



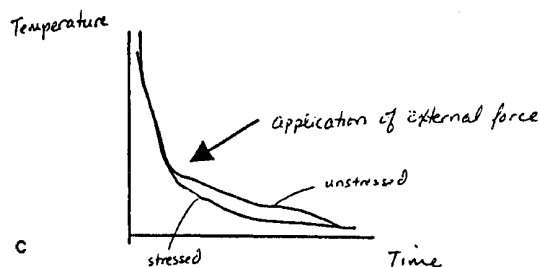
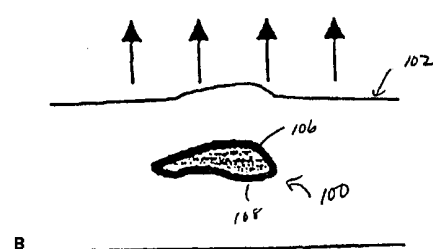
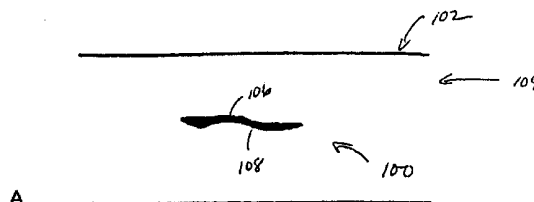
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(54) Title: METHOD AND APPARATUS FOR DETECTING KISSING UNBOND DEFECTS

(57) Abstract

An apparatus and an active thermographic method for detecting subsurface defects in a specimen (104), particularly kissing unbond defects, includes heating the specimen, applying a force to the surface (102) of the specimen to shift and separate the walls of a defect, and obtaining thermographic images of the specimen over time to monitor the heat flow through the specimen and detect thermal discontinuities. Because kissing unbond defects normally have good physical contacts, and therefore, good thermal conductivity, between its walls, these defects can go undetected in conventional active thermographic methods. By distorting the surface of the specimen, the kissing unbond defect is enlarged enough to generate sufficient thermal contrast for the defect to appear in the thermographic images.



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METHOD AND APPARATUS FOR DETECTING KISSING UNBOND DEFECTS

TECHNICAL FIELD

5 The present invention is directed to a method and apparatus for detecting subsurface defects in a specimen, and more particularly to a method and apparatus for detecting kissing unbond defects.

BACKGROUND ART

10 Active thermographic methods are often used to detect subsurface defects in a test specimen; that is, defects that are not readily ascertainable by viewing the specimen's surface. Active thermographic methods are often preferred because they are non-destructive and because they are capable of quickly locating subsurface defects over a large surface area. These methods usually involve heating the surface of the specimen
15 and monitoring the subsequent heat signature radiated over a period of time from the specimen by way of an infrared camera. Subsurface air gaps or vacuums within the tested specimen are good thermal insulators when compared with the surrounding material and will therefore appear as a high-contrast thermal discontinuity in the thermographic image sequence due to the differences in heat flow between the defect and the surrounding
20 defect-free area.

 In some cases, however, the subsurface defect does not appear clearly in the thermographic image sequence because the walls of the defect are in mechanical contact, allowing at least some heat flow across the defect. This type of defect is often called a "kissing unbond" defect and is illustrated in Figure 1A. As can be seen in Figure 1A, the
25 upper 106 and lower 108 walls of the defect 100 touch each other. Conventional active thermographic methods often cannot detect this type of defect because the mechanical

contact between the walls of the defect provides partial thermal conduction rather than a large thermal discontinuity, thereby decreasing the thermal contrast in the thermographic images. This sometimes occurs in bonded or laminated structures, where unbonded, partially bonded, or delaminated areas in the joint may appear completely bonded in the thermographic image sequence.

There is a need for a device and method that can detect a kissing unbond subsurface defect in a non-destructive manner via active thermographic techniques.

SUMMARY OF THE INVENTION

Accordingly, the present invention detects a kissing unbond-type subsurface defect in a specimen by changing the dimensions of the defect while or immediately after the part is heated. The specimen's surface temperature is monitored over time to detect the defect. More particularly, the invention includes an image generator, such as an infrared camera, and means for changing the pressure on a surface of the specimen being tested to stress and unstress the specimen. The pressure changes cause the walls of the kissing unbond defect to move relative to each other, separating and/or shifting the walls of the defect to create thermal discontinuities in the specimen and increase the thermal contrast between the defect and the surrounding material. The pressure changes can include applying a vacuum to generate a tensile force on the surface of the specimen, which displaces the specimen surface at areas containing kissing unbond defects, or applying acoustic, ultrasonic, or mechanical energy at selected time intervals to shift unbonded surface with respect to each other. As the degree of contact in the defect's walls is altered, sequential thermographic images of the sample are obtained over time as heat flows through the specimen, revealing defects that may otherwise be undetectable by conventional means.

BRIEF DESCRIPTION OF THE DRAWINGS

Figures 1A, 1B and 1C illustrate a kissing unbond defect and its corresponding temperature vs. time trace before and during application of a tensile force on a specimen's surface above the defect;

Figure 2 illustrates a first embodiment of a kissing unbond defect detector according to the invention;

Figure 3 illustrates a second embodiment of the inventive kissing unbond defect detector;

Figure 4 illustrates a third embodiment of the inventive kissing unbond defect detector; and

Figures 5A and 5B illustrate a fourth embodiment of the inventive kissing unbond defect detector.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figures 1A and 1B illustrate a kissing unbond defect 100 before and during application of a tensile force on a surface 102 of a specimen 104 to be tested. As explained above and as shown in Figure 1A, the walls of the kissing unbond defect 100 may allow partial transfer of heat across the defect 100, causing marginal thermal contrast with respect to the surrounding material and rendering the defect 100 virtually undetectable via conventional methods.

Figure 1B illustrates what happens to the kissing unbond defect 100 when tensile force is applied to the specimen surface 102 directly above the defect 100. If there is no defect in the area where the tensile force is applied, the tensile force causes little or no surface displacement. If, however, the tensile force is applied to the surface 102 directly

above a defect 100, as shown in Figure 1B, the force will create a noticeable surface displacement as the walls 106, 108 of the defect 100 separate or otherwise change in their degree of contact, creating an air gap or enclosed vacuum having different thermal characteristics than the surrounding material in the specimen 104.

5 To detect thermal contrasts in the specimen 104 indicating the presence of a defect 100, one embodiment of the invention includes comparing the temperature vs. time trace of each pixel in the image of an unstressed specimen with the temperature vs. time trace of each pixel in the image of a stressed specimen. Any differences in the two traces, indicating a change in the dynamic heat flow characteristic in the stressed specimen as the specimen 104 cools, indicates the presence of a sub-surface defect. An example of such a comparison is illustrated in Figure 1C, which illustrates a noticeable change in the temperature vs. time trace of the stressed specimen as force is applied. In this example, the sub-surface defect causes the specimen 100 to cool noticeably faster in the defect area than the unstressed sample over time. If the defect did not exist, the traces for both the stressed and the unstressed specimens would have been the same.

Figure 2 illustrates one embodiment of the present invention. The apparatus shown in Figure 2 includes a sealed enclosure 200, a heater, such as flashlamps 202, and an infrared camera 204. The enclosure should be sealed in an airtight manner so it can hold air pressure variations in a constant, measurable way. Although the figure shows that the enclosure 200 has an opening 206, preferably gasketed, for accommodating a lens 208 on the camera 204, the enclosure 200 can also be constructed with a window through which the lens 208 and/or the flashlamps 202 can project onto the specimen 104. Note that it is preferable to place the flashlamps 202 within the enclosure 200 since it may be difficult to find window materials that pass both infrared and visible wavelengths at acceptable levels for accurate monitoring. Possible window materials include zinc

sulfide, zinc selenide, germanium, silicon, and any other material that is transparent in the wavelength band of the camera. The specific material chosen will depend on the infrared camera's 204 wavelength and the type of heater being used to heat the specimen. In short, the window material may be any material that is transparent in the wavelength band of the camera, has sufficient rigidity to withstand vacuum pressure, has the ability to withstand thermal cycling, and resists discoloration over time.

The sealed enclosure 200 preferably has a skirt 210 made out of a flexible material, such as rubber or an elastomeric polymer, to form a vacuum seal on the surface 102 of the specimen 104. The skirt 210 may also include holes 211 leading to the interior of the enclosure 200. A pump fitting 212 attached to the sealed enclosure 200 is connected to a pump (not shown) for increasing and decreasing the air pressure inside the enclosure 200.

To maintain the airtightness of the enclosure 200, all openings, such as the opening accommodating the infrared camera lens 208, should be sealed or fitted with gaskets. The pump can vary the air pressure inside the enclosure 200 by pumping air into or pulling air out of the enclosure 200, thereby distorting the surface 102 of the specimen 104 and shifting the walls of the kissing unbond defect 100. To detect a kissing unbond defect, the flashlamps 202 heat the surface 102 of the specimen 104, and the pump varies the pressure inside the enclosure 200 to vary the degree of contact between the walls 106, 108 of the kissing unbond defect 100, if one exists at the enclosure's 200 location.

The infrared camera 204 generates a series of thermographic images over time of the de-pressurized and/or pressurized images to capture information about the thermal energy flow through the specimen as the specimen 104 cools. As explained above with respect to Figures 1A and 1B, kissing unbond defects will tend to enlarge when the enclosure 200 is de-pressurized, thereby creating a thermal discontinuity, because the

vacuum will distort the surface 102 above the defect 100 to a greater degree than the surface 102 of the material surrounding the defect 100. The thermographic image sequence generated by the camera 204 can be sent to a display monitor or computer (not shown) for further analysis, if desired. It is important to note that although the use of vacuum pressure is believed to be a preferred way to distort the surface 102, other techniques for distorting surface 102 are contemplated, such as physically loading the specimen (through tension, compression, shear, etc.) or vibrating the specimen (such as via ultrasonic means).

Figure 3 illustrates a variation of the apparatus explained above by including an infrared transparent window 300 inside the enclosure 200, dividing the enclosure 200 into a first section 302 and a second section 304. The window 300 must create an airtight separation between the first and second sections 302, 304 so that the second section 304 can maintain variances in its air pressure. As in the first embodiment, the camera 204 and flashlamps 202 can be arranged outside the enclosure 200, or alternatively the camera lens 208 and/or the flashlamps 202 can be disposed inside the first section 302 of the enclosure 200, as illustrated in Figure 3. The pump (not shown) is arranged to inject air into and/or withdraw air from only the second section 304 through the pump fitting 212, without varying the air pressure in the first section 302. De-pressurizing the second section 304 will pull on the surface of the specimen and shift the walls of any kissing unbond defects 100 below the surface, causing thermal contrast that is detectable by the infrared camera 204. In this embodiment, because the pump has to inject and remove air only from the second section 304 rather than from the entire enclosure 200, pressure changes can be conducted more quickly and with a smaller pump due to the reduced volume of the second section 304.

The devices shown in Figures 2 and 3 are particularly appropriate for evaluating smaller specimens 104 because the enclosure 200 only has to be moved a few times to cover the entire surface area of the specimen 104. For specimens having a larger surface area, however, individually testing small sections of the specimen 104 can be time-

5 consuming because the enclosure 200 must be repositioned and re-pumped at each new location when the infrared camera 204 generates the thermographic image sequence for the new location. Figure 4 illustrates another embodiment of the present invention where the pressure of the air surrounding the entire specimen 104 can be changed all at once rather than in individual small sections. The embodiment includes a sealed chamber 400

10 large enough to enclose the specimen 104. If the camera 204 and heater, such as a flashlamp 202, are both located inside the chamber 400, power cords and connectors can be run through gasketed ports (not shown) to the outside of the chamber 400 without compromising the airtightness of the chamber 400. Alternatively, as shown in Figure 4, the chamber can include a transparent window 402 so that either the camera 204 or the

15 flashlamps 202, or both, can be located outside the chamber 400. As explained above, the window 402 material is selected based on the camera wavelength and on the type of heater used. In this embodiment, the pump (not shown) pressurizes and/or de-pressurizes the entire chamber 400 via the pump fitting 212, thereby closing and/or opening all of the kissing unbond defects 100 in the specimen 104 at virtually the same time. Like the

20 previously described embodiments, the flashlamps 202 heat the surface of the specimen before or during the pressure changes and the camera 204 generates active thermographic images to monitor the heat flow through the specimen 104. The specimen 104 and/or camera 204 can be repositioned to obtain thermographic image sequences for all surfaces of the specimen 104.

Yet another embodiment of the present invention is shown in Figures 5A and 5B. In this embodiment, heat is preferably provided by at least one low-power lamp 602 that continuously directs heat to the specimen surface 102. As a result, the surface temperature of the specimen 104 rises at a steady state or in a slow monotonic fashion while the specimen 104 is in an unstressed state. When the specimen 104 reaches a steady state temperature, the thermal energy from the lamps 602 is dissipated through the specimen 104 at the same rate that the energy is being absorbed. Further, for a sufficiently thick specimen 104, the specimen 104 will cool generally via smooth conduction of thermal energy from the surface being heated to the cooler rear portion of the specimen 104. Applying an external force to the specimen 104 will disrupt this equilibrium around the kissing unbond defect 100 and thereby generate sufficient thermal contrast for the defect 100 to be thermographically detectable. As illustrated in Figure 5A, stressing the disbonded area can be conducted via ultrasound, acoustic, or mechanical energy through an attachment 604 coupled to the specimen's surface 102. Further, as can be seen in Figure 6B, applying the external force in a discrete, systematic manner over time will create noticeable discontinuities in the temperature vs. time trace of the specimen 104 as the external force creates subsurface pockets that interrupt the flow of thermal energy through the specimen 104. The embodiment illustrated in Figures 5A and 5B is particularly suitable for inspecting coated metallic specimens, where the metallic specimen tends to be a better heat conductor than the coating. Any delaminations or weak bonding areas between the coating and the substrate tend to act as kissing unbond defects and can be stressed by the external force, making them detectable by the infrared camera 204.

Note that with all of the above disclosed embodiments, there are many ways and sequences in which to heat the specimen 104, vary the pressure on and around the

specimen 104, and generate thermographic image sequences without departing from the scope of the invention. For example, the pump can generate a vacuum within the enclosure 200 or chamber 400, shifting the walls of any kissing unbond defects 100, before or during heating while the camera 204 generates a thermographic image sequence
5 as the specimen 104 heats and cools. Alternatively, the kissing unbond defects 100 can be alternately stressed and unstressed by varying the pressure inside the enclosure 200 or chamber 400 or by starting and stopping force application and comparing the active thermographic images of the stressed specimen and the unstressed specimen. Thus, the invention can effectively detect kissing unbond defects 100 that would ordinarily go
10 undetected by conventional active thermographic methods simply by displacing the surface 102 above the defect 100 to increase the thermal contrast between the defect 100 and the surrounding material. Further, the heat input can also be varied and sent in the form of a pulse, a step, modulated or continuously applied. The specific sequence in which the heating, stress application, and image generating steps are conducted does not
15 matter in the invention as long as the stress changes at least one dimension of the kissing unbond defect to render it visible via active thermographic methods.

The manner in which the stressed image and the unstressed image are evaluated can be selected from various methods. Calculating/viewing the difference between the sums of the stressed images and the unstressed images is one way to compare the two
20 images. Alternatively, histograms of the stressed and unstressed images can be compared, such as according to the method described in co-pending patent application Serial No. 08/608,901 entitled "Method of Interpreting Thermographic Data For Non-Destructive Evaluation," incorporated herein by reference. Other methods include applying of a mathematical correlation function to correlate the two sets of images,
25 viewing an image displaying the ratio between the stresses and unstressed images, and

visually comparing the stressed and unstressed images without conducting additional calculations.

The application and removal of stress on the specimen can be repeated several times during a single heating cycle. Alternatively, separate heating cycles can be
5 conducted when generating the stressed and unstressed images. Note that regardless of the specific method and device used to stress/unstress the specimen and monitor heat flow through the specimen, the methods and devices will reveal only kissing unbond defects because other defects that are detectable via conventional active thermographic methods will appear identical in the stressed and unstressed images and will therefore cancel each
10 other out when the two images are compared.

It should be understood that various alternatives to the embodiments of the invention described herein may be employed in practicing the invention. It is intended that the following claims define the scope of the invention and that the method and apparatus within the scope of these claims and their equivalents be covered thereby.

CLAIMS

WHAT IS CLAIMED IS:

1. A method for non-destructive evaluation of a specimen, comprising the
5 steps of:

directing heat onto the specimen;

applying a force onto a surface of the specimen; and

generating an infrared image to detect the presence of a subsurface defect,

wherein the application of the force onto the surface of the specimen exacerbates a
10 thermal discontinuity proximate to the subsurface defect.

2. The method of claim 1, wherein the applying step includes decreasing air
pressure in a vicinity of the specimen to change the at least one dimension of the
subsurface defect.

15

3. The method of claim 1, wherein the applying step includes disturbing the
specimen using ultrasonic, acoustic or mechanical energy.

4. The method of claim 1, wherein the applying step includes:
20 placing the specimen in a chamber; and
generating a vacuum in the chamber to change at least one dimension of the
subsurface defect.

5. The method of claim 1, wherein the applying step includes:
25 placing a sealed enclosure on the surface of the specimen; and

generating a vacuum in the sealed enclosure to change the at least one dimension of the subsurface defect.

6. The method of claim 5, wherein the sealed enclosure is divided into two
5 sections such that the vacuum generated in said generating step produces a vacuum in one of the two sections.

7. The method of claim 1, wherein said applying step includes increasing and decreasing the pressure on the specimen surface, wherein said generating step includes
10 generating a first thermographic image when the pressure is increased and generating a second thermographic image when the pressure is decreased, and wherein the method further comprises the step of comparing the first and second active thermographic images to detect the subsurface defect.

15 8. The method of claim 7, wherein the generating step generates a plurality of first thermographic images and a plurality of second thermographic images over time, and wherein the comparing step is conducted by calculating the difference of the sums of the first thermographic images and the second thermographic images.

20 9. The method of claim 7, wherein the generating step generates a plurality of first thermographic images and a plurality of second thermographic images over time, and wherein the comparing step includes generating histograms corresponding to the plurality of first and second thermographic images and comparing the histograms for the plurality of first thermographic images with the histograms for the plurality of second
25 thermographic images.

10. The method of claim 7, wherein the generating step generates a plurality of first thermographic images and a plurality of second thermographic images over time, and wherein the comparing step includes mathematically correlating the plurality of first
5 thermographic images with the plurality of second thermographic images.

11. The method of claim 7, wherein the generating step generates a plurality of first thermographic images and a plurality of second thermographic images over time, and wherein the comparing step includes viewing an image corresponding to the ratio
10 between the plurality of the first thermographic images and the plurality of the second thermographic images.

12. The method of claim 7, wherein the generating step generates a plurality of first thermographic images and a plurality of second thermographic images over time, and
15 wherein the comparing step includes visually comparing the plurality of first thermographic images and the plurality of second thermographic images.

13. The method of claim 7, wherein the applying step includes placing the specimen in a chamber before said generating step.
20

14. The method of claim 7, wherein the applying step includes placing a sealed enclosure on the specimen surface before said generating step.

15. A method for non-destructive evaluation of a specimen, comprising the
25 steps of:

directing heat onto the specimen;
placing a sealed enclosure on the specimen surface;
applying a vacuum to at least a portion of a surface of the specimen by decreasing
the air pressure in the sealed enclosure; and
5 generating an infrared image to detect the presence of a subsurface defect,
wherein the vacuum from the applying step enlarges at least one dimension of the
subsurface defect to create a thermal discontinuity.

16. The method of claim 15, wherein the sealed enclosure is divided into two
10 sections such that the vacuum generated in said applying step produces a vacuum in one
of the two sections.

17. The method of claim 15, wherein said applying step further includes the
step of increasing the air pressure in the sealed enclosure, wherein said generating step
15 includes generating a first active thermographic image when the pressure is increased and
generating a second active thermographic image when the pressure is decreased, and
wherein the method further comprises the step of comparing the first and second active
thermographic images to detect the subsurface defect.

20 18. An apparatus for non-destructive evaluation of a specimen, comprising:
a heat-sensitive image generator that generates thermographic images;
a heater that increases the temperature of the specimen; and
means for applying a force to a surface of the specimen, wherein the applying
means changes at least one dimension of a subsurface defect in the specimen to create a
25 thermal discontinuity.

19. The apparatus of claim 18, wherein said heater is at least one flashlamp that directs heat to the specimen surface.

5 20. The apparatus of claim 18, wherein said distorting means includes:
a sealed enclosure that is placed on the specimen's surface; and
a vacuum pump that generates a vacuum inside the sealed enclosure.

21. The apparatus of claim 20, wherein the sealed enclosure is divided into
10 two sections, and wherein the vacuum pump generates the vacuum inside the sealed enclosure in one of the two sections.

22. The apparatus of claim 20, wherein the heater is a flashlamp disposed inside the sealed enclosure to direct light to the specimen surface.

15

23. The apparatus of claim 18, wherein said distorting means includes:
a chamber for holding the specimen; and
a vacuum pump that generates a vacuum inside the chamber.

20 24. The apparatus of claim 23, wherein the chamber includes a window, wherein the heater is a flashlamp located outside the chamber and directs light through the window to heat the specimen, and wherein at least part of the image generator is located outside the chamber.

25. The apparatus of claim 23, wherein the chamber includes a window, wherein the heater is a flashlamp located inside the chamber and directs light on the specimen to heat the specimen, and wherein at least part of the image generator is located outside the chamber.

5

26. The apparatus of claim 23, wherein at least one of the heater and the image generator are located inside the chamber.

27. The apparatus of claim 18, wherein said heater is a lamp that continuously
10 directs heat to the specimen, and wherein said applying means includes an attachment that couples to the surface of the specimen to apply the force.

28. The apparatus of claim 27, wherein said attachment provides the force via ultrasonic, acoustic, or mechanical energy.

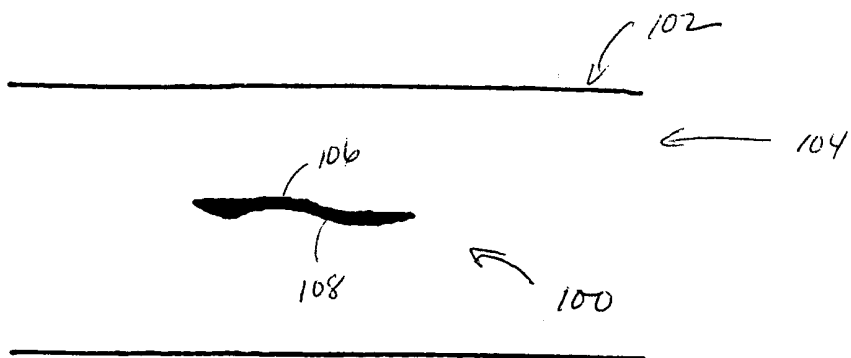


FIG. 1A

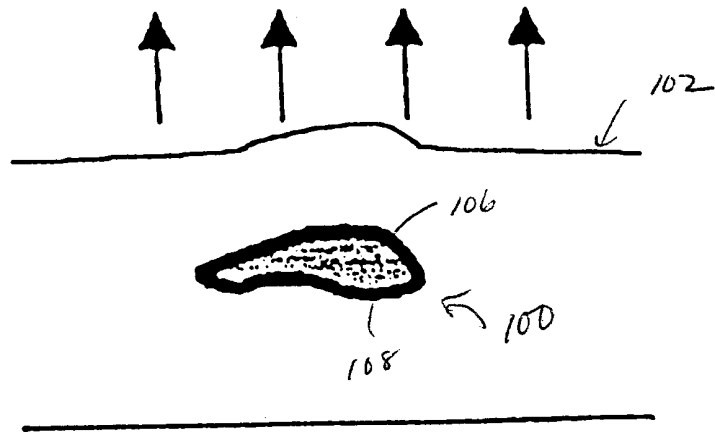


FIG. 1B

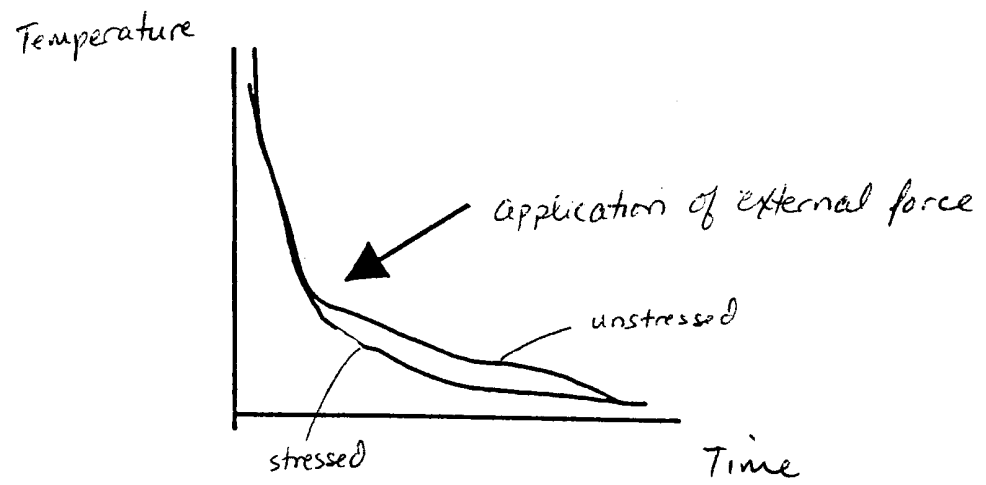


FIG 1C

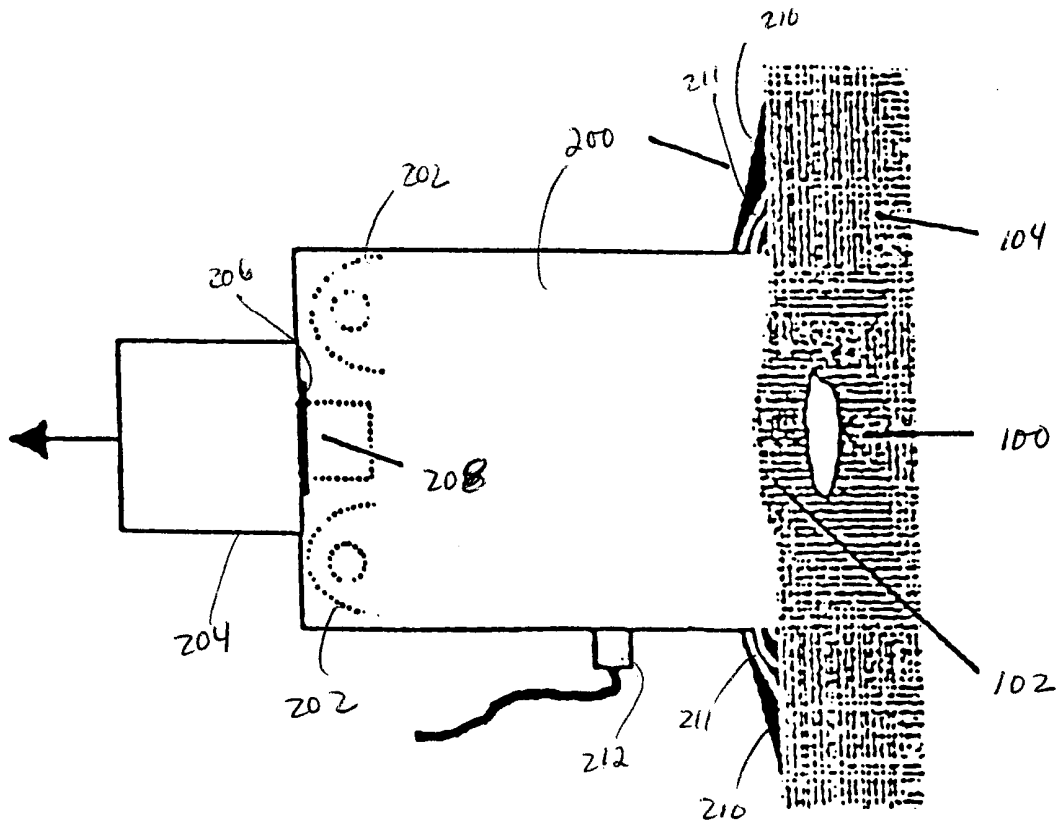


FIG. 2

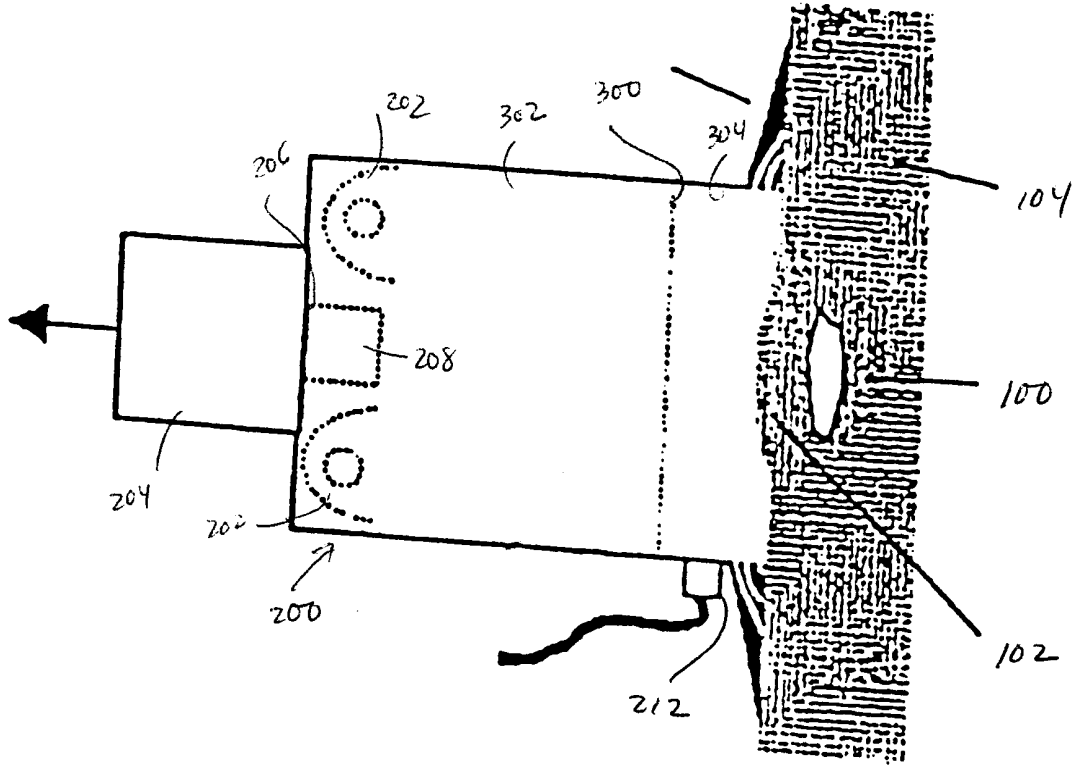


FIG. 3

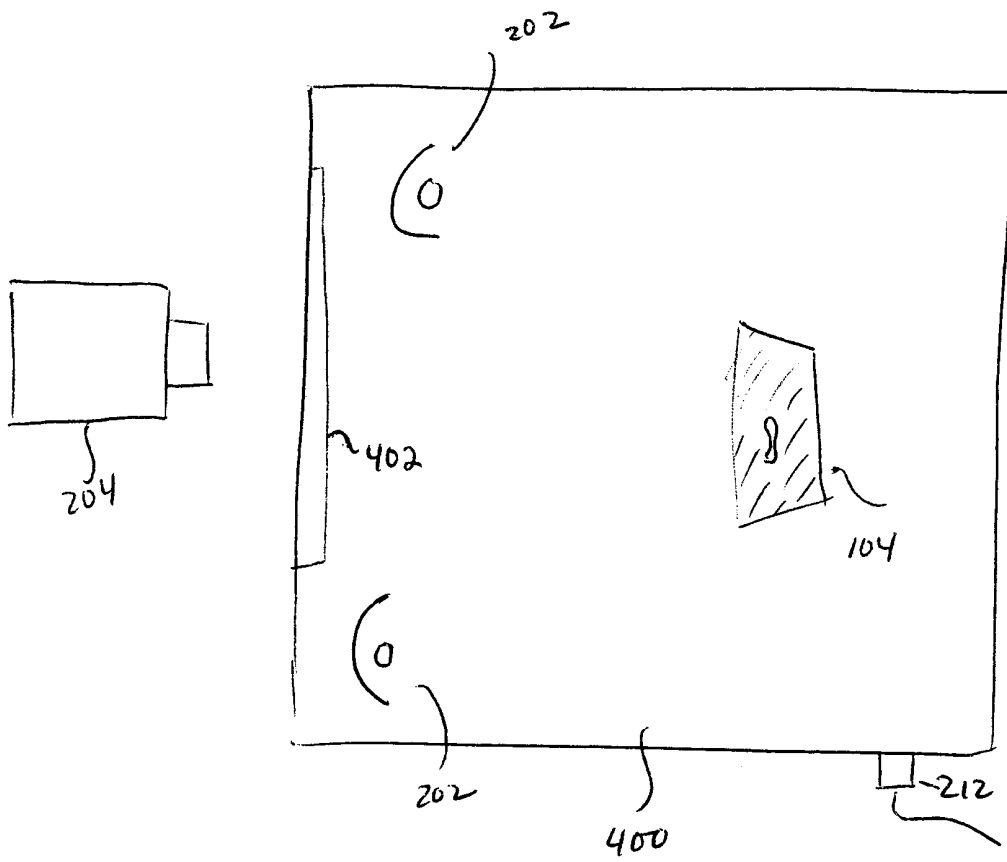


FIG. 4

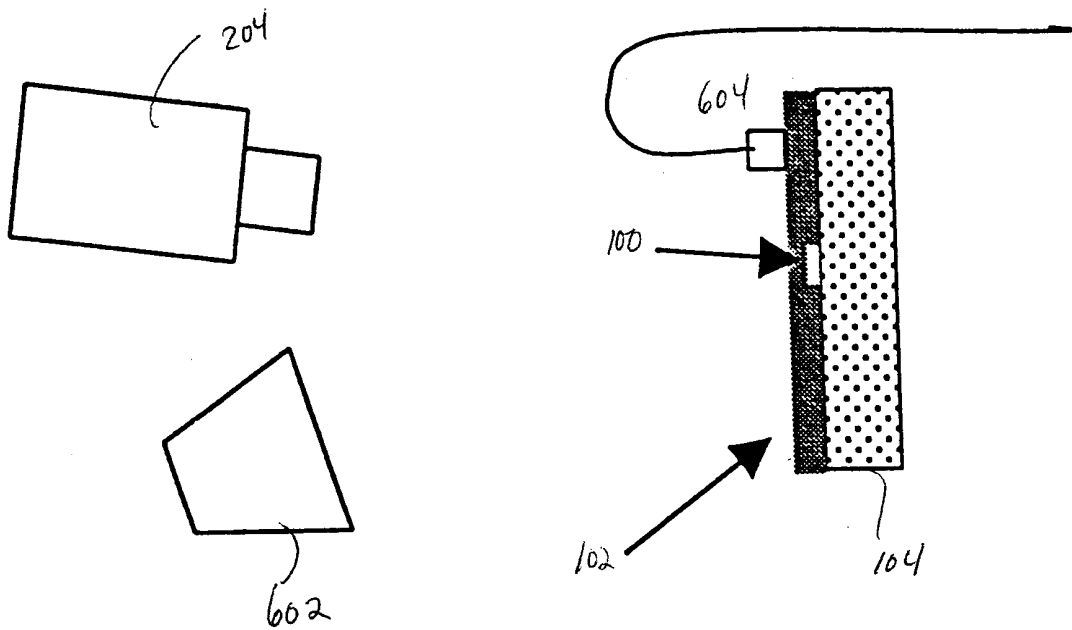


FIG. 5A

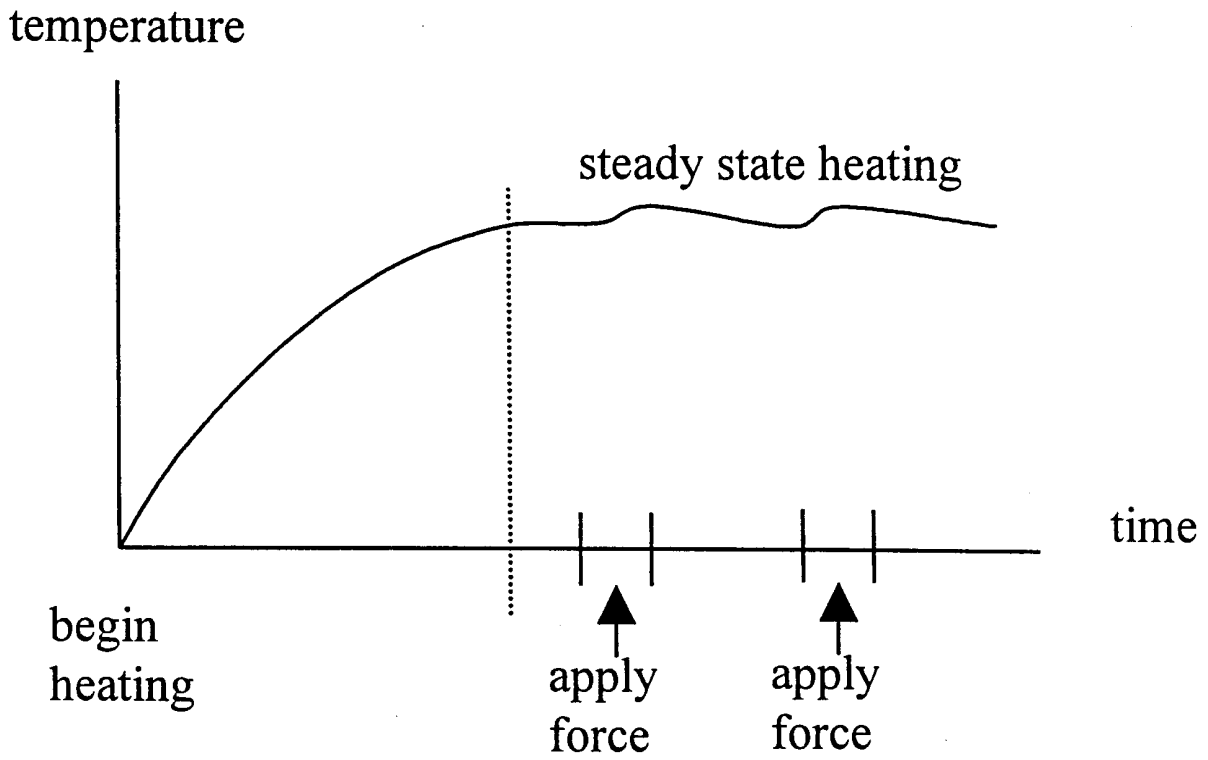


FIG. 5B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/09175

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :G01N 25/72, 29/04, 29/06
US CL :374/5, 50; 250/330

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 374/4, 5, 6, 7, 50, 137; 250/330, 332, 342, 358.1

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

USPTO APS WEST 2.0 search terms: semiconductor, wafer, substrate, temperature, testing, unbond, defect, image, pressure, vacuum, pressure, force, chamber, ultrasound

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,201,841 A (LEBEAU et al.) 13 April 1993 (13.04.1993), see entire document.	1-4, 18-19, 23, 27-28
Y	US 5,396,068 A (BETHEA) 07 March 1995 (07.03.1995), see entire document.	1-4, 18-19, 23, 27-28
A	US 3,599,476 A (CORBETT) 17 August 1971 (17.08.1971), see entire document.	1-28
A	US 4,752,140 A (CIELO et al.) 21 June 1988 (21.06.1988), abstract.	1-28
A	US 4,860,687 A (FRIJLINK) 29 August 1989 (29.08.1989), col. 1.	4, 13, 23
A	GB 2164147 A (HALASE III, et al.) 12 March 1986 (12.03.1986), abstract.	1-28

Further documents are listed in the continuation of Box C. See patent family annex.

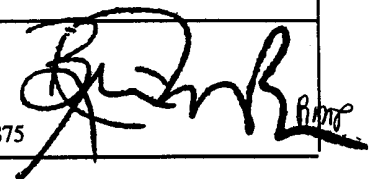
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"E" earlier document published on or after the international filing date	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
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"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search
19 JUNE 2000

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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JA 0151046 A (YASHIMA) 29 August 1984 (29.08.1984), abstract.	1-28
A	SU 1081510 A (TOMSK) 23 March 1984 (23.03.1984), abstract.	1-28
A	KUTZSCHER, et al. Thermal and Infrared Methods For Nondestructive Testing Of Adhesive-Bonded Structures. 27th National Fall Conference Of The American Society For Nondestructive Testing. October 1967. Pages 143-148.	1-28
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A	SU 0879452 (DYATLOV) 07 November 1981 (07.11.1981), abstract.	1-28