

CONTAINMENT DEVICE AND SYSTEM FOR LASER ABLATION

Cross-reference to Related Applications

[0001] The present application claims the benefit of the Singapore patent application No. 10201805673P filed on 29 June 2018, the entire contents of which are incorporated herein by reference for all purposes.

Technical Field

[0002] Various embodiments generally relate to a containment device for laser ablation, and a laser ablation system. In particular, various embodiments generally relate to a containment device for laser ablation of composite materials, and a laser ablation system for composite materials.

Background

[0003] The extensive use of composite materials, for example carbon fiber reinforced polymer (CFRP), in the aerospace industry, given their high strength and low density, has prompted the development of techniques and methods to repair components made of these composite materials. Different types of damages can be found on the structural components made of composite materials, such as cracks, holes or thermal spots. Traditional methods applied in the removal of affected sections include mechanical machining, abrasive water jets and manual sanding by pneumatic tools. Given the abrasive nature of the composite materials such as CFRP, mechanical tools may wear fast. On the other hand, high pressure abrasive water jets may induce further defects on the composite materials by the penetration of liquid or abrasive particles into the laminates which may deter the structural performance of the elements. Manual sanding is currently the preferred method employed in composite material removal during composite repair. However, it is a labour intensive operation which relies heavily on the skills and experience of operators, who require long periods of training and they have to be certified to perform this operation. The repeatability and quality of the removal process may also be inconsistent.

[0004] Recently, lasers have been explored for cutting, drilling and for selective removal of composite material layers during repairing applications. The advantages of lasers to

process composite materials include their high material removal precision given their focussing capability into very small spot sizes and flexible transmission through optical fibres to specific points on the work pieces. Application of laser for selective removal of composite materials that has been explored currently includes direct scanning of ultraviolet (UV) laser on the composite laminates. This type of laser system generally yields a very low material removal rate. Another application of laser for selective removal of composite materials include employing a carbon dioxide (CO₂) laser to cut the composite laminates and employing a mechanical brushing method to remove the composite material. Further, laser systems with picosecond pulse duration have also been explored in selective removal of composite materials. However, the processing rates are very slow. In addition, high power continuous wave (CW) fibre laser systems have also been tested for this application. However, the main problem in laser removal of composite material is the high heat input during the process which may induce thermal damage on the treated composite laminate. Other significant problems observed are the presence of multiple debris and fumes generated in the process. Typically, fume extractor systems are employed or deployed directly to the laser work zone to clear fumes and debris generated in laser removal operations. The fumes during laser processing of the composite materials may be toxic.

[0005] Currently, direct scanning of laser beam over an area of a composite material involves ablation of the polymer matrix and the reinforcing carbon fibres following a predetermined scanning method. Specific profiles may be needed in the repair process of composite laminates in the aerospace industry. They may be step and taper scarfing profiles. Specific depth to width scarfing ratios may be established by different aircraft manufacturers in their service and repair guidelines. Typically, the depth to width scarfing ratio may be 1:30 or 1:50, i.e. material is removed following 1 unit in depth (vertical direction) by 30 or 50 units in width (horizontal direction). However, the main challenge in this operation is the heat generated by the laser beam given the substantial amount of material that needs to be removed. Heavy thermal damage on the composite materials may typically be induced. To mitigate the thermal damage issue, gas jets have been employed or deployed directly to the laser work zone. Therefore, the ablation process may be assisted with a gas jet. FIG. 1 shows a schematic diagram of an adapted gas jet assisted laser removal technique that has been practiced. Compressed air (or gas) knife jets may be delivered at 5 bars of pressure through flat nozzles with an extraction nozzle (for example, of a fume extractor) placed in the opposite direction. This arrangement may facilitate the removal of the

generated fumes and debris from the removal process. This technique may improve the laser ablation results in terms of quality of the ablated sections. In particular, clear defined steps may be observed on the ablated composite laminates. However, this method has the disadvantage of concentrating the heat load on the opposite site of the flat nozzles, which may lead to thermal damage on the opposite side.

[0006] Accordingly, there is a need for a more effective device for laser ablation that may eliminate or resolve the thermal damage issue in laser removal of composite materials.

Summary

[0007] According to various embodiments, there is provided a containment device for laser ablation. The device may include an endless wall structure forming a continuous loop defining a central volume of space. The endless wall structure may have an endless base edge portion and an endless upper edge portion. The endless wall structure may include one or more exhaust outlet orifices in the endless wall structure. The device may further include an inflow manifold lined along the endless upper edge portion of the endless wall structure. The inflow manifold may have a plurality of outlets and at least one inlet. The device may further include a plurality of nozzles. Each of the plurality of outlets of the inflow manifold may be respectively provided with at least one of said nozzles. Respective nozzle may extend into the central volume of space.

[0008] According to various embodiments, there is provided a laser ablation system. The system may include the containment device as described herein. The system may further include a laser scanner module. The laser scanner module may include a laser directed towards the central volume of space in a direction from the upper edge portion towards the endless base edge portion.

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Brief description of the drawings

[0009] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments are described with reference to the following drawings, in which:

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FIG. 1 shows a schematic diagram of an adapted gas jet assisted laser removal technique practiced in the prior art;

FIG. 2A shows a containment device 200 for laser ablation according to various embodiments;

FIG. 2B to FIG. 2D show various cross-sectional views of the containment device 200 of FIG. 2A according to various embodiments;

5 FIG. 3 shows a cross-section of the heat exchanger 360 according to various embodiments;

FIG. 4A shows the recorded temperature on laser removal of composite materials under the laser ablation system with the containment device 200 of FIG. 2A to FIG. 2D according to various embodiments;

10 FIG. 4B shows a layout of the thermocouple positions for recording the temperature data in FIG. 4A;

FIG. 4C shows the recorded temperature on laser removal of composite materials under the laser ablation system with knife gas jets by flat nozzles of FIG. 1; and

15 FIG. 4D shows a layout of the thermocouple positions for recording the temperature data in FIG. 4C.

Detailed description

[00010] Embodiments described below in the context of the apparatus are analogously valid for the respective methods, and vice versa. Furthermore, it will be understood that the embodiments described below may be combined, for example, a part of one embodiment
20 may be combined with a part of another embodiment.

[00011] It should be understood that the terms “on”, “over”, “top”, “bottom”, “down”, “side”, “back”, “left”, “right”, “front”, “lateral”, “side”, “up”, “down” etc., when used in the following description are used for convenience and to aid understanding of relative positions or directions, and not intended to limit the orientation of any device, or structure or any part
25 of any device or structure. In addition, the singular terms “a”, “an”, and “the” include plural references unless context clearly indicates otherwise. Similarly, the word “or” is intended to include “and” unless the context clearly indicates otherwise.

[00012] Various embodiments relate to a containment device for laser ablation, and a laser ablation system. In particular, various embodiments generally relate to a containment
30 device for laser ablation of composite materials, and a laser ablation system for composite

materials. According to various embodiments, laser ablation is a process of removing material from a solid surface by irradiating it with a laser beam. According to various embodiments, the materials undergoing laser ablation are composite materials. According to various embodiments, laser ablation may include removing of material with a pulsed laser beam or a continuous wave laser beam. According to various embodiments, laser ablation may include, but not limited to, laser scarfing or laser removal or laser machining to remove material from the solid surface. According to various embodiments, composite materials are materials made from two or more constituent materials, which are significantly different from each other, that exhibit characteristics different from the individual constituent materials when combined together. According to various embodiments, the composite materials may include fibers (e.g. carbon, glass, aramid etc.) embedded in a host matrix (e.g. phenolic, polyester, epoxy etc.). For example, the composite material may include carbon fiber reinforced polymer (CFRP).

[00013] Various embodiments relate to improving the cooling process for laser ablation (or scarfing) of composite material (e.g. CFRP material) to avoid serious thermal damage to the laser ablated (or scarfed) composite material. According to various embodiments, uniform cooling over the surface of the composite material may be generated which may reduce the heat load and the extent of the heat affected zone during laser ablation.

[00014] According to various embodiments, the laser ablation system may include the containment device of the various embodiments. According to various embodiments, the containment device may be configured to trap the generated debris and fumes during laser ablation. According to various embodiments, the containment device may be configured to effectively and efficiently remove the trapped debris and fumes. According to various embodiments, the containment device may be configured to improve the cooling process during laser ablation. According to various embodiments, the containment device may be configured to facilitate uniform cooling across the laser work surface of the composite material undergoing laser ablation.

[00015] Various embodiments relate to a configuration of nozzles for delivering gas towards the laser processed areas. Various embodiments relate to an effective containment devices to trap the debris and fumes generated during laser ablation. Various embodiments relate to incorporating a circular array of nozzles, e.g. conical nozzles, and radial exhaust outlets into a containment chamber of the containment device so as to improve the cooling effect on composite panels undergoing laser ablation (or scarfing). According to various

embodiments, the configuration of the nozzles may maximise the removal of debris and fumes generated in the laser ablation (or scarfing) process. According to various embodiments, multiple high speed air (or gas) jets may be applied to assist the removal of debris generated in the process and to protect the optics of the laser system. According to various embodiments, these high pressure air (or gas) jets may also reduce the temperature of the material being processed which may minimize the heat effects induced by the laser beam. Furthermore, various embodiments may include a customized air (or gas) heat exchanger to reduce the temperature of the air (or gas) that may be delivered in the process. Various embodiments may also employ a vortex tube or vortex pipe which given its construction may enable reducing the air (or gas) temperature. According to various embodiments, the compressed air (or gas) may be supplied at an inlet point of the vortex tube or vortex pipe, and the vortex flow of the vortex tube or vortex pipe may generate a hot and a cold gas flow streams respectively.

[00016] According to various embodiments, the removal of debris and fumes from the laser ablation process may be improved with the deployment of the circular array of nozzles and the radial exhaust outlets which may capture more effectively the amount of debris generated and the fumes. According to various embodiments, it may be important to remove the fumes during laser ablation because the fumes generated may be toxic. According to various embodiments, the debris ejected given their high surface energy may trap many of the chemical compounds released in the laser removal process. According to various embodiments, cooled compressed air may be delivered for assisting the removal process. According to various embodiments, a customised heat exchanger may be employed to reduce the temperature of the compressed air. Various embodiments may include integration of a 3D scanner with a mechanical fixture, including enclosure and holding device for ablation of composite materials from curved/three dimensional surfaces. Various embodiments may also include the use of a high power Nd:YAG (neodymium-doped yttrium aluminium garnet) pulsed laser to conduct the removal process.

[00017] FIG. 2A shows a containment device 200 for laser ablation according to various embodiments. FIG. 2B to FIG. 2D show various cross-sectional views of the containment device 200 of FIG. 2A according to various embodiments. According to various embodiments, the containment device 200 may include an endless wall structure 210 forming a continuous loop defining a central volume of space 212. According to various embodiments, the endless wall structure 210 may be a closed loop structure surrounding or

encircling the central volume of space 212 so as to delineate or demarcate the central volume of space 212. According to various embodiments, the central volume of space 212 may be the inner space bound by the endless wall structure 210. According to various embodiments, the central volume of space 212 may form a containment chamber of the containment device
5 200.

[00018] According to various embodiments, the endless wall structure 210 may include an endless base edge portion 214 and an endless upper edge portion 216. According to various embodiments, the endless base edge portion 214 may be a continuous edge portion of the endless wall structure 210 which may define a base opening 215 which may provide
10 access to the central volume of space 212 via a base side of the central volume of space 212 through the base opening 215. According to various embodiments, the endless upper edge portion 216 may be a continuous edge portion of the endless wall structure 210 which may define an upper opening 217 which may provide access to the central volume of space 212 via an upper side of the central volume of space 212 through the upper opening 217.
15 According to various embodiments, the endless wall structure 210 with the endless base edge portion 214 and the endless upper edge portion 216 may define a hollow cavity there-through extending from the endless base edge portion 214 to the endless upper edge portion 216. According to various embodiments, the base side of the central volume of space 212 and the upper side of the central volume of space 212 may be opposite sides of the central
20 volume of space 212. According to various embodiments, a center (or a radial center) of the base opening 215 may be aligned to a center (or a radial center) of the upper opening 217 such that the endless base edge portion 214 and the endless upper edge portion 216 may be arranged in a coaxial manner.

[00019] According to various embodiments, the endless wall structure 210 may include
25 one or more exhaust outlet orifices 218 in the endless wall structure 210. According to various embodiments, each of the one or more exhaust outlet orifices 218 may be a hole through the endless wall structure 210 so as to provide access to the central volume of the space 212 through a thickness direction of the endless wall structure 210. According to various embodiments, each of the one or more exhaust outlet orifices 218 may be a through-
30 hole extending from an interior wall surface 211 to an exterior wall surface 219 of the endless wall structure 210.

[00020] According to various embodiments, the containment device 200 may include an inflow manifold 220 lined along the endless upper edge portion 216 of the endless wall

structure 210. According to various embodiments, the inflow manifold 220 may be arranged or disposed to follow a profile of the endless upper edge portion 216. According to various embodiments, the inflow manifold 220 may be abutting the endless upper edge portion 216 and extending alongside the endless upper edge portion 216. According to various
 5 embodiments, the inflow manifold 220 may be a tubular structure.

[00021] According to various embodiments, the inflow manifold 220 may include a plurality of outlets 222 and at least one inlet 224. According to various embodiments, the plurality of outlets 222 may be directed towards the central volume of space 212 and the at least one inlet 224 may be directed in a direction outwards (or radially outwards) of the
 10 endless wall structure 210. According to various embodiments, the at least one inlet 224 may be configured for coupling with a fluid source for flowing the fluid into the inflow manifold 220. According to various embodiments, each of the plurality of outlets 222 may be configured for the fluid to flow out of the inflow manifold 220. According to various embodiments, the inflow manifold 220 may be configured to direct the inflow fluid into the
 15 central volume of space 212. According to various embodiments, the fluid may include air, compressed air, gas, or compressed gas.

[00022] According to various embodiments, the containment device 200 may include a plurality of nozzles 230. According to various embodiments, each nozzle 230 may be a conical nozzle. According to various embodiments, each of the plurality of outlets 222 of
 20 the inflow manifold 220 may be respectively provided with at least one of said nozzles 230. According to various embodiments, the respective nozzle 230 may extend into the central volume of space 212. According to various embodiments, each of the plurality of outlets 222 of the inflow manifold 220 may be fluidly connected to respective one of said nozzles 230. According to various embodiments, each of the plurality of nozzles 230 may be
 25 configured to direct the fluid, which is coming out from a corresponding outlet 222, through said nozzle 230 in a predetermined manner. According to various embodiments, each of the plurality of nozzles 230 may be configured to direct the fluid to come out in the form of a spray, a jet, or a stream.

[00023] According to various embodiments, the endless wall structure 210 may be of a
 30 funnel-shaped shape. According to various embodiments, the endless upper edge portion 216 may be wider than the endless base edge portion 214. According to various embodiments, the endless upper edge portion 216 may be of a larger size or may be broader than the endless base edge portion 214. According to various embodiments, the upper opening 217 defined

by the endless upper edge portion 216 may have a larger area or a bigger width (or diameter) than the base opening 215 defined by the endless base edge portion 214. According to various embodiments, the endless wall structure 210 may taper from the endless upper edge portion 216 towards the endless base edge portion 214. According to various embodiments, the endless wall structure 210 may become continuously narrower or gradually decrease in size in a direction from the endless upper edge portion 216 to the endless base edge portion 214.

[00024] According to various embodiments, the inflow manifold 220 may be lined along the endless upper edge portion 216 in a manner so as to form an inwardly overhanging extension from the endless upper edge portion 216 which suspends over the central volume of space 212. According to various embodiments, the inflow manifold 220 may be disposed on top of the endless upper edge portion 216 with a portion of the inflow manifold 220 protruding sideways from the endless upper edge portion 216 and inwards towards the center of the upper opening 217 so as to form an overhang cover which partially cover the central volume of space 212 along the endless upper edge portion 216.

[00025] According to various embodiments, the endless upper edge portion 216 may include an inward curl portion. Accordingly, the endless upper edge portion 216 may include a curled profile which is directed inwardly towards the center of the upper opening 217. According to various embodiments, the endless upper edge portion 216 may be curved radially inwards towards the center of the upper opening 217.

[00026] According to various embodiments, each of the plurality of outlets 222 of the inflow manifold 220 may include a spout 223 extending into the central volume of space 212. According to various embodiments, the spout 223 may be a pipe-like or a tube-like protrusion extending from the respective outlet 222 and into the central volume of space 212, and which the fluid may be conveyed there-through.

[00027] According to various embodiments, a connection portion 232 of each of the plurality of nozzles 230 may be respectively coupled to a corresponding outlet of the plurality of outlets 222 of the inflow manifold 220 via a ball and socket joint. Accordingly, the ball and socket joint may allow multidirectional movement and rotation of the respective nozzle 230 with respect to the corresponding outlet 222.

[00028] According to various embodiments, the spout 223 of the respective outlet 222 may include a socket 225 and the connection portion 232 of the corresponding nozzle 230 may be of a ball-like shape. According to various embodiments, the ball-like connection

portion 232 of the corresponding nozzle 230 may engage or be fitted into the socket 225 of the spout 223 of the respective outlet 222 in a manner such that the nozzle 230 may be moved and/or rotated multi-directionally relative to spout 223 of the outlet 222. According to various embodiments, the socket 225 of the spout 223 of the outlet 222 may be located near or at a longitudinal end portion of the spout 223. According to various embodiments, each spout 223 may be so fixed with respect to the inflow manifold 220. According to various embodiments, each pair of spout 223 and nozzle 230 may form an articulated nozzle arrangement.

[00029] According to an example embodiment, for example as shown in FIG. 2A to FIG. 2D, the inflow manifold 220 may include five outlets 222. In this embodiment, four of the five outlets 222 may be equally spaced from each other along the inflow manifold 220, and a fifth outlet 222 may be disposed between two of the four equally spaced outlets 222. Accordingly, four of the five outlets 222 of the inflow manifold 220 may be located in positions corresponding to the four cardinal directions (or cardinal points) of the endless wall structure 210. In this embodiment, the fifth outlet 222 may be located in a position that corresponds to an intercardinal (or intermediate) direction halfway between two adjacent cardinal directions of the endless wall structure 210.

[00030] In this embodiment, the containment device 200 may include five nozzles 230. Each of the five nozzles 230 may be coupled to a respective outlet of the five outlets 222 of the inflow manifold 220. In this embodiment, respective nozzle 230 of respective outlet of the four equally spaced outlets 222 of the inflow manifold 220 may be configured to direct a spray towards the base opening 215 formed by the endless base edge portion 214 of the endless wall structure 210 with a spray axis angled off a vertical axis by an angle of $30^\circ \pm 10^\circ$ and aimed off the center of the base opening 215 about the vertical axis in a manner such that a horizontal component of a vector of the spray axis may be parallel to a line tangent to a predetermined circle. The predetermined circle may be coaxial with the centre of the base opening 215, may be smaller in diameter than the base opening 215 and may be in a same horizontal plane with the base opening 215 (or set inside the base opening 215). The predetermined circle may be application specific and may approximate a desired size of a circular path of the swirl flow to be generated and contained within the containment device 200. The vertical axis may be parallel to a central axis passing through the center of the base opening 215 and perpendicular to the base opening 215. Respective nozzles 230 may be pointed or oriented in a manner such that all jets from all the nozzles may

cooperatively generate the swirl flow about a central axis of the containment device 200 (or all the nozzles 230 may give or direct respective jet in a same rotational direction about the central axis of the containment device 200. In this embodiment, respective nozzle 230 of the four equally spaced outlets 222 of the inflow manifold 220 may be directed downwards
 5 towards the base opening 215 with the spray axis at a slant angle of $30^{\circ} \pm 10^{\circ}$ measured with respect to the vertical axis, and rotated through an angle about the vertical axis in a manner so as to direct a spray towards a perimeter of the predetermined circle in order to generate the swirl flow. Accordingly, the respective spray axis of the respective nozzle 230 of the four equally spaced outlets 222 may intersect with the perimeter of the predetermined
 10 circle. In this embodiment, respective nozzle 230 of the fifth outlet 222 of the inflow manifold 220 may be configured to direct a spray towards the center of the base opening 215. In this embodiment, a spray axis of the fifth nozzle 230 (or the center-directed nozzle 230) may intersect the center of the base opening 215.

[00031] In this embodiment, the five outlets 222 of the inflow manifold 220 may be
 15 respectively provided with a spout 223. Accordingly, the inflow manifold 220 may include five spouts 223 extending into the central volume of space 212. In this embodiment, four of the five spouts 223 may be equally spaced from each other along the inflow manifold 220, and a fifth spout 223 may be disposed between two of the four equally spaced spouts 223. In this embodiment, four of the five spouts 223 of the inflow manifold 220 may be
 20 respectively angled off the vertical axis by an angle of $30^{\circ} \pm 10^{\circ}$ with respective free longitudinal end of respective spout 223 aimed off the center of the base opening 215 by an angle about the vertical axis in a manner such that a horizontal component of a longitudinal axis of the respective spout 223 may be parallel to a line tangent to the predetermined circle, which may be coaxial with the centre of the base opening 215, smaller in diameter than the
 25 base opening 215 and in the same horizontal plane with the base opening 215 (or set inside the base opening 215). In this embodiment, respective free longitudinal end of the fifth spout 223 may be directed towards the center of the base opening 215 in a manner such that a longitudinal axis of the fifth spout 223 may intersect the center of the base opening 215.

[00032] While the embodiment as shown in FIG. 2A and FIG.2B is described to include
 30 five outlets 222 in the inflow manifold 220, it is understood that according to various embodiments, the inflow manifold 220 may include multiple outlets 222 (or the plurality of outlets 222). Accordingly, in various embodiments, the inflow manifold 220 may include two or three or four or five or six or seven or eight or more outlets 222 or any suitable

number of outlets 222. According to various embodiments, the inflow manifold 220 may include N number of outlets 222, whereby N is at least two (or two or more), or at least three (or three or more). According to various embodiments, the containment device 200 may include a corresponding number of nozzles 230. Accordingly, the containment device 200
5 may include N number of nozzles.

[00033] According to various embodiments, when N is at least two, the N number of outlets 222 may be spaced equally along the inflow manifold 220. According to various embodiments, the plurality of outlets 222 of the inflow manifold 220 may be the N number of outlets 222. According to various embodiments, respective nozzle 230 of the respective
10 N number of equally spaced outlets 222 of the inflow manifold 220 may be configured to direct a spray towards the base opening 215 formed by the endless base edge portion 214 of the endless wall structure 210 with a spray axis angled off a vertical axis by an angle of $30^\circ \pm 10^\circ$ and whose orientation about the vertical axis is in a manner such that a horizontal component of a vector of the spray axis may be parallel to a line tangent to a predetermined
15 circle (or such that the spray axis lies in a same vertical plane with the line tangent to the predetermined circle), wherein the predetermined circle is coaxial with the base opening 215 and is of a smaller diameter than the base opening 215 and in a same horizontal plane with the base opening 215, whereby the vertical plane is perpendicular to the horizontal plane. The predetermined circle may be application specific and may approximate a desired
20 size of a circular path of the swirl flow to be generated and contained within the containment device 200. The vertical axis may be parallel to the central axis passing through the center of the base opening 215 and perpendicular to the base opening 215. According to an example embodiment (not shown), the inflow manifold 220 may include three outlets 230 spaced equally apart from each other along the inflow manifold 220. According to various
25 embodiments, respective nozzle 230 of the three equally spaced outlets 222 of the inflow manifold 220 may be configured to direct a spray towards the base opening 215 formed by the endless base edge portion 214 of the endless wall structure 210 with a spray axis angled off a vertical axis by an angle of $30^\circ \pm 10^\circ$ and whose orientation about the vertical axis is such that the spray axis lies in a same vertical plane with a line tangent to a predetermined
30 circle, wherein the predetermined circle is coaxial with the base opening 215 and is of a smaller diameter than the base opening 215 and in a same horizontal plane with the base opening 215, whereby the vertical plane is perpendicular to the horizontal plane. The predetermined circle may be application specific and may approximate a desired size of a

circular path of the swirl flow to be generated and contained within the containment device 200. The vertical axis may be parallel to the central axis passing through the center of the base opening 215 and perpendicular to the base opening 215.

[00034] According to various other embodiments, when N is at least three, a $(N - X)$ number of outlets 222 may be spaced equally along the inflow manifold 220, whereby X may be at least one (or one or more). According to various embodiments, a first subset of the plurality of outlets 222 of the inflow manifold 220 may be the $(N - X)$ number of outlets 222. According to various embodiments, a second subset of the plurality of outlets 222 of the inflow manifold 220 may be the remaining X number of outlets 222. According to various embodiments, respective nozzle 230 of the respective $(N - X)$ number of equally spaced outlets 222 of the inflow manifold 220 may be configured to direct a spray towards the base opening 215 formed by the endless base edge portion 214 of the endless wall structure 210 with a spray axis angled off a vertical axis by an angle of $30^\circ \pm 10^\circ$ and whose orientation about the vertical axis is such that the spray axis lies in a same vertical plane with a line tangent to a predetermined circle, wherein the predetermined circle is coaxial with the base opening 215 and is of a smaller diameter than the base opening 215 and in a same horizontal plane with the base opening 215, whereby the vertical plane is perpendicular to the horizontal plane. The predetermined circle may be application specific and may approximate a desired size of a circular path of the swirl flow to be generated and contained within the containment device 200. The vertical axis may be parallel to the central axis passing through the center of the base opening 215 and perpendicular to the base opening 215. According to various embodiments, each of the remaining X outlets 222 may be located in a position that is halfway between two corresponding adjacent outlets 222 of the $(N-X)$ number of outlets. According to various embodiments, respective nozzle 230 of each of the remaining X outlets 222 of the N number of outlets 222 may be configured to direct a spray towards the center of the base opening 215. According to various embodiments, the spray axis of these center-directed nozzles 230 may intersect the center of the base opening 215. According to an example embodiment (not shown), the inflow manifold 220 may include sixteen outlets 230. In this embodiment, N may be sixteen and X may be two. Accordingly, fourteen of the sixteen outlets may be spaced equally apart from each other along the inflow manifold 220. According to various embodiments, respective nozzle 230 of the fourteen equally spaced outlets 222 of the inflow manifold 220 may be configured to direct a spray towards the base opening 215 formed by the endless

base edge portion 214 of the endless wall structure 210 with a spray axis angled off a vertical axis by an angle of $30^{\circ} \pm 10^{\circ}$ and whose orientation about the vertical axis is in a manner such that a horizontal component of a vector of the spray axis may be parallel to a line tangent to a predetermined circle (or such that the spray axis lies in a same vertical plane with the line tangent to the predetermined circle), wherein the predetermined circle is coaxial with the base opening 215 and is of a smaller diameter than the base opening 215 and in a same horizontal plane with the base opening 215, whereby the vertical plane is perpendicular to the horizontal plane. The predetermined circle may be application specific and may approximate a desired size of a circular path of the swirl flow to be generated and contained within the containment device 200. The vertical axis may be parallel to the central axis passing through the center of the base opening 215 and perpendicular to the base opening 215. According to various embodiments, each of the remaining two outlets 222 may be located in a position that is halfway between two corresponding adjacent outlets 222 of the fourteen number of outlets. According to various embodiments, respective nozzle 230 of each of the remaining two outlets 222 of the sixteen number of outlets 222 may be configured to direct a spray towards the center of the base opening 215. According to various embodiments, the spray axis of these center-directed nozzles 230 may intersect the center of the base opening 215.

[00035] According to various embodiments, the containment device 200 may include an exhaust manifold 240 running alongside the exterior wall surface 219 of the endless wall structure 210. According to various embodiments, the exhaust manifold 240 may be extending along the exterior wall surface 219 of the endless wall structure 210 in a manner so as to loop around the endless wall structure 210. According to various embodiments, the one or more exhaust outlet orifices 218 in the endless wall structure 210 may respectively be connected to the exhaust manifold 240 via respective connecting tube 250. According to various embodiments, one connecting tube 250 may connect one exhaust outlet orifice 218 in the endless wall structure 210 to the exhaust manifold 240. According to various embodiments, the respective connecting tube 250 may be extending radially from the endless wall structure 210 to the exhaust manifold 240.

[00036] According to various embodiments, the exhaust manifold 240 may include a closed terminal end 242 and an opened terminal end 244. Accordingly, the exhaust manifold 240 may be closed at one end and may be opened at the other end. According to various embodiments, the exhaust manifold 240 may have an increasing cross-sectional area or

internal diameter from the closed terminal end 242 to the opened terminal end 244. According to various embodiments, the cross-sectional area of the exhaust manifold 240 may become continuously broader or gradually increase in size along the exhaust manifold 240 from the closed terminal end 242 to the opened terminal end 244. Accordingly, the exhaust manifold 240 may have a profile similar to a curved blow horn.

[00037] Referring back to the example embodiment of FIG. 2A to FIG. 2D, in this embodiment, the endless wall structure 210 may include eight exhaust outlet orifices 218 equally spaced along the endless wall structure 210. In this embodiment, the eight exhaust outlet orifices 218 may be distributed and located at the four cardinal directions and the four intercardinal (or intermediate) directions of the endless wall structure 210 respectively. In this embodiment, each exhaust orifice 218 may be located immediately underneath the inflow manifold 220. In this embodiment, each exhaust orifice 218 may be at a position sheltered by the portion of the inflow manifold 220 protruding inwardly sideways which forms the overhang cover.

[00038] While the embodiment as shown in FIG. 2A and FIG. 2B is described to include eight exhaust outlet orifices 218 in the endless wall structure 210, it is understood that according to various embodiments, the endless wall structure 210 may include one or more exhaust outlet orifices 218 (or at least one exhaust orifices 218). Accordingly, in various embodiments, the endless wall structure 210 may include one or two or three or four or five or six or seven or eight or more exhaust outlet orifices 218 or any suitable number of exhaust outlet orifices 218.

[00039] According to various embodiments, the containment device 200 may include a fume extractor (not shown) connected to the opened terminal end 244 of the exhaust manifold 240. According to various embodiments, the fume extractor may create a suction at the opened terminal end 244 of the exhaust manifold 240 such that suction may in turn be generated at each of the exhaust orifice 218 of the endless wall structure 210.

[00040] According to various embodiments, the endless wall structure 210 may form a continuous circular loop. According to various embodiments, the inflow manifold 220 may include a ring-shaped tube. According to various embodiments, the exhaust manifold 240 may include an opened-ring-shape tube.

[00041] According to various embodiments, the containment device 200 may include an air supply (not shown) connected to the at least one inlet 224 of the inflow manifold 220. According to various embodiments, the air supply may be configured to provide compressed

air into the inflow manifold 220. Accordingly, the manifold 220 may direct the compressed air to the plurality of nozzles 230 which may deliver high speed air sprays (or jets) into the central volume of space 212 defined by the endless wall structure 210 such that the high speed air spray (or jets) may create a flow of air that may cool the base opening 215 region of the endless wall structure 210 and that may carry debris and fumes to circulate along an inner surface of the endless wall structure 210 into a whirl which may then be sucked out from the one or more exhaust orifice 218 in the endless wall structure 210. According to various embodiments, the air supply may be a cold air supply. The cold air supply may enhance the cooling effect of the high speed air jets.

10 **[00042]** According to various embodiments, the cold air supply may include a heat exchanger 360 (see FIG. 3) configured to supply cold air to the at least one inlet 224 of the inflow manifold 220. FIG. 3 shows a cross-section of the heat exchanger 360 according to various embodiments. According to various embodiments, the heat exchanger 360 may include a vacuum flask 362 having a vacuum chamber 361 filled with coolant media 363 (or coolant element). The heat exchanger 360 may further include a copper coil 364 immersed in the coolant media 363 within the vacuum chamber 361. The copper coil 364 may further include an inlet 365 for inflow of compressed air at room temperature and an outlet 367 for outflow of cooled compressed air for flowing into the at least one inlet 224 of the inflow manifold 220.

20 **[00043]** According to various embodiments, the cold air supply may include a vortex tube (not shown) with a cold air outlet of the vortex tube connected to the at least one inlet 224 of the inflow manifold 220. According to various embodiments, the vortex tube may separate a compressed air into a hot stream and a cold stream which may respectively exit from respective ends of the vortex tube.

25 **[00044]** According to various embodiments, the containment device 200 may include one or more mechanical fixture or vacuum pad (not shown) configured to couple the endless wall structure 210 to a work surface. According to various embodiments, the one or more mechanical fixture or vacuum pad may couple the endless wall structure 210 to the work surface in a manner such that the endless base edge portion 214 of the endless wall structure 210 may be placed on the work surface. Accordingly, the endless base edge portion 214 of the endless wall structure 210 may form a skirting around the work surface.

30 **[00045]** According to various embodiments, a laser ablation system (not shown) may include the containment device 200 as described herein. According to various embodiments,

the laser ablation system may further include a laser scanner module (not shown). According to various embodiments, the laser scanner module may include a laser (not shown) directed towards the central volume of space 212 in a direction from the upper edge portion 216 towards the endless base edge portion 214. According to various embodiments, the laser scanner module may be configured to control a steering of a laser beam emitted from the laser. According to various embodiment, the laser of the laser scanner module may be disposed and oriented such that a laser beam emitted from the laser may be projected in the direction from the upper edge portion 216 towards the endless base edge portion 214.

[00046] According to various embodiments, the laser of the laser scanner module may be directed towards a radially central portion of the central volume of space 212 at the level of the endless base edge portion 214. According to various embodiments, the laser beam emitted from the laser may be directed to remove materials from a work surface within the endless base edge portion 214.

[00047] Referring back to the embodiment of FIG. 2A to FIG. 2D, the embodiment may deliver high speed air (or gas) jets by an array of five conical nozzles (or nozzles 230). In this embodiment, each conical nozzle may have an exit diameter of 1 mm. In this embodiment, all of the five conical nozzles may be supplied with compressed air from an inlet tubular manifold (or inflow manifold 220) running on the top perimeter of the containment chamber (or the endless upper edge portion 216 of the endless wall structure 210). In this embodiment, four of the nozzles 230 may be distributed every 90° on the perimeter at the upper section of the supporting structure of the containment chamber (or the endless upper edge portion 216 of the endless wall structure 210). In this embodiment, the nozzles 230 may direct respective compressed air (or gas) jet stream at 45° counter-clockwise and approximately 30° downwards towards the surface of the sample (or the work surface). In this embodiment, this may effectively sweep a stream of air (or gas) over the surface of the sample (or the work surface) which may cool said surface and blows fumes and debris away from the processed area. In this embodiment, the fifth nozzle 230 may be located in between two nozzles 230, also at the upper section. In this embodiment, the fifth nozzle 230 may direct its compressed air jet stream towards the middle of the processing area which may minimise any uncovered section. In this embodiment, each nozzle 230 may have a degree of adjustment given their semi-spherical connecting sockets from their cylindrical base supports (or ball and socket joint).

[00048] According to various embodiments, the containment chamber wall profile (or a profile of the endless wall structure 210) may have a gentle gradient (or slide) which may improve the movement of the compressed air carrying both the fumes and debris generated in the laser ablation process. According to various embodiments, the upper section of the
 5 containment chamber (or the upper section of the endless wall structure 210) may have a series of circular exhaust outlets orifices 218 (or exhaust outlet) which may be connected to the exhaust manifold 240 through connecting tubes 250.

[00049] Referring to the the embodiment of FIG. 2A to FIG. 2D, in this embodiment, a total of eight exhaust outlets orifices 218 may be provided. In this embodiment, each
 10 exhaust outlet orifices 218 may have a diameter of 20 mm. In this embodiment, the eight exhaust outlets orifices 218 may be distributed evenly with a distribution angle of 45° on the upper inner side of the containment chamber wall (or the endless wall structure 210). In this embodiment, the eight exhaust outlets orifices 218 may be located in a concave section formed by the containment chamber wall (or the endless wall structure 210) and the gas inlet
 15 manifold (or the inflow manifold 220) which may maximise the capture of the fumes and debris. According to various embodiments, protruding marks (or raised markings) on the chamber wall (or the interior wall surface 211 of the endless wall structure 210) may be located axially with all exhaust outlets orifices 218 (or may be aligned to respective axial directions of the respective exhaust outlets orifices 218). According to various
 20 embodiments, these protruding marks may facilitate positioning of the conical nozzles. According to various embodiments, the exhaust manifold 240 may be a blind pipe with an increasing diameter from the furthest outlet exit (or a position connected to the further exhaust outlet orifice 218) till reaching a 50.4 mm diameter at a connecting point for the hose of the fume extractor unit. According to various embodiments, the exhaust manifold
 25 240 may be configured to maintain the air (or gas) speed extraction equal on all exhaust outlet orifices 218. According to various embodiments, the generated air (or gas) flow may follow a whirl circulation movement which may be enhanced by the air (or gas) suction exerted by the fume extractor connected to the exhaust manifold 240. According to various embodiments, this flow pattern may improve the cooling effect of the processed surface (or
 30 work surface) and assist in the removal of the fumes and debris generated in the laser ablation process.

[00050] FIG. 4A shows a graph 401 illustrating the recorded temperature on laser removal of composite materials under the laser ablation system with the containment device 200 of

FIG. 2A to FIG. 2D according to various embodiments. FIG. 4B shows a layout 402 of the thermocouple positions for recording the temperature data in graph 401. FIG. 4C shows a graph 403 illustrating the recorded temperature on laser removal of composite materials under the laser ablation system with knife gas jets by flat nozzles of FIG. 1. FIG. 4D shows a layout 404 of the thermocouple positions for recording the temperature data in graph 403. As shown, the measured temperature in laser removal of composite materials experiments (whereby CFRP was used) under the same process conditions but under different gas jet delivery methods shows improved cooling results in FIG. 4A, i.e. the laser ablation system with the containment device 200 of FIG. 2A to FIG. 2D, as compared to FIG. 4B, i.e. the laser ablation system with knife gas jets by flat nozzles of FIG. 1. Further, the recorded average temperature reduction, under the laser ablation system with the containment device 200 of FIG. 2A to FIG. 2D as compared to the laser ablation system with knife gas jets by flat nozzles of FIG. 1, was 31.8% for the removal of the glass cover and 21.4% for the removal of carbon fibres. Furthermore, the time to cool down the laser irradiated CFRP composite to a temperature below 27 °C was 44.2% faster for the laser ablation system with the containment device 200 of FIG. 2A to FIG. 2D as compared to the laser ablation system with knife gas jets by flat nozzles of FIG. 1. According to various embodiments, the removal of debris and fumes generated in the laser ablation (or scarfing) process was also improved by the containment device 200 of FIG. 2A to FIG. 2D given the radial exhaust outlet orifices 218 and the swirl flow generated. According to various embodiments, this may be particularly advantageous as fumes generated during laser ablation (or scarfing) may be toxic given the chemical decomposition of the polymer matrix.

[00051] According to various embodiments, there may be concurrent use of a heat exchanger, for example the heat exchanger 300 of FIG. 3, to reduce the temperature of the compressed air that may be delivered for assisting the removal of composite materials. Referring to FIG. 3, according to various embodiments, the heat exchanger 300 may be made up of a copper tube coil 364 immersed in a reservoir with a coolant element 363 such as ice or dry ice. According to various embodiments, the temperature drop of the assist gas jet may reduce further the temperature of the laser irradiated CFRP surfaces.

[00052] According to various embodiments, an additional option for cooling the compressed air may be the employment of a vortex tube. According to various embodiments, the vortex tube may have an inlet point which receives a compressed air at certain pressure and, by its physical construction, the vortex tube may yield a portion of hot

and cool air streams to opposite exhaust points. According to various embodiments, the gas temperature reduction may be proportional to the volume of hot air extracted at the outlet valve.

[00053] According to various embodiments, a high power Nd:YAG (1.064 μm) laser may be employed for the removal process as it shows high material removal rate given its average power and optical design. According to various embodiments, the laser removal process may only make use of assist gas jet while the laser is continuously irradiating the material. According to various embodiments, the laser beam may be delivered perpendicular to the sample surface by galvanometer scanner, with multiple passes of the laser beam to remove the required number of carbon fibres layers with the required profile. According to various embodiments, the laser beam may be first focused at the top surface of the laminates, as the removal process progresses, the focal position may gradually be adjusted below the surface to ablate deeper layers of carbon fibres.

[00054] According to various embodiments, the laser removal of composite materials for composite repair on curved surfaces such as the typical airplane fuselage structures may require employing a three-dimensional (3D) laser scanner system into a mechanical fixture devise. According to various embodiments, the projected working space of such laser scanner may be provided with an enclosure to block laser beam irradiation, the fumes generated and noise from the process. According to various embodiments, an extractor system may be implemented to remove fumes and ejected particles being ablated by the laser beam and expelled by the assisting gas jet. According to various embodiments, the surface and geometry of the materials to be removed may be defined by initial inspection process, preferably, an automated inspection process employing non-destructive techniques which supplies data on the dimensions and geometry configuration of the composite structure to be repaired may be conducted.

[00055] According to various embodiments, the laser scanner may be integrated with mechanical fixture device and the enclosure may be located into position where the composite repair is required. According to various embodiments, the circular array of nozzles may be also attached to its working position by a mechanical fixture or vacuum pads. According to various embodiments, the laser ablation process may be automated by means of computer control and the feedback system by an inline CCD camera (through the lens) and a lighting system. According to various embodiments, image processing software may be implemented for detection of the carbon fibres orientation. According to various

embodiments, a detection of different carbon fibres orientation may trigger an instruction to the laser system to scan on the next layer. According to various embodiments, adjustment on the focal plane position may be effected according to the depth of the layer carbon fibres being removed. For composites with unidirectional carbon fibres, according to various
 5 embodiments, the stepped profile ablated on the composite laminate may be defined by the dimension of the repair section and compliance with the 1:30 ratio on vertical to horizontal material removal in composite scarfing repairs.

[00056] Various embodiments may include a configuration of a circular array of nozzles for assisting laser removal process of CFRP composite material. Various embodiments may
 10 include a configuration of a radial exhaust manifold for the removal of fumes and debris generated in laser removal of CFRP composites material. According to various embodiments, the high pressure and precise direction of the gas jets delivered may generate improve cooling effect of the gas jet in the removal of CFRP composite laminates. According to various embodiments, the configuration and distribution of the multiple
 15 nozzles may generate a swirl flow which may sweep over the laser irradiated surface and which may enhance the cooling effect. According to various embodiments, the impingent force of the high velocity gas jets may exerts a shear stress on the surface of laser irradiated CRFP composites which may assist in clearing laser trimmed carbon fibres. According to various embodiments, the flow rate and delivery angle of the assisting media may be
 20 optimized to remove the desired areas and layers of composite laminates. According to various embodiments, the radial distribution of exhaust outlets may enhance the swirl flow generated. According to various embodiments, the swirl flow action may improve the removal of fumes and debris from the process area which may improve laser–material interaction and the efficiency of the process. According to various embodiments, a uniform
 25 temperature distribution may be achieved by the developed swirl cooling gas chamber. According to various embodiments, the use of a heat exchanger may reduce the temperature of the assisting gas jet without affecting its pressure. According to various embodiments, the kinetic energy of the cooled gas jet may be improved while released by delivery nozzle. According to various embodiments, the temperature recorded in the process may be reduced
 30 which may limit the heat load in the processed composite panel. According to various embodiments, rapid cooling may minimize the possibility chemical modification of the polymer matrix. According to various embodiments, reduction of the average laser removal process temperature may limits structural changes on the CFRP composites. According to

various embodiments, precise scarfing profiles in the aerospace maintenance, repair and operations (MRO) sector may be achieved. According to various embodiments, toxic fumes and debris generated may be better contained and captured by the containment device of the various embodiments. According to various embodiments, a flexible hose may be
 5 connected to the exhaust manifold to capture fumes and debris generated in the laser scarfing process. According to various embodiments, mechanical fixture or vacuum pad may be included to fix the nozzle array at curved aircraft fuselages structures for composite removal for composite repair.

[00057] Various embodiments may include integration of a 3D laser scanner with
 10 mechanical fixture device for ablation of curved/three dimensional composite laminate surfaces. According to various embodiments, the laser removal system may have an enclosure to block laser irradiation, fumes and noise from the removal process. According to various embodiments, an extraction system may remove fumes and ejected particles from the laser removal (ablation) process. According to various embodiments, a three
 15 dimensional computer-aided-design (CAD) model of the curved composite surface/section may be employed to generate the laser scanning path for the removal process. According to various embodiments, the laser removal process of CFRP composite laminates may be automated with computer control and with a process feedback system. Various embodiments may include a laser inline camera in combination with image analysis
 20 software to update the laser system control on the layer of carbon fibres to be removed.

[00058] Various embodiments may be used for laser ablation of CFRP laminates with unidirectional fibres. According to various embodiments, the size and location of the stepped profile may be defined by the area to be ablated (repaired) and compliance with the 1:30 ratio on vertical to horizontal material removal in composite scarfing repairs.

[00059] Multiple experiments have been conducted on the laser removal process of
 25 composite laminates in a layer by layer method using a working prototype developed based on the containment device according to the various embodiments. The heat exchanger has also been tested with ice as the coolant media and the temperature of the air (or gas) was observed to be reduced by 18 °C. The experimental results have shown good performance
 30 for the removal of composite materials from flat CFRP panels by high power Nd:YAG laser. The capability to generate step and taper scarfing profiles is also demonstrated in the experiments.

[00060] Various embodiments may be industrially applied in the repair of composite laminates in the aerospace MRO sector, as well as, other industrial sectors which require the repair of composite laminates.

[00061] The following pertain to various embodiments.

5 **[00062]** According to various embodiments, there is provided a containment device for laser ablation. The device may include an endless wall structure forming a continuous loop defining a central volume of space. The endless wall structure may have an endless base edge portion and an endless upper edge portion. The endless wall structure may include one or more exhaust outlet orifices in the endless wall structure. The device may further include
10 an inflow manifold lined along the endless upper edge portion of the endless wall structure. The inflow manifold may have a plurality of outlets and at least one inlet. The device may further include a plurality of nozzles. Each of the plurality of outlets of the inflow manifold may be respectively provided with at least one of said nozzles. Respective nozzle may extend into the central volume of space.

15 **[00063]** According to various embodiments, the endless wall structure may be of a funnel-like shape. According to various embodiments, the endless upper edge portion may be wider than the endless base edge portion and the endless wall structure may taper from the endless upper edge portion towards the endless base edge portion.

[00064] According to various embodiments, the inflow manifold may be lined along the
20 endless upper edge portion in a manner so as to form an inwardly overhanging extension from the endless upper edge portion which suspends over the central volume of space.

[00065] According to various embodiments, the endless upper edge portion may include an inward curl portion.

[00066] According to various embodiments, each of the plurality of outlets of the inflow
25 manifold may include a spout extending into the central volume of space.

[00067] According to various embodiments, a connection portion of each of the plurality of nozzles may be respectively coupled to a corresponding outlet of the plurality of outlets of the inflow manifold via a ball and socket joint.

[00068] According to various embodiments, the plurality of outlets of the inflow manifold
30 may be equally spaced from each other along the inflow manifold. According to various embodiments, each of the respective nozzle of the plurality of outlets of the inflow manifold that are equally spaced may be configured to direct a spray towards an opening formed by the endless base edge portion of the endless wall structure with a spray axis angled off a

vertical axis by an angle of $30^\circ \pm 10^\circ$ and whose orientation about the vertical axis is such that the spray axis may lie in a same vertical plane with a line tangent to a predetermined circle, wherein the predetermined circle is coaxial with the base opening and is of a smaller diameter than the base opening and in a same horizontal plane with the base opening, and wherein the vertical plane is perpendicular to the horizontal plane. According to various embodiments, the predetermined circle may be application specific and may approximate a desired size of a circular path of the swirl flow to be generated and contained within the containment device 200. According to various embodiments, the vertical axis may be parallel to a central axis passing through a centre of the opening.

10 **[00069]** According to various embodiments, a first subset of the plurality of outlets of the inflow manifold may be equally spaced from each other along the inflow manifold, and each of a second subset of the plurality of outlets may be disposed between two of the first subset of the plurality of outlets, wherein the number of the outlets in the second subset is less than the number of outlets in the first subset. According to various embodiments, each of the
15 respective nozzle of the first subset of the plurality of outlets that are equally spaced may be configured to direct a spray towards an opening formed by the endless base edge portion of the endless wall structure with a spray axis angled off a vertical axis by an angle of $30^\circ \pm 10^\circ$ and whose orientation about the vertical axis is such that the spray axis lies in a same vertical plane with a line tangent to a predetermined circle, wherein the predetermined circle
20 is coaxial with the base opening and is of a smaller diameter than the base opening and in a same horizontal plane with the base opening, and wherein the vertical plane is perpendicular to the horizontal plane. According to various embodiments, the predetermined circle may be application specific and may approximate a desired size of a circular path of the swirl flow to be generated and contained within the containment device 200. According to various
25 embodiments, the vertical axis may be parallel to a central axis passing through a centre of the opening. According to various embodiments, the central axis may be perpendicular to the opening.

[00070] According to various embodiments, the respective nozzle of each of the second subset of the plurality of outlets may be configured to direct a spray towards the centre of
30 the opening.

[00071] According to various embodiments, the device may further include an exhaust manifold running alongside an exterior wall surface of the endless wall structure. According

to various embodiments, the one or more exhaust outlet orifices in the endless wall structure may be respectively connected to the exhaust manifold via respective connecting tube.

[00072] According to various embodiments, the exhaust manifold may have a closed terminal end and an opened terminal end.

- 5 **[00073]** According to various embodiments, the exhaust manifold may have an increasing diameter or an increasing cross-sectional area from the closed terminal end to the opened terminal end.

[00074] According to various embodiments, the endless wall structure may include eight exhaust outlet orifices equally spaced along the endless wall structure. According to various
10 embodiments, each exhaust orifice may be located immediately underneath the inflow manifold.

[00075] According to various embodiments, the device may further include a fume extractor connected to the opened terminal end of the exhaust manifold.

[00076] According to various embodiments, the device may further include a fume
15 extractor connected to the one or more exhaust outlet orifices of the endless wall structure.

[00077] According to various embodiments, the endless wall structure may form a continuous circular loop. According to various embodiments, the inflow manifold may include a ring-shaped tube.

[00078] According to various embodiments, the at least one inlet of the inflow manifold
20 may be connected to a cold air supply.

[00079] According to various embodiments, the cold air supply may include a heat exchanger configured to supply cold air to the at least one inlet of the inflow manifold. According to various embodiments, the cold air supply may include a vortex tube with a cold air outlet of the vortex tube connected to the at least one inlet of the inflow manifold.

25 **[00080]** According to various embodiments, the device may further include one or more mechanical fixture or vacuum pad configured to couple the endless wall structure to a work surface.

[00081] According to various embodiments, there is provided a laser ablation system. The system may include the containment device as described herein. The system may further
30 include a laser scanner module. According to various embodiments, the laser scanner module may include a laser directed towards the central volume of space in a direction from the upper edge portion towards the endless base edge portion.

[00082] According to various embodiments, the laser may be directed towards a radially central portion of the central volume of space at the level of the endless base edge portion.

[00083] According to various embodiments, the laser scanner module may be integrated with the containment device.

5 **[00084]** Various embodiments have provided a containment device and/or a laser ablation system which may eliminate or resolve the thermal damage issue in laser removal of composite materials. Various embodiments may improve or enhance cooling of the work surface during laser ablation via uniform cooling. Various embodiments may also be more effective and efficient in removing debris and fumes generated during laser ablation.

10 **[00085]** While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes, modification, variation in form and detail may be made therein without departing from the scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the
15 meaning and range of equivalency of the claims are therefore intended to be embraced.

Claims

1. A containment device for laser ablation, the device comprising:
 - an endless wall structure forming a continuous loop defining a central volume of space, the endless wall structure having an endless base edge portion and an endless upper edge portion, and wherein the endless wall structure comprises one or more exhaust outlet orifices in the endless wall structure;
 - an inflow manifold lined along the endless upper edge portion of the endless wall structure, the inflow manifold having a plurality of outlets and at least one inlet; and
 - a plurality of nozzles, wherein each of the plurality of outlets of the inflow manifold is respectively provided with at least one of said nozzles, and wherein respective nozzle extends into the central volume of space.
2. The device as claimed in claim 1, wherein the endless wall structure is of a funnel-like shape, wherein the endless upper edge portion is wider than the endless base edge portion and the endless wall structure tapers from the endless upper edge portion towards the endless base edge portion.
3. The device as claimed in claim 1 or 2, wherein the inflow manifold is lined along the endless upper edge portion in a manner so as to form an inwardly overhanging extension from the endless upper edge portion which suspends over the central volume of space.
4. The device as claimed in any one of claims 1 to 3, wherein the endless upper edge portion comprises an inward curl portion.
5. The device as claimed in any one of claims 1 to 4, wherein each of the plurality of outlets of the inflow manifold comprises a spout extending into the central volume of space.
6. The device as claimed in any one of claims 1 to 5, wherein a connection portion of each of the plurality of nozzles is respectively coupled to a corresponding outlet of the plurality of outlets of the inflow manifold via a ball and socket joint.

7. The device as claimed in any one of claims 1 to 6, wherein the plurality of outlets of the inflow manifold is equally spaced from each other along the inflow manifold, wherein each of the respective nozzle of the plurality of outlets of the inflow manifold that are equally spaced is configured to direct a spray towards an opening formed by the endless base edge portion of the endless wall structure with a spray axis angled off a vertical axis, which is parallel to a central axis passing through a centre of the opening, by an angle of $30^{\circ} \pm 10^{\circ}$ and whose orientation about the vertical axis is such that the spray axis lies in a same vertical plane with a line tangent to a predetermined circle, wherein the predetermined circle is coaxial with the base opening and is of a smaller diameter than the base opening and in a same horizontal plane with the base opening, and wherein the vertical plane is perpendicular to the horizontal plane.

8. The device as claimed in any one of claims 1 to 6, wherein a first subset of the plurality of outlets of the inflow manifold is equally spaced from each other along the inflow manifold, and each of a second subset of the plurality of outlets is disposed between two of the first subset of the plurality of outlets, wherein a number of outlets of the second subset is less than a number of outlets of the first subset, wherein each of the respective nozzle of the first subset of the plurality of outlets that are equally spaced is configured to direct a spray towards an opening formed by the endless base edge portion of the endless wall structure with a spray axis angled off a vertical axis, which is parallel to a central axis passing through a centre of the opening, by an angle of $30^{\circ} \pm 10^{\circ}$ and whose orientation about the vertical axis is such that the spray axis lies in a same vertical plane with a line tangent to a predetermined circle, wherein the predetermined circle is coaxial with the base opening and is of a smaller diameter than the base opening and in a same horizontal plane with the base opening, and wherein the vertical plane is perpendicular to the horizontal plane.

9. The device as claimed in claim 8, wherein the respective nozzle of each of the second subset of the plurality of outlets is configured to direct a spray towards the centre of the opening.

10. The device as claimed in any one of claims 1 to 9, further comprising an exhaust manifold running alongside an exterior wall surface of the endless wall structure, wherein the one or more exhaust outlet orifices in the endless wall structure is respectively connected to the exhaust manifold via respective connecting tube.
11. The device as claimed in claim 10, wherein the exhaust manifold has a closed terminal end and an opened terminal end.
12. The device as claimed in claim 11, wherein the exhaust manifold has an increasing diameter from the closed terminal end to the opened terminal end.
13. The device as claimed in any one of claims 1 to 12, wherein the endless wall structure comprises eight exhaust outlet orifices equally spaced along the endless wall structure, and wherein each exhaust orifice is located immediately underneath the inflow manifold.
14. The device as claimed in any one of claims 11 to 13, further comprising a fume extractor connected to the opened terminal end of the exhaust manifold.
15. The device as claimed in any one of claims 1 to 14, wherein the endless wall structure forms a continuous circular loop, and wherein the inflow manifold comprises a ring-shaped tube.
16. The device as claimed in any one of claims 1 to 15, wherein the at least one inlet of the inflow manifold is connected to a cold air supply.
17. The device as claimed in claim 16, wherein the cold air supply comprises a heat exchanger configured to supply cold air to the at least one inlet of the inflow manifold, or a vortex tube with a cold air outlet of the vortex tube connected to the at least one inlet of the inflow manifold.

18. The device as claimed in any one of claims 1 to 17, further comprising one or more mechanical fixture or vacuum pad configured to couple the endless wall structure to a work surface.

19. A laser ablation system, comprising:
the containment device according to any one of claims 1 to 18; and
a laser scanner module , wherein the laser scanner module comprises a laser directed towards the central volume of space in a direction from the upper edge portion towards the endless base edge portion.

20. The laser ablation system according to claim 19, wherein the laser is directed towards a radially central portion of the central volume of space at the level of the endless base edge portion.