A Laser Cleaning Apparatus and Method

Field

The present invention relates to a laser cleaning apparatus and method.

Background

The combination of seawater and steel marine vessels or offshore structures often results in severe corrosion problems and/or marine growth leading to reduction of hydrodynamic efficiency. To reduce the problem, shipbuilders typically apply preventative and/or protective coatings to the steel plates. However, application of such coatings is expensive and frequent recoating is often required for commercial vessels. In order to maximise the lifetime of the coatings, various factors such as paint quality and preparation and cleaning of the steel plates before coating application need to be considered.

One such cleaning method is abrasive blasting, which is frequently used to remove marine growth and existing coatings. A stream of abrasive materials is forcibly projected against the steel plates to remove the coatings and/or growth on the steel plates and/or roughen the surface to provide an anchoring profile for paint coatings. Over the years, abrasive blasting has been established as the industry standard for cleaning raw materials used to build new ships, as well as for removing contaminants and deteriorated paint for repairing ships. However, due to the presence of toxic dusts and high noise levels produced by abrasive blasting, the resulting severe environmental hazards posed serious health concerns for the operators as well as the residents staying in the vicinity of those blasting spots. Further, maintenance of blasting equipments, safety control, treatment of blasting waste, and the raw abrasives results in a significant cost.

Summary

According to a first aspect of the invention, there is provided a method for ablating material from a steel surface of a marine structure. The method may comprise selecting parameters including the wavelength, line density, frequency, power, peak power density, scanning speed, area, pulse energy, distance, surface temperature, scanning time and/or scanning pattern according to a

desired surface roughness, surface reflection and/or depth of the material to ablate, and directing pulsed coherent light onto an area of the steel surface coated with the material according to the selected parameters.

Using the method may avoid environmental hazards arising from usage of conventional cleaning techniques such as chemical cleaning and abrasive blasting. Blasting chambers may not be required and the method may be performed in situ. As a result, cost savings may be achieved. Moreover, the quality of the cleaning may provide an improvement on the lifetime of applied marine coatings.

Preferably, the method may further comprises varying the distance of the light to the surface, and generating a sound selected to be within a range of approximately 90% from a peak sound level when the distance is within a focal zone. In addition, the method may comprise performing spot ablation.

Preferably, the desired surface roughness may be selected to be between 10 μm to 25 μm, and the desired surface reflection may be selected to be a normalised value of between 0.5 units to 1.0 units. Further, the desired depth of the material to ablate may preferably be selected to be less than or equal to 5 μm, whereas the wavelength may be selected to be between 1055 nm to 1075 nm.

Yet preferably, the line density may be selected to be between 50% to 75% of the line width of the pulsed coherent light, while the frequency may be selected to be between 16 KHz to 100 KHz. The power may be selected to be between 400 Watts to 2000 Watts. The peak power density may be selected to be between 0.3 MW/cm^2 and 100 MW/cm^2, and the scanning speed may be selected to be between 10 m/s to 15 m/s. The pulse energy may be selected to be between 20 mJ to 200 mJ. Furthermore, the distance may be selected to be equal to or less than 22 cm from the steel surface.

More preferably, the surface temperature of the area may be selected to be heated to between 60 °C to 90 °C during ablation when the scanning time may be selected to be between 20 seconds to 60 seconds for attaining a surface cleanliness of at least Swedish Standard SA2.5 or equivalent.

Additionally, the scanning pattern may be selected to be at least one of, relative to the shape of the area, horizontally moving the light across the area, vertically moving the light across the area, forward-diagonally moving the light across the area, and backward-diagonally moving the light across the area.

Moreover, the method may further comprise subdividing the steel surface into a set of processing areas, each area being sequentially indexed and includes the material to ablate, and sequentially ablating the material from a first area of the set, and subsequent areas of the set based on the determined sequential index.

Yet more preferably, the method may further comprise performing selective layer ablation, wherein the material includes an upper layer and a bottom layer having different material properties, and the peak power density may be selected to have a value higher than the ablation threshold of the upper layer and lower than the ablation threshold of the bottom layer. Specifically, the upper layer may be a black paint layer and the bottom layer may be a red paint layer, and the peak power density may be selected to be between 1 MW/cm^2 and 5 MW/cm^2.

Preferably, the desired surface roughness may be selected according to the equation: $Y = A * x^2 + B * x + C$, where Y is the surface roughness, x is the line density, and A, B and C are predetermined constants.

Preferably, the desired surface reflection may be selected according to the equation: $Y = A * \exp(B * x) + C$, where Y is the surface reflection, x is the pulse energy, and A, B and C are predetermined constants.

Preferably, the desired surface reflection may be selected according to the equation: $Y = A + B * x$, where Y is the surface reflection, x is the power, and A, and B are predetermined constants.

Preferably, the desired depth of material to ablate may be selected according to the equation: $Y = A * \exp(-B * x) + C$, where Y is the ablation depth, x is the scanning speed, and A, B and C are predetermined constants.

According to a second aspect of the invention, there is provided a laser cleaning apparatus comprising a fibre laser source, a hand held device, and a plurality of acoustic sensors. The hand held device may be coupled to the fibre laser source, and may controllably emit pulsed coherent light. The plurality of acoustic sensors may be connected to the hand held device, and configured to determine a focus position for focusing the light onto a steel surface of a marine structure to ablate material on the steel surface.

Preferably, the emitted light may have a selected wavelength of between 1055 nm to 1075 nm, a selected frequency of between 16 and 100 KHz, and a selected power of between 400 Watts to 2000 Watts. In addition, the apparatus may further comprise a temperature sensor connected to the hand held device for measuring a temperature of the steel surface. Moreover, the apparatus may further comprise a debris suction device attached to the hand held device to actively receive the material ablated from the steel surface. In particular, the apparatus may further comprise a covering configured to facilitate the active receipt of the ablated material by the debris suction device, wherein the covering is attached to the hand held device at the face where the scale is attached.

Yet more preferably, the apparatus may further comprise an adjustable scale attached at a first end to the hand held device at a face where the light is emitted and configured with a roller at a second end, wherein the hand held device is guided by the roller for moving on the steel surface when ablation is performed.

The laser cleaning apparatus may allow laser treating the steel surfaces of vessels to become economically feasible. It may also improve the precision, selectivity and/or flexibility of cleaning steel surfaces of vessels over conventional techniques and/or a reduction in cost.

It should be apparent that features relating to one aspect of the invention may also be applicable to the other aspects of the invention.

These and other aspects of the invention will be apparent from and elucidated with reference to the embodiments described hereinafter.

The present invention also provides any one of the embodiments disclosed below and indicated with the numbers 1 to 31.

1. A method for ablating material from a steel surface of a marine structure, the method comprises:

selecting parameters including the wavelength, line density, frequency, power, peak power density, scanning speed, area, pulse energy, distance, surface temperature, scanning time and/or scanning pattern according to a desired surface roughness, surface reflection, surface cleanliness and/or depth of the material to ablate; and

directing pulsed coherent light onto an area of the steel surface coated with the material according to the selected parameters.

2. 2. The method of claim 1 further comprising

varying the distance of the light to the surface,

generating a sound selected to be within a range of approximately 90% from a peak sound level when the distance is within a focal zone.

3. The method of claim 1 or 2 further comprising performing spot ablation.

4. The method of any preceding claim, wherein the desired surface roughness is selected to be between 10 μm to 25 μm.

5. The method of any preceding claim, wherein the desired surface reflection is selected to be a normalised value of between 0.5 units to 1.0 units.

6. The method of any preceding claim, wherein the desired depth of the material to ablate is selected to be less than or equal to 5 μm.

7. The method of any preceding claim, wherein the wavelength is selected to be between 1055 nm to 1075 nm.

8. The method of any preceding claim, wherein the line density is selected to be between 50% to 75% of the line width of the pulsed coherent light.

9. The method of any preceding claim, wherein the frequency is selected to be between 16 KHz to 100 KHz.

10. The method of any preceding claim, wherein the power is selected to be between 400 Watts to 2000 Watts.

11. The method of any preceding claim, wherein the peak power density is selected to be between 0.3 MW/cm^2 and 100 MW/cm^2.

12. The method of any preceding claim, wherein the scanning speed is selected to be between 10 m/s to 15 m/s.

13. The method of any preceding claim, wherein the pulse energy is selected to be between 20 mJ to 200 mJ.

14. The method of any preceding claim, wherein the distance is selected to be equal to or less than 22 cm from the steel surface.

15. The method of any preceding claim, wherein the surface temperature is selected to be between 60 °C to 90 °C during ablation.

16. The method of any preceding claim, wherein the scanning time is selected to be between 20 seconds to 60 seconds.

17. The method in claim 16, wherein the surface cleanliness is selected to be in accordance with at least Swedish Standard SA2.5 or equivalent.

18. The method of any preceding claim, wherein the scanning pattern is selected to be at least one of, relative to the shape of the area, horizontally moving the light across the area, vertically moving the light across the area, forward-diagonally moving the light across the area, and backward-diagonally moving the light across the area.

19. The method of any preceding claim, further comprises:

subdividing the steel surface into a set of processing areas, each area being sequentially indexed and includes the material to ablate; and

sequentially ablating the material from a first area of the set, and subsequent areas of the set based on the determined sequential index.

20. The method of any preceding claim further comprising performing selective layer ablation,

wherein the material includes an upper layer and a bottom layer having different material properties, and the peak power density is selected to have a value higher than the ablation threshold of the upper layer and lower than the ablation threshold of the bottom layer.

21. The method of claim 20, wherein the upper layer is a black paint layer and the bottom layer is a red paint layer, and the peak power density is selected to be between 1 MW/cm^2 and 5 MW/cm^2.

22. The method of any preceding claim, wherein the desired surface roughness is selected according to the equation: $Y = A * x^2 + B * x + C$,

where Y is the surface roughness;

x is the line density; and

A, B and C are predetermined constants.

23. The method of any preceding claim, wherein the desired surface reflection is selected according to the equation: $Y = A * \exp(B * x) + C$,

where Y is the surface reflection;

x is the pulse energy; and

A, B and C are predetermined constants.

24. The method of any preceding claim, wherein the desired surface reflection is selected according to the equation: $Y = A + B * x$,

where Y is the surface reflection;

x is the power; and

A, and B are predetermined constants.

25. The method of any preceding claim, wherein the desired depth of material to ablate is selected according to the equation: $Y = A * \exp(-B * x) + C$,

where Y is the ablation depth;

x is the scanning speed; and

A, B and C are predetermined constants.

26. A laser cleaning apparatus comprising:

a fibre laser source;

a hand held device coupled to the fibre laser source, and to controllably emit pulsed coherent light; and

a plurality of acoustic sensors connected to the hand held device, and configured to determine a focus position for focusing the light onto a steel surface of a marine structure to ablate material on the steel surface.

27. The apparatus of claim 26, wherein the emitted light has a selected wavelength of between 1055 nm to 1075 nm, a selected frequency of between 16 and 100 KHz, and a selected power of between 400 Watts to 2000 Watts.

28. The apparatus of any of claims 26 to 27, further comprising a temperature sensor connected to the hand held device for measuring a temperature of the steel surface.

29. The apparatus of any of claims 26 to 28, further comprising a debris suction device attached to the hand held device to actively receive the material ablated from the steel surface.

30. The apparatus of any of claims 26 to 29, further comprising an adjustable scale attached at a first end to the hand held device at a face where the light is emitted and configured with a roller at a second end,

wherein the hand held device is guided by the roller for moving on the steel surface when ablation is performed.

31. The apparatus of claim 30 when dependent on claim 29, further comprising a covering configured to facilitate the active receipt of the ablated material by the debris suction device,

wherein the covering is attached to the hand held device at the face where the scale is attached.

Brief Description of the Drawings

Embodiments of the invention are disclosed hereinafter with reference to the accompanying drawings, in which:

Figure 1 is a schematic diagram of a laser cleaning apparatus according to an embodiment of the invention;

Figure 2 shows a side view of a hand held device of the laser cleaning apparatus of Figure 1, in which laser beams are emitted from the device;

Figure 3 is a flow diagram of a method for ablating material from a steel surface of a marine structure using the device of Figure 2;

Figure 4 is a line chart depicting the relationship between the scanning densities of the laser beams and the corresponding roughness of the ablated steel surface;

Figure 5 is a line chart depicting the relationship between the frequencies and corresponding pulse energies of the laser beams;

Figure 6 is a line chart depicting the relationship between the pulse energies of the laser beams and the (normalised) surface reflection of the ablated steel surface;

Figure 7 is a line chart depicting the relationship between the laser power of the laser beams and the (normalised) surface reflection of the ablated steel surface;

Figure 8 is a line chart depicting the relationship between a focus position of the device of Figure 1 for directing the emitted laser beams at the steel surface, and the corresponding detected sound volume at the position;

Figure 9 is a line chart depicting the change in steel surface temperature during and after exposure to the emitted laser beams, in which the observation was performed for different repetition passes;

Figure 10 is a line chart depicting the relationship between the scanning speed of the laser beams and the corresponding depth of material ablated from the steel surface;

Figure 11 is a line chart depicting the relationship between the scanning speed of the laser beams and the (normalised) surface reflection of the ablated steel surface;

Figure 12 is a line chart depicting the relationship between the scanning pattern for moving the laser beams across the steel surface, and the corresponding roughness of the steel surface after treatment;

Figure 13 illustrates spot ablation using the device of Figure 2, versus conventional abrasive blasting, according to the prior art;

Figure 14 is a flow diagram of a method for ablating a large area on the steel surface using the device of Figure 2;

Figure 15 illustrates is a methodology for processing a large area of the steel surface for incorporation into use by the method of Figure 14;

Figure 16 is a flow diagram of a method for performing selective layer ablation using the device of Figure 2; and

Figure 17 shows a side view of the device of Figure 2 configured as a stationary workstation setup.

Detailed Description

Figure 1 shows a laser cleaning apparatus 50 according to a first embodiment of the invention, which includes a high-power fibre laser source 52 being temperature regulated by a cooling unit 54, and a portable hand held device 100 (hereinafter device). Particularly, the laser cleaning apparatus 50 is configured for removing mill scale, surface layers such as rust, contaminants, existing coatings that are formed/found on surfaces of steel plates of a marine structure (e.g. a vessel) using laser ablation.

When in operation, laser beams are generated by the fibre laser source 52 and relayed to the device 100 via optical cables 56. The optical cables 56 may span a length of up to hundred metres to facilitate deployment of the device 100 at a convenient distance from the fibre laser source 52, which allows an operator to carry out laser treatment on the entire marine vessel or a desired portion. Further, the device 100 specifically comprises a fume suction component 58 and optical components 60 to facilitate emission of the received laser beams on a targeted surface 62. In addition, the fume suction component 58 and optical components 60 are electrically coupled to a controller 64, which also controls the cooling unit 54 and fibre laser source 52. Particularly, the controller 64 may be a programmable logic controller (PLC) or an industrial personal computer (PC), for storing the necessary laser generation parameters. The operator may then retrieve the preset settings (if required) from the controller 64 when operating the laser cleaning apparatus 50. Moreover, the controller 64 also controls the

laser beams to do processing in a rectangular-based manner, so that the emitted beams may be used for surface preparation and cleaning.

Figure 2 shows the portable hand held device 100 in greater detail. The device 100 may also be termed as a "hand-held wand", which is designed to be largely similar, in terms of device handling, to hand held devices used in conventional abrasive blasting.

The device 100 comprises a processing head 102 and a handle 104, which is removably attached to the processing head 102. The handle 104 provides an extended, ergonomically designed section to be held by the operator by both hands at 2 locations, allowing long hours of operation when using the device 100. The combined length of the handle 104 and the processing head 102, when attached together, may be around 650 mm for ease of handling. The processing head 102, at the end opposed to where the handle 104 is attached, includes a galvanometer (not shown) for guiding the laser beams to be emitted, an array of sensors 106 to determine the necessary processing parameters and a lens 108 for focusing the emitted laser beams (e.g. pulsed coherent light). The lens 108 acts to direct and focus the laser onto desired areas of the steel surface, and is also externally covered by a removable protection window, which is configured not to substantially alter the optical properties of the emitted laser beams.

An adjustable scale 112 is attached to the processing head 102 near the lens 108. The scale 112 includes a roller 114 at one end, and is extendable or retractable (manually or automatically) in length to achieve a required working distance for directing the laser beams from the device 100 to the steel surfaces, and to also act as a support, when the operator moves the device 100 on the steel surfaces during laser ablation. Under this arrangement, the roller 114 enables the device 100 to be smoothly moved across the steel surface.

The array of sensors 106, they include acoustic sensors and temperature sensors (e.g. infrared or thermometric sensors), which are respectively for detecting a distance between the lens 108 and steel surfaces, and for measuring a current temperature of the steel surfaces subsequent to heating by the laser

beams. A contamination sensor is also included in the array of sensors 106 to monitor for the amount of debris contamination coated on the protection window of the lens 108. A visual alert (e.g. a blinking light indicator) is provided to the operator (to clean the protection window) if the contamination reaches a sufficiently high level to hinder the ablating efficacy of the emitted laser beams.

A debris suction device, being part of the fume suction component 58, is installed within the processing head 102 to suck debris ablated (i.e. dust or contaminants) from the steel surfaces, so that air pollution around the vicinity where the laser ablation is carried out is minimised. A knife edge suction with a minimum power of 1kWatts, and an air suction flow of less than or equal to 390 m^3/h may be used. Further, the suction inlet of the debris suction device is formed substantially perpendicular to the targeted surface 62. Such an arrangement ensures almost all of the ablated debris can be sucked into the debris suction device. A suction hose (or tube) 116 is also removably connected to the debris suction device to transport the received debris to a central collection point, which may be integrated with the fibre laser source.

A protective hood 118 is attached to the processing head 102, enclosing the lens 108, and adjustable scale 112. The hood 118 has a sufficiently large front opening to allow the laser to be emitted and ensure that the ablated debris are sucked into the suction device. Further, the hood 118 may be formed of any light metal such as anodised aluminium and/or thin stainless steel.

For tidiness and ease of handling the device 100, the optical cables 110 and suction hose 116 are housed within a conduit in the controlling handle 104. The electrical cables (not shown) which carry signals and power to the electronic components in the processing head 102 are also housed in the controlling handle 104. The controlling handle 104 is further configured with a start button 120 and an emergency stop button 122, appropriately positioned on the top upper surface of the controlling handle 104 to enable them to be easily operated using the thumb. Both buttons 120, 122 are of the push-and-lock type button.

For safety considerations, if the emergency stop button 122 is locked in the stop position, the processing head 102 is prevented from being started even if the start button 120 is pressed.

Figure 3 illustrates a flow diagram of a method 200 for ablating material from an area of a steel surface. At 202, laser parameters are selected by the operator. Specifically, the group of parameters may include the line (scanning) density, frequency, laser power, scanning speed, scanning area, pulse energy, distance (to the steel surface), and/or scanning time. More details regarding each parameter are provided with reference to subsequent drawings. The selection is carried out based on a desired surface roughness, surface reflection and/or depth of the material to ablate.

At 204, the laser is generated (by the fibre laser source based on the parameters) and directed through the lens 108 onto the area of the steel surface that needs to be treated. The operator also uses the device 100 to guide him to position the device 100 at a focusing position (i.e. distance) relative to the steel surface, at where the laser beams are at their greatest efficacy. This position detection is performed by using the acoustic sensor included in the array of sensors 106 (i.e. acoustic detection). When the optimal focusing position is located, the adjustable scale 112 is extended or retracted accordingly based on a measured separating distance required between the lens 108 and the steel surface. More details regarding the locating of the focusing position will be later described with reference to Figure 8. At 206, the operator rests the device 100 against the steel surface, contacting through the roller 114, and then focuses the laser beams onto the area of the steel surface.

In 208, the operator slowly guides and moves the device 100, using a range of movements (i.e. scanning patterns), across the entire area so that all parts of the area (coated with the material) are thoroughly laser ablated. During this process, the surface temperature of the area exposed to the laser beams is monitored by the temperature sensors in the array of sensors 106 to ensure the correct (approximate) ablation temperature, to avoid damage to the steel surface. Particularly, the range of movements for moving the device 100, relative to the steel surface, include horizontally moving the device 100,

vertically moving the device 100, forward-diagonally (45°) moving the device 100, and/or backward-diagonally (45°) moving the device 100. The effectiveness of each movement, in terms of successfully ablating the material, will be described later in relation to Figure 12. This step is then repetitively performed for a number of passes until the material is deemed completely or satisfactorily removed from the steel surface, based on a visual inspection by the operator.

Figure 4 is a line chart 300 illustrating the relationship between the line (scanning) densities of the laser beams and the corresponding roughness of the ablated steel surface. A line density is defined as the gap between two neighbouring scanning lines. It is evident from the chart 300 that the average roughness (dimensions) of the steel surface after treatment is approximately between 10 μm to 25 μm (i.e. refer to Y-axis of the chart 300), which corresponds to a line density range of between 25% to 100% being used. In addition, the overlapping of the scanning lines may be useful for performing slight adjustments to the surface roughness (if so desired), which is described as having a variation defined in the form of second-order polynomial equation (1) as:

$$Y = A * x^2 + B * x + C \qquad (1)$$

wherein in equation (1), "*Y*" is the surface roughness, "*x*" is the line density (defined as a percentage of the laser beam size), and "*A*", "*B*" and "*C*" are all mathematical constants, which are determined empirically. It is apparent from Figure 4 that a relatively smooth surface is obtainable by using a line density in the range of 50% to 75%. It is further to be appreciated that the data set in Figure 4 are obtained with reference to the following experimental conditions: the laser power is rated at 450 Watts, while the laser frequency is 16 KHz, and the scanning speed is 15 m/s.

Figure 5 shows another line chart 400 depicting the relationship between the frequencies and corresponding pulse energies of the laser beams. In particular, the pulse energies at two different laser outputs of 60% (i.e. the lower line plotted with the square dots) and 100% (i.e. the upper line plotted with the circular dots) were measured. From the chart 400, it is ascertained that in order to obtain high pulse

energies, the laser frequency needs to be at approximately 16 KHz (i.e. refer to X-axis of the chart 400), which consequently results in generation of pulse energies of approximately between 20 mJ to 40 mJ (i.e. refer to Y-axis of the chart 400) by the laser beams, with a maximum output of 500 Watts in this instance. More particularly, it is to be appreciated that the laser power (i.e. "*P*"), pulse energy (i.e. "*E*"), and laser frequency (i.e. "*f*") are interrelated as defined in a generic equation (2):

$$P = f * E \qquad (2)$$

It has also been ascertained (empirically) in separate studies that adopting laser frequencies of above 16 kHz helps with eliminating occurrences of distinct and scattered cleaning lines, and reducing (loud) audible noises that might otherwise be uncomfortable for the operator. It is also to be appreciated that for hard materials/contaminations (e.g. rust or millscale), the laser beams need to be configured with high pulse energy and/or high energy density. However, for softer materials (e.g. paint or marine growth), the laser beams may be configured with relatively low pulse energy and/or low energy density. Therefore, the frequency parameter for configuring the laser beams may be selected from a range of between 16 KHz and 100kHz depending on the application. Further the pulse energy may be selected from a range of between 20 mJ to 200 mJ depending on the application.

Separately, Figure 6 is a line chart 500 illustrating the relationship between the pulse energies of the laser beams and the (normalised) surface reflection of the ablated steel surface. More specifically, this relationship is defined by equation (3):

$$Y = A * \exp(B * x) + C \qquad (3)$$

wherein in equation (3), "*Y*" is the surface reflection, "*x*" is the pulse energy, and "*A*", "*B*" and "*C*" are all mathematical constants being empirically determined and may or may not have similar values to those in Equation (1). A higher surface reflection value indicates that the surface is smoother (i.e. lower surface roughness and therefore reflects more light), and vice-versa. For application by the present invention, it is desirable to obtain reflection values of close to unity

(i.e. 1.0 units). Specifically, the chart 500 shows that for pulse energies of between 20 mJ to 40 mJ (as determined in Figure 5), reflection values of close to unity (i.e. between 0.5 units to 1.0 units) are obtainable (i.e. refer to Y-axis of the chart 500). Following on, the pulse energy parameter for configuring the laser beams is selected to be between 20 mJ to 40 mJ. It is also highlighted that the data set in Figure 6 are obtained under the following experimental conditions: a laser power of 450 Watts, a line density of 0.3 mm, and a scanning speed of 15 m/s.

Figure 7 shows a line chart 600 depicting the relationship between laser power of the laser beams and the (normalised) surface reflection of the ablated steel surface. This relationship can be described using equation (4):

$$Y = A + B * x \qquad (4)$$

wherein in equation (4), "*Y*" represents the surface reflection, "*x*" represents the laser power, and "*A*" and "*B*" are mathematical constants, which are determined empirically. It is also to be appreciated that the values of "*A*" and "*B*" in equation (4) may or may not have similar values to those in equation (1) or (3). Particularly, for the range of reflection values approximately between 0.5 units to 1.0 units (i.e. refer to Y-axis of the chart 600), it is determined that a high laser power of between 400 Watts to 500 Watts, for these conditions, is required (i.e. refer to X-axis of the chart 600) to effectively remove the surface oxide to provide a brighter surface for the ablated steel. In particular, the selected power is preferably 450 Watts. It is to be further appreciated that the data set in Figure 7 are obtained by configuring the experimental conditions as: a laser frequency of 16 KHz, with a line density of 0.3 mm, and a scanning speed of 15 m/s. In addition, the cleaning efficiency of the laser beams is influenced by the total energy input. For alternative applications, the power may be chosen to be within 400 to 2000 watts.

Figures 8 and 9 relate to focusing of the laser beams and heat management of the steel surfaces exposed to the emitted laser beams. In particular, Figure 8 is a line chart 700 illustrating the relationship between the focusing position of the device 100, and the corresponding detected sound volume at a position, whereas Figure 9 shows a line chart 800 about the change in steel surface

temperature during and after exposure to the emitted laser beams, performed for different repetition passes.

Referring to Figure 8, it is ascertained that in order to locate the focusing position (which is influenced by a set of parameters configured for the laser beams) for positioning the device 100, the acoustic detection of a sound volume of a drop from a peak sound level is considered acceptable (i.e. refer to Y-axis of the chart 700), which indicates that the distance of the current position of the device 100 to the focusing point is approximately aligned, with a deviation of ± 1 cm. In particular, a 10% drop from its peak sound level indicates a deviation of ± 1 cm from the focusing point. In other words, at the distances of ± 1 cm away from the focusing point, the detected sound volume is within a range of approximately 90% from the peak sound level. More specifically, the detected sound volume is sharp when device 100 is at the focusing point, relative to the steel surface. Conversely, when the device 100 is moved out of position (i.e. further away or closer to the steel surface), the detected sound volume reduces sharply. This apparent change in sound volume provides a useful guide for the operator to locate the optimal focusing position for the device 100. It has been determined empirically that the focusing point is not to be more than 22 cm from the steel surface. It is to be appreciated that the acoustic detection is performed in whichever frequency the laser beams are configured; for the case of Figure 8, the laser frequency is set at 16 KHz. In addition, the detection is conducted using the acoustic sensors included in the array of sensors 106 as described in Figure 2.

During the process of ablating the undesired material from the steel surface, the steel surface is heated to a relatively high temperature. More specifically, the ablation is successfully effected due to localised vaporization (of the treated area on the steel surface) at a high energy density, or alternatively burning at relatively low energy density. However the temperature may be controlled to avoid damage to the underlying material being ablated (e.g. the steel surface). The temperature of the steel surface is measured using the temperature sensors, included within the array of sensors 106.

Figure 9 specifically shows that when the time period (i.e. scanning time) is below 10 seconds, there is negligible heat generated on the steel surface. The surface temperature however starts increasing appreciably with further continuous exposure, and reaches a temperature of between 60°C to 90°C (i.e. refer to Y-axis of the chart 800), which is equivalent to a time period of between 20 seconds to 60 seconds (i.e. refer to X-axis of the chart 800), depending on the size of the scanning areas and number of passes/repetitions performed. This temperature range is considered low compared to the melting point of steel. It should also be mentioned that exposing the steel surface to several passes of the laser beams was needed to attain a surface cleanliness of Swedish Standard SA2.5 or equivalent. On this basis, the scanning time parameter for configuring the laser beams is selected to be between 20 seconds to 60 seconds. It is to be appreciated that the data set in Figure 9 are obtained by configuring the experimental conditions as: the laser beams have a wavelength of between 1055 nm to 1075 nm, a frequency of 16 KHz, a laser power of 450 Watts, and a line density of 0.2 mm. The scanning speed is set at 10 m/s.

With reference to Figures 10 and 11, both line charts 900, 1000 therein are directed at illustrating the relationships between the scanning speed of the laser beams versus the resulting depth of material ablated or the (normalised) surface reflection of the ablated steel surface respectively. The scanning speed is defined to be the moving speed of the laser beams. It is ascertained from Figure 10 that higher scanning speeds of the laser beams result in low overlapping of the laser spots, in terms of different depths of material being ablated in an exponential manner, according to equation (5):

$$Y = A * \exp(-B * x) + C \qquad (5)$$

wherein in equation (5), "*Y*" is the ablation depth, "*x*" is the scanning speed, and "*A*", "*B*" and "*C*" are mathematical constants, which are determined empirically and may or may not have similar values to those in Equation (1), (3) or (4). In addition, the effective amount of laser beams exposed on the steel surface at an instance is reduced at higher scanning speeds (i.e. leads to shorter exposure time at a certain spot). According to Figure 10, this higher scanning speed is determined to be between 10 m/s to 15 m/s (i.e. refer to X-axis of the chart 900).

Consequently, this results in a low removal rate of the surface layer of the steel (i.e. the overall amount of material ablated is considerably lesser), which is approximately less than 5 μm (i.e. refer to Y-axis of the chart 900), when the laser power is 450 Watts and frequency of 16 kHz.

Following on, Figure 11 shows that for the same range of higher scanning speeds (i.e. 10 m/s to 15 m/s), the surface reflection values are approximately between 0.5 units to 1.0 units (i.e. refer to Y-axis of the chart 1000), which are similar to the results previously determined in Figures 6 and 7. Essentially, at higher scanning speeds, the treated steel surface appears brighter since there is reduced ablation. Moreover, at higher scanning speeds, the material removal rate is considerably more uniform, which in turn provides a smoother treated surface leading to higher reflection values as shown in Figure 11. Therefore, the scanning speed parameter for configuring the laser beams is selected to be between 10 m/s to 15 m/s. It is to be further noted that the data sets in both Figures 10 and 11 are obtained under these experimental conditions: a laser power of 450 Watts, a frequency of 16 KHz, and a line density of 0.3 mm.

As described in step 208 of Figure 3, the operator may use a range of movements (i.e. scanning patterns) to move and guide the device 100 across the area to be treated. These movements include horizontally moving the device 100, vertically moving the device 100, forward-diagonally (45°) moving the device 100, and/or backward-diagonally (45°) moving the device 100. Figure 12 correspondingly shows, in a line chart 1100, the effectiveness of each type of movement for ablating the steel surface, measured in terms of the surface roughness. The ascertained surface roughness is approximately between 10 μm to 25 μm (in line with the data of Figure 4), with respect to different types of movements adopted. However, the option of using a mixture of movements seems particularly more advantageous as opposed to utilising only a single or dual type of movements, as evident from the lowest surface roughness result obtained by the former (see data set corresponding to the "*VHFB*" index indicated on the X-axis of the chart 1100). The mixture of movements in guiding the device 100 may provide a more uniform removal of the surface layer, which results in a relatively smoother surface with a lower roughness after ablation. It is to be noted that the data set of Figure 12 are obtained under these

experimental conditions: a laser power of 450 Watts, a frequency of 16 KHz, and a scanning speed of 15 m/s.

In summary, the desired surface roughness is between 10 μm to 25 μm, the desired surface reflection (normalised) value is between 0.5 units to 1.0 units, and the desired depth of material to ablate is less than or equal to 5 μm.

A second embodiment is now described. Figures 13 (A) to (C) illustrates the applicability and suitability of the device 100 for performing spot ablation. Conventional abrasive blasting is usable only for wide area blasting. Figure 13 (A), according to the prior art, shows a ship (steel) hull on which there are sporadic spots of defects (e.g. contaminants). Based on conventional abrasive blasting techniques, the minimum size of the surface area treatable is restricted by the spraying resolution of the nozzle. The treatment of small defects (such as those shown in Figure 13 (A)) requires the abrasive blasting to be performed over a wider area (rather than at a localised spot) to ensure all the defects are covered, as shown in Figure 13 (B). In contrast, the device 100 is easily configurable to perform spot ablation as shown in Figure 13 (C), by directing the laser beams only onto the area coated with the material, due to ease of controlling and focusing the laser beams for that purpose. It will be appreciated that the directing of the laser beams onto the specific areas to be worked on may be performed manually (by the operator through using the device 100) or alternatively carried out automatically by a computer program which utilises image processing technologies for those purposes. As a result, laser ablation, performed using the device 100 of the present invention, is more effective and economical for performing spot cleaning of the steel plates.

A third embodiment is now described. Figure 14 depicts a flow diagram of a method 1300 for ablating a large area (coated with undesired material) on the steel surface using the device 100. To simplify the explanation, the method 1300 will be described together with Figures 15 (A) and (B), which show two different sets 1400a, 1400b of optimised scanning areas, together with their respective large scanning area. In 1302, a large scanning area 1402, 1412 (i.e. an area on the steel surface) is first logically subdivided into a set of smaller processing areas 1404, 1414. Each smaller processing area 1404, 1414

includes the material to be ablated, and is formed with reference to a template processing area 1406, 1416, which is prior determined and optimised according to application requirements. For example, the processing area 1406 in Figure 15 (A) is square-shaped, while the processing area 1416 in Figure 15 (B) is rectangular-shaped. Next, in 1304, a sequential index is assigned to each smaller processing area 1404, 1414. This assignation is done lengthwise or columnwise with respect to the large scanning area 1402, 1412. Further, in 1306, the parameters related to configuration of the laser beams emitted by the device 100 are subsequently selected. This step is similar to 202 of Figure 3, and is therefore not repeated for the sake of brevity. In a final step 1308, with reference to the determined sequence in 1304, each processing area 1404, 1414 is laser treated using the series of steps 204 to 208 afore described in Figure 3. The step 1308 is iterated until the last processing area 1404, 1414 of the large scanning area 1402, 1412 has been treated.

According to a fourth embodiment, Figure 16 shows a flow diagram of a method 1500 for performing selective layer ablation. Selective layer ablation is performed when the material on the steel surface includes an upper layer and a bottom layer having different material properties, and only the upper layer needs to be removed. In 1502, the peak power density of the emitted laser beams is adjusted based on a desired result. Specifically, the peak power density is adjusted to have a value higher than the ablation threshold of the upper layer and lower than the ablation threshold of the bottom layer, so that the laser treatment has no effect on the bottom layer. It will be appreciated that the peak power density is tweaked using the adjustable implement on the controlling handle 104, previously described with reference to Figure 2. In 1504, the series of steps 202 to 206 afore described in Figure 3 are performed on the upper layer of the material. The ablation is stopped when the operator considers the upper layer satisfactorily removed, while the bottom layer remains intact on the steel surface, in 1506.

As an example, the upper layer is a black paint layer and the bottom layer is a red paint layer, and the peak power density is adjusted to be between 1 Megawatts/cm^2 and 5 Megawatts/cm^2. In a next example, typical paint coatings are removable using a peak power density of above 0.3 Megawatts/cm^2, without

suffering from carbonization effect that may lead to forming of char debris, whereas rust and mill scale are removable with a peak power density of above 6 Megawatts/cm^2.

According to a fifth embodiment, Figure 17 shows the device 100 being re-configured and integrated as a stationary workstation setup 1600. In particular, all the components in the stationary workstation setup 1600 are exactly similar to that as described for the device 100 of Figure 2, except that the optical cables 56, electrical cables, and suction hose 116 are now housed in an electrical conduit 1602, which is permanently fixed to a location, such as the walls adjacent to where the stationary workstation setup 1600 is. Therefore, for the sake of brevity, the description of those like components will not be repeated here. The operation of the stationary workstation setup 1600 is such that the surface to be cleaned and treated is first placed under the processing head 102, and the cleaning surface is then subsequently moved by an x-y-z table or a conveyor for performing laser ablation.

While the invention has been illustrated and described in detail in the drawings and foregoing description, such illustration and description are to be considered illustrative or exemplary, and not restrictive; the invention is not limited to the disclosed embodiments. Other variations to the disclosed embodiments can be understood and effected by those skilled in the art in practising the claimed invention. For example, the device 100 may be used for treating other materials, such as aluminium alloy, nickel alloy, titanium, and stainless steel, ceramics, composites, wood and etc. The device 100 may also be used to ablate or clean structures that are not marine-based. In order to perform laser ablation on the different materials and surfaces, the laser parameters may be selected based on the application requirements. In addition, the device 100, when configured in spot ablation mode, may be used for cleaning bolts, nuts or supporting brackets which are installed in nuclear plants and/or refinery plants. In another variation, the device 100 may be fitted to a free end of a robotic arm, a climbing elevator, or a cherry picker, which is remotely controlled by an operator from the ground level using a console, or automatically controlled according to a software program. Moreover, the device 100, controller 64, fibre laser source 52, and cooling unit 54 may all be integrated onto a mobile work base to facilitate moving

the laser cleaning apparatus 50 to a required location for conveniently performing laser ablation.

Claims

1. A laser cleaning apparatus comprising:

a fibre laser source;

a hand held device coupled to the fibre laser source, and to controllably emit pulsed coherent light to ablate material from a steel surface of a marine structure; and

a plurality of acoustic sensors connected to the hand held device, and configured to determine a focus position for focusing the light onto the steel surface .

2. The apparatus of claim 1, wherein the emitted light has a selected wavelength of between 1055 nm to 1075 nm, a selected frequency of between 16 and 100 KHz, and a selected power of between 400 Watts to 2000 Watts.

3. The apparatus of claim 1 or 2, further comprising a temperature sensor connected to the hand held device for measuring a temperature of the steel surface.

4. The apparatus of any of claims 1 to 3, further comprising a debris suction device attached to the hand held device to actively receive the material ablated from the steel surface.

5. The apparatus of any of claims 1 to 4, further comprising an adjustable scale attached at a first end to the hand held device at a face where the light is emitted and configured with a roller at a second end,

wherein the hand held device is guided by the roller for moving on the steel surface when ablation is performed.

6. The apparatus of claim 5 when dependent on claim 31, further comprising a covering configured to facilitate the active receipt of the ablated material by the debris suction device,

wherein the covering is attached to the hand held device at the face where the scale is attached.

7. The apparatus of any one of claims 1 to 6, wherein material includes mill scale.

8. The apparatus of one of claims 1 to 7, wherein the hand held device is coupled to the fibre laser source with an optical cable.

9. The apparatus of claim 8, wherein the optical cable is up to a hundred metres in length.