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(21) International Application Number: PCT/GB95/02703 (22) International Filing Date: 20 November 1995 (20.11.95) (30) Priority Data: 9423277.4 18 November 1994 (18.11.94) GB (71) Applicant (for all designated States except US): THE UNIVERSITY OF NOTTINGHAM [GB/GB]; University Park, Nottingham NG7 2RD (GB). (72) Inventors; and (75) Inventors/Applicants (for US only): HOWDLE, Steven, Melvyn [GB/GB]; The University of Nottingham, University Park, Nottingham NG7 2RD (GB). ANTONOV, Eugene Nikolaevich [RU/RU]; The University of Nottingham, University Park, Nottingham NG7 2RD (GB). BAGRATASHVILI, Viktor Nikolaivich [RU/RU]; The University of Nottingham, University Park, Nottingham NG7 2RD (GB). POPOV, Vladimir Karpovich [RU/RU]; The University of Nottingham, University Park, Nottingham NG7 2RD (GB). SOBOL, Emil Naumovich [RU/RU]; The University of Nottingham, University Park, Nottingham NG7 2RD (GB).			(74) Agent: LOCK, Howard; Swindell & Pearson, 48 Friar Gate, Derby DE1 1GY (GB). (81) Designated States: AL, AM, AT, AU, BB, BG, BR, BY, CA, CH, CN, CZ, DE, DK, EE, ES, FI, GB, GE, HU, IS, JP, KE, KG, KP, KR, KZ, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, TJ, TM, TT, UA, UG, US, UZ, VN, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG), ARIPO patent (KE, LS, MW, SD, SZ, UG). Published <i>Without international search report and to be republished upon receipt of that report.</i>
(54) Title: LASER DEPOSITION OF COATINGS (57) Abstract A method of coating a substrate by laser deposition comprises a pre-deposition laser treatment of a surface of the substrate prior to coating. Coating may be carried out on plastics or polymeric materials below the softening temperature. The substrate may be a medical or dental implant, and the coating an apatite or hydroxyapatite. The composition, biocompatibility and stability to dissolution in fluids of the coating may be controlled by selection of at least one laser deposition characteristic.			

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Laser Deposition of Coatings

The present invention concerns the coating of substrates using laser deposition (laser sputtering) techniques, and relates in particular, although not exclusively, to deposition of biocompatible coatings, particularly of apatite-based (calcium phosphates) based materials.

Medical and dental implants and prostheses are normally formed from metals or alloys which can provide sufficient mechanical strength for the intended purpose. However, corrosion products from degradation of these materials may give rise to tissue irritation and inflammation. This problem is frequently overcome by giving the implant a biocompatible coating. The mineral basis of bone is calcium hydroxyapatite $[\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2]$, and this and other calcium phosphates are thus commonly used for this purpose. Techniques employed for the coating process include RF plasma spraying, electrophoretic deposition, sol-gel chemical methods and laser sputtering. There are, however, drawbacks associated with each of these methods, and in particular it has hitherto been difficult to achieve satisfactory adhesion of the coating to the substrate. Moreover, the coating process

normally requires the substrate to be maintained at a temperature of approximately 400 to 500°C in order to achieve adequate coating, but this precludes the use as the substrate of materials having relatively low melting points such as polymers and plastics.

The present invention seeks to mitigate or obviate these or other difficulties and to provide improved coating methods and coated substrates.

According to a first aspect of the invention there is provided a method of coating a substrate by laser deposition which method comprises a pre-deposition laser treatment of a surface of the substrate prior to coating.

Preferably, the laser is a pulsed laser.

The pre-deposition laser treatment may be carried out using the same laser as the deposition process. The treatment may be effected by scanning the substrate surface with the laser.

Preferably the pre-deposition laser treatment is carried out immediately prior to the coating process. Alternatively, the substrate may be retained between treatment and coating in an appropriate controlled

atmosphere.

Preferably the coating applied comprises an apatite or hydroxyapatite.

The laser deposition coating process may be carried out at a temperature less than 500°C, and in particular at ambient temperature.

The method may further comprise a step of heating the coated substrate to a temperature higher than that at which the coating process was carried out to change or modify the morphology of the coating.

The invention further provides a method of coating a metallic substrate according to any of the preceding paragraphs.

A second aspect of the invention provides a method of coating a substrate of a polymer or a plastics material by laser deposition, wherein the coating process is carried out at a temperature below the melting or softening temperature of the substrate.

Preferably, the laser is a pulsed laser.

The method may include a pre-deposition laser

treatment of a surface of the substrate prior to coating.

The laser treatment may be carried out using the same laser as the deposition process. The treatment may be achieved by scanning the substrate surface with the laser.

Preferably the laser treatment step is carried out immediately prior to the coating process. Alternatively, the substrate may be retained between treatment and coating in an appropriate controlled atmosphere.

Preferably the coating applied comprises an apatite or hydroxyapatite.

According to a third aspect of the invention there is provided a method of coating a substrate, the method comprising applying a first stage coating by a method according to the first or second aspect of the invention, and subsequently applying a second stage coating to increase the thickness of the coating layer.

The second stage coating may be applied by a second laser deposition step. The second laser deposition step may employ one or more deposition

parameters or characteristics different from the first.

Alternatively, the second stage coating may be applied by plasma spraying or any other suitable technique.

According to a fourth aspect of the invention there is provided a method of coating a substrate by laser deposition comprising controlling at least one laser deposition characteristic selected from the group comprising laser fluence, vacuum chamber atmosphere and vacuum gas pressure, whereby to control the composition and/or microparticle distribution of the laser deposited coating.

The laser fluence and/or chamber gas pressure may be selected to control the macroparticle size distribution.

The chamber gas pressure, chamber atmosphere, and/or the laser fluence may be selected to control the composition of the coating.

The laser fluence may be controlled within the range of 0.5 to 20 J/cm², preferably 0.5 to 11 J/cm².

The laser fluence may be controlled within the range of 2 to 15 J/cm², preferably at substantially 9 J/cm².

Alternatively, the laser fluence is controlled within the range of 0.7 to 11 J/cm², preferably within the range of 2 to 4 J/cm².

Alternatively, the laser fluence may be controlled within the range 0.5 to 10 J/cm², preferably it is controlled at substantially 5 J/cm².

The vacuum gas pressure may be controlled within the range of 0.001 to 100Pa, preferably within the range of 2 to 100Pa, more preferably it is controlled at substantially 4Pa.

The vacuum chamber atmosphere may comprise air. Carbon dioxide and/or water may be bled into the atmosphere. This would have the effect of altering the composition of the coating.

According to a fifth aspect of the invention there is provided, a method of coating a substrate by laser deposition comprising controlling at least one laser deposition characteristic selected from the group comprising laser fluence, vacuum chamber atmosphere and

vacuum gas pressure, whereby to control the stability to dissolution in fluids of the laser deposited coating.

The vacuum chamber gas pressure may be controlled within the range of 0.001 to 100Pa, preferably 2 to 100Pa, more preferably it is controlled at substantially 4Pa.

The stability to dissolution of a laser deposited apatite or hydroxyapatite coating in a body fluid or a simulated body fluid may be controlled by the method.

The laser fluence may be controlled within the range of 0.5 to 20 J/cm², preferably 0.5 to 11 J/cm².

The laser fluence may be controlled within the range 2 to 15 J/cm², preferably 9 J/cm².

Alternatively, the laser fluence may be controlled within the range of 0.7 to 11 J/cm² preferably within the range of 2 to 4 J/cm².

Alternatively, the laser fluence may be controlled within the range 0.5 to 10J/cm², preferably it is controlled at substantially 5 J/cm².

The vacuum chamber atmosphere may comprise air. Carbon dioxide and/or water may be bled into the atmosphere. This would have the effect of altering the composition of the coating.

According to a sixth aspect of the invention there is provided a substrate having a coating applied by a method as hereinbefore described. The coating may comprise an apatite or hydroxyapatite. The substrate may comprise a metal, an alloy, a polymer or a plastics material.

Preferably the coating (target) has an absorptivity sufficient to allow evaporation at accessible values of laser fluence.

According to a seventh aspect of the invention there is provided a medical or dental implant having a coating applied by a method according to the first, second or third aspect of the invention. The coating may comprise hydroxyapatite or an apatite.

Embodiments of invention will be further described for the purposes of illustration only with reference to the following examples and the accompanying drawings in which:-

Fig. 1 is a graph of film adhesion as a function

of fluence for various targets;

Fig. 2 represents FT-IR spectra of various films;

Fig. 3 shows size distribution of macroparticles relative to volume for hydroxyapatite coatings;

Fig. 4 shows average nearest neighbour distance between macroparticles in two different size ranges;

Fig. 5 shows average calcium/phosphorus ratio relative to pressure in deposition chamber; and

Fig. 6 shows average calcium/phosphorus ratio for hydroxyapatite coatings against distance from centre of ablation plume.

Example 1 and Comparative Example

Experimental

Samples of, respectively, hydroxyapatite (HA), natural apatite (NA) and bone tissue were used as targets for apatite film deposition by KrF-excimer laser, $\lambda = 248$ nm (EMG-203 Lambda Physik). The focussed UV laser beam was scanned periodically across the target in order to avoid the formation of deep craters in the target. The laser pulse repetition rate was 5 Hz pulse energy up to 300 mJ (controlled by attenuator) and laser pulse fluence on the target was $0.7-11 \text{ J/cm}^2$. The target to substrate distance was 3.5 cm and a Ti foil target (0.05 mm thickness) was used as substrate for

deposition (titanium is an important implant material). The film thickness was varied from ~ 0.1 to $\sim 2 \mu\text{m}$ and the deposition rate was in the range 0.02 to 5 $\text{\AA}/\text{pulse}$. Residual air pressure in the vacuum cell was maintained at $3 \cdot 10^{-2}$ Torr.

The deposited apatite films were examined by scanning electron microscopy (SEM), Fourier Transform infra-red spectroscopy (FT-IR) and Raman spectroscopy. The film adhesion was determined by a scratch test. The scratching was made by a corundum point with $57 \mu\text{m}$ radius. The adhesive force was determined by the maximum vertical load which could be applied to the point, without stripping the film from the substrate.

Results

The films deposited from HA (Comparative Example) and NA samples were mirror-like and scanning electron micrographs showed smooth surfaces with round shaped particles of $1-10 \mu\text{m}$ in size. Both the quantity and the size of particles was controlled by increasing the laser fluence. The films deposited from bone tissue were much more spongy and round shaped particles appeared only at the fluences more than $\sim 5 \text{ J}/\text{cm}^2$.

The adhesion of the films on Ti substrates against

fluence is shown in Fig. 1. With a substrate temperature of 400°C, both HA and NA films have excellent adhesion with a maximum fluence near 2-4 J/cm². Conversely, the adhesion of films obtained at room temperature from HA and bone was quite low. The most striking results were obtained with films prepared from NA at room temperature. In the fluence range 2-4 J/cm² those films have practically the same adhesion level as the films deposited at 400°C.

The films were investigated by FT-IR spectroscopy. The vibration bands of the phosphate ions (PO₄³⁻) of HA appear in the range 550-610 cm⁻¹ and 1000-1100 cm⁻¹ respectively. The film spectra, obtained from NA, and the initial spectra of HA and NA are given in Fig. 2.

Note the close similarities between the spectra of HA and NA. The FT-Raman spectra of HA and NA films are also almost identical at the same laser fluences and substrate temperatures. As the laser fluence is increased the maximum of the main absorption peak in the FT-IR spectra shifts to lower frequencies. A particularly striking feature of the spectra obtained at 400°C is the strong feature near 1110 cm⁻¹.

These data show that there is no direct correlation between the spectral features and the adhesion pro-

perties. However for different targets and substrate temperatures the chemical composition and physical state (i.e. amorphous/crystalline) may be investigated by spectral methods without destruction of the materials.

Example 2

The experiments of Example 1 were repeated with the addition of a laser precleaning step in which the deposition laser was first used to scan the surface of the substrate to be coated immediately prior to the deposition process. Results of initial scratch tests indicate significantly greater adhesion of coatings with inclusion of the precleaning step compared with the adhesion of coatings applied under identical conditions but excluding laser precleaning. Spectroscopic and microscopic investigation indicates that, other than the adhesion differences, the coatings are identical. The improved adhesion may be due to changes to interface properties induced by the laser precleaning.

Where the apatite coating process is preceded by a laser precleaning step and is carried out at relatively low temperatures, the apatite coating achieved is amorphous rather than crystalline. Its mechanical adhesion properties appear, however, better than those of crystalline coatings formed using conventional

techniques. If a crystalline coating is particularly required, a metal substrate initially coated at relatively low temperature may be subsequently heat-treated in order to cause the amorphous coating to be converted to crystalline.

It will be appreciated that modifications may be made within the scope of the invention, in particular regarding the techniques and conditions employed in the coating process, and the substrates and target materials which may be employed. If a laser precleaning step is employed, the substrate may be retained between cleaning and coating in a suitably controlled atmosphere, if coating is not to be carried out immediately.

The surface properties of the coating may be predetermined by selection of appropriate laser deposition characteristics such as laser fluence, vacuum chamber atmosphere and residual gas pressure in the chamber. The distribution of macroparticles, their sizes, and the overall chemical composition of the coating can be determined by these parameters. The biocompatibility of the coatings i.e. the way in which cells interact with the surface, is very closely dependent upon the macroparticle distribution and chemical composition. Fine control over the biocompatibility of the coatings produced is therefore

possible. The properties may be tuned for the particular application of an implant to be coated, for example cell interaction with an artificial heart valve should be discouraged to prevent blockage and failure, whereas strong cell interaction and growth is encouraged with a hip replacement. The stability to dissolution in fluids of the coatings may also be controlled by selection of deposition characteristics such as laser fluence and vacuum chamber residual gas pressure. At a relatively high and constant laser fluence value, raising the chamber residual gas pressure lowers the measured calcium/phosphorus ratio in hydroxyapatite to the stoichiometric ratio of $\text{Ca/P}=1.67$ and increases the erosion resistance of the coating. At higher laser fluences the erosion resistance is increased.

Example 3

Apatite films were deposited on substrates at ambient temperature in an evacuable chamber with residual pressure (P_r) controlled from 2 to 100 Pa. Laser deposition was achieved with a KrF laser operated at a pulse duration of 20 ns and pulse repetition rate of 10 Hz. The laser fluence (F) was varied from 0.5 to 10 J/cm^2 and the substrate was fixed at a distance of 2 cm from the target. Substrate materials were commercial Ti foil ($300 \mu\text{m}$ thickness) and Ti-Al-V alloy.

Hydroxyapatite (HA) and dense crystalline natural apatite (NA) were used as targets. The laser deposited films, typically 0.2 to 1.2 μm in thickness, were examined by SEM and EDAX analysis. From the SEM micrographs, all macroparticles measuring more than 0.2 μm in diameter were counted in order to calculate average distances between the macroparticles (MP) and to obtain the distribution of the MP by volume. EDAX analysis allows measurement of the local stoichiometry and thus the Ca/P ratio of the smooth surface, the MP, and an average across an area of the film.

It was observed that (1) MP are different in shape, size, and Ca/P ratio. A number of MP of irregular shape were observed for low laser fluences ($F \sim 1 \text{ J/cm}^2$). For higher fluences ($F > 2.5 \text{ J/cm}^2$), almost all MP have regular spherical shapes. For $F \sim 5 \text{ J/cm}^2$, many MP have a characteristic tablet shape, with a depression in the center. (2) The number of large MP (ie $5 \mu\text{m}$ diameter), their combination volume, and their spatial distribution relative to the center of the ablation plume, depends on the laser fluence and the apatite target. The MP distribution was analysed by calculating the volume occupied by MP of one particular size range (Figure 3). The maximum volume observed in each case is determined by the deposition conditions. As F increases, this maximum moves to the

larger MP sizes (Fig. 3), and the average distance between the largest sized MP is seen to decrease (Fig. 4). The distribution of smaller particles does not appear to depend on laser fluence. (3) The Ca/P ratio is strongly dependent upon gas pressure in the chamber (Fig. 5), the laser fluence, and upon the area of deposition relative to the center of the ablation plume (Fig. 6). For small P_r and F values, films are rich with Ca near the center of the plume. As the distance (R) from the center of deposition region increases, the Ca/P ratio decreases. For high F , the Ca/P ratio increases with R . It was established that there is a certain value of fluence, which depends on the pressure, and results in a uniform distribution of Ca and P regardless of R . (4) The Ca/P ratio is close to 1.7 (the composition in bulk HA) for almost all MP. Some MP obtained from the NA targets have Ca/P ratio of 1.4 which corresponds to the ratio expected for $\text{Ca}_3(\text{PO}_4)_2$. Accurate measurement of the Ca/P ratio of very small particles (diameter $0.5\mu\text{m}$) is precluded because of the limited resolution of EDAX detection in the experiments. The Ca/P ratio is usually greater than 1.7 in the smooth film.

The method of the invention may be used to apply a first-stage coating to a substrate, the thickness of the coating subsequently being increased in a second-stage

process, which may use plasma spraying or another suitable technique. Alternatively, the second stage may be a further pulsed laser deposition, which may use different deposition and laser parameters from the first.

It is noted that whilst the invention is described herein with particular reference to the application of biocompatible coatings to medical and dental implants, its scope is not limited in this respect. Moreover, the invention may be applied to organic and metallic as well as to inorganic coatings. The ability to deposit such coatings on polymers or plastics at ambient temperatures may find use in the production of filters (for example for blood products) or of polymeric materials with novel electrical or optical properties.

Whilst endeavouring in the foregoing specification to draw attention to those features of the invention believed to be of particular importance it should be understood that the Applicant claims protection in respect of any patentable feature or combination of features hereinbefore referred to and/or shown in the drawings whether or not particular emphasis has been placed thereon.

Claims:-

1. A method of coating a substrate by laser deposition which method comprises a pre-deposition laser treatment of a surface of the substrate prior to coating.
2. A method according to Claim 1, in which the pre-deposition laser treatment is carried out using the same laser as the deposition process.
3. A method according to Claim 1 or Claim 2, in which the treatment is effected by scanning the substrate surface with the laser.
4. A method according to any of the preceding Claims, in which the pre-deposition laser treatment is carried out immediately prior to the coating process.
5. A method according to any of Claims 1 to 3, in which the substrate is retained between treatment and coating in an appropriate controlled atmosphere.
6. A method according to any of the preceding Claims, in which the coating applied comprises an apatite or hydroxyapatite.

7. A method according to any of the preceding Claims, in which the laser deposition process is carried out at a temperature less than 500°.
8. A method according to Claim 7, in which the laser deposition process is carried out at ambient temperature.
9. A method according to any of the preceding Claims and comprising a step of heating the coated substrate to a temperature higher than that at which the coating process was carried out to change or modify the morphology of the coating.
10. A method according to any of the preceding Claims in which the substrate is metallic.
11. A method of coating a substrate of a polymer or a plastics material by laser deposition, wherein the coating process is carried out at a temperature below the melting or softening temperature of the substrate.
12. A method according to Claim 11 and including a pre-deposition laser treatment of a surface of the substrate prior to coating.
13. A method according to Claim 12, in which the laser

treatment is carried out using the same laser as the deposition process.

14. A method according to Claim 12 or Claim 13, in which the treatment is achieved by scanning the substrate surface with the laser.

15. A method according to any of Claims 12 to 14, in which the pre-deposition laser treatment step is carried out immediately prior to the coating process.

16. A method according to any of Claims 12 to 14, in which the substrate is retained between treatment and coating in an appropriate controlled atmosphere.

17. A method according to any of Claims 11 to 16, in which the coating applied comprises an apatite or hydroxyapatite.

18. A method according to any of Claims 1 to 10 wherein the substrate is a polymer or a plastics material and the coating process is carried out at a temperature below the melting or softening temperature of the substrate.

19. A method of coating a substrate, the method comprising applying a first stage coating by a method

according to any of the preceding Claims, and subsequently applying a second stage coating to increase the thickness of the coating layer.

20. A method according to Claim 19, in which the second stage coating is applied by a second laser deposition step.

21. A method according to Claim 20, in which the second deposition step uses one or more deposition or laser parameters different from the first.

22. A method according to Claim 19, in which the second stage coating is applied by plasma spraying.

23. A method of coating a substrate by laser deposition comprising controlling at least one laser deposition characteristic selected from the group comprising laser fluence, vacuum chamber atmosphere and vacuum gas pressure, whereby to control the composition and/or microparticle distribution of the laser deposited coating.

24. A method according to Claim 23, in which the laser fluence and/or chamber gas pressure is selected to control the macroparticle size distribution.

25. A method according to Claim 24, in which the chamber gas pressure, chamber atmosphere, and/or the laser fluence are selected to control the composition of the coating.

26. A method of coating a substrate by laser deposition comprising controlling at least one laser deposition characteristic selected from the group comprising laser fluence, vacuum chamber atmosphere and vacuum gas pressure, whereby to control the stability to dissolution in fluids of the laser deposited coating.

27. A method according to Claim 26 for controlling the stability to dissolution of a laser deposited apatite or hydroxyapatite coating in a body fluid or a simulated body fluid.

28. A method according to any of Claims 23 to 27 wherein the laser fluence is maintained within the range of 0.5 to 20 J/cm².

29. A method according to Claim 28 wherein the laser fluence is maintained within the range of 0.7 to 11 J/cm².

30. A method according to Claim 29 wherein the laser fluence is maintained within the range of 2 to 4

J/cm².

31. A method according to any of Claims 23 to 28 wherein the laser fluence is maintained within the range 0.5 to 10 J/cm².

32. A method according to Claim 30 wherein the laser fluence is maintained at substantially 5 J/cm².

33. A method according to any of Claims 23 to 28 wherein the laser fluence is maintained within the range of 2 to 15 J/cm².

34. A method according to Claim 33 wherein the laser fluence is maintained at substantially 9 J/cm².

35. A method according to any of Claims 23 to 34 wherein the vacuum gas pressure is maintained within the range of 0.001 to 100Pa.

36. A method according to Claim 35 wherein the vacuum gas pressure is maintained within the range of 2 to 100Pa.

37. A method according to Claim 35 or 36 wherein the vacuum gas pressure is maintained at substantially 4Pa.

38. A method according to any of Claims 23 to 37 wherein the vacuum chamber atmosphere is air.

39. A method according to Claim 38 wherein carbon dioxide and/or water can be bled into the atmosphere.

40. A method according to any of Claims 23 to 39 including the pre-deposition laser treatment step according to any of Claims 1 to 11.

41. A substrate having a coating applied by a method according to any of the preceding Claims.

42. A substrate according to Claim 41, in which the coating comprises an apatite or a hydroxyapatite.

43. A substrate according to Claim 41 or Claim 42 in which the substrate comprises a metal, an alloy, a polymer or a plastics material.

44. A substrate according to any of Claims 41 to 43 in which the substrate is titanium.

45. A medical or dental implant comprising a substrate to which a coating has been applied by a method according to any of Claims 1 to 39.

46. An implant according to Claim 45, in which the coating comprises an apatite or a hydroxyapatite.

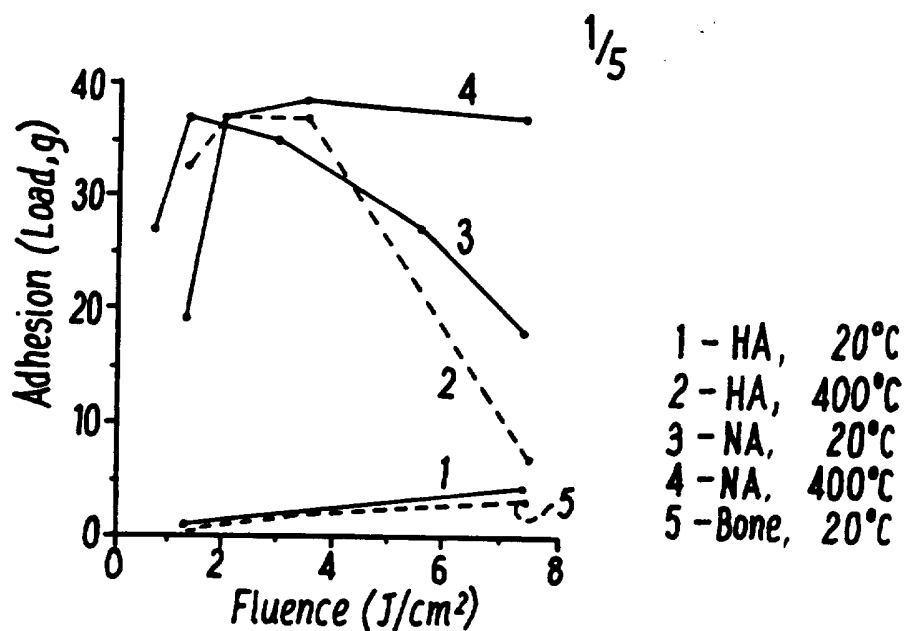
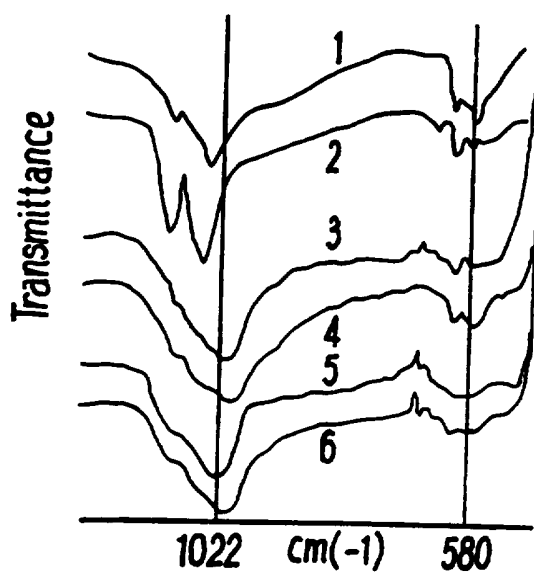
47. An implant according to Claim 45 or 46 in which the substrate comprises a metal, an alloy, a polymer or a plastics material.

48. An implant according to any of Claims 45, 46 and 47 in which the substrate is titanium.

49. A method of coating a substrate substantially as hereinbefore described with reference to any one of the Examples.

50. A coated substrate substantially as hereinbefore described with reference to any one of the Examples.

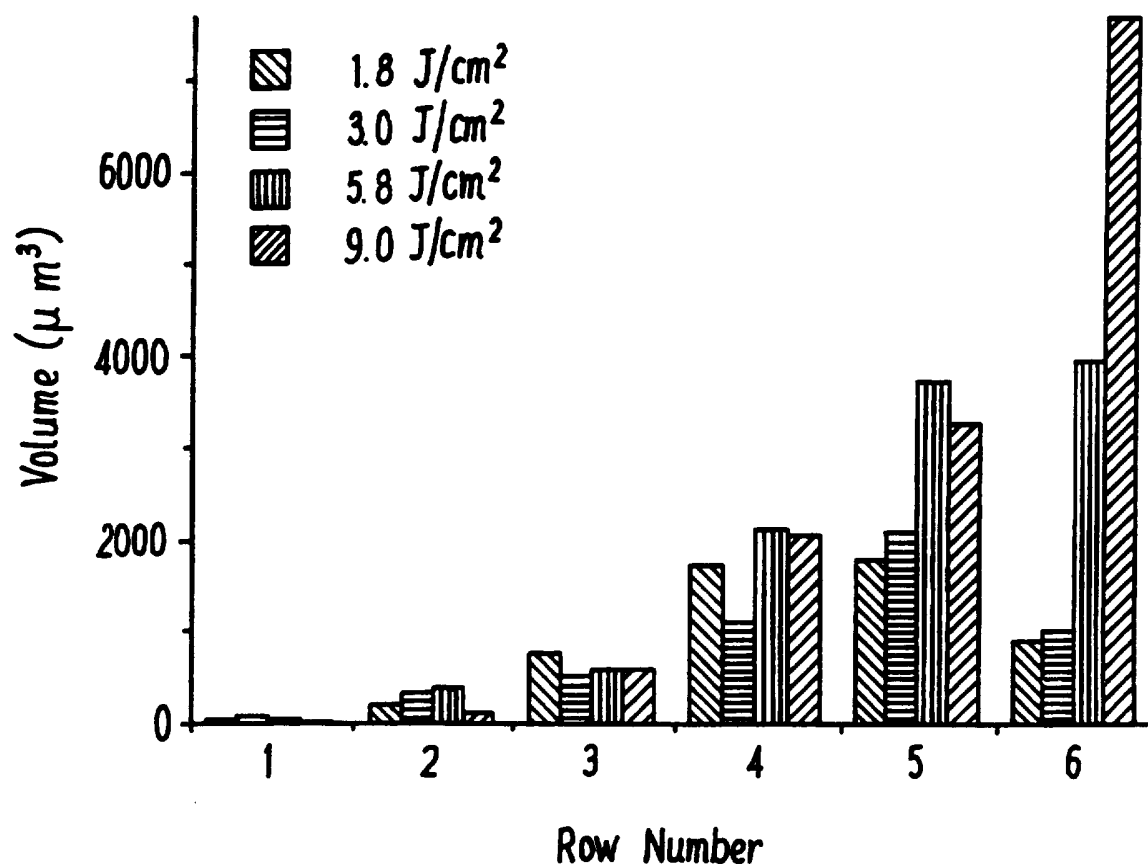
51. Any novel subject matter or combination including novel subject matter herein disclosed, whether or not within the scope of or relating to the same invention as any of the preceding claims.

**FIG. 1**

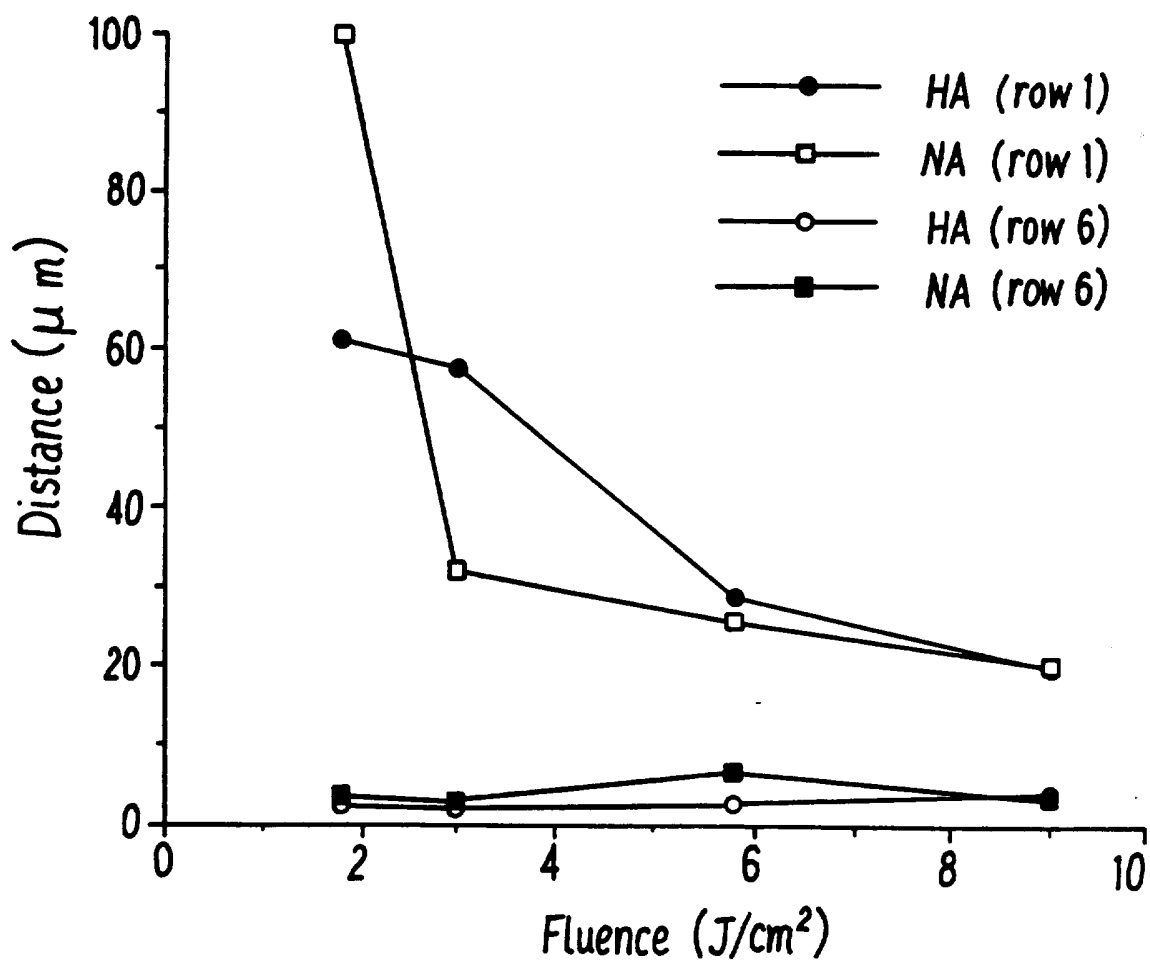
FT-IR spectra of NA - (1),
 HA - (2) and NA films: at 20°C
 2 J/cm^2 - (3), 7.3 J/cm^2 - (4);
 at 400°C, 2 J/cm^2 - (5)
 7.3 J/cm^2 - (6)

FIG. 2

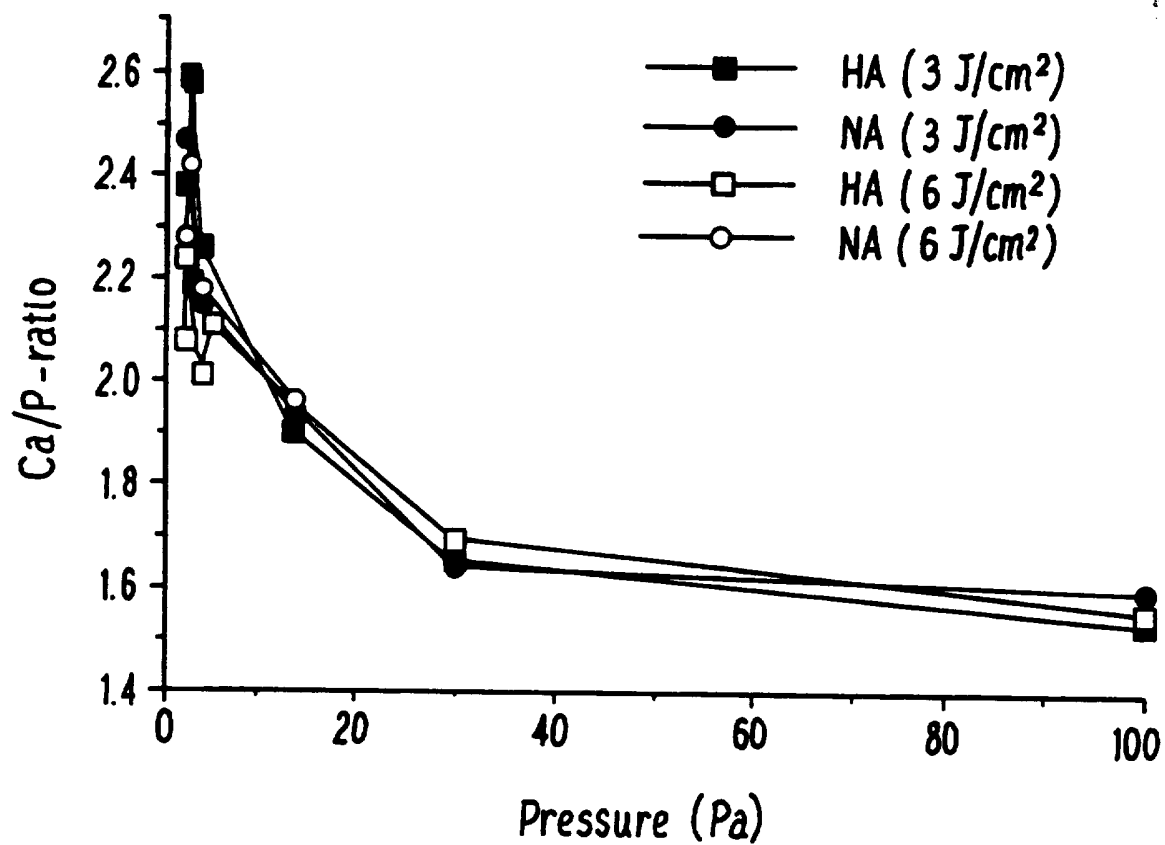
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**FIG. 3**

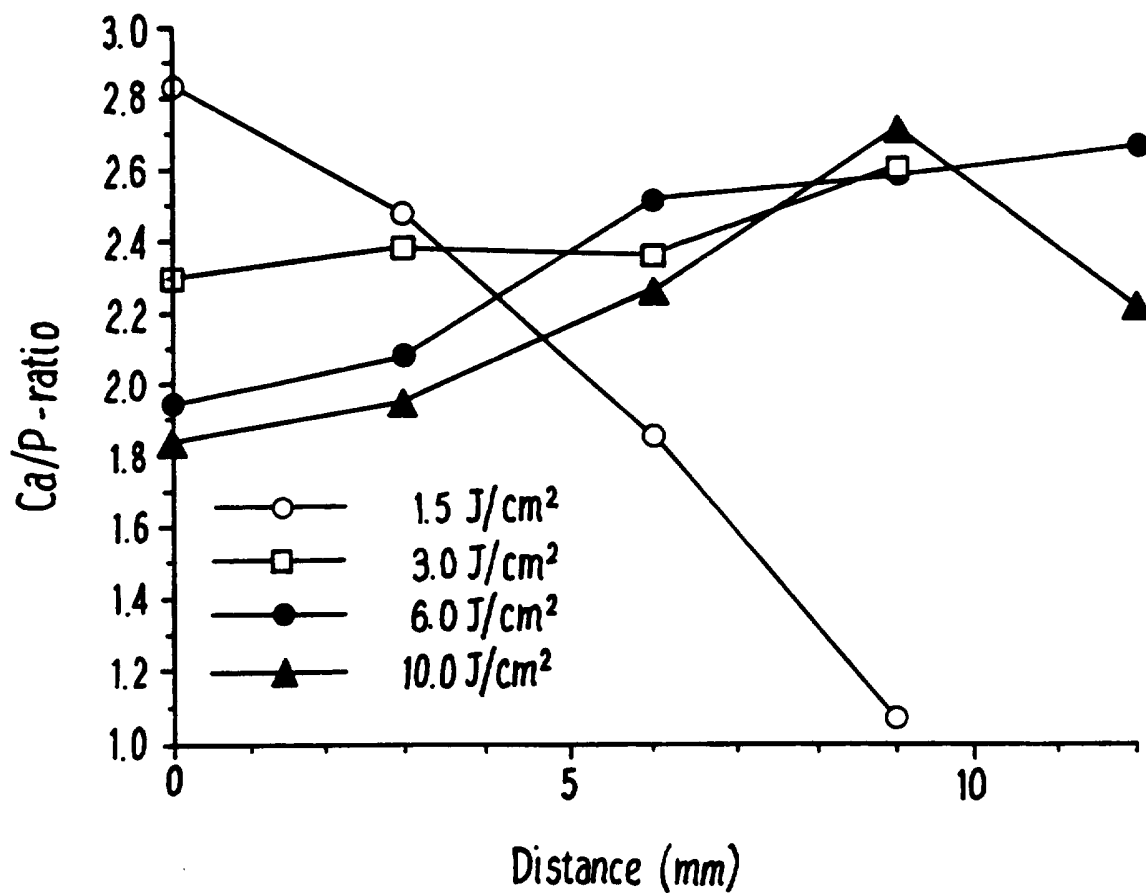
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**FIG. 4**

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**FIG. 5**

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**Fig. 6**