min, plus préférentiellement de 2 à 10 µm/min.
9. Procédé selon l'une quelconque des revendications précédentes, la membrane plasmique étant maintenue pendant 1 à 120 minutes, préférentiellement 1 à 30 minutes.
- 55 10. Procédé selon l'une quelconque des revendications précédentes, le pH de l'électrolyte étant de 3,0 à 12,0, plus préférentiellement de 4,0 à 8,0, plus préférentiellement de 5,0 à 7,0.

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11. Procédé selon l'une quelconque des revendications précédentes, la concentration de la solution d'électrolyte étant de 1 % à 25 % p/v (c'est-à-dire 1 g à 25 g de composés chimiques dans 100 ml d'eau), préférablement de 2 % à 10 % p/v.

5 **12.** Procédé selon l'une quelconque des revendications précédentes, la pièce à usiner possédant une rugosité initiale du fait qu'elle a été fabriquée par l'un quelconque parmi les procédés suivants : une coulée en sable, une coulée de précision, une fabrication additive, une coupe de métal, telle qu'un sciage de métal, un façonnage de métal, un perçage de métal, un fraisage de métal ou un tournage de métal, un laminage à chaud, un forgeage, un oxycoupage, préférablement une fabrication additive.

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(a)

(b)

(c)

(d)

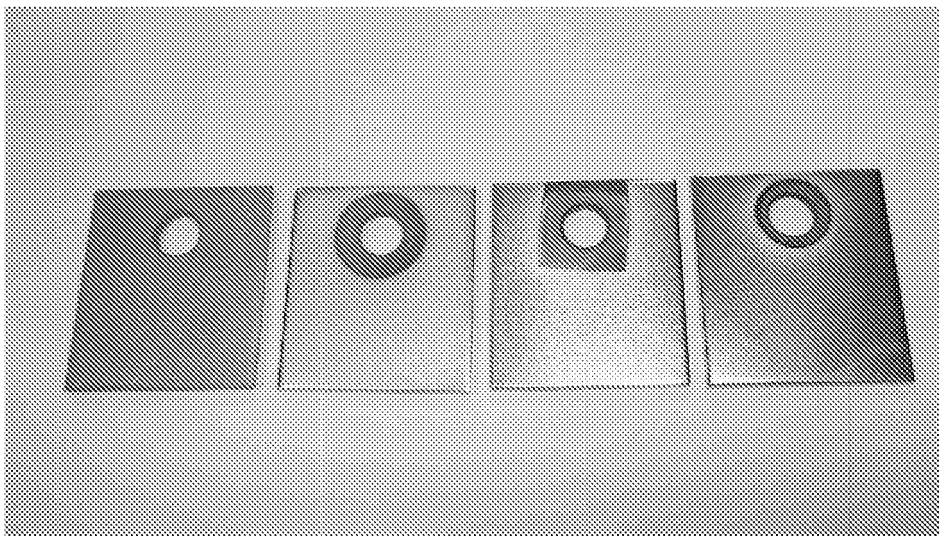
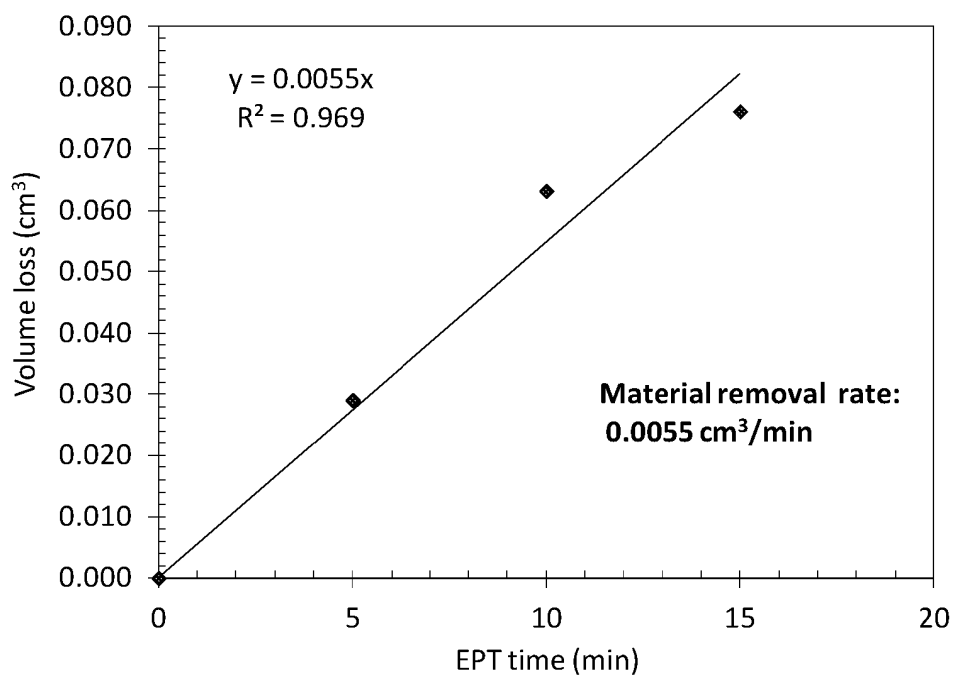
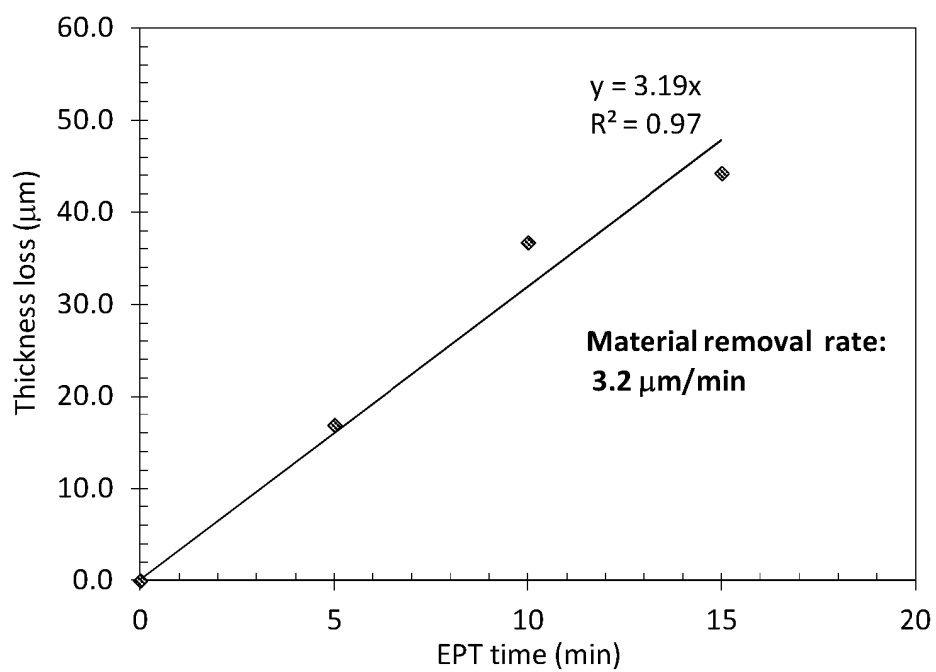
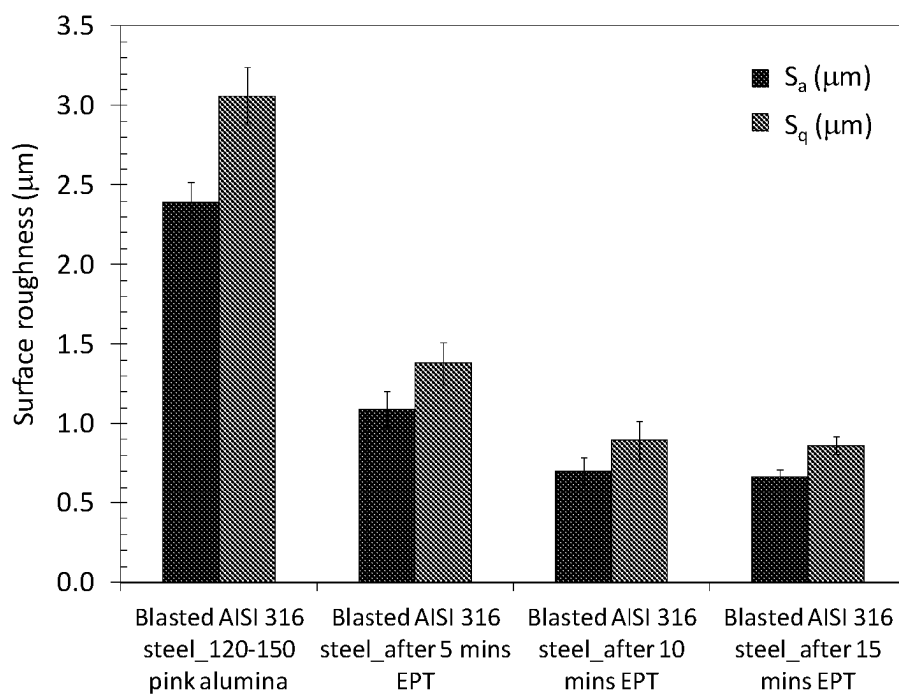
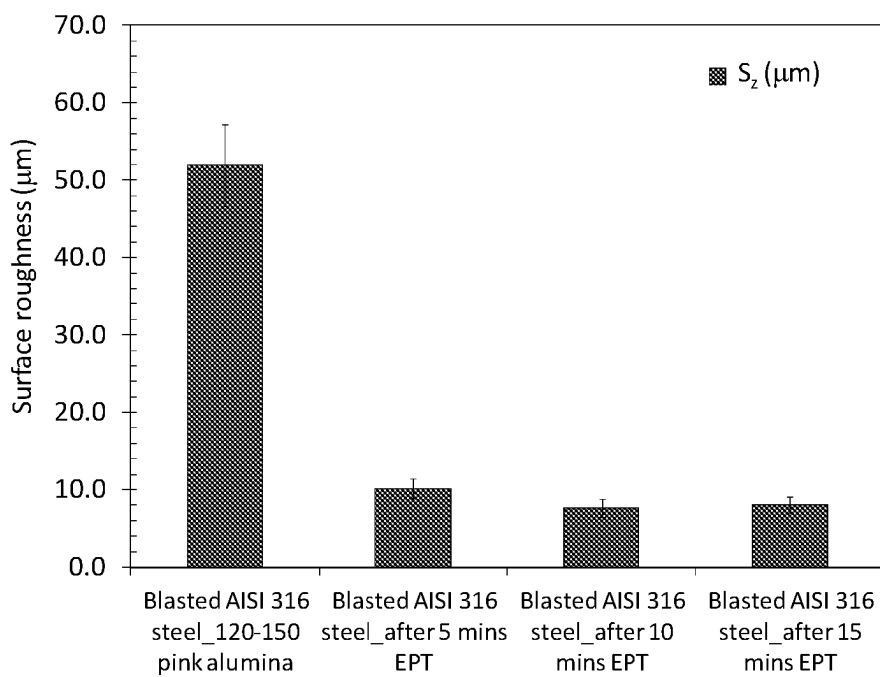


Fig. 1

**Fig. 2a****Fig. 2b**

**Fig. 3a****Fig. 3b**

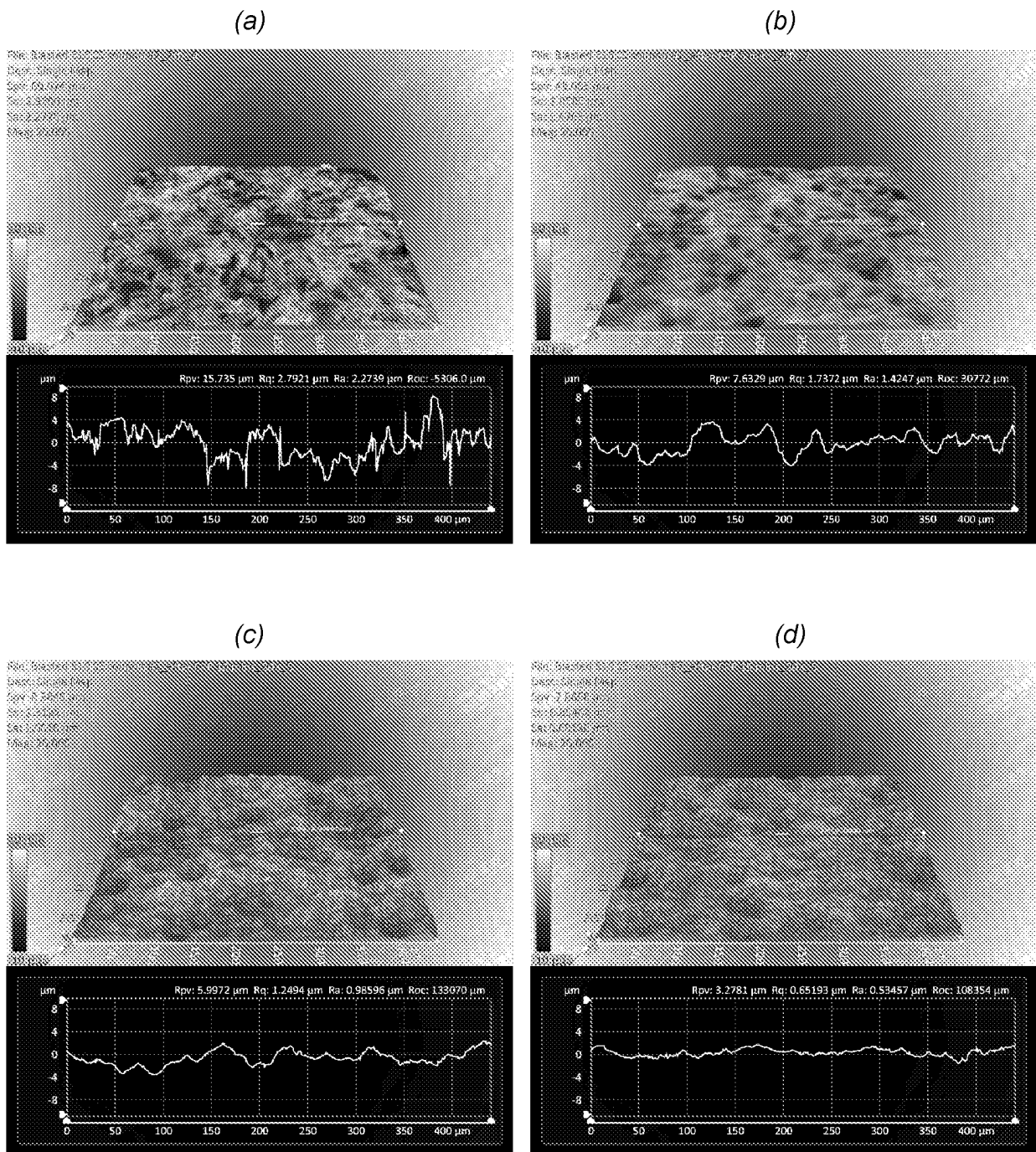


Fig. 4

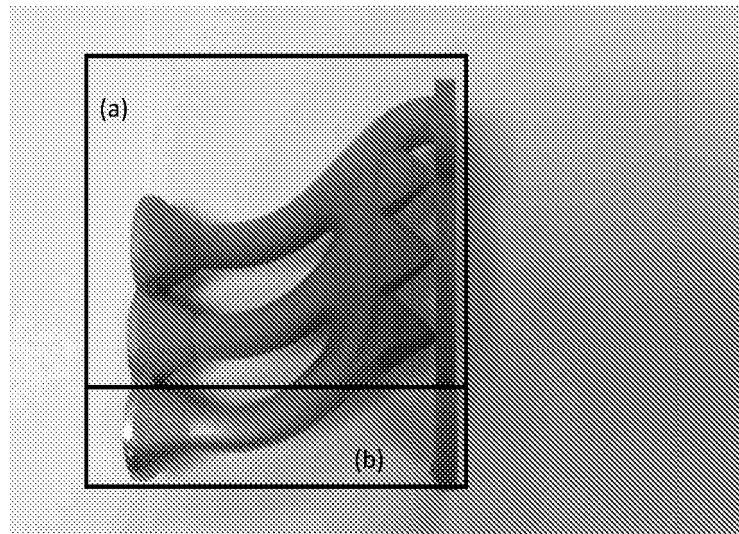


Fig. 5

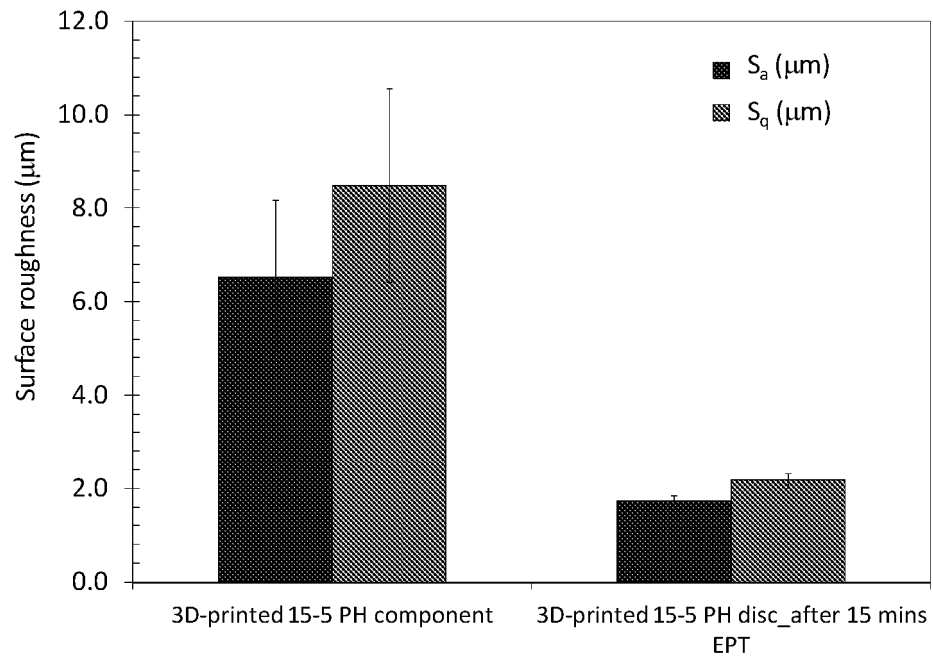


Fig. 6a

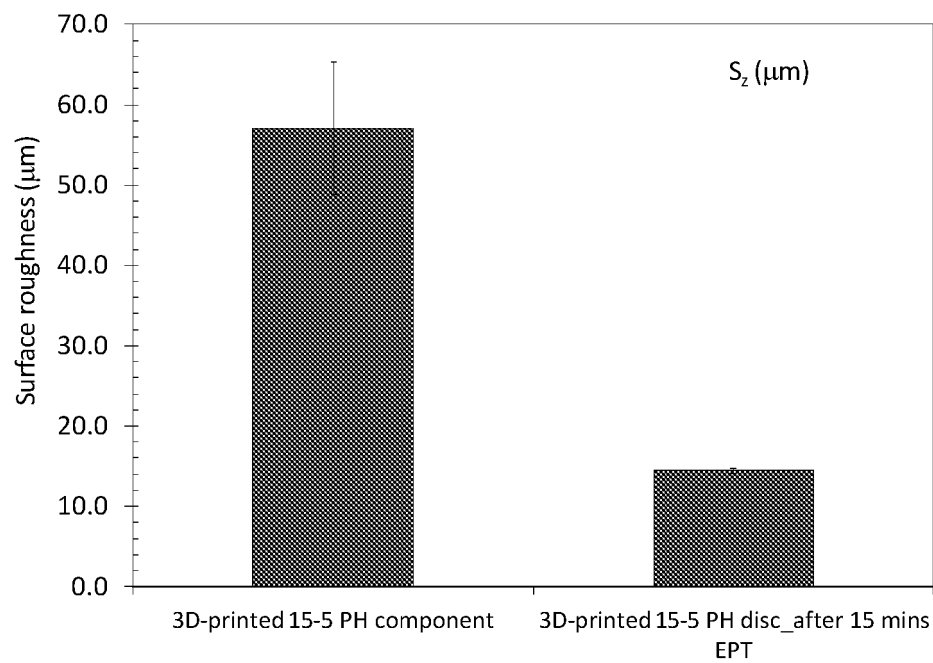


Fig. 6b

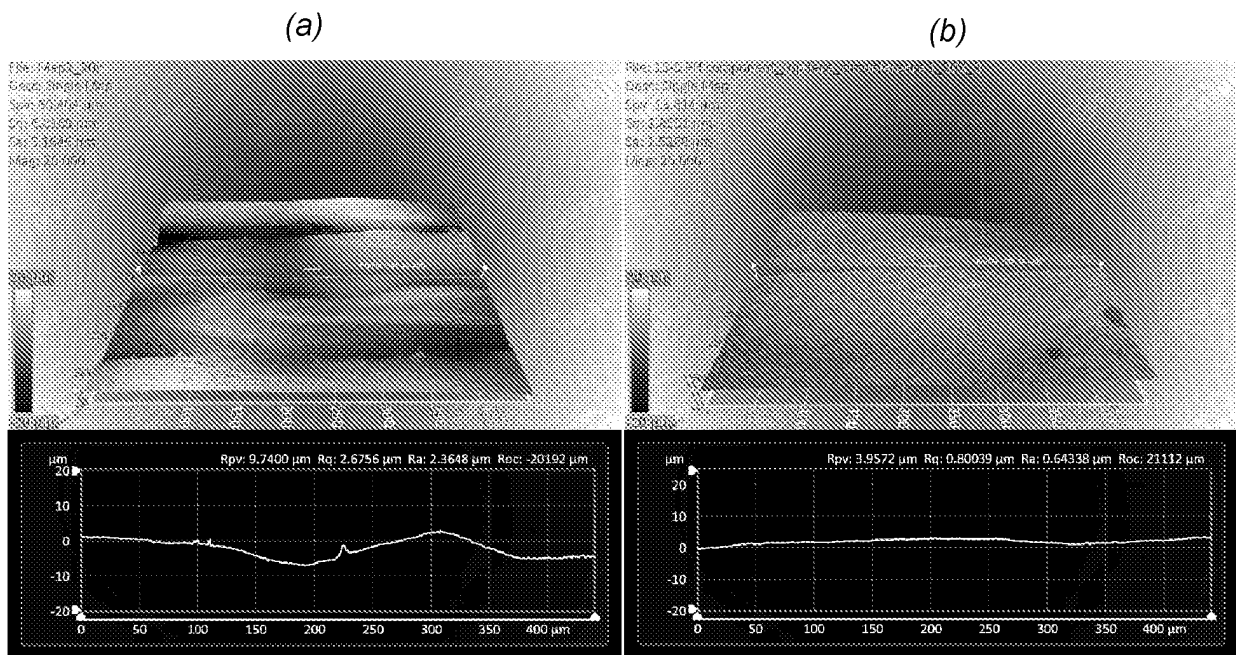


Fig. 7

REFERENCES CITED IN THE DESCRIPTION

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