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LASER COATING REMOVAL

STATEMENT OF GOVERNMENT INTEREST

[0001] The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

CROSS REFERENCE TO OTHER PATENT APPLICATIONS

[0002] None.

BACKGROUND OF THE INVENTION

(1) Field of the Invention

[0003] The present invention relates to coating removal and more particularly to a method for removing paint or other coatings from a substrate using a laser and without damaging the substrate.

(2) Description of the Prior Art

[0004] Paints and other types of protective coatings, which provide immunity to corrosion, insulation and other uses, are designed to adhere to the substrate to which the coatings are applied and to resist removal. Generally, however, coatings need to be removed and replaced over time as part of regular maintenance and corrosion prevention or inhibition.

[0005] Paint removal can be accomplished by impinging the surface to be stripped with particles such as plastic media, steel shot, sand and even liquids. In aluminum aircraft, paint removal can be accomplished using frozen CO_2 pellets, without much concern about damaging the underlying substrate. However, in composite aircraft, firing dry ice pellets at the surface will remove the paint, but the collective impacts tend to damage the composite material.

[0006] Likewise, lasers can be used to remove coatings via ablation. However, control of the laser to ablate the coating, but not cut into the composite surface itself, has been difficult to achieve. The increasing use of composite materials for aircraft, as well as ship superstructures, and manned and unmanned vehicles, makes the need for a coating removal method that does not harm the substrate material ever more important.

SUMMARY OF THE INVENTION

[0007] Accordingly, it is an object of the present invention to provide a method for removing paint or other coatings from a substrate without damaging the substrate.

[0008] Another object of the present invention is to provide a precise way of controlling a laser for use in coating removal.

[0009] A further object of the present invention is to confine a heating effect of a laser to the coating layer without extending into the underlying substrate.

[0010] In accordance with these and other objects made apparent hereinafter, a system and method of using a laser for removing paint or other coatings from a substrate is provided. The frequency of the laser can be determined based on the properties of heat conduction with a periodically varying temperature as a boundary condition. Accordingly, the thermal penetration depth varies with the thermal diffusivity of the coating and the frequency of the temperature-based boundary condition. The heating effect of the laser is confined to the coating without extending into the underlying substrate. Thus, the system and method described herein provides a precise way of controlling a laser for use in coating removal.

[0011] In one embodiment, a method of removing a coating from a substrate includes determining a laser threshold intensity, wherein a small increase in intensity from a laser directed at the coating begins to remove a layer of the coating, and a small decrease in intensity results in no removal of the layer. The method also includes measuring a threshold temperature, T_1, of the coating when the laser is directed at the coating at the threshold intensity and determining a pulse frequency ω (the number of laser pulses per second) for the laser based on a chosen layer removal depth d and a diffusivity α of the coating, wherein $d \approx \sqrt{\alpha/\omega}$ such that a small increase in the threshold temperature, T_1, begins to remove a layer of the coating. Once the threshold temperature, T_1, is determined; the determination supports the determination of depth ***d***, the lower depth of which is defined by the threshold temperature. In other words, at the depth ***d***, the temperature is decreased enough so that no paint is removed and no damage occurs.

[0012] The method also includes determining an initial temperature, T_0, which higher than the threshold temperature, the pulse frequency and the diffusivity, wherein

$$T(x,t) = T_1 = T_0 e^{i\omega t - x\sqrt{i\omega / \alpha}}$$

. The method also includes the step of choosing an initial intensity for the laser to generate the initial temperature T_0; controlling the laser to operate at the pulse frequency and the initial intensity; and directing the controlled laser at the coating to remove the chosen depth of the layer.

[0013] Furthermore, determining the initial intensity includes measuring temperatures of the coating at varying intensities so as to obtain a relationship between the temperatures and the varying intensities. Additionally, choosing the initial intensity is based on the relationship between the temperatures and the varying intensities.

[0014] The method further includes choosing the layer removal depth to require a plurality of laser passes to remove the coating. The removal depth can progressively lessen with increasing passes. The laser can be deactivated between each pass such that the coating cools between passes. Alternately, the laser is moved from a previous location to a new location between each pass such that the coating at the previous location cools between passes.

[0015] In one embodiment, a system for removing a chosen layer depth, d, of a coating from a substrate includes a laser directed at the coating; a controller programmed to operate the laser; and processor readable medium disposed in the controller. The processor readable medium contains instructions for operating the laser at an initial intensity I_0 and pulse frequency ω so determined as to remove the layer depth without damage to the substrate.

[0016] The instructions further include instructions for obtaining a look-up table of laser intensities versus coating temperature and instructions for choosing a threshold temperature T_1 from the look-up table based on laser threshold intensity, wherein a small increase in the threshold intensity begins to remove a layer of the coating. Instructions include determining the pulse frequency based on a relationship wherein $d \approx \sqrt{\alpha/\omega}$ and α is a diffusivity of the coating. Also included are instructions for determining an initial temperature T_0 based on a relationship wherein $T(x,t) = T_1 = T_0 e^{i\omega t - x\sqrt{i\omega/\alpha}}$ and instructions for choosing the initial intensity from the look-up table based on the initial temperature.

[0017] Other objects, features and advantages of the present invention including various novel details of construction and combinations of parts, will now be more particularly described with reference to the accompanying drawings and pointed out in the claims. It will be understood that the particular assembly embodying the invention is shown by way of illustration only and not as a limitation of the invention. The principles and features of this invention may be employed in various and numerous embodiments without departing from the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] Reference is made to the accompanying drawings in which is shown an illustrative embodiment of the invention, from which its novel features and advantages will be apparent, wherein corresponding reference characters indicate corresponding parts throughout the several views of the drawings and wherein:

[0019] **FIG. 1** is a schematic view of a laser coating removal system of the present invention; and

[0020] **FIG. 2** is a block diagram of a method for controlling a laser for coating removal.

DETAILED DESCRIPTION OF THE INVENTION

[0021] Referring now to the drawings, and more particularly to **FIG. 1**, there is shown a schematic illustration of laser coating removal system **10**. Laser **12** is directed at object **14**, as indicated by laser beam **12a**. For illustration purposes, the object **14** is shown in cross-section. The object **14** consists of substrate **14a**, on which a coating **14b** has been applied at a thickness ***D***. A controller **16** controls the laser **12** so as to pulse beam **12a** at a frequency designed to ablate a predetermined thickness ***d*** of the coating layer **14b** (as indicated in phantom in **FIG. 1**) as the laser moves over the object **14** in the direction of arrow **18.**

[0022] To determine the pulse frequency for the laser beam **12a**; a consideration of the properties of heat conduction with a periodically varying temperature, ***T***, as a boundary condition can be utilized. A periodic temperature boundary condition applied to a semi-infinite medium will lead to a temperature distribution governed by:

[0023] $$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2},$$ **[1]**

[0024] where ***α*** is the thermal diffusivity of the material.

[0025] If ***T*** has a harmonic time dependence, then the solution takes the following form:

[0026] $$T(x,t) = T_0 e^{i\omega t - x\sqrt{i\omega/\alpha}},$$ **[2]**

[0027] where ***ω=2πf*** is the angular frequency of the temperature-based boundary condition. It can be observed that the temperature decays rapidly with increasing depth. The thermal penetration distance, ***d***, can be approximated by $\sqrt{\alpha/\omega}$.

[0028] The above analysis also leads to a constant temperature term, $T_0/2$, which would penetrate through the entire medium. However, the constant term is an artifact arising from the assumption of harmonic time dependence (i.e., the assumption that the laser pulses have been heating the surface for an infinite amount of time).

[0029] In practice, the amount of time for the "constant" term to penetrate to a given depth can be estimated by solving a heat conduction problem via separation of variables. For example, consider a semi-infinite medium at zero temperature at time $t = 0$, after which a constant heat source is applied to the surface. (The medium in this model would have the same thermal diffusivity as the coating being removed.)

[0030] The solution for transient heat conduction for $t > 0$ would estimate the time required before the temperature below the thermal penetration distance will exceed a threshold temperature, based on the laser intensity, the pulse frequency, and thermal diffusivity.

[0031] Any unacceptable heating at depths below the paint layer due to the “constant” term can be avoided by moving the laser so that the laser only sends a limited number of pulses at a time at any one location, limiting the amount of time that any one location is heated in accordance with the solution above. The laser would move to remove the paint to another location, before returning back to the original location to remove any remaining paint or coating.

[0032] Alternatively, the laser can be periodically shut off to allow the substrate to cool before resuming the paint removal at the original location. The latter approach would increase the time for paint removal on an object but the approach would also minimize the uncertainty about damaging the substrate. It would also have less complexity, since the laser would not have to move from a location until the paint is completely removed from the location.

[0033] Referring now to **FIG. 2**, there is shown a block diagram of a method **100** for laser coating removal. The method **100** begins at block **102**, where threshold intensity, I_1, for the laser **12** is determined experimentally by adjusting the laser intensity to the point where a small increase in intensity will just begin to remove a layer of coating **14b**, and a small decrease in intensity will result in no layer at all being removed.

[0034] During the process of adjusting the laser intensity, surface temperatures of the coating **14b** are measured for a range of laser intensities (block **104**), so as to obtain a temperature/intensity relationship. The relationship can be in the form of a look-up table or curve plot, such that the laser intensity can be obtained for a given temperature, or vice versa. The surface temperature of the coating **14b** under the influence of threshold intensity I_1 is considered the threshold temperature, T_1.

[0035] At block **106**, a determination is made as to the depth, ***d***, of the coating **14b** to be removed in one pass of the beam **12a** over the coating **14b**. Generally, multiple passes are made such that the removal process is better controlled and the substrate **14a** is not damaged. Based on the chosen depth, the angular frequency of the temperature-based boundary condition, ω, or laser pulse frequency, is determined from $d \approx \sqrt{\alpha/\omega}$ at block **108**.

[0036] Using Equation **[2]**, with $T(x,t) = T_1$ and $x = d$, a value is obtained for T_0 (block **110**). Based on the temperature/intensity relationship obtained for varying intensities at block **104**, the laser intensity, I_0, corresponding to T_0 is chosen (block **112**). From the prior analysis, it is seen that T_0 will decay to T_1 at the selected depth, ***d***, with no damage below this depth.

[0037] By controlling the pulse frequency, ω, and intensity, I_0, of the laser **12** in accordance with the above; the controller **16** can assure that only the desired depth, ***d***, of the coating **14b** is removed (block **114**). Controller program product **16a** disposed on a processor readable medium **16b** (both shown in phantom in **FIG. 1**) can have instructions programmed thereon for prompting the controller **16** to operate the laser **12** in the above manner.

[0038] Thus, the system **10** and method **100** described herein provide a more precise way of controlling the laser **12** for use in removal of the coating **14b**. The heating effect of the laser **12** is confined to the coating **14b** without extending into the underlying substrate **14a**. The system **10** and method **100** are based on the properties of heat conduction with a periodically varying temperature as a boundary condition. This has the effect of inducing a thermal penetration depth, ***d***, that varies as $\sqrt{\alpha/\omega}$, where $\boldsymbol{\alpha}$ is the thermal diffusivity and $\boldsymbol{\omega}$ is the angular frequency of the temperature-based boundary condition.

[0039] This effect is applied to the laser heating of the coating **14b**. For coatings such as paints, the thermal diffusivity, $\boldsymbol{\alpha}$, is approximately $2\times10^{-7} m^2/s$, and the coating thickness varies from 10 microns to 70 microns. Based on the above analysis, limiting the laser influence to 1 micron can be done with a laser pulsed at 1-MHz frequency. If the pulse takes the form of a square wave; Fourier series decomposition shows that the 1-MHz frequency component is dominant - with a few important harmonics at higher frequencies. The higher-frequency harmonics will be confined to even shallower penetration depths.

[0040] Thus, a laser pulsed in this way will automatically confine any heating (and thus the resulting paint ablation) to the upper 1-micron depth without any damage to the underlying substrate. The laser can then remove another 1-micron thick layer, and will continue until the paint layer is removed. Alternatively, thicker layers can be removed at first, and then thinner layers can be removed to avoid disturbing the substrate when the remaining coating thickness is small.

[0041] The foregoing description of the preferred embodiments of the invention has been presented for purposes of illustration and description only. It is not intended to be exhaustive or to limit the invention to the precise form disclosed; and obviously many modifications and variations are possible in light of the above teaching.

[0042] It will be understood that many additional changes in the details, materials, steps and arrangement of parts, which have been herein described and illustrated in order to explain the nature of the invention, may be made by those skilled in the art within the principle and scope of the invention as expressed in the appended claims.

LASER COATING REMOVAL

ABSTRACT OF THE DISCLOSURE

A system and method of using a laser is provided for removing coatings from a substrate. The frequency of the laser pulses can be determined based on the properties of heat conduction with a periodically varying temperature as a boundary condition. Accordingly, a thermal penetration depth varies with the thermal diffusivity of the coating and the angular frequency of the temperature-based boundary condition. The heating effect of the laser is confined to the coating without extending into the underlying substrate. Thus, the system and method described herein provide a way of controlling a laser for the removal of a coating.

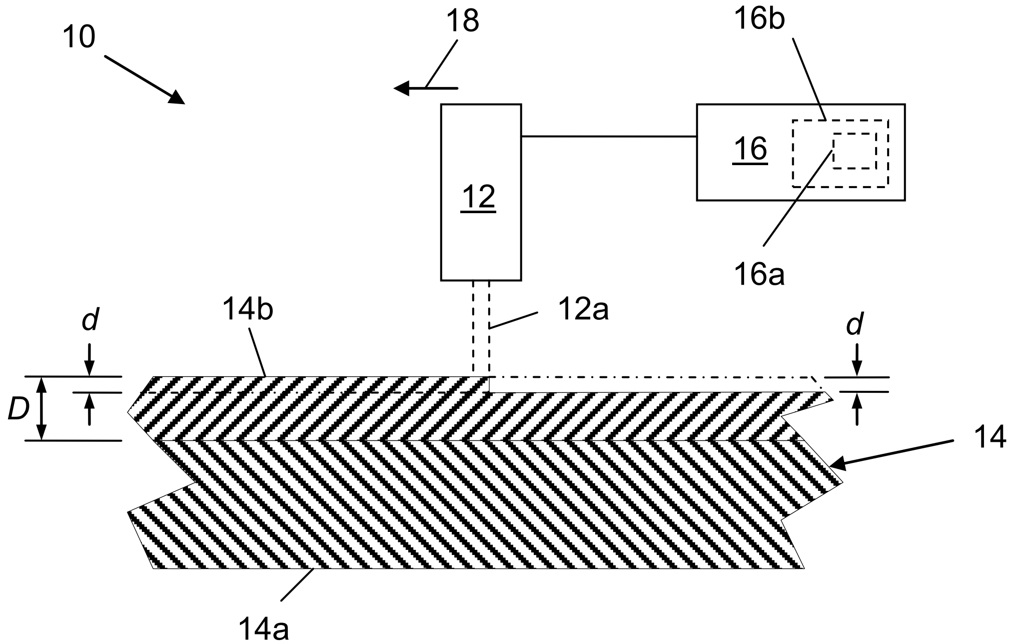
10
18
16b
16
12
16a
d
14b
12a
d
D
14
14a

FIG. 1

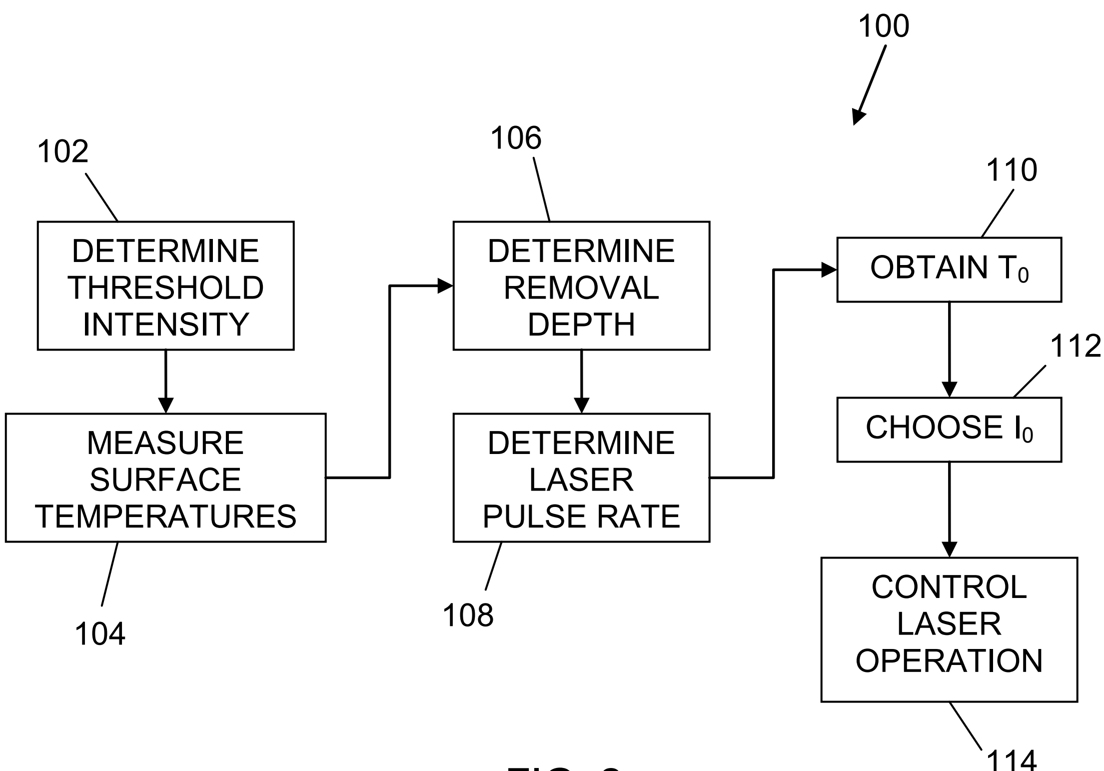
100
102
106
110
DETERMINE THRESHOLD INTENSITY
DETERMINE REMOVAL DEPTH
OBTAIN T_0
112
MEASURE SURFACE TEMPERATURES
DETERMINE LASER PULSE RATE
CHOOSE I_0
104
108
CONTROL LASER OPERATION
114

FIG. 2