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An agency of Industry Canada

CA 2897690 C 2017/11/28

(11)(21) **2 897 690**

(12) **BREVET CANADIEN**
CANADIAN PATENT

(13) **C**

(22) **Date de dépôt/Filing Date:** 2015/07/17
(41) **Mise à la disp. pub./Open to Public Insp.:** 2016/02/28
(45) **Date de délivrance/Issue Date:** 2017/11/28
(30) **Priorité/Priority:** 2014/08/28 (US14/472,300)

(51) **Cl.Int./Int.Cl.** ***G01N 3/06*** (2006.01)
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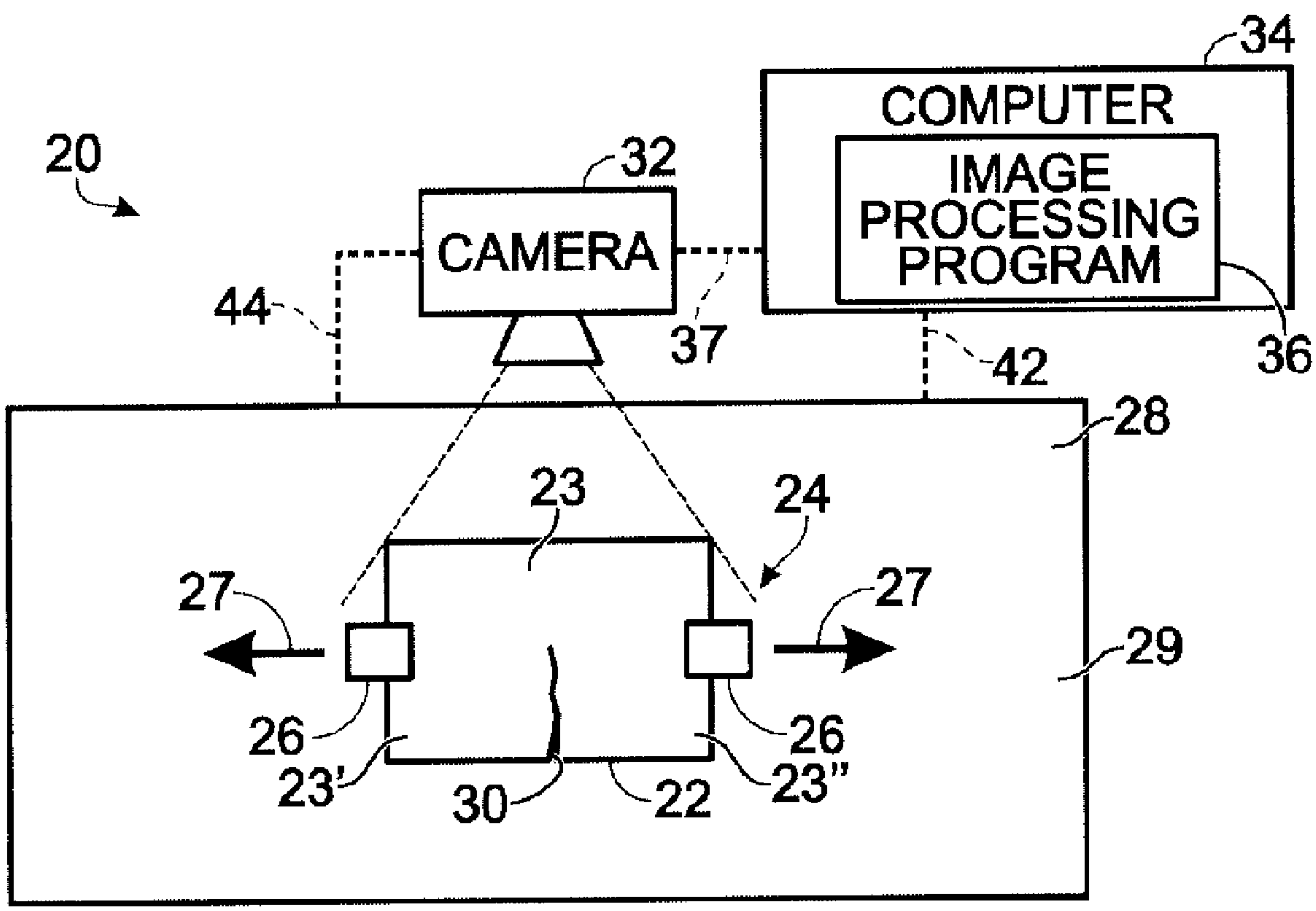
(54) **Titre : MECANISMES ET METHODES DE DETECTION DE LA CROISSANCE D'UNE FISSURE**
(54) **Title: SYSTEMS AND METHODS FOR DETECTING CRACK GROWTH**



(57) **Abrégé/Abstract:**
A system and method for detecting crack propagation in a material test specimen may include color contrasting a surface of a test specimen, acquiring a plurality of photographic images of the specimen during application of a stress load, processing the plurality of images to detect characteristics of pixels that are outside a baseline range of pixel characteristics indicative of a contrast between a crack in the test specimen and the color contrasted surface of the test specimen, and generating an output of a strain energy release rate based on changes in detected crack length over time.

Abstract

A system and method for detecting crack propagation in a material test specimen may include color contrasting a surface of a test specimen, acquiring a plurality of photographic images of the specimen during application of a stress load, processing the plurality of images to detect characteristics of pixels that are outside a baseline range of pixel characteristics indicative of a contrast between a crack in the test specimen and the color contrasted surface of the test specimen, and generating an output of a strain energy release rate based on changes in detected crack length over time.

SYSTEMS AND METHODS FOR DETECTING CRACK GROWTH

Field

This disclosure relates to specimen testing. More specifically, the disclosed embodiments relate to systems and methods for detecting crack growth in a test specimen during application of a stress load.

Background

Structural components and/or other materials may be tested to determine their material characteristics. Determining the material characteristics of a structural component and/or material may be important in determining, for example, whether or not that component or material is suitable for a particular use. In some tests, a specimen that is representative of a particular structural component and/or material may be selected. During the test, one or more forces may be applied to the test specimen to determine the characteristics of that specimen. In some tests, one or more forces may be applied to induce and/or propagate a crack in the test specimen. In those tests, measuring the crack length and the associated load provides information regarding the material characteristics of the test specimen. An example of a material characteristic that may be calculated based on the crack length and associated load is the strain energy release rate.

X-ray imaging equipment has been used to detect and measure cracks in test specimens. The X-ray imaging equipment can capture and process a limited number of images over a particular time period, such as about one image over a three-second period. Additionally, the cracks shown on the X-ray images typically are manually measured by a person using a ruler or tape measure (either physical or digital). Material characteristics are then calculated based on the measured crack length.

However, material characteristics of a test specimen may not be accurately determined or calculated using the above method. For example, only a limited number of X-ray images may be obtained during propagation of a crack in a test specimen as compared to the speed of a digital camera. Additionally, the cracks in the X-ray images may not be accurately measured by a person using a ruler; because x-ray images consist of averaged frames, there may be no clear indication of where a crack ends. Inaccurate determination of material characteristics may lead to selection of a component or material that is not suitable for its intended use, which may lead to premature failure of that component or material while in service.

Summary

The present disclosure provides a method of detecting crack propagation in a material test specimen. In some embodiments, the method may include color contrasting a surface of a test specimen and acquiring a plurality of photographic images of the specimen during application of a stress load. In some embodiments, the method may include processing the plurality of images to detect characteristics of pixels that are outside a baseline range of pixel characteristics indicative of a contrast between a crack in the test specimen and the color contrasted surface of the test specimen. In some embodiments, the method may include generating an output of a strain energy release rate based on changes in detected crack length over time.

The present disclosure provides a system for detecting crack propagation in a material test specimen. In some embodiments, the system may include a test platform configured to support a material test specimen on a background. The material test specimen may have a top surface color contrasting a surface color of the background. In some embodiments, the system may include a camera directed toward the test platform and configured to acquire a plurality of photographic images of a test specimen located on the platform during application of a stress load to the test specimen. In some embodiments, the system may include an image processing program that receives the plurality of photographic images. The image processing program may be configured to detect, in the plurality of photographic images, pixel characteristics that are outside a baseline range of pixel characteristics, and measure changes in a detected crack length based on the detected pixel characteristics.

The present disclosure provides a method of detecting crack propagation in a material test specimen. In some embodiments, the method may include supporting a material test specimen over a background. The specimen may have a top surface color contrasting a surface color of the background. In some embodiments, the method may include applying a stress load to the specimen and acquiring multiple photographic images of an extending crack length in the specimen during the applying step. In some embodiments, the method may include detecting pixel characteristics that are different from pixel characteristics associated with the top surface color to measure crack length in the specimen.

In one embodiment, there is provided a method of detecting crack propagation in a material test specimen. The method involves color contrasting a surface of a test specimen with a surface color of a background, supporting the test specimen over the background, acquiring a plurality of photographic images of the specimen during application of a stress load, processing the plurality of images to detect characteristics of pixels that are outside a baseline range of pixel characteristics indicative of a contrast between the background revealed through a crack in the test specimen and the color contrasted surface of the test specimen, and generating an output of a strain energy release rate based on changes in detected crack length over time.

In another embodiment, there is provided a system for detecting crack propagation in a material test specimen. The system includes a test platform configured to support a material test specimen on a background. The background has a surface color selected to provide a color contrast with a top surface color of the test specimen. The system further includes a camera directed toward the test platform and configured to acquire a plurality of photographic images of the test specimen located on the platform during application of a stress load to the test specimen. The system further includes an image processing program that receives the plurality of photographic images, and that is configured to: detect, in the plurality of photographic images, pixel characteristics of the background revealed through a crack in the test specimen; and measure changes in a detected crack length based on the detected pixel characteristics.

In another embodiment, there is provided a method of detecting crack propagation in a material test specimen. The method involves selecting a surface color of a background in a test platform and supporting a material test specimen over the background. The specimen has a top surface color contrasting the surface color of the background. The method further involves applying a stress load to the specimen, acquiring multiple photographic images of an extending crack length in the specimen during the applying step, and detecting pixel characteristics of the background revealed through a crack in the specimen that are different from pixel characteristics associated with the top surface color of the specimen to measure crack length in the specimen.

The features and functions may be achieved independently in various embodiments of the present disclosure, or may be combined in yet other embodiments, further details of which can be seen with reference to the following description and drawings.

Brief Description of the Drawings

Fig. **1** is a schematic diagram of an illustrative crack detection system.

Fig. **2** is a schematic diagram of an illustrative test specimen prior to formation of a crack.

Fig. **3** is a schematic diagram of the test specimen of Fig. **2** during formation and/or propagation of a crack.

Fig. **4** is a schematic diagram of the test specimen of Fig. **2** during propagation of the crack of Fig. **3**.

Fig. **5** is an illustrative graph showing load vs. displacement for the stress load applied to the test specimen of Fig. **2**.

Fig. **6** is a schematic diagram of pixels of an illustrative photographic image of the test specimen of Fig. **2** showing illustrative red values for those pixels.

Fig. **7** is a schematic diagram of pixels of an illustrative photographic image of the test specimen of Fig. **2** showing illustrative green values for those pixels.

Fig. **8** is a schematic diagram of pixels of an illustrative photographic image of the test specimen of Fig. **2** showing illustrative blue values for those pixels.

Fig. **9** is a schematic diagram of pixels of an illustrative photographic image of the test specimen of Fig. **4** showing illustrative red values for those pixels.

Fig. **10** is a schematic diagram of pixels of an illustrative photographic image of the test specimen of Fig. **4** showing illustrative green values for those pixels.

Fig. **11** is a schematic diagram of pixels of an illustrative photographic image of the test specimen of Fig. **4** showing illustrative blue values for those pixels.

Fig. **12** is a schematic diagram of an illustrative matrix generated based on the schematic diagrams of Figs. **9-11**.

Fig. **13** is a flowchart depicting an illustrative method of crack growth detection.

Fig. **14** is a schematic diagram of various components of an illustrative data processing system.

Description

Overview

Various embodiments of systems and methods for detecting crack growth are described below and illustrated in the associated drawings. Unless otherwise specified, a system or method and/or its various components may, but are not required to, contain at least one of the structure, components, functionality, and/or variations described, illustrated, and/or incorporated herein. Furthermore, the structures, components, functionalities, and/or variations described, illustrated, and/or incorporated herein in connection with the present teachings may, but are not required to, be included in other similar systems and methods. The following description of various embodiments is merely exemplary in nature and is in no way intended to limit the disclosure, its application, or uses. Additionally, the advantages provided by the embodiments, as described below, are illustrative in nature and not all embodiments provide the same advantages or the same degree of advantages.

Aspects of the systems and methods for detecting crack growth may be embodied as a computer method, computer system, or computer program product. Accordingly, those aspects may take the form of an entirely hardware embodiment, an entirely software embodiment (including firmware, resident software, micro-code, and the like), or an embodiment combining software and hardware aspects, all of which may generally be referred to herein as a “circuit,” “module,” or “system.” Furthermore, aspects of the systems and methods for detecting crack growth may take the form of a computer program product embodied in a computer-readable medium (or media) having computer readable program code/instructions embodied thereon, such as instructions to process a plurality of photographic images to detect characteristics of pixels (as further discussed below).

Any combination of computer-readable media for the systems and methods for detecting crack growth may be utilized. Computer-readable media can be a computer-readable signal medium and/or a computer-readable storage medium. A computer-readable storage medium may include an electronic, magnetic, optical, electromagnetic, infrared, and/or semiconductor system, apparatus, or device, or any suitable combination of these. More specific examples of a computer-readable storage medium may include the following: an electrical connection having one or more wires, a portable computer diskette, a hard disk, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), an optical fiber, a portable compact disc read-only memory (CD-ROM), an optical storage device, a magnetic storage device, and/or any suitable combination of these and/or the like. In the context of this disclosure, a computer-readable storage medium may include any suitable tangible medium that can contain or store a program for use by or in connection with an instruction execution system, apparatus, or device.

A computer-readable signal medium may include a propagated data signal with computer-readable program code embodied therein, for example, in baseband or as part of a carrier wave. Such a propagated signal may take any of a variety of forms, including, but not limited to, electro-magnetic, optical, and/or any suitable combination thereof. A computer-readable signal medium may include any computer-readable medium that is not a computer-readable storage medium and that is capable of communicating, propagating, or transporting a program for use by or in connection with an instruction execution system, apparatus, or device, such as the system for detecting crack growth of the present disclosure.

Program code for detecting crack growth embodied on a computer-readable medium may be transmitted using any appropriate medium, including but not limited to wireless, wireline, optical fiber cable, RF, and/or the like, and/or any suitable combination of these.

Computer program code for detecting crack growth may be written in one or any combination of programming languages, including an object-oriented programming language such as Java, Smalltalk, C++, and/or the like, and conventional procedural programming languages, such as the C programming language. The program code may execute entirely on a user's computer, partly on the user's computer, as a stand-alone software package, partly on the user's computer and partly on a remote computer, or entirely on the remote computer or server. In the latter scenario, the remote computer may be connected to the user's computer through any type of network, including a local area network (LAN) or a wide area network (WAN), and/or the connection may be made to an external computer (for example, through the Internet using an Internet Service Provider).

Aspects of systems and methods for detecting crack growth are described below with reference to flowchart illustrations and/or block diagrams of methods, apparatuses, systems, and/or computer program products according to aspects of the present disclosure. Each block and/or combination of blocks in a flowchart and/or block diagram may be implemented by computer program instructions. The computer program instructions may be provided to a processor of a general purpose computer, special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer or other programmable data processing apparatus, create means for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks, such as processing photographic images and generating output from that processing.

The computer program instructions for detecting crack growth can also be stored in a computer-readable medium that can direct a computer, other programmable data processing apparatus, and/or other device to function in a particular manner, such that the instructions stored in the computer-readable medium produce an article of manufacture including instructions which implement the function/act specified in the flowchart and/or block diagram block or blocks.

The computer program instructions for detecting crack growth can also be loaded onto a computer, other programmable data processing apparatus, and/or other device to cause a series of operational steps to be performed on the device to produce a computer-implemented process such that the instructions which execute on the computer or other programmable apparatus provide processes for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks, such as processing photographic images and generating output from that processing.

Any flowchart and/or block diagram in the drawings is intended to illustrate the architecture, functionality, and/or operation of possible implementations of systems, and methods for detecting crack growth. In this regard, each block may represent a module, segment, or portion of code, which comprises one or more executable instructions for implementing the specified logical function(s). In some implementations, the functions noted in the block may occur out of the order noted in the drawings. For example, two blocks shown in succession may, in fact, be executed substantially concurrently, or the blocks may sometimes be executed in the reverse order, depending upon the functionality involved. Each block and/or combination of blocks may be implemented by special purpose hardware-based systems (or combinations of special purpose hardware and computer instructions) that perform the specified functions or acts for detecting crack growth.

Definitions

"Color contrast" refers to a surface of a test specimen that has a color that is different from the color of the interior of that specimen and/or from the color of a background. For example, the test specimen may be provided with a color contrasted top surface or layer. Alternatively, or additionally, a color contrast may be applied to the surface of the test specimen, such as a color contrast coating.

"Highly contrasted" refers to a surface of a test specimen that has a color with a mean and standard deviation for each of Red, Blue, and Green intensities such that each pixel of the background or sub-material (interior of specimen) contains at least one RGB component with a value outside the surface's mean value ± three standard deviations.

"Pixel characteristics" refers to intensity, hue, lumosity, and/or saturation of the pixel.

"Pixel intensity" refers to the shade or level of the pixel that varies based on the color depth or the number of bits. For examples, the intensity values range from **0**-**255** for **24**-bit ("true color").

"Strain energy release rate" is the energy dissipated during fracture per unit of newly created fracture surface area.

Specific Examples, Major Components, and Alternatives

The following examples describe selected aspects of exemplary systems and methods for crack growth detection. These examples are intended for illustration and should not be interpreted as limiting the entire scope of the present disclosure. Each example may describe one or more distinct embodiments, and/or contextual or related information, function, and/or structure.

*Example **1**:*

This example describes an illustrative crack propagation detection system **20** and an illustrative test specimen **22**; see Figs. **1**-**5**.

Test specimen **22** may include a single component or may include multiple components. In some examples, test specimen may be a single sheet or plate, which may include a bend or a notch (such as a cutout). In other examples, test specimen **22** may be a composite material having two or more constituent materials with significantly different physical or chemical properties. For example, the constituent materials may include a matrix (or bond) material, such as a resin (e.g., thermoset epoxy) and a reinforcement material, such as a plurality of fibers (e.g., a woven layer of carbon fibers). Test specimen may include a surface **23** (such as a top surface), which may be a color contrasted surface. In some examples, surface **23** may include a color contrasting coating **23**'. The color contrast coating may be a film, a paint (such as a spray paint), a stain, a varnish, a lacquer, a glaze, and/or other suitable coating. In some examples, such as when test specimen includes two or more layers, surface **23** may be a color contrasted top layer **23**".

Crack propagation detection system **20** may include a test platform **24**. Test platform **24** may include any suitable structure configured to support test specimen **22** and/or apply stress load(s) to the test specimen. Test platform **24** may include one or more holder assemblies **26**, which may include any suitable structure configured to attach to suitable portion(s) of test specimen **22**. The holder assemblies may, for example, include clamps, grips, fixtures, etc. to attach to the test specimen. Test platform **24** may apply stress load(s) through holder assemblies **26** and/or separate from those assemblies. For example, when the test platform performs a fracture toughness test on the test specimen, the holder assemblies may be used to displace the test specimen in opposite directions, as shown in **27**. Alternatively, such as when the test platform performs a double cantilevered beam test on test specimen **22**, a blade or other structure separate from the holder assemblies may be inserted between and/or through layers of the test specimen. The stress load(s) applied to test specimen **22** may, for example, include tensile, compressive, and/or torsional forces. The test platform may be configured to apply the stress load(s) at any suitable constant or variable rate. For example, test platform **24** may apply stress load(s) via a constant or variable displacement rate, via constant or variable force(s), etc. In some examples, test platform **24** may be in the form of a loading and/or testing chamber.

Test platform **24** also may include a background **28**. Background **28** may include a surface (or surface coating) **29**. In some examples, the test platform may be configured to support test specimen **22** on or over background **28**. For example, test platform **24** may support test specimen **22** such that a camera (discussed below) may capture photographic images of test specimen **22** against background **28**. In some examples, surface **23** of test specimen **22** may be color contrasted (or highly contrasted) relative to background **28** (or to surface **29** of that background). For example, as shown in Figs. **2**-**4**, a test specimen having a light green surface **23** is placed against a background having a white surface **29**. The test specimen may be subjected to a constant displacement from the test platform resulting in variable load as shown in Fig. **5** as a crack **30** propagates through the test specimen.

As shown in Fig. **5**, the test specimen may initially exhibit linear elastic behavior. Near a maximum load (or at a critical load), the crack may begin to propagate and increase in size (which may be nearly instantaneously) leading to a drop in the load. As the crack propagates in Figs. **3-4**, the white surface of the background (or sub-material) may be seen through the crack. After the load drops, the test specimen may be able to take on more load again until the crack increases in size once more leading to another drop in the load. The increase and decrease of the load may continue until ultimate failure of the test specimen. Alternatively, a cut or notch may be introduced in the test specimen, such as prior to Fig. **3**, resulting in propagation of crack **30** in Figs. **3-4**. Crack **30** has a crack length L in Fig. **4**.

Although Figs. **2-4** show a test specimen having a crack **30** that reveals a portion of the background, the test specimen may have a crack **30** that reveals only the internal component(s) of the test specimen. For example, when test specimen includes multiple layers, crack **30** may reveal only one or more layers (such as one or more inner layers) and not the background. When crack **30** is not expected to reveal the background, the surface **23** may alternatively, or additionally, be color contrasted relative to the color of the interior of the test specimen, such as one or more inner layers of that specimen.

Crack propagation detection system **20** may include a camera **32**. The camera may include any suitable structure configured to acquire multiple photographic images of test specimen **22**, such as before, during, and/or after application of a stress load to the test specimen. Camera **32** may, for example, be a charge-coupled device (CCD) camera, a complementary metal-oxide semiconductor (CMOS) camera, and/or any suitable camera. The camera may be positioned to acquire photographic images of test specimen **22**, such as against background **28**.

Crack propagation detection system **20** may include a data processing system, such as a computer **34**, having an image processing program **36**. The image processing program may receive the photographic images from camera **32** and may be configured to process those images. For example, image processing program **36** may receive photographic images from camera **32** via communication path **37**, which may include wireless or wired connections. Additionally, image processing program **36** may be configured to detect pixel characteristics of those images or portion(s) of those received images. In some examples, the image processing program **36** may perform cropping of the images and/or focus on only particular portion(s) of those images.

The image processing program **36** may, for example, be configured to determine pixel characteristics of a representative portion **38** of surface **23** prior to formation of a crack, pixel characteristics of an analysis portion **40** of surface **23** that includes a propagating crack, pixel characteristics of any other suitable portion(s) of test specimen **22**, etc. Representative portion **38** may have a color (or at least one pixel characteristic) that is representative of the surface color of the test specimen, while analysis portion **40** may include the area of the test specimen in which crack **30** is expected to form and/or propagate. In some examples, representative portion **38** and analysis portion **40** may be the same portion (as shown in Figs. **2-4**), such as when the image processing program processes one or more photographic images of the test specimen that were taken prior to and during crack formation. In other examples, the representative portion may be a different portion from analysis portion **40** (generally indicated at **38**' in Fig. **3**), such as when image processing program **36** does not process photographic images of the test specimen that were taken prior to crack formation.

Image processing program **36** may be configured to measure changes in a detected crack length based on detected pixel characteristics, such as pixel characteristics that are outside a baseline range of pixel characteristics and/or that are not associated with the color of surface **23** of test specimen. Image processing program **36** may be configured to generate an output of one or more material characteristics, such as a strain energy release rate, based on propagation of crack length. In some examples, crack propagation system **20** may include a wired or wireless communication path **42** between computer **34** and test platform **24**. For example, computer **34** may receive stress load data from the test platform via communication path **42**. In some examples, crack propagation system **20** may include a wired or wireless communication path **44** between camera **32** and test platform **24**. For example, camera **32** may receive stress load data from test platform **24** and associate that data with the photographic images acquired by the camera. In some examples, camera **32** may communicate with computer **34** such that computer **34** polls test platform **24** for stress load data when camera **32** acquires photographic images.

Example 2:

This example describes an image processing program **36** suitable for use with crack propagation detection system **20** as described in Example **1**; see Figs. **6-12**.

Image processing program **36** may be configured to determine pixel characteristics of the photographic images, such as pixel intensities, hue, lumosity, and saturation. For example, when the photographic images are black-and-white images, the image processing program may be configured to determine the intensity for each pixel varying from black at the lowest intensity to white at the highest intensity, such as ranging from **0** to **255**. When the photographic images are colored images, image processing program **36** may be configured to determine the intensities for each primary color, namely red, green, and blue (RGB). For example, the determined intensities for each primary color may range from **0** to **255** with a **24**-bit color scheme.

Figs. **6-8** show illustrative results of image processing program **36** analyzing pixels **46** and their intensities (or intensity values) **48** for representative portion **38** of test specimen **22** for each primary color (e.g., red **50**, green **52**, and blue **54**). Based on the analysis, the image processing program may determine a baseline range of pixel values, such as a baseline range for each primary color, and/or may determine the pixel values associated with surface **23** of test specimen **22**. For example, the baseline pixel intensities for representative portion **38** in Fig. **2** are the following:

- Red pixel values that range from **0-12** with an average of **6** and a standard deviation of **2.5**;
- Green pixel values that range from **150-200** with an average of **175** and a standard deviation of **10**; and

- Blue pixel values that range from **1-7** with an average of **4** and a standard deviation of **4**.

Alternatively, or additionally, the above pixel values are associated with surface **23** of test specimen. The pixel intensities of Figs. **6-8** represent a light green surface **23** of test specimen **22**.

The image processing program also may be configured to determine pixel intensities for each primary color (e.g., red **56**, green **58**, and blue **60**) for analysis portion **40**. Figs. **9-11** show illustrative results of image processing program **36** analyzing pixels **62** and their intensities **64** for analysis portion **40** of test specimen **22** for each primary color. As shown in Figs. **9-11**, the intensities for most pixels for each primary color remained about the same except for **29** pixels of the **240** pixels shown in Figs. **6-8**. In those **29** pixels, the pixel intensities increased to **250-255** for each primary color representing the white background that can be seen because of the crack in the light green surface of the test specimen.

Based on the determined pixel intensities, image processing program **36** may be configured to detect pixel intensities that are outside a baseline range of pixel intensities and/or that are different from the pixel intensities associated with color contrasted surface **23**, which may be indicative of a contrast between crack **30** in test specimen **22** and surface **23** of that specimen. In the above example, the image processing program may be configured to detect: (a) pixel intensities among the red pixels that are different from the range of **0-12** of pixel intensities (or that are outside the baseline range of **0-12**); (b) pixel intensities among the green pixels that are different from the range of **150-200** of pixel intensities (or that are outside the baseline range of **150-200**); and (c) pixel intensities among the blue pixels that are different from the range of **1-7** of pixel intensities (or that are outside the baseline range of **1-7**).

In some examples, image processing program **36** may be configured to detect pixel intensities that are outside a baseline range of pixel intensities and/or that are different from the pixel intensities associated with color contrasted surface **23** by at least a preselected margin for one or more of the primary colors. The preselected margin may be any suitable margin. For example, the preselected margin may be a constant intensity value, such as **25**, **50**, or **100**. Alternatively, the preselected margin may be based on the range or standard deviation of pixel intensities for one or more primary colors. The preselected margin may be, for example, at least one half of the difference between highest and lowest pixel intensities. In the above example, the preselected margins may be as follows: red = **6**, green = **25**, blue = **4**. Image processing program **36** may be configured to detect pixel intensities that are at least the highest intensity value of the baseline range plus (or minus) the selected margin. In the above example, the image processing program may be configured to detect red pixel intensities that are **18** or higher (**12**+**6**), green pixel intensities that are **225** or higher (**200**+**25**) or **125** or lower (**150**-**25**), and/or blue pixel intensities that are **11** or higher (**7**+**4**).

In some examples, the preselected margin may be based on a highly contrasted surface **23** relative to the background. For example, the preselected margin may be at least three standard deviations for each RGB intensity, respectively, as found in the representative portion of the test specimen.

Fig. **12** shows an illustrative matrix **66** that may be generated by image processing program **36** based on processing performed in Figs. **6**-**11**. The matrix may include a plurality of result values **68**. In some examples, each result value **68** may represent a pixel **62**. The result values may indicate whether the image processing program detected surface **23** or detected crack **30**. For example, result values may be a "**0**" indicating that surface **23** was detected or a "**1**" indicating that crack **30** was detected. In some examples, image processing program **36** may assign a "**0**" to a pixel of analysis portion **40** if the intensity of that pixel is within the baseline range of pixel intensities (or is within the baseline range plus a preselected margin of pixel intensities) and/or is the same as the pixel intensities associated with surface **23**. In contrast, image processing program **36** may assign a "**1**" to a pixel of analysis portion **40** if the intensity of that pixel is outside the baseline range of pixel intensities (or is outside the baseline range of pixel intensities by at least a preselected margin) and/or is different from the pixel intensities associated with surface **23**.

In some examples, image processing program **36** may calculate crack length L based on the longest column or row of pixels with a result value of "**1**". The longest column or row of "**1**"s may include one or more "**0**"s, particularly if the crack is not linear, as shown in Fig. **4**. For example, the image processing program may identify the longest column or row of pixels with a result value of "**1**," count the number of pixels in that column or row, and then convert the number of pixels into a crack length measurement based on pixels per length conversion. The pixels per length conversion may be based on a characteristic dimension in one or more photographic images. For example, if the photographic image shows only the entire width of the specimen (without showing the background), then the pixels per length conversion is based on the width of the specimen and the number of pixels across that width.

In some examples, image processing program **36** may calculate crack length L for one or more photographic image and may associate a stress load for each calculated crack length. The calculated crack length and associated load may be used by the image processing program to calculate one or more material characteristics, such as a strain energy release rate. For example, the image processing program may calculate strain energy release rate using the equation below.

Equation **1**: $G := [\partial U/\partial A]_P = - [\partial U/\partial A]_u$

Here, G is the strain energy release rate, U is the elastic energy of the system, A is the crack area (equal to crack length multiplied by thickness), P is the load, and u is displacement. The image processing program may calculate strain energy release rates using other equations, such as the equations provided in ASTM International D **5045-99** (Reapproved **2007**): *Standard Test Methods for Plane-Strain Fracture Toughness and Strain Energy Release Rate of Plastic Materials*, June **2007**, **9** pages.

Although image processing program **36** is shown to determine crack length based on pixel intensities, the image processing program may additionally, or alternatively, determine crack length based on detecting and comparing hue, lumosity, saturation, and/or other pixel characteristics. For example, the image processing program may determine the hue (or hue value) for each pixel in the representative portion and determine if there are pixels in the analysis portion with hues outside a baseline range and/or are different from hues associated with the representative portion, which may be indicative of a contrast between a crack and the test specimen.

Example 3:

This example describes a method for detecting crack propagation in material test specimen; see Fig. **13**.

Fig. **13** depicts multiple steps of a method, which may be performed in conjunction with crack propagation system **20** according to aspects of the present disclosure. Although various steps of method **100** are described below and depicted in Fig. **13**, the steps need not necessarily all be performed, and in some cases may be performed in a different order than the order shown.

Method **100** may include a step **102** of color contrasting a surface of a test specimen. Color contrasting the surface may include applying a color contrasting coating to the surface of the test specimen, such as spray painting the surface. In some examples, the coating may exhibit a highly contrasting color relative to the surface color of the background. When the test specimen includes two or more layers, color contrasting the surface may include providing a color contrasting top layer. Alternatively, or additionally, color contrasting the surface may include selecting a surface color of a background that color contrasts the surface of the test specimen. When the test specimen is a composite material test specimen, color contrasting may be performed on a surface of that specimen.

Method **100** may include a step **104** of supporting the test specimen over a background (or background area). At step **104**, the test specimen may be supported such that the surface color of the background may be visible through a crack in the test specimen.

Method **100** may include a step **106** of applying a stress load to the test specimen. When holder assemblies are used to attach to portions of the test specimen, step **106** may include moving one or more of those holder assemblies apart, together, and/or in torsion to apply the stress load. Alternatively, the holder assemblies may hold the test specimen in place while a stress load from another component of a test platform is applied. The applied stress load may, for example, be a constant or variable force and/or be a constant or variable displacement of the test specimen. At step **108**, photographic images of the test specimen may be acquired prior to, during, and/or after application of the stress load.

Method **100** may include a step **110** of processing the photographic images. At step **110**, one or more of the photographic images may be processed to determine a baseline range of pixel characteristics and/or pixel characteristics associated with the surface of the test specimen. At step **110**, the photographic images may be processed to detect characteristics of pixels that are outside a baseline range of pixel characteristics and/or that are different from pixel characteristics associated with the color of the surface of the test specimen, which may be indicative of a contrast between a crack in the test specimen and the surface of that specimen. In some examples, the photographic images may be processed to detect characteristics of pixels that are outside a baseline range of pixel characteristics by a preselected margin, such as at least one half of the difference between highest and lowest pixel characteristic values or three standard deviations. The pixel characteristics may, for example, include intensity, hue, lumosity, and/or saturation.

Method **100** may include a step **112** of generating output. At step **112**, the output may include measured crack length(s) and/or stress load(s) associated with those length(s). Alternatively, or additionally, the output may include a strain energy release rate based on changes of detected crack length over time and/or propagation of the crack length.

*Example **4**:*

This example describes a data processing system **900** in accordance with aspects of the present disclosure. In this example, data processing system **900** is an illustrative data processing system for implementing computer **34** of crack propagation detection system **20** in Fig. **1**; See Fig. **14**.

In this illustrative example, data processing system **900** includes communications framework **902**. Communications framework **902** provides communications between processor unit **904**, memory **906**, persistent storage **908**, communications unit **910**, input/output (I/O) unit **912**, and display **914**. Memory **906**, persistent storage **908**, communications unit **910**, input/output (I/O) unit **912**, and display **914** are examples of resources accessible by processor unit **904** via communications framework **902**.

Processor unit **904** serves to run instructions for software that may be loaded into memory **906**, such as instructions to process a plurality of photographic images to determine pixel characteristics. Processor unit **904** may be a number of processors, a multi-processor core, or some other type of processor, depending on the particular implementation. Further, processor unit **904** may be implemented using a number of heterogeneous processor systems in which a main processor is present with secondary processors on a single chip. As another illustrative example, processor unit **904** may be a symmetric multi-processor system containing multiple processors of the same type.

Memory **906** and persistent storage **908** are examples of storage devices **916**. A storage device is any piece of hardware that is capable of storing information, such as, for example, without limitation, data, program code in functional form, and other suitable information either on a temporary basis or a permanent basis. For example, storage devices **916** may store crack measurement data obtained from the processing of the photographic images.

Storage devices **916** also may be referred to as computer readable storage devices in these examples. Memory **906**, in these examples, may be, for example, a random access memory or any other suitable volatile or non-volatile storage device. Persistent storage **908** may take various forms, depending on the particular implementation.

For example, persistent storage **908** may contain one or more components or devices. For example, persistent storage **908** may be a hard drive, a flash memory, a rewritable optical disk, a rewritable magnetic tape, or some combination of the above. The media used by persistent storage **908** also may be removable. For example, a removable hard drive may be used for persistent storage **908**.

Communications unit **910**, in these examples, provides for communications with other data processing systems or devices. In these examples, communications unit **910** is a network interface card. Communications unit **910** may provide communications through the use of either or both physical and wireless communications links. For example, communications unit **910** may provide for communications with test platform **24** and/or camera **32**.

Input/output (I/O) unit **912** allows for input and output of data with other devices that may be connected to data processing system **900**. For example, input/output (I/O) unit **912** may provide a connection for user input through a keyboard, a mouse, and/or some other suitable input device. Further, input/output (I/O) unit **912** may send output to a printer. Display **914** provides a mechanism to display information to a user, such as information regarding the measured crack lengths and/or calculated strain energy release rates.

Instructions for the operating system, applications, and/or programs may be located in storage devices **916**, which are in communication with processor unit **904** through communications framework **902**. In these illustrative examples, the instructions are in a functional form on persistent storage **908**. These instructions may be loaded into memory **906** for execution by processor unit **904**. The processes of the systems and methods for detecting crack growth may be performed by processor unit **904** using computer-implemented instructions, which may be located in a memory, such as memory **906**. The computer-implemented instructions may, for example, include instructions to process photographic images and generate output from that processing.

These instructions are referred to as program instructions, program code, computer usable program code, or computer readable program code that may be read and executed by a processor in processor unit **904**. The program code in the different embodiments may be embodied on different physical or computer readable storage media, such as memory **906** or persistent storage **908**.

Program code **918**, such as image processing program **36**, is located in a functional form on computer readable media **920** that is selectively removable and may be loaded onto or transferred to data processing system **900** for execution by processor unit **904**. Program code **918** and computer readable media **920** form computer program product **922** in these examples. In one example, computer readable media **920** may be computer readable storage media **924** or computer readable signal media **926**.

Computer readable storage media **924** may include, for example, an optical or magnetic disk that is inserted or placed into a drive or other device that is part of persistent storage **908** for transfer onto a storage device, such as a hard drive, that is part of persistent storage **908**. Computer readable storage media **924** also may take the form of a persistent storage, such as a hard drive, a thumb drive, or a flash memory, that is connected to data processing system **900**. In some instances, computer readable storage media **924** may not be removable from data processing system **900**. For example, image processing program **36** may be stored in computer readable storage media that is not removable from computer **34**.

In these examples, computer readable storage media **924** is a physical or tangible storage device used to store program code **918** (such as image processing program **36**) rather than a medium that propagates or transmits program code **918**. Computer readable storage media **924** is also referred to as a computer readable tangible storage device or a computer readable physical storage device. In other words, computer readable storage media **924** is a media that can be touched by a person.

Alternatively, program code **918** may be transferred to data processing system **900** using computer readable signal media **926**. Computer readable signal media **926** may be, for example, a propagated data signal containing program code **918**. For example, computer readable signal media **926** may be an electromagnetic signal, an optical signal, and/or any other suitable type of signal. These signals may be transmitted over communications links, such as wireless communications links, optical fiber cable, coaxial cable, a wire, and/or any other suitable type of communications link. In other words, the communications link and/or the connection may be physical or wireless in the illustrative examples.

In some illustrative embodiments, program code **918** (such as image processing program **36**) may be downloaded over a network to persistent storage **908** from another device or data processing system through computer readable signal media **926** for use within data processing system **900**, such as computer **34**. For instance, program code stored in a computer readable storage medium in a server data processing system may be downloaded over a network from the server to data processing system **900**. The data processing system providing program code **918** may be a server computer, a client computer, or some other device capable of storing and transmitting program code **918**.

The different components illustrated for data processing system **900** are not meant to provide architectural limitations to the manner in which different embodiments of the systems and methods for detecting crack growth may be implemented. The different illustrative embodiments may be implemented in a data processing system including components in addition to and/or in place of those illustrated for data processing system **900**. Other components shown in Fig. **14** can be varied from the illustrative examples shown. The different embodiments may be implemented using any hardware device or system capable of running program code, such as image processing program **36**. As one example, data processing system **900** may include organic components integrated with inorganic components and/or may be comprised entirely of organic components excluding a human being. For example, a storage device may be comprised of an organic semiconductor.

In another illustrative example, processor unit **904** may take the form of a hardware unit that has circuits that are manufactured or configured for a particular use, such as detecting crack growth. This type of hardware may perform operations without needing program code to be loaded into a memory from a storage device to be configured to perform the operations.

For example, when processor unit **904** takes the form of a hardware unit, processor unit **904** may be a circuit system, an application specific integrated circuit (ASIC), a programmable logic device, or some other suitable type of hardware configured to perform a number of operations, such as processing photographic images and generating output from that processing. With a programmable logic device, the device is configured to perform the number of operations. The device may be reconfigured at a later time or may be permanently configured to perform the number of operations. Examples of programmable logic devices include, for example, a programmable logic array, a programmable array logic, a field programmable logic array, a field programmable gate array, and other suitable hardware devices. With this type of implementation, program code **918** may be omitted, because the processes for the different embodiments are implemented in a hardware unit.

In still another illustrative example, processor unit **904** may be implemented using a combination of processors found in computers and hardware units. Processor unit **904** may have a number of hardware units and a number of processors that are configured to run program code **918**, such as image processing program **36**. With this depicted example, some of the processes of detecting crack growth may be implemented in the number of hardware units, while other processes of detecting crack growth may be implemented in the number of processors.

In another example, a bus system may be used to implement communications framework **902** and may be comprised of one or more buses, such as a system bus or an input/output bus. Of course, the bus system may be implemented using any suitable type of architecture that provides for a transfer of data between different components or devices attached to the bus system.

Additionally, communications unit **910** may include a number of devices that transmit data, receive data, or both transmit and receive data, such as pixel characteristics data and crack detection data. Communications unit **910** may be, for example, a modem or a network adapter, two network adapters, or some combination thereof. Further, a memory may be, for example, memory **906**, or a cache, such as that found in an interface and memory controller hub that may be present in communications framework **902**.

The flowcharts and block diagrams described herein illustrate the architecture, functionality, and operation of possible implementations of systems and methods for detecting crack growth according to various illustrative embodiments. In this regard, each block in the flowcharts or block diagrams may represent a module, segment, or portion of code, which comprises one or more executable instructions for implementing the specified logical function or functions. It should also be noted that, in some alternative implementations, the functions noted in a block may occur out of the order noted in the drawings. For example, the functions of two blocks shown in succession may be executed substantially concurrently, or the functions of the blocks may sometimes be executed in the reverse order, depending upon the functionality involved.

In other arrangements of the methods and systems disclosed herein, additional examples are provided:

In accordance with one embodiment, there is provided a method of detecting crack propagation in a material test specimen, includes color contrasting a surface of a test specimen; acquiring a plurality of photographic images of the specimen during application of a stress load; processing the plurality of images to detect characteristics of pixels that are outside a baseline range of pixel characteristics indicative of a contrast between a crack in the test specimen and the color contrasted surface of the test specimen; and generating an output of a strain energy release rate based on changes in detected crack length over time.

Color contrasting a surface of a test specimen may include applying a color contrasting coating to the surface of the test specimen.

Color contrasting a surface of a test specimen may include providing a color contrasting top layer.

The method may further include supporting the test specimen over a background, wherein color contrasting a surface of a test specimen includes selecting a surface color of the background that color contrasts the surface of the test specimen.

The method may include processing at least one image of the plurality of images to determine a baseline range of pixel characteristics.

Processing at least one image of the plurality of images may include processing a portion of the at least one image, the portion being representative of the color of the surface of the test specimen.

Acquiring a plurality of photographic images of the specimen may include acquiring a plurality of photographic images of the specimen during application of a stress load provided by displacing the test specimen at a constant rate.

The method may further include acquiring a plurality of photographic images before applying the stress load.

Processing the plurality of images to detect characteristics of pixels may include processing the plurality of images to detect intensities of pixels.

Processing the plurality of images to detect intensities of pixels may include processing the plurality of images to detect intensities of pixels that are outside a baseline range of pixel intensities by a preselected margin of at least one half of the difference between highest and lowest pixel intensities for at least one primary color.

Color contrasting a surface of a test specimen may include color contrasting a surface of a composite material test specimen.

In accordance with another embodiment, there is provided a system for detecting crack propagation in a material test specimen, including a test platform configured to support a material test specimen on a background, the material test specimen having a top surface color contrasting a surface color of the background; a camera directed toward the test platform and configured to acquire a plurality of photographic images of a test specimen located on the platform during application of a stress load to the test specimen; and an image processing program that receives the plurality of photographic images, and that is configured to detect, in the plurality of photographic images, pixel characteristics that are outside a baseline range of pixel characteristics, and measure changes in a detected crack length based on the detected pixel characteristics.

The material test specimen may have a top surface coating which is highly contrasted relative to the surface coating of the background.

The image processing program may be further configured to generate an output of a strain energy release rate based on propagation of crack length.

In accordance with another embodiment, there is provided a method of detecting crack propagation in a material test specimen, including supporting a material test specimen over a background, the specimen having a top surface color contrasting a surface color of the background; applying a stress load to the specimen; acquiring multiple photographic images of an extending crack length in the specimen during the applying step; and detecting pixel characteristics that are different from pixel characteristics associated with the top surface color to measure crack length in the specimen.

The method may further include generating an output of a strain energy release rate based on propagation of the crack length.

The method may further include applying a coating on the test specimen exhibiting a highly contrasting color relative to the surface color of the background.

The method may further include detecting pixel characteristics of a portion of at least one image of the multiple photographic images, the portion being representative of the top surface color of the test specimen.

The method may further include determining pixel characteristics associated with the top surface color from the detected pixel characteristics.

Detecting pixel characteristics may include detecting pixel intensities that are different from pixel intensities associated with the top surface color to measure crack length in the specimen.

The different embodiments of the systems and methods of detecting crack propagation in a material test specimen described herein may provide several advantages over known solutions. For example, the illustrative embodiments of the system and method of detecting crack propagation described herein may allow acquiring of crack formation and propagation data at a much higher rate over known solutions. Additionally, and among other benefits, illustrative embodiments of the system and method of detecting crack propagation described herein may allow more accurate determination of material characteristics of components and structures. No system or device known to the inventors at this time can perform these functions, particularly in a materials testing environment. Thus, the illustrative embodiments described herein are particularly useful for determining material characteristics of components and structures, such as to determine whether those components and structures are suitable for a particular use. However, not all embodiments described herein provide the same advantages or the same degree of advantage.

The disclosure set forth above may encompass multiple distinct embodiments with independent utility. Although each of these embodiments has been disclosed in its preferred form(s), the specific embodiments thereof as disclosed and illustrated herein are not to be considered in a limiting sense, because numerous variations are possible. The subject matter of the embodiments includes all novel and nonobvious combinations and subcombinations of the various elements, features, functions, and/or properties disclosed herein. The following claims particularly point out certain combinations and subcombinations regarded as novel and nonobvious.

EMBODIMENTS IN WHICH AN EXCLUSIVE PRIVILEGE OR PROPERTY IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A method of detecting crack propagation in a material test specimen, comprising:

color contrasting a surface of a test specimen with a surface color of a background;

supporting the test specimen over the background;

acquiring a plurality of photographic images of the specimen during application of a stress load;

processing the plurality of images to detect characteristics of pixels that are outside a baseline range of pixel characteristics indicative of a contrast between the background revealed through a crack in the test specimen and the color contrasted surface of the test specimen; and

generating an output of a strain energy release rate based on changes in detected crack length over time.

2. The method of claim **1**, wherein color contrasting a surface of a test specimen includes applying a color contrasting coating to the surface of the test specimen.

3. The method of claim **1**, wherein color contrasting a surface of a test specimen includes providing a color contrasting top layer.

4. The method of any one of claims **1** to **3**, wherein color contrasting a surface of a test specimen includes selecting the surface color of the background that color contrasts the surface of the test specimen.

5. The method of any one of claims **1** to **4**, further comprising:

processing at least one image of the plurality of images to determine a baseline range of pixel characteristics.

6. The method of claim **5**, wherein processing at least one image of the plurality of images includes processing a portion of the at least one image, the portion being representative of the color of the surface of the test specimen.

7. The method of any one of claims **1** to **6**, wherein acquiring a plurality of photographic images of the specimen includes acquiring a plurality of photographic images of the specimen during application of a stress load provided by displacing the test specimen at a constant rate.

8. The method of any one of claims **1** to **7**, further comprising:

acquiring a plurality of photographic images before applying the stress load.

9. The method of any one of claims **1** to **8**, wherein processing the plurality of images to detect characteristics of pixels includes processing the plurality of images to detect intensities of pixels.

10. The method of claim **9**, wherein processing the plurality of images to detect intensities of pixels includes processing the plurality of images to detect intensities of pixels that are outside a baseline range of pixel intensities by a preselected margin of at least one half of the difference between highest and lowest pixel intensities for at least one primary color.

11. The method of any one of claims **1** to **10**, wherein color contrasting a surface of a test specimen includes color contrasting a surface of a composite material test specimen.

12. A system for detecting crack propagation in a material test specimen, comprising:

a test platform configured to support a material test specimen on a background, the background having a surface color selected to provide a color contrast with a top surface color of the test specimen;

a camera directed toward the test platform and configured to acquire a plurality of photographic images of the test specimen located on the platform during application of a stress load to the test specimen; and

an image processing program that receives the plurality of photographic images, and that is configured to:

detect, in the plurality of photographic images, pixel characteristics of the background revealed through a crack in the test specimen, and

measure changes in a detected crack length based on the detected pixel characteristics.

13. The system of claim **12**, wherein the material test specimen has a top surface coating which is highly contrasted relative to the surface coating of the background.

14. The system of claim **12** or **13**, wherein the image processing program is further configured to generate an output of a strain energy release rate based on propagation of crack length.

15. A method of detecting crack propagation in a material test specimen, comprising:

selecting a surface color of a background in a test platform;

supporting a material test specimen over the background, the specimen having a top surface color contrasting the surface color of the background;

applying a stress load to the specimen;

acquiring multiple photographic images of an extending crack length in the specimen during the applying step; and

detecting pixel characteristics of the background revealed through a crack in the specimen that are different from pixel characteristics associated with the top surface color of the specimen to measure crack length in the specimen.

16. The method of claim **15**, further comprising:

generating an output of a strain energy release rate based on propagation of the crack length.

17. The method of claim **15** or **16**, further comprising:

applying a coating on the test specimen exhibiting a highly contrasting color relative to the surface color of the background.

18. The method of any one of claims **15** to **17**, further comprising:

detecting pixel characteristics of a portion of at least one image of the multiple photographic images, the portion being representative of the top surface color of the test specimen.

19. The method of claim **18**, further comprising:

determining pixel characteristics associated with the top surface color from the detected pixel characteristics.

20. The method of any one of claims **15** to **19**, wherein detecting pixel characteristics includes detecting pixel intensities that are different from pixel intensities associated with the top surface color to measure crack length in the specimen.

Fig. 1

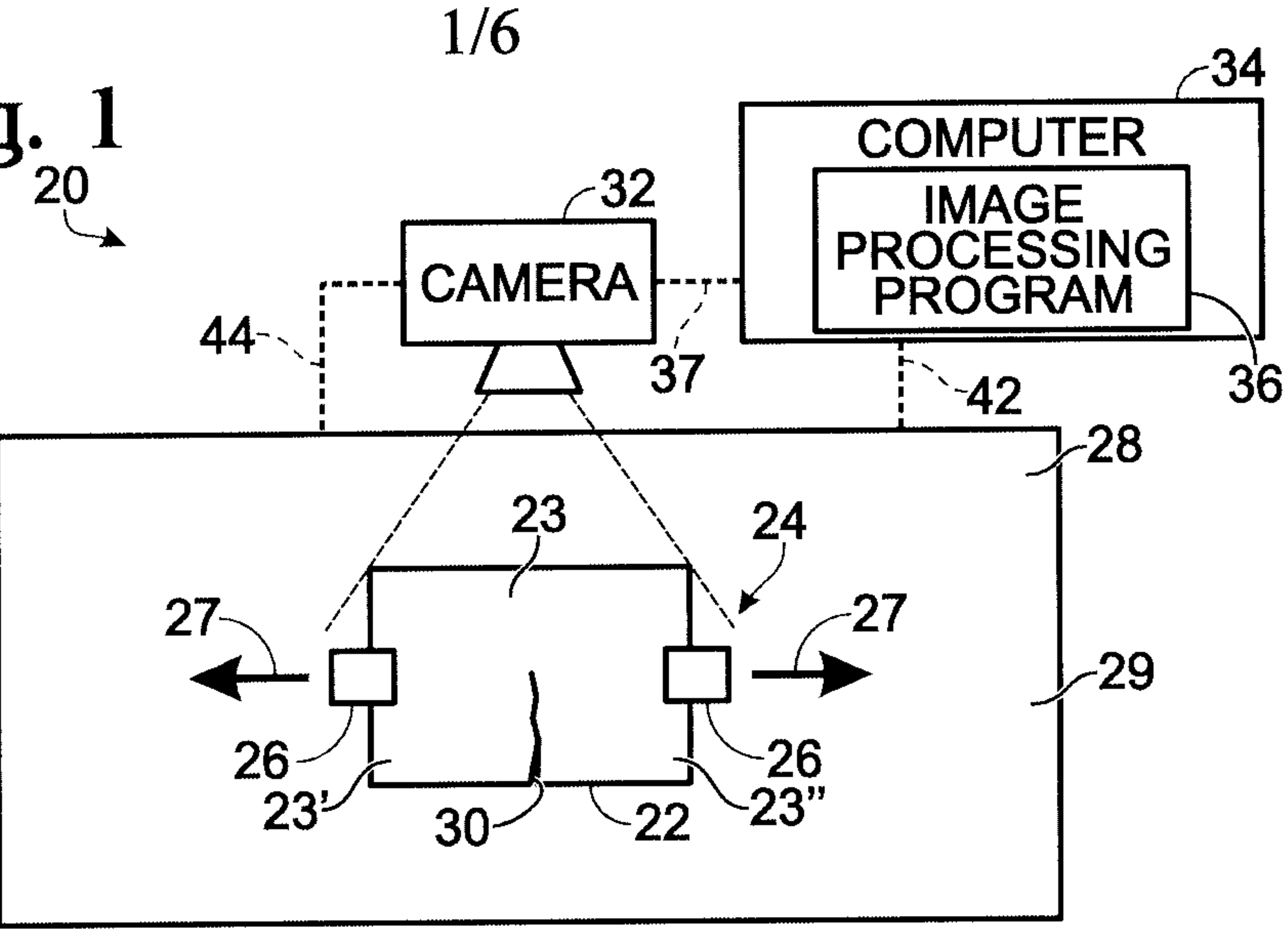


Fig. 2

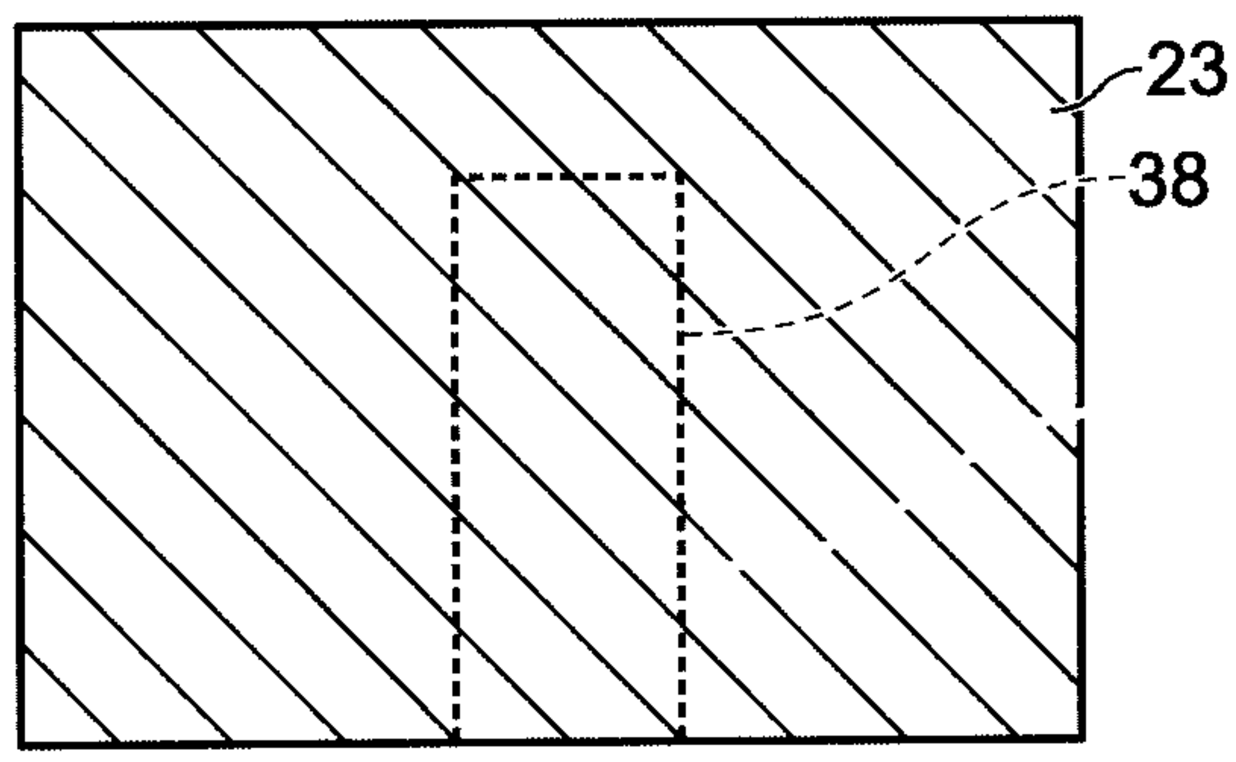


Fig. 3

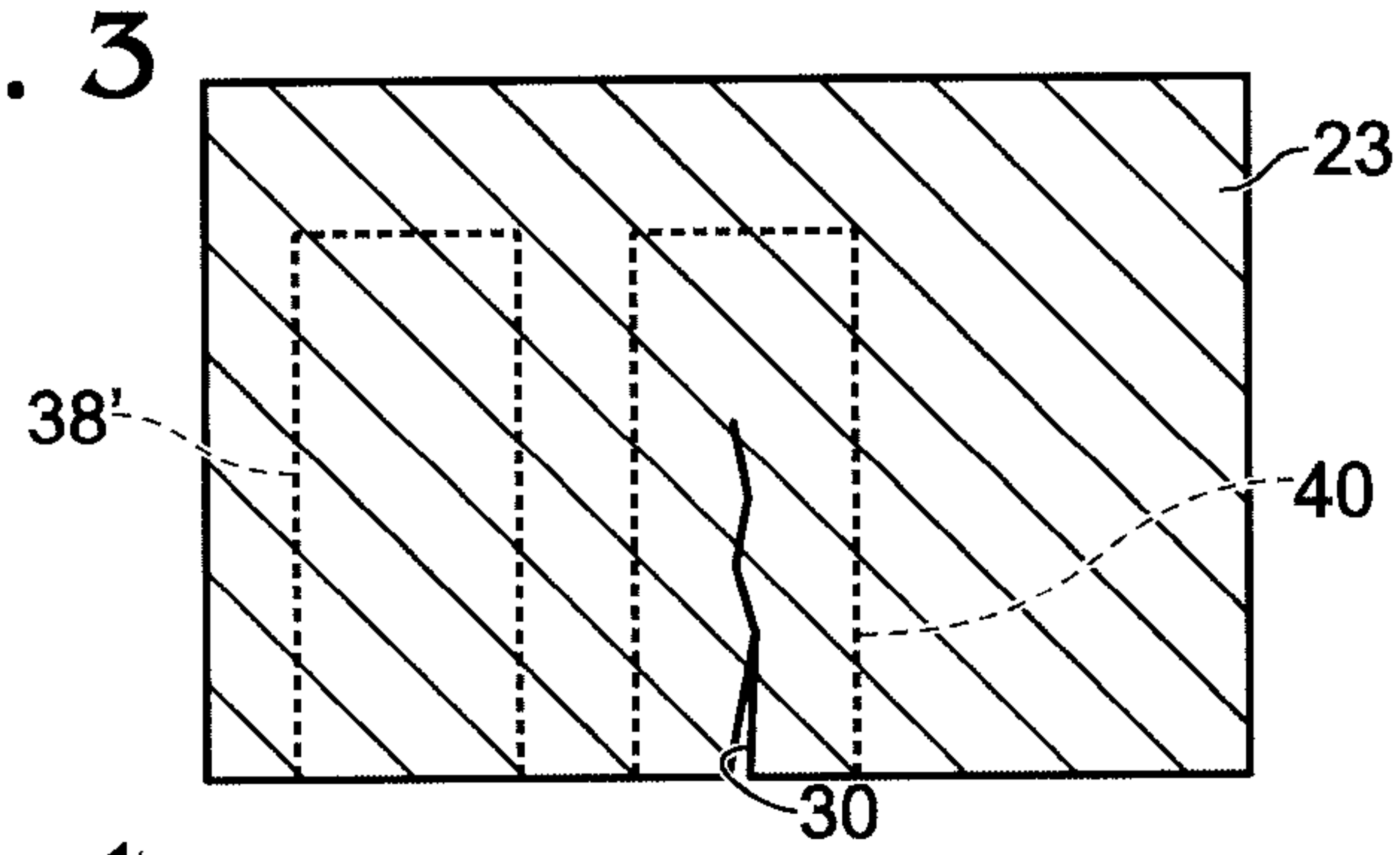
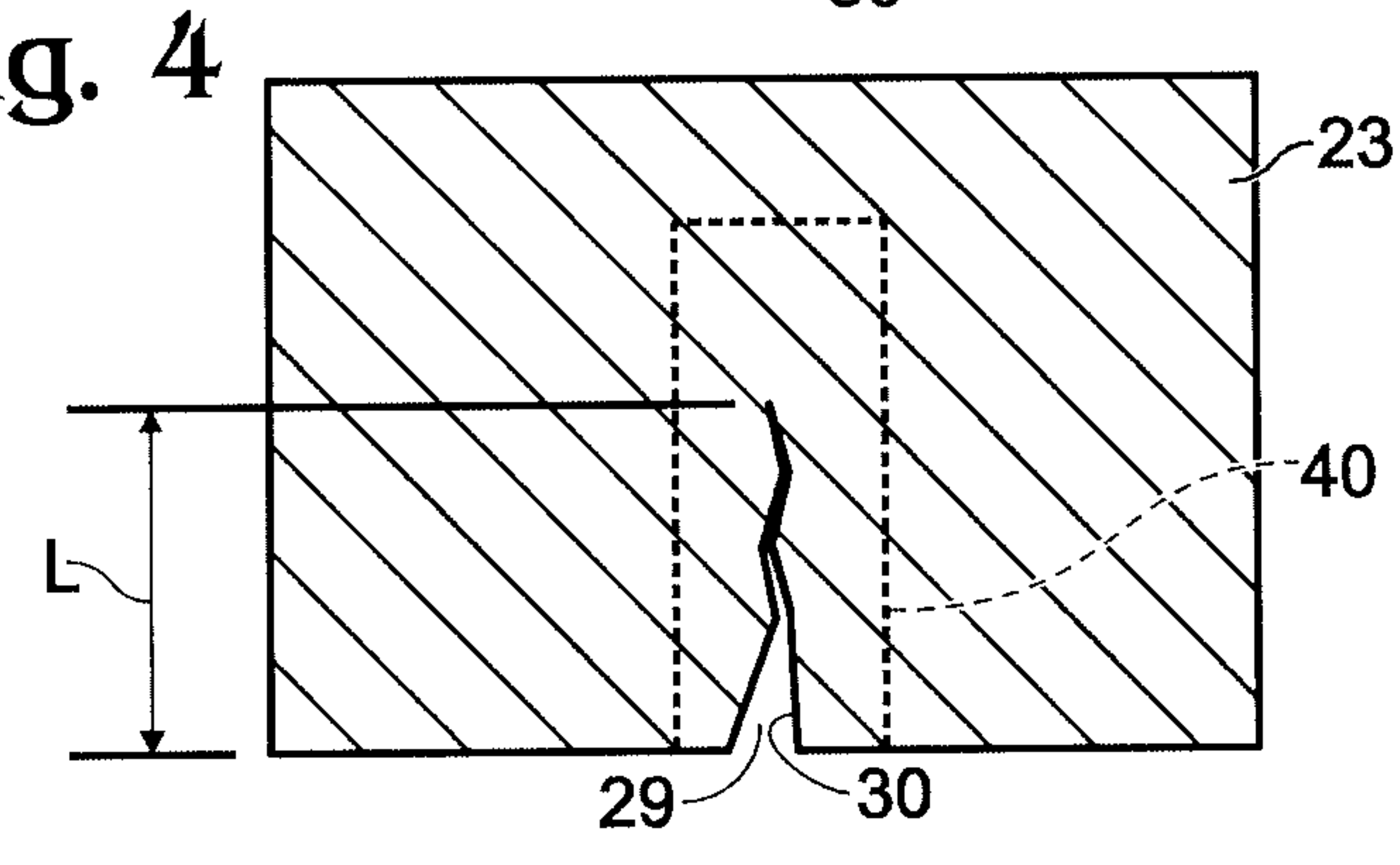


Fig. 4



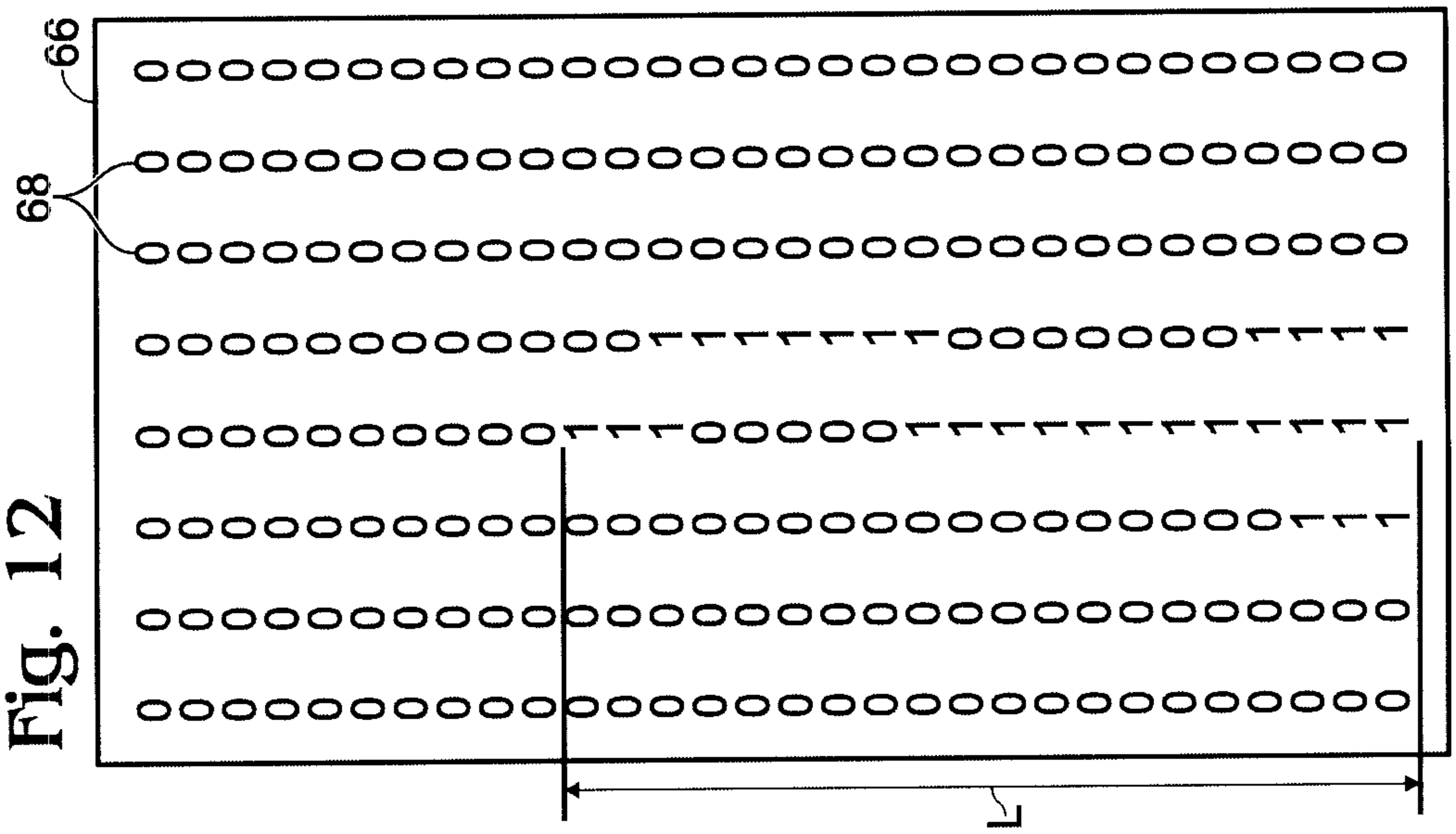


Fig. 12

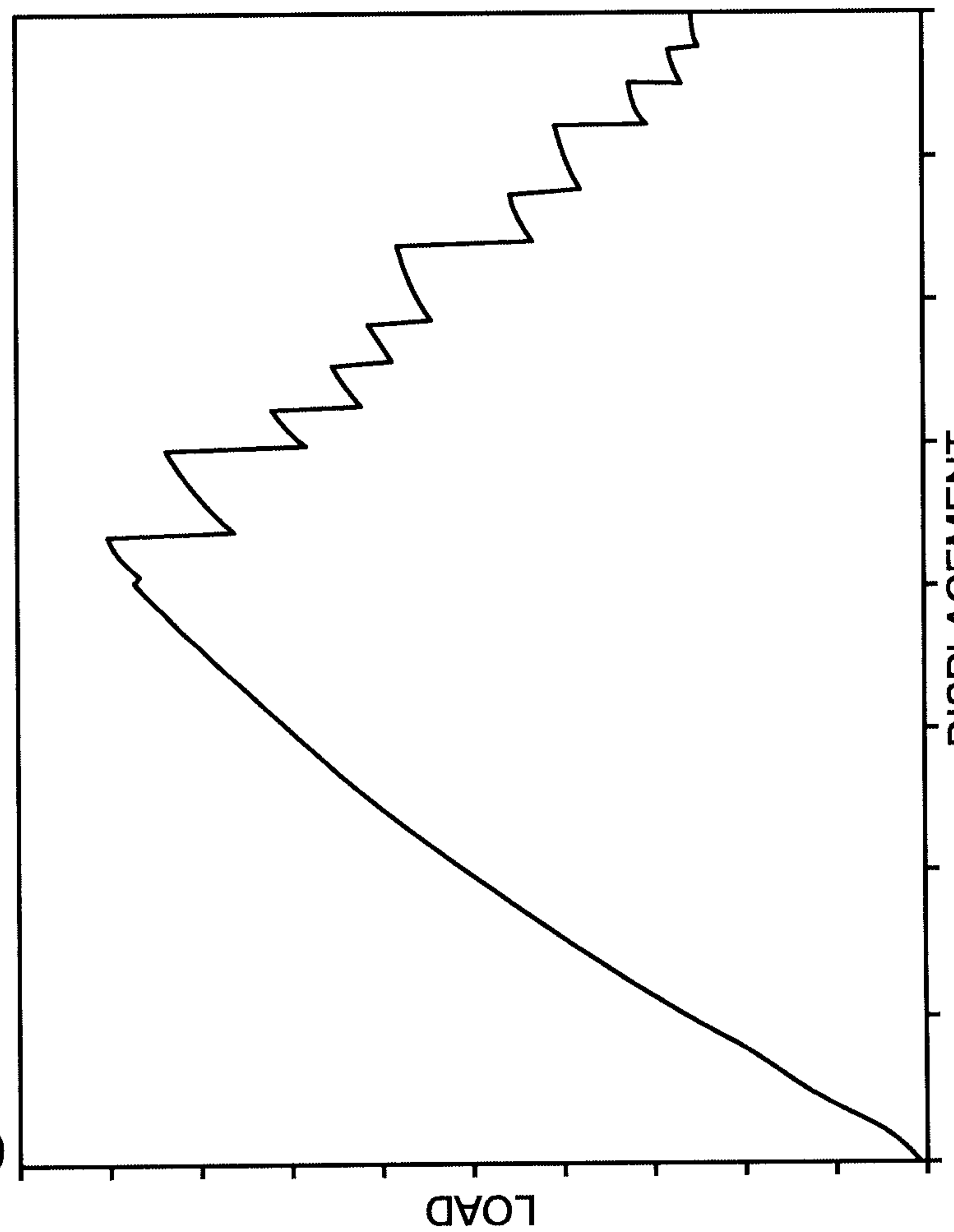


Fig. 5

Fig. 6

50

RED

12	8	6	4	0	5	12	10
2	10	5	10	9	11	5	9
1	11	8	1	3	5	8	11
10	2	3	11	2	12	9	6
11	5	12	4	10	9	4	4
0	9	5	10	7	1	10	0
9	1	2	6	11	3	4	4
10	7	0	7	0	4	12	2
5	6	1	9	5	10	9	1
2	12	8	0	6	8	5	8
5	4	3	10	2	11	3	0
0	7	11	7	12	6	1	3
8	2	9	10	6	9	8	7
3	10	0	2	8	1	11	9
1	5	2	11	0	3	4	2
9	0	12	6	4	2	11	3
12	6	4	8	9	12	5	0
4	10	3	1	2	7	8	4
11	2	12	6	7	4	10	1
8	11	5	10	0	9	3	7
9	7	1	4	10	1	0	5
0	3	7	6	8	4	2	3
8	1	2	1	1	7	8	12
3	7	11	5	2	11	11	7
10	5	12	9	10	12	5	9
7	11	8	3	0	3	8	6
12	5	9	7	12	7	1	0
2	0	1	12	8	11	4	0
4	3	7	2	7	4	5	1
10	12	3	6	8	6	9	3

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Fig. 7

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GREEN

150	165	178	163	164	169	188	155
189	151	200	171	153	172	173	154
174	156	161	170	175	186	177	157
188	157	192	181	152	183	176	194
187	194	168	159	198	165	190	200
162	191	185	182	189	162	181	180
195	176	155	193	158	153	192	173
161	197	154	151	196	178	193	166
160	175	200	184	175	163	183	190
177	168	181	173	174	171	156	185
169	159	157	150	177	169	191	157
166	195	166	189	165	164	195	170
199	184	183	156	188	185	194	161
196	197	178	167	191	151	186	189
175	152	193	176	160	152	187	160
180	175	198	159	155	175	192	187
193	190	163	170	171	172	195	180
158	169	160	189	196	175	167	181
197	153	199	154	183	177	158	165
167	182	171	189	164	161	197	184
186	175	185	186	199	168	182	173
175	173	166	151	189	163	159	191
170	175	194	175	156	188	199	174
155	150	175	167	192	171	162	187
175	159	190	172	175	175	153	198
184	195	157	175	200	178	197	168
189	162	161	174	183	199	167	185
163	198	191	193	153	150	189	158
164	177	154	151	172	189	196	155
187	182	181	180	165	176	169	152

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Fig. 8

54

BLUE

1	2	4	2	7	6	5	3
6	4	3	5	1	4	2	7
2	5	1	4	6	3	6	2
4	3	2	7	5	7	1	6
5	7	6	3	4	1	4	2
3	7	2	4	1	5	6	3
7	1	4	3	6	4	2	7
6	5	2	7	3	1	4	4
2	7	3	1	2	5	5	6
4	6	5	2	6	3	7	1
5	1	7	4	7	2	6	3
3	6	1	5	2	3	5	4
4	1	7	3	6	5	4	2
1	3	6	2	5	7	6	1
5	4	2	4	1	6	3	7
4	6	7	3	5	1	7	2
2	5	7	6	1	4	3	4
4	7	1	5	4	2	5	6
1	2	4	6	3	5	7	3
5	1	3	2	7	6	1	4
7	6	2	5	3	1	4	2
3	5	7	1	4	6	2	4
4	2	1	6	3	5	7	5
6	5	3	4	1	7	2	7
4	3	6	2	7	5	6	1
1	7	4	5	3	2	3	6
4	1	2	6	3	5	7	4
3	2	3	7	1	6	5	1
4	5	3	1	6	2	4	7
1	4	2	3	5	6	1	7

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Fig. 9

RED

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12	8	6	4	0	5	12	10
2	10	5	10	9	11	5	9
1	11	8	1	3	5	8	11
10	2	3	11	2	12	9	6
11	5	12	4	10	9	4	4
0	9	5	10	7	1	10	0
9	1	2	6	11	3	4	4
10	7	0	7	0	4	12	2
5	6	1	9	5	10	9	1
2	12	8	0	6	8	5	8
5	4	3	**255**	2	11	3	0
0	7	11	**251**	12	6	1	3
8	2	9	**250**	**255**	9	8	7
3	10	0	2	**253**	1	11	9
1	5	2	11	**251**	3	4	2
9	0	12	6	**253**	2	11	3
12	6	4	8	**255**	12	5	0
4	10	3	1	**255**	7	8	4
11	2	12	**253**	**250**	4	10	1
8	11	5	**255**	0	9	3	7
9	7	1	**252**	10	1	0	5
0	3	7	**251**	8	4	2	3
8	1	2	**253**	1	7	8	12
3	7	11	**250**	2	11	11	7
10	5	12	**252**	10	12	5	9
7	11	8	**253**	0	3	8	6
12	5	9	**250**	**254**	7	1	0
2	0	**251**	**251**	**250**	11	4	0
4	3	**253**	**250**	**254**	4	5	1
10	12	**250**	**251**	**253**	6	9	3

64

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Fig. 10

GREEN

58

150	165	178	163	164	169	188	155
189	151	200	171	153	172	173	154
174	156	161	170	175	186	177	157
188	157	192	181	152	183	176	194
187	194	168	159	198	165	190	200
162	191	185	182	189	162	181	180
195	176	155	193	158	153	192	173
161	197	154	151	196	178	193	166
160	175	200	184	175	163	183	190
177	168	181	173	174	171	156	185
169	159	157	**251**	177	169	191	157
166	195	166	**252**	165	164	195	170
199	184	183	**253**	**255**	185	194	161
196	197	178	167	**251**	151	186	189
175	152	193	176	**255**	152	187	160
180	175	198	159	**251**	175	192	187
193	190	163	170	**250**	172	195	180
158	169	160	189	**251**	175	167	181
197	153	199	**252**	**255**	177	158	165
167	182	171	**250**	164	161	197	184
186	175	185	**253**	199	168	182	173
175	173	166	**252**	189	163	159	191
170	175	194	**250**	156	188	199	174
155	150	175	**251**	192	171	162	187
175	159	190	**253**	175	175	153	198
184	195	157	**255**	200	178	197	168
189	162	161	**251**	**252**	199	167	185
163	198	**252**	**251**	**252**	150	189	158
164	177	**251**	**255**	**253**	189	196	155
187	182	**252**	**253**	**254**	176	169	152

64

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Fig. 11

BLUE

60

1	2	4	2	7	6	5	3
6	4	3	5	1	4	2	7
2	5	1	4	6	3	6	2
4	3	2	7	5	7	1	6
5	7	6	3	4	1	4	2
3	7	2	4	1	5	6	3
7	1	4	3	6	4	2	7
6	5	2	7	3	1	4	4
2	7	3	1	2	5	5	6
4	6	5	2	6	3	7	1
5	1	7	**253**	7	2	6	3
3	6	1	**253**	2	3	5	4
4	1	7	**253**	**253**	5	4	2
1	3	6	2	**252**	7	6	1
5	4	2	4	**254**	6	3	7
4	6	7	3	**252**	1	7	2
2	5	7	6	**253**	4	3	4
4	7	1	5	**253**	2	5	6
1	2	4	**251**	**251**	5	7	3
5	1	3	**254**	7	6	1	4
7	6	2	**250**	3	1	4	2
3	5	7	**255**	4	6	2	4
4	2	1	**252**	3	5	7	5
6	5	3	**254**	1	7	2	7
4	3	6	**251**	7	5	6	1
1	7	4	**254**	3	2	3	6
4	1	2	**253**	**253**	5	7	4
3	2	**254**	**253**	**255**	6	5	1
4	5	**250**	**251**	**255**	2	4	7
1	4	**251**	**252**	**255**	6	1	7

64

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Fig. 13

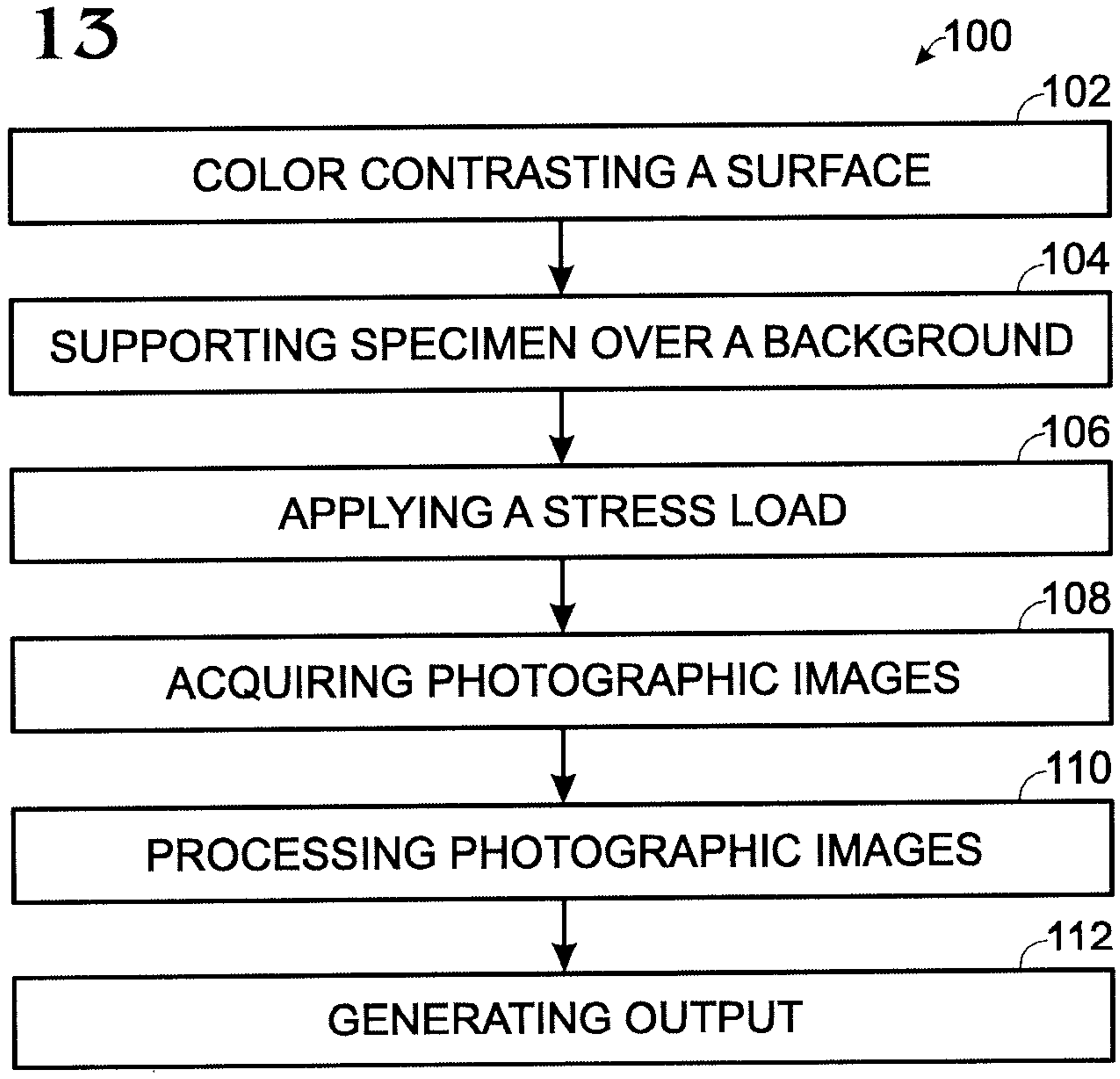
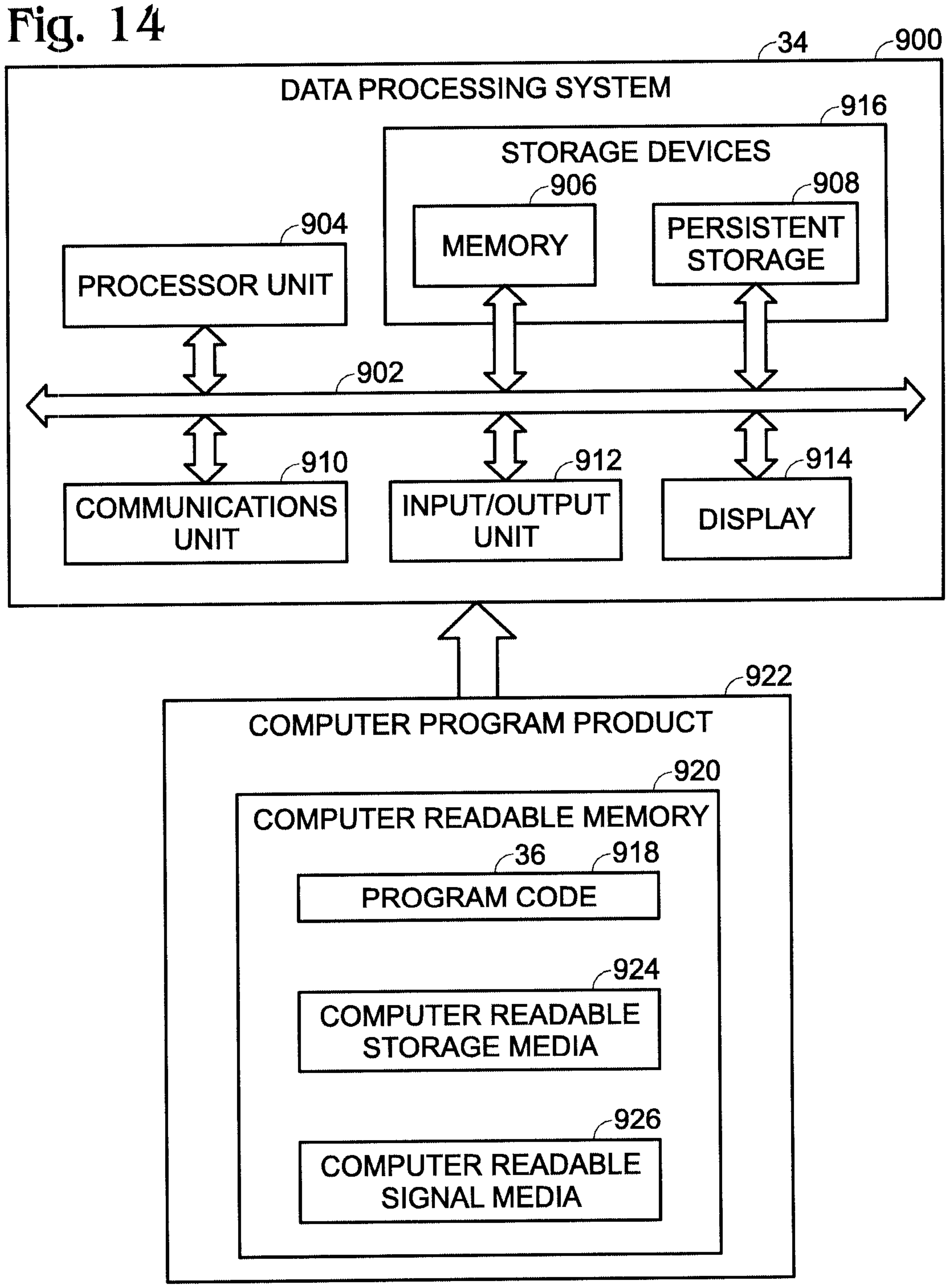
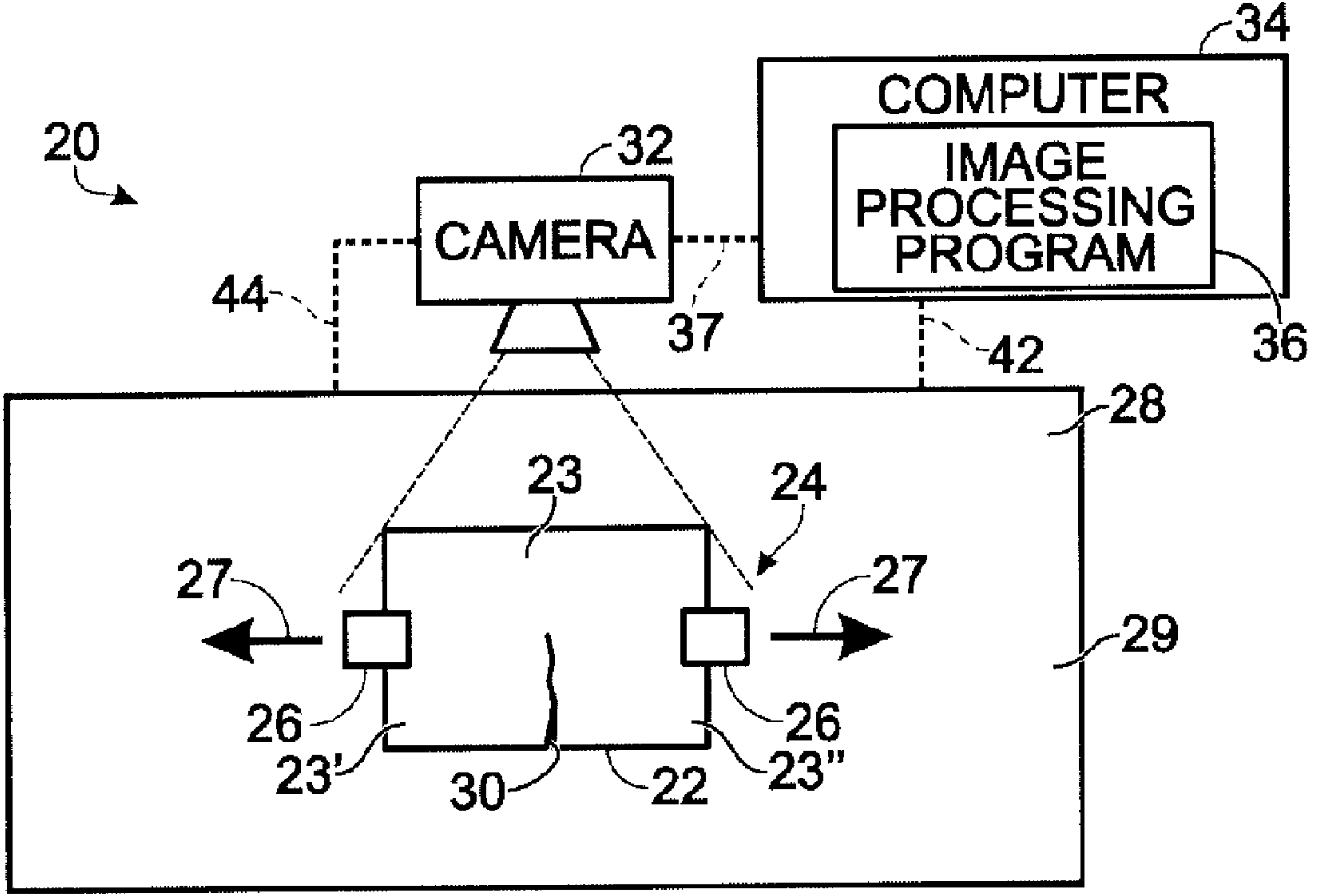

100
102
COLOR CONTRASTING A SURFACE
104
SUPPORTING SPECIMEN OVER A BACKGROUND
106
APPLYING A STRESS LOAD
108
ACQUIRING PHOTOGRAPHIC IMAGES
110
PROCESSING PHOTOGRAPHIC IMAGES
112
GENERATING OUTPUT

Fig. 14


34
900
DATA PROCESSING SYSTEM
916
STORAGE DEVICES
906
908
904
MEMORY
PERSISTENT STORAGE
PROCESSOR UNIT
902
910
912
914
COMMUNICATIONS UNIT
INPUT/OUTPUT UNIT
DISPLAY
922
COMPUTER PROGRAM PRODUCT
920
COMPUTER READABLE MEMORY
36
918
PROGRAM CODE
924
COMPUTER READABLE STORAGE MEDIA
926
COMPUTER READABLE SIGNAL MEDIA



34
COMPUTER
IMAGE
PROCESSING
PROGRAM
20
32
CAMERA
44
37
36
42
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26
23'
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23"