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================= **THERMAL AND OPTICAL METHODS** ================

An Integrated Approach between Pulsed Thermography (PT), Near-Infrared (NIR) Reflectography and Sandwich Holography (SH) for Wooden Panel Paintings Advanced Monitoring[1]

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An integrated approach between Pulsed Thermography (PT), Near-Infrared (NIR) Reflectography and Sandwich Holography (SH)

Abstract—The durability of an exterior finish is affected by the characteristics of the wood. Satisfactory finish life is usually more difficult to achieve on woods of higher density. All wood shrinks as it loses moisture and swells as it absorbs moisture, but some *species* are more stable than others. *Species* that shrink and swell the most cause more stress on paint films than woods that are more stable [1]. To this end, let us recall that a painting on wood can be considered as a layered structure: The wood support is coated with a number of superposed priming layers made from mixtures of gesso and glue. A frequent fault resulting from such a system is the formation of detached regions inside the layered structure caused by the shrinkage process of the wood support [2]. Obviously, wood deteriorates more rapidly in warm, humid regions with respect to cool or dry places [3]. The influence of wood conditions on surface coatings is a *critical point* that should be monitored and that depends on environmental parameters such as microclimate. To prevent and control the effects, keeping costs down, a non-destructive monitoring of wood support behavior under thermal stress is needed. In this work, an integrated approach based on traditional and innovative (HI, PT and NIR) techniques was conducted on a primed support of *poplar* wood with a complex-shape surface containing areas of artificial defects at several depths due to the influence of the support on the various layers. The obtained results could be arranged, if integrated into a multidisciplinary approach, in order to define and design the conservation of the wooden artifacts.

Key words: holographic interferometry, pulsed thermography, near-infrared reflectography, defect, wood

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INTRODUCTION

Paintings on wooden surfaces are extremely widespread, both historically and geographically. A major issue in the conservation of panels is the behavior and structural movement of the wooden support, especially due to fluctuations in environmental conditions [4]. In this work, holographic interferometry, infrared thermography and near-infrared reflectography have been employed in order to detect fabricated and real defects at several depths (Fig. 1). The choice of a complex surface, compared to a plane surface, usually used in the traditional panel painting, has confirmed the excellence of the techniques also on a composite structure out of the norm.

The increasing deterioration of our artistic patrimony has accelerated the efforts to search for new methods for diagnosis of its state of conservation, because apart from the immense costs of restoration, the damages, in particular cases, could lead to the irretrievable loss of the artwork. The study of internal stress (due to variations of environmental parameters or external load) in frescoes, panel paintings or statues, the analysis of the behavior of small deformations or material discontinuities, in wooden or mural supports, and a knowledge of incipient and invisible flaws are a priority task for the preservation of these objects [5].

The concept of using laser interferometry for artwork structural analysis is based on the inherent property of holographic interferometry to allow a light wave, diffusely scattered by an object, to be holographically recorded and reconstructed with precision such that it can be interferometrically compared with light scattered by the same object at another instant in time. Several HI techniques exist [6, 7]. The more relevant to the present study is Sandwich Holography (SH) [8], that was found to be useful for a better localization of defects.

Nevertheless, holographic techniques are difficult to apply in situ, principally because of the strict stability requirements and high costs [9]. Other interferometric portable techniques, such as ESPI, might be used, although image resolution is greater for HI and can be considered as a benchmark. Another possibility is to use infrared thermography, which is a non-contact, non-invasive and nondestructive testing and evaluation (NDT&E) method [10]. However, problems such as non-uniform heating, emissivity variations, environmental reflections and surface geometry have a great impact on raw thermal data [11]. Advanced signal processing techniques must be used most of the time to improve defect contrast.

In the case of panel painting inspection, three IR spectral bands are of interest: (1) the near infrared band (NIR) between 0.75 and 2.5 μm, (2) the mid wave infrared (MWIR) between 3 and 5 μm, and (3) the long wave infrared (LWIR) between 7 and 14 μm. There exist some fundamental differences between the NIR and MWIR-LWIR bands being somehow complementary for the NDT&E of artworks. In one hand, NIR reflectography is employed for the assessment of ancient paintings providing information underneath the painting layers. IR thermography, on the other hand, exploits the principle of heat diffusion gradients on dissimilar materials for the detection and, in some cases, the characterization of subsurface anomalies [12]. The use of NIR reflectography, as link among holographic and thermographic techniques has been of great help in the identification and validation of simulated defects.

For the PT technique, the specimen surface is stimulated with a short heat pulse, and the cooling down process is recorded with an infrared camera for several seconds. The acquired data is then processed to improve defect contrast and signal–to–noise ratio (SNR). Several processing techniques exist, from a basic cold image subtraction to more advanced techniques [13]. The more relevant to the present study are: principal component thermography (PCT) [14], which reorganizes data into new components or projections that take into account the main spatiotemporal variances of the sequence, and pulsed phase thermography (PPT) [15, 16], which transforms data from the time domain to the frequency domain in order to obtain phase delay images or *phasegrams* that have an improved defect contrast.

In this work, we present the results of the experimental investigations carried out over an artwork with simulated deterioration problems, and discuss the advantages and the limits of the various methods.

HOLOGRAPHIC INTERFEROMETRY (HI) – SANDWICH HOLOGRAPHY TECHNIQUE (SH)

Holography was born out of a very challenging technological problem: The need to improve the resolution of the electron microscope, which was limited by the spherical aberration of the electron lenses. Gabor, therefore, invented a two-step process, the first step involving recording without the lenses, and the second step as reconstruction. The technique was demonstrated with micro-objects and with spatially and temporally filtered radiation from a mercury lamp. This arrangement was necessary because high resolution recording materials and coherent sources were not available at that time.

After its invention in 1948, holography remained practically dormant until the arrival of the laser, since a long coherence length source was needed to record a hologram of an object. Earlier recordings of three-dimensional objects were made on Kodak 649F plates, and the results were very impressive. Holography, therefore, came to be known as three-dimensional photography. It, however, is more than ordinary 3D photography, since it provides 3D views with changing perspectives.

Holography records the complex amplitude of a wave coming from an object rather than the intensity distribution in the image, as is the case in photography. The recording of the complex amplitude is accomplished by interferometry inasmuch as all the detectors in the optical regime are energy detectors. Therefore, a reference wave is added to the object wave at the recording plane. The recording is done on a variety of media (photoemulsions, photopolymers, thermoplastics, etc.).

The record, called hologram, is like a window with a memory. Different perspectives of the scene are seen through different portions of the hologram. In addition, to recording holograms of 3D objects, several new applications of holography have emerged, holographic interferometry being one of these.

Holographic interferometry (HI), which provides interferometric comparison of real objects or events separated in time and space, is a technique of unparalleled applications. Various kinds of HI have been developed – for example, real-time, double-exposure, and time-averaged HI. Furthermore, it can be performed with one, two, or more reference waves, which can be of the same or different wavelengths. The reference wave can come from the side of the hologram as the object wave, or from the other side of the hologram. HI can be performed with a continuous wave laser or a pulsed laser [17].

In this work, we have analyzed the specimen by Sandwich Holography technique. The fringes in conventional interferometric holography appear because the object either moved or changed its shape between the first and the second exposure. Many times, however, it is not easy to eliminate the effect of the rigid body movements of the object, and to determine the deformations due to loads or stresses. An elegant solution is the sandwich hologram invented by

Abramson [18].

In Sandwich Holography, a pair of holographic plates are simultaneously exposed by placing them in the same holder, with their emulsions towards the object, and with the anti-halation backing removed from the front plate. Two sandwiches at least must be exposed, one without any stress of the object and the second after the stress is introduced, as shown in Fig. 2.

Upon reconstruction, both sandwich holograms will reconstruct the object without any fringes.

However, if the sandwich holograms are now formed by the pairs of plates A_1 with B_2 or by B_1 with A_2, the reconstructed image of the object will show the fringes. By manipulating the Sandwich hologram during the reconstruction it is possible the elimination of spurious movements in order to better highlight the anomalies.

In this manner, the fringe pattern due to the object stresses is easily isolated [19].

In the original technique proposed by *Abramson*, the fringe manipulation is realized by tilting the sandwich with respect to its initial position. Subsequently, *Amadesi, S., et al.* [20], and *Paoletti, D., et al.* [21], have proposed a new method of fringe manipulation by shearing one hologram plate with respect to the other with help of an accurately adjustable plate holder. There are several advantages in using this new version of the method. For example, a number of holograms can be made, each one recording a single state of the object, in a temporal sequence. Afterwards the plates can be combined in pairs as desired, allowing one to compare any two hologram plates to study interferometrically any changes in object, in order to have a quasi-continuous monitoring of the object response to external stress. Probably the most important advantage of sandwich holography is the possibility of manipulating the fringe pattern; it allows us to eliminate unwanted fringes caused by rigid body motion of the object investigated. In fact, as the two reconstructed images can be moved with respect to each other, spurious movements of the object between the exposures can be compensated by a movement of the holographic image during reconstruction. Moreover, the possibility of a posteriori manipulation of the fringe pattern permits an evaluation of local deformation even in presence of large displacement of the object under study (about 1000 fringes can be eliminated by a simple sandwich-hologram tilt or shearing). In some instances, for a large three-dimensional structure, where the tension stresses are not distributed uniformly, we can effectuate a compensation over local regions.

Practically, a continuous scanning of the specimen can be done by shifting the center of maximum sensitivity of the fringe pattern in order to produce a clear display of a flaw, with a configuration that outlines the flaw and gives an approximate indication of its size and shape. In our opinion, this versatility of the sandwich hologram is of particular interest in art diagnostics.

Finally, by manipulating the sandwich pair, a system of linear fringes can be added to or subtracted from the interferogram; these fringes act as a spatial heterodyne carrier. The combination of carrier fringes and deformation fringes gives a resultant pattern suitable for quantitative analysis of deformation [22, 23].

Many problems of double-exposure and real-time holography are so resolved, but there are also some disadvantages: The plates must be repositioned with high accuracy during reconstruction, the freedom of fringe manipulation also contains the seeds of possible errors, and to achieve the built-in accuracy of double exposure, one must record reference points to guarantee that the fringe pattern being observed reflects actual object changes rather than being a pattern created by moving the images relative to one another. A correct use of the technique generally requires the worker to construct a special holographic plate holder that readily allows fringe manipulation. Figure 3 shows the SH configuration used in this work. An argon (λ = 514·5-nm) continuous-wave laser of 1·2-W power was employed as the source of coherent light.

PULSED THERMOGRAPHY (PT)

Pulsed thermography is a well-known NDT technique allowing fast inspection of large surfaces extensively investigated [11, 24]. Data acquisition is fast and straightforward, as illustrated in Fig. 4.

The specimen surface is submitted to a *short* pulse (a few milliseconds), and the temperature decay is register using an infrared camera and stored as a 3D matrix composed by *N* thermograms, where *x* and *y* are the spatial coordinated, and *t* is the time. The temperature of a point on the surface in a semi-infinite isotropic solid decreases by conduction as predicted by the 1D solution of Fourier's Equation (1) for a Dirac pulse and shown in Fig. 4 [25].

(1)

$$T(0,t) = T_0 + \frac{Q}{e\sqrt{\pi \cdot t}}$$

Where $e = (k\rho c_P)^{1/2}$ [m] is the effusivity, which is a thermal property that measures the material ability to exchange heat with its surroundings. PT data is generally processed to improve defect visibility and to performed quantitative characterization of defects.

The Fourier transform provides a valuable tool to convert the signal from the temperature-time space to a phase-frequency space but it does so through the use of sinusoidal basis functions, which may not be the best choice for representing transient signals, which are the temperature profiles typically found in pulsed thermography. Singular value decomposition (SVD) is an alternative tool to extract spatial and temporal data from a matrix in a compact or cimplified manner. Instead of relying on a basis function, SVD is an eingenvector-based transform that forms an orthonormal space. SVD is close to principal component analysis (PCA) with the difference that SVD simultaneously provides PCAs in both row and column spaces.

The SVD of an MN matrix A (M > N) can be calculated, as can be seen in Eq. (2) [14].

(2) $$A = URV^{T}$$

Where *U* is a *MN* orthogonal matrix, *R* being a diagonal *NN* matrix (with singular values of *A* present in the diagonal), V^T is the transpose of an NN orthogonal matrix (characteristic time).

Hence, in order to apply the SVD to thermographic data, the 3D thermogram matrix representing time and spatial variations has to be reorganized as a 2D MN matrix *A*. This can be done by rearranging the thermograms for every time as columns in *A*, in such a way that time variations will occur column-wise, while spatial variations will occur row-wise. Under this configuration, the columns of *U* represent a set of orthogonal statistical modes known as empirical orthogonal functions (EOF) that describes spatial variations of data [14, 26]. On the other hand, the principal components (PCs), which represent time variations, are arranged row-wise in matrix V^T. The first EOF will represent the most characteristic variability of the data; the second EOF will contain the second most important variability, and so on. Usually, original data can be adequately represented with only a few EOFs. Tipically, a 1000 thermogram sequence can be replaced by 10 or less EOFs.

In pulsed phase thermography (PPT) [15, 16] data is transformed from the time domain to the frequency domain using the 1D discrete Fourier transform (DFT). This Equation is shown in Eq. (3):

(3) $$F_n = \Delta t \sum_{k=0}^{N-1} T(k\Delta t) \exp^{(-j2\pi nk/N)} = \mathrm{Re}_n + j\,\mathrm{Im}_n$$

Where *j* is the imaginary number (j^2= -1), n designates the frequency increment (*n* = 0, 1, …, N), Δt is the sampling interval, and *Re* and *Im* are the real and the imaginary parts of the transform, respectively. In this case, real and imaginary parts of the complex transform are used to estimate the amplitude *A*, and the phase ϕ, as can be seen in Eq. (4):

(4) $$\phi_n = \tan^{-1}\left(\frac{\mathrm{Im}_n}{\mathrm{Re}_n}\right) \quad \text{and} \quad A_n = \sqrt{\mathrm{Re}_n^2 + \mathrm{Im}_n^2}$$

The phase is of particular interest in NDE given that is less affected than raw thermal data by environmental reflections, emissivity variations, non-uniform heating, surface geometry and orientation.

The two techniques just described are intended to process PT data.

NEAR-INFRARED (NIR) REFLECTOGRAPHY

When exposing a painting to a broad-band light source (from ultraviolet to the far IR), part of the radiation will be absorbed by, another fraction of the radiation will be transmitted through and the rest will be reflected from the incident surface, depending on the radiation wavelength and the material being radiated. For instance, a visible camera will capture the light (in the visible spectrum 0.35- to 0.75-μm) reflected from the painting surface, providing information about colors and textures. The NIR part of the radiation, which contains practically no thermal emissions, can penetrate thin layers of painting before being reflected back to the surface from a non-absorbing media such as the preparation surface (usually made of chalk and gypsum) and will eventually be absorbed by carbon–based (or other absorbing) elements, if present. Most of the oil paints used for panel painting (usually linseed oil with inorganic suspended oxide or mineral salt pigments [27]) are transparent to NIR light, whilst carbon derivatives (graphite and charcoal) are opaque in this spectral region.

The transparency in the NIR band is a complex function of the optical characteristics of (1) the pigment color (with brown and gray being in general more transparent than some light colors, whilst black is the most opaque [27]), (2) the underdrawing material, (3) the paint layer thickness (typically a fraction of millimeters [28]), and (4) the detector wavelength (transparency increases between 1.0 and 2.5 μm for different configurations [29], generally showing a peak near to 2 μm [30]). A NIR camera can be used to reconstruct two-dimensional (2D) images, i.e. reflectograms, of the reflected light under the painting layers. Interesting applications include the detection of guiding sketches and signatures (opaque to NIR radiation) drawn by the artist prior to the application of painting layers; the detection of hidden paintings (painters often use a previously painted canvas or changes their mind during the painting progression), the monitoring of the restoration processes required on aging cultural heritage artworks, and the detection of intentional and unintentional alterations.

NIR reflectography has been studied since the 1930s. At the beginning, photographic films were used. Although NIR photography works are interesting, restrictions on the spectral band (0.7- to 0.9-μm) and time delays (due to film development) limited the wide spread of the technique (an interesting NIR photography investigation can be found in [31]). It wasn't until the 1960s, after the work of Van Asperen de Boer [32, that the use of Vidicon cameras (0.9- to 2.0-μm) first and digital cameras (1.1- to 5-μm) later, began to be used routinely by many recognized art Museums [33–35]. The next generation of NIR reflectography systems is the multi-spectral (up to 14 spectral bands) single-point scanners, which considerably diminish the effects of optical and geometrical non-uniformities with respect to multi-detectors arrays [28, 36]. These systems, however, are slow, heavy, and too complex to be commercialized at the moment (year 2010). The use of commercial NIR cameras and the required accessories (lenses, filters, and light sources) is still the preferred alternative for artwork inspection given its easiness of operation compared to single-point scanners.

DESCRIPTION OF THE SPECIMEN, NATURE OF THE DEFECTS AND COMPARATIVE RESULTS

During the early 1980s, sandwich holography was found to be useful for a better localization of defects [8]. By manipulating the fringe pattern, as already mentioned, it is possible to explore the surface of the subject in order to define the defect contours in the best way. The specimen in Figs. 5a and 5c, with a base of x = 36-cm, y = 13.5-cm and variable thickness, was made with simulated defects close to real defects, of various depths and several configurations

(Fig. 5d); it resembles a typical layered structure of a wooden panel, as used in paintings since the 13^{th} century (Fig. 1). In Fig. 5a is reported the position of the defects. The wood is coated with some priming layers, which constitute the basis for the painting. These layers, made of a mixture of gesso and glue, are thinner and more fragile than the support (Fig. 5b).

Expansion and contraction of the support due to daily fluctuations of the ambient parameters can produce large strains and eventually cracks in the priming layers, as they become less flexible with age (defects 11, 15).

Furthermore, abrupt changes of humidity and temperature or heat exposure may also cause unpredictable stress distributions in the heterogeneous materials of the support (defects 1, 3, 4, 5, 7, 9, 10, 14 in Fig. 5a), with consequent damage to the painting. All these mechanisms may lead to the formation of detachments and cracks (defects 1, 11). It is very important to know how the presence of support cracks and discontinuities alter the movements of the painted surface.

In addition, destructive insects can attack wooden artifacts and cause serious damages. During their growth, the larvae make tunnels in the wood; they may become very extensive, reducing the interior of a panel without any external signs of damage (defects 2, 6). Defects in painted structures may also be due to intrinsic factors such as irregular wood grain or structural anomalies. A force acting across the grain can cause the wood to collapse by compression or to break by tension [5]. Because of the defect's type and the composite nature of the panel, the test sample was studied in ambient drift and thermal drift by HI. Figure 6a shows the sandwich reconstruction of the panel examined in ambient drift.

One can see that the flaws located in concavity are more evident than those in convexity regions. Figs. 6b and 6c shows a manipulated fringe pattern from the sandwich hologram of the same panel in thermal drift; note that, by shearing the sandwich hologram, the location of the flaws in convexity regions is more defined.

Furthermore, real defects were identified both by PCT, PPT and SH and circumscribed by a white dashes circles (Figs. 6b, 6e and 6f), while others, circumscribed by a black dashes circles, were only identified by holographic interferometry (Fig. 6b). Also, PCT and PPT detect real defects not identified by SH (Figs. 6e and 6f, red dashes circles). Although it was possible to identify flaws from the raw thermogram in Figure 6d, PCT and PPT considerably improved defect detectability and were essential to confirm others anomalies created artificially below the layers.

The post processing approach was essential, in particular, for defects 9, 10, and 14 simulating loose knots. A similar conclusion can be drawn for defects 12 and 13 concerning a possible machine burn on the wooden support. Only defect 7, situated in a narrow convexity has not been confirmed neither by raw thermogram, PCT, PPT or NIR reflectography.

This technique, as expected, was able to identify only very superficial defects (Figs. 6g and 6h). Moreover, manipulation of the fringe pattern has allowed us also to confirm the shape of defects 9, 10, 11, 13 (Fig. 6b).

CONCLUSIONS

The tests carried out during this research showed that the holographic interferometry is an effective technique, in the SH version, for testing panel paintings with a complex surface; it is comparable in accuracy with other techniques such as, in our case, pulsed thermography.

Some drawbacks of holographic interferometry, in particular the sensitivity to environmental disturbances when a continuous-wave laser is employed, prevent its use outside specialized laboratories. However, there are some advantages, namely the full-field visualization, which provides a more representative description of the state of integrity of the sample and constitutes valuable information in guiding a more detailed examination (Fig. 6b).

A major concern when using a diagnostic technique is of course to preserve the integrity of the artwork piece. HI succeeds on this matter. The panel is inspected on a controlled environment and is submitted to only slight distresses (temperature change). Also the ambient drift has provided good results (Fig. 6a).

Moreover, a correspondence between the anomalies of the fringe patterns and the most common types of defects (Fig. 5d) has been demonstrated through the integration of NIR reflectography and PT techniques on the test sample (Figs. 6a –6h).

Raw thermographic data allowed us to detect or at least to infer the existence of 8 of the 15 defects. Nevertheless, advanced signal processing as PCT and PPT techniques, help us to improve defect contrast and the amount of defects detected (14), as well as to reduce the impact of non-uniform heating and detect real flaws not identified by SH (Figs. 6e and 6f).

It was not possible to confirm the presence of defect 7 by PT or NIR reflectography.

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FIGURE CAPTIONS

Fig. 1. A schematic cross-section of a typical panel painting.

Fig. 2. Sandwich holography.

Fig. 3. Experimental configuration for Sandwich Holography (SH) HI.

Fig. 4. Experimental configuration for pulsed thermography and NIR reflectography.

Fig. 5. (a) Top of view of the specimen and identification of the fabricated defects – in red the *loose knot*, in dark the *wormholes*, in violet the *checking*, in yellow the *pitch*, in sky-blue the *machine burn*, in dark-blue the *tight knot*, (b) front of view of the specimen, (c) back of view of the specimen, (d) simulated defects and explanations [37].

Fig. 6. (a) A sandwich hologram reconstruction, (b) a first manipulation of the fringe pattern, (c) a second manipulation of the fringe pattern, (d) Raw thermogram at t = 0.06 s, e) Principal Component Thermography 3rd Component, f) PPT phasegram at f = 0.055 Hz, g) and h) NIR reflectograms using a wide spectrum source and a InGaAs camera (0.9 μm – 1.7 μm) at two different angles.

An integrated approach between Pulsed Thermography (PT), Near-Infrared (NIR) Reflectography and Sandwich Holography (SH)

FIGURES

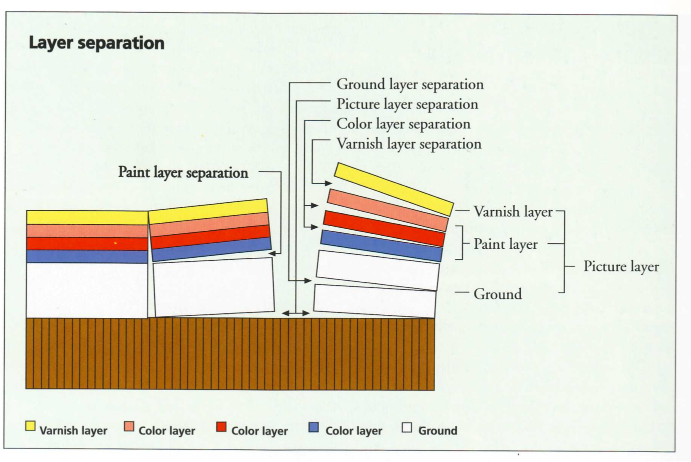


Fig. 1.

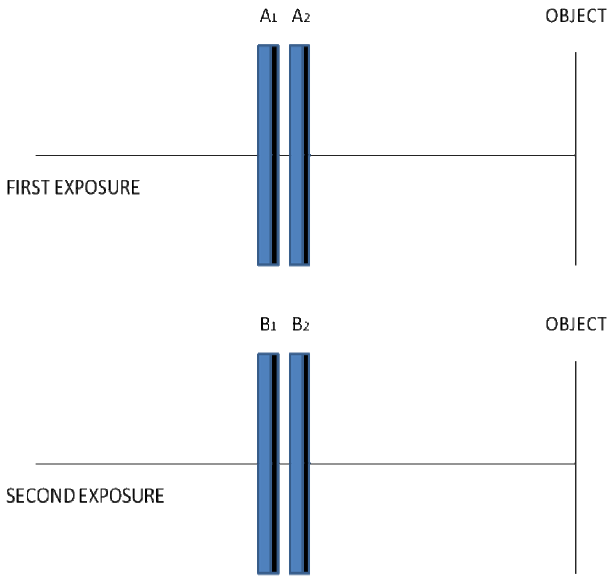


Fig. 2.

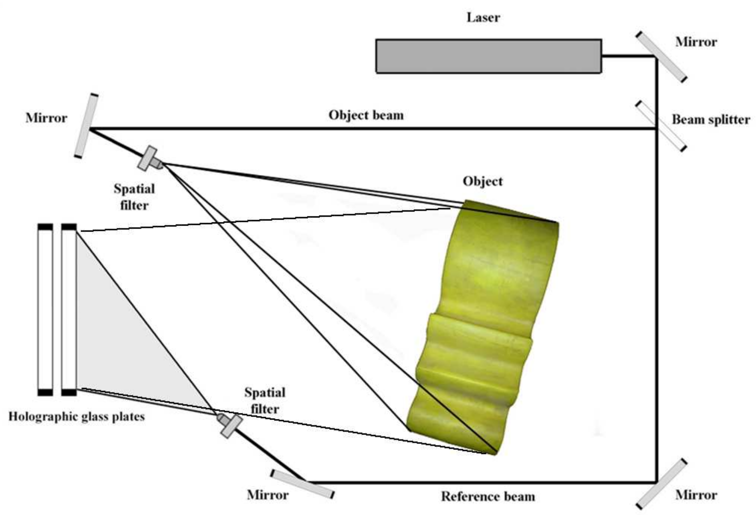

Laser
Mirror
Mirror
Object beam
Beam splitter
Spatial
filter
Object
Spatial
filter
Holographic glass plates
Mirror
Reference beam
Mirror

Fig. 3.

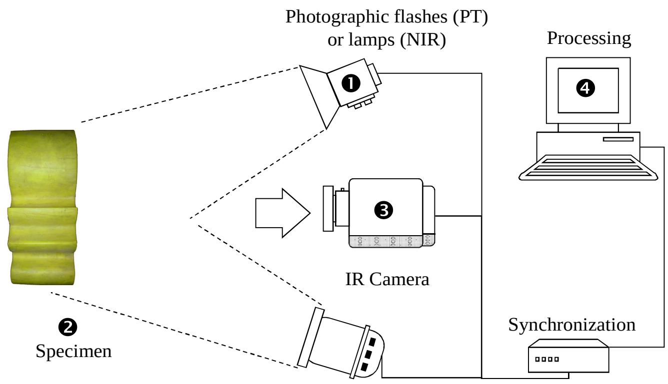
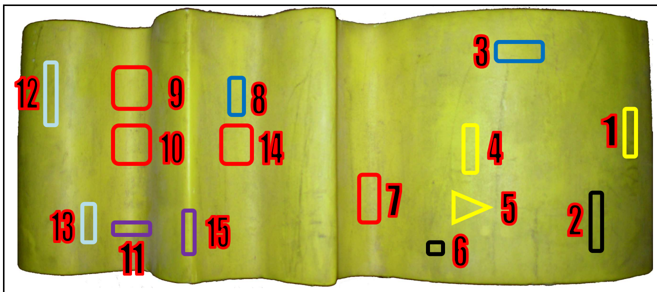
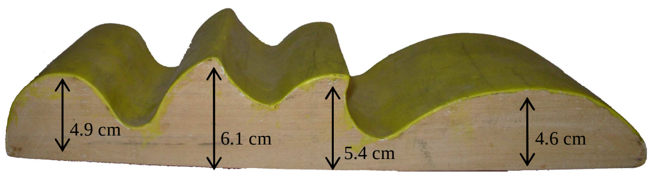

Photographic flashes (PT)
or lamps (NIR)
Processing
❶
❹
❸
IR Camera
❷
Specimen
Synchronization

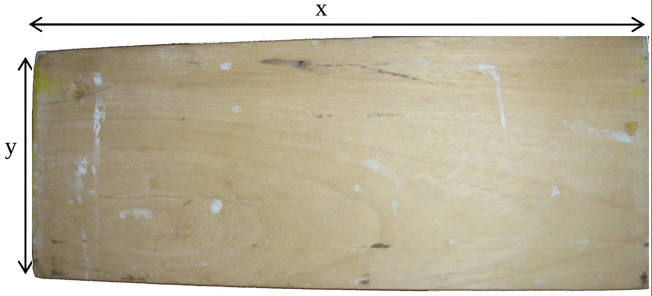
Fig. 4.



(a)



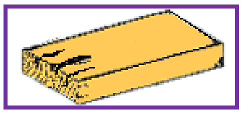
(b)



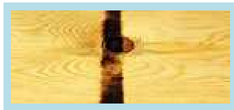
(c)

@Pitch@: an accumulation of resinous material on the surface or in pockets below the surface of wood. Also called gum or sap (defects 1, 4, 5).

@Checking@: a crack in the wood structure of a piece, usually running lengthwise (defects 11, 15).



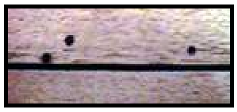
@Machine burn@: a darkening of the wood due to overheating by the machine knives or rolls when pieces are stopped in a machine (defects 12, 13).



@Loose knot@: a knot that cannot be relied upon to remain in place in the piece. Caused by a dead branch that was not fully integrated into the tree before it was cut down (defects 7, 9, 10, 14).

@Tight knot@: a knot fixed by growth or position in the wood structure so that it firmly retains its place in the surrounding wood (3, 8).

@Wormholes@: small holes in the wood caused by insects and beetles (defects 2, 6).



(d)

Fig. 5.

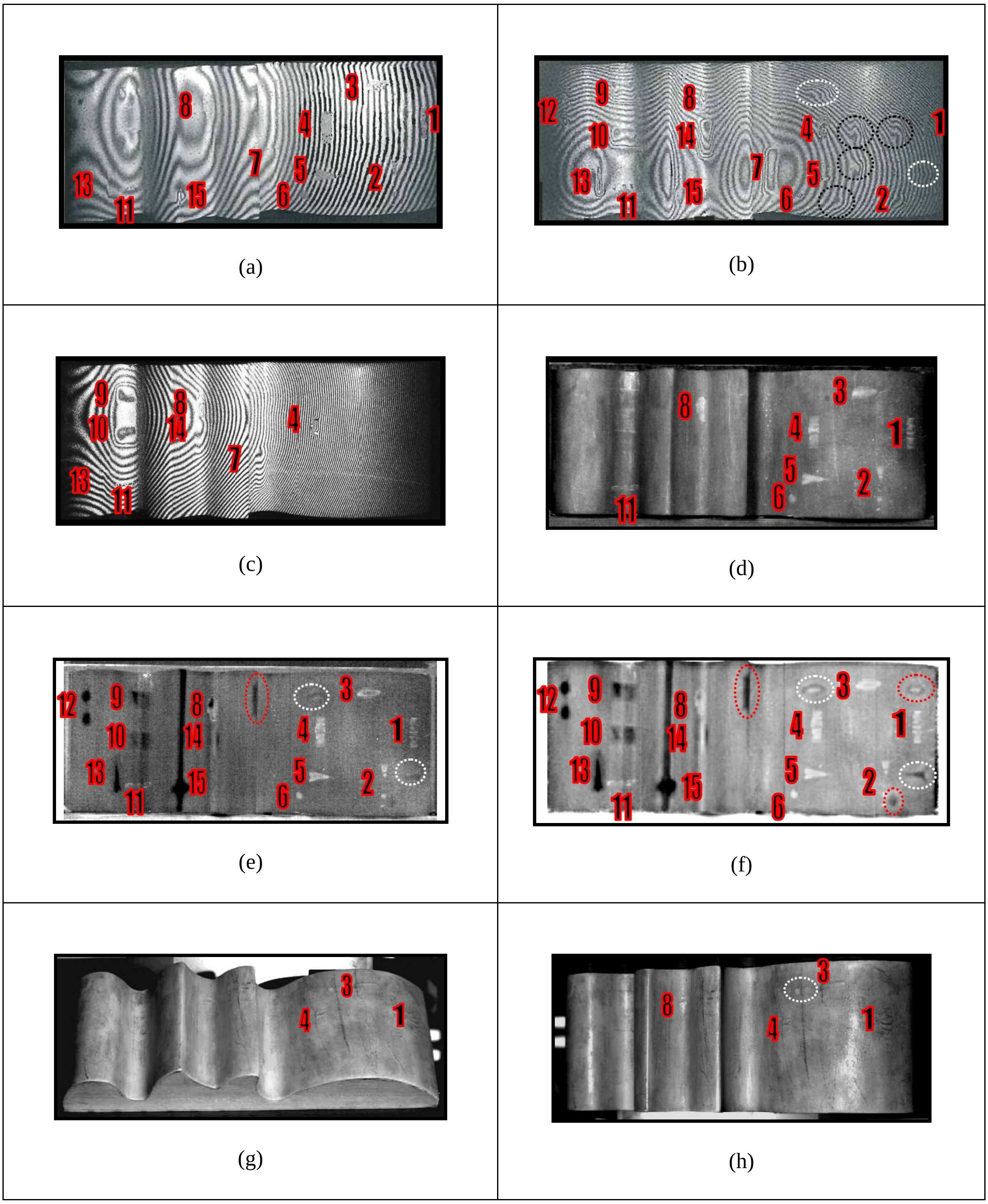


Fig. 6.