TV-Holography on a Microscopic Scale: Deformation Monitoring on Polychrome Terracotta Warriors

Gerd Gülker, Klaus D. Hinsch, and Arne Kraft

Carl von Ossietzky University Oldenburg, Department of Physics, 26111 Oldenburg, Germany

Abstract. TV-holography is used for deformation monitoring on coloured fragments of the famous 2000-years-old Chinese Terracotta Army. The colour layers show extreme sensibility to humidity changes. The aim of the investigations is to estimate the influence and suitability of several conservation agents and procedures. Due to the occurrence of small scale deformation areas the field of view had to be reduced. A microscopic system was constructed and typical object deformations due to shrinkage and swelling are presented. To investigate the individual layers of the multilayered objects a short-coherent superluminescence diode instead of a laser diode is used in a further modification. By changing the path length of one of the interfering beams it is possible to select a region limited in depth where deformations shall be measured even if it is located below the surface. First results on an artificial test object demonstrate the capabilities of this new short-coherence TV-holography system.

1 Introduction

In recent years TV-holography or electronic speckle pattern interferometry (ESPI) has become a powerful tool in the real-time observation of object vibrations and micro deformations. In several applications it could be demonstrated that TV-holography is also well suited for the investigation of deterioration processes in works of art [1,2].

In this contribution we present investigations on very delicate and fascinating ancient objects: we monitor deformations on coloured fragments of the famous 2000-years-old terracotta army of the first Chinese emperor. This probably one of the most spectacular archaeological find of this century consists of more than 7000 life-sized clay soldiers, horses, wooden wagons and bronze weapons. One problem in the preservation of these objects is, that the multilayered colours, which partly exist on the terracotta, are very fragile. They show immense sensibility to humidity changes resulting in deformations due to shrinkage and swelling. Since the excavation led to a desiccation of the terracotta figures, the remnants of the paint layers are extremely endangered to fall off. In order to develop suitable methods of conservation TV-holographic measurements are performed during cycles of humidity changes to estimate the influence and suitability of several conservation agents and procedures.

Due to the specific nature of the problem the TV-holography system was modified in two ways. First of all we saw that humidity-induced deformations occur on small sub-areas of the surface with extensions below one square millimeter. It was thus necessary to reduce the field of view during the investigations to only a couple of these sub-areas. For that reason, deformation monitoring was performed through a microscope. In the first part of this paper we focus on this modification.

While performing microscopic TV-holographic investigations we realized the importance of sub-surface deformation measurements, which leads to a second, quite new modification of the method. We saw that the deformations measured during humidity changes seemed to be mainly a result of only ground layer movements, while the upper colour layer(s) seemed to be relatively constant. To verify this presumption it is necessary to separate the deformation measuremnet of the ground layer from those of the upper layer(s). Since interferometric information is only given if the difference in path length between two superimposing beams is less then the coherence length of the light source, a TV-holography set up was designed with a low-coherence light source. In the second part of this contribution, the new method of short coherence TV-holography is described and first results on an artificially layered test object are presented.

2 Microscopic TV-Holography

The underlying principles of TV-holography are well-known nowadays and comprehensively described in literature, e.g. in [3]. Normally the method is used to monitor deformations of objects with sizes ranging from a few centimeters to some meters. There are only few articles in literature dealing with TV-holography in a microscopic mode. Examples are vibration monitoring of the basilar membrane [4] or deformation measurements around crack tips [5]. A very fundamental discussion of microscopic TV-holography can be found in [6]. In this application, a microscopic arrangement firstly is combined with spatial phase shifting, which, as we will see later, minimizes decorrelation effects and strongly benefits from the big speckles coming along with the magnification.

In Fig. 1 a scheme of the used setup is shown. The light from a HeNe laser illuminates the test specimen under a small angle in respect to the viewing direction. Thus, mainly the out-of-plane component of the deformation vector is registered. To perform humidity variations during the measurements, the objects under investigations are inserted in a small computer controlled climatic chamber where they can be exposed to well defined ambient temperature and relative humidity. The geometry of the climatic chamber as well as the kind of climatization requires quite long a distance between the object's surface and the front lens of the imaging system. For this reason the scattered light from the object is imaged by a long working distance Zeiss SV 8 microscope onto the target of a Sony XC 75 CCD camera. With this telescopic-type microscope and with the front objective lens PLS 100 mm only a moderate magnification of about 6.4x can be achieved leading to a minimum field of view of about 0.9x1.2 mm^2. This proved to be enough for most of our applications.

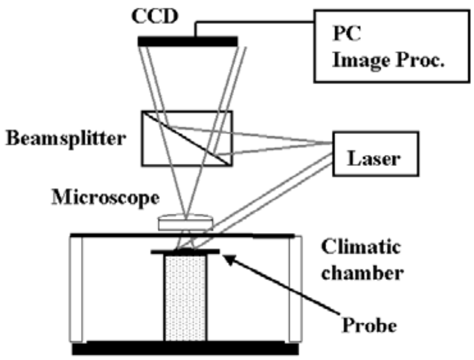

Fig.1. Scheme of the setup used for microscopic TV-holography measurements.

A part of the laser light is separated to act as a reference beam. It is guided to a beam splitter just in front of the CCD camera and is superimposed to the object beam. The virtual source point of the reference beam is located in the plane of the aperture with a small but well defined horizontal shift out of the center of the aperture. Thus a linear phase shift is generated across the image. This so-called spatial phase shift method permits the calculation of the phase map. After loading the object the phase map is calculated again and is subtracted from the origin phase map resulting in a mod-2π phase representation of the occurred deformations. To evaluate the phase maps we use the Fourier transform method.

The use of spatial phase shifting in this arrangement is favourable for two reasons. Firstly, in case of magnification small displacements of the scattering surface or small disturbances result in a big change of the speckle pattern and lead to speckle decorrelation. The simultaneous recording of phase shifted images reduces this effect. Secondly, in case of magnified imaging the mean speckle size increases which is a need for spatial phase shifting. In many application this leads to no further loss in spatial resolution and object light intensity.

3 Deformation Monitoring on Terracotta Fragments

In a series of experiments deformation measurements were performed on a couple of terracotta fragments partly covered with pigmented layers and on several pieces of isolated ground layers. The samples were subjected to different conservation treatments.

In Fig. 2 a typical result obtained with microscopic TV-holography is shown. In Fig. 2a a photograph of one of the investigated coloured fragments with a diagonal extension of about 6 cm is shown. It is a part of a breast armour of a warrior and shows the typical black ground layers partly covered with a red pigmented layer. The fragment is treated with HEMA, a new monomeric conservation agent which replaces water in the colour layers. After applying this to the fragment it is hardened by electronic beam polymerization. During the measurements the fragment was inserted in the climatic box and exposed to several humidity cycles while the resulting deformations were continuously monitored.

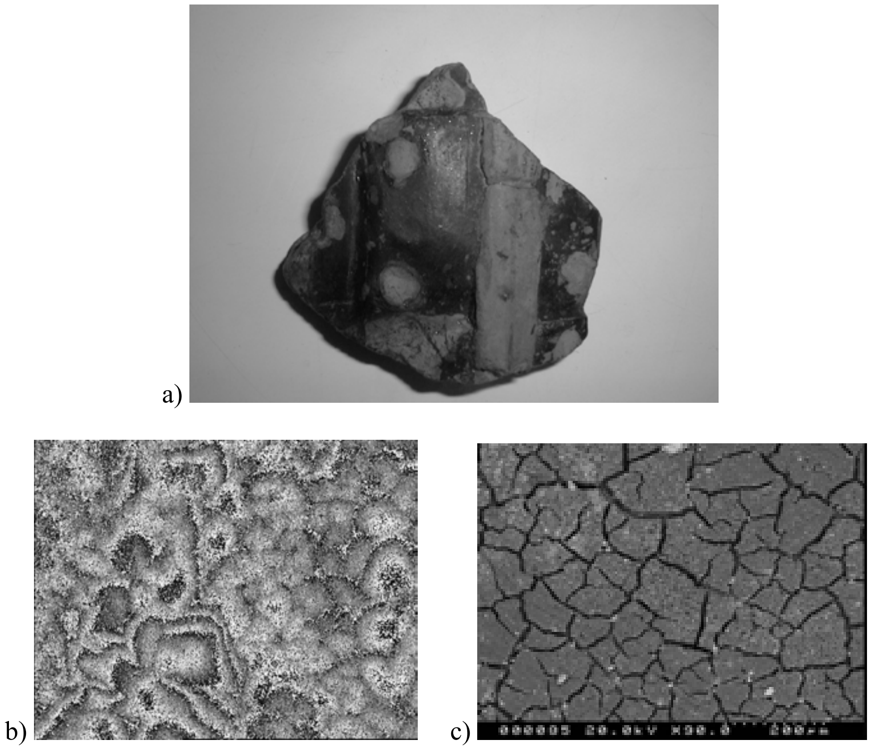

Fig.2: Investigation of coloured terracotta fragment. a) Original fragment, part of breast armour, b) Mod-2π phase map of deformation due to humidity change from 70 % -79% r.h. Area size: 0.9x1.2 mm^2. c) SEM micrograph of nearly same size and location taken one year later.

In Fig. 2b a mod-2π phase map representing the displacements of an area of 0.9x1.2 mm^2 is shown obtained during a humidity change from 70% to 79% r.h. A complex structure of separated deformation areas appeared which showed to be typical throughout all measurements on probes treated with HEMA. The sub-areas of about 100 – 200 µm diameter undergo bowl-shaped deformation in the order of 1 µm, the bowls becoming more flat with increasing humidity.

Evaluation of the result in Fig. 2b indicates first of all that the spatial resolution and thus the microscopic imaging is well adapted to the extensions of the appeared deformation areas. Without this magnified imaging the behaviour of the individual sub areas would not have been recognizable in this clearness. Secondly we saw that the conservation treatment leads to a drastic reduction of the deformation due to humidity changes. On untreated ground layers we found displacements of more then 10 µm during a humidity change of only 1 % r.h.

Although, the pattern shown in Fig. 2b were alarming at this time due to the occurrence of pronounced stress in the layers which was not expected. It must be noticed that up to this time visual microscopic inspection show a totally intact surface. No cracks in the colour layers could be recognized. In Fig. 2c it is shown that our suspicions came true. Here a SEM-micrograph of similar size at nearly the same location only one year later is shown. Several cracks are visible exactly along the edges of the bowl-shaped deformation areas in Fig. 2b. This net-like crack system which is well known and quite common on antique paintings could be a result of tension between the different layers. To verify this and for a better adaption of the conservation agent it is necessary to investigate the different layers separately. We decided to modify our setup to perform depth selective deformation measurements. In the next chapter this modification is discussed and first results on an artificial probe are presented.

4 Low-Coherence TV-holography

There are a few methods to separate light reflected from a region of interest from an unwanted background [7]. One possibility is to use gating techniques where ultra fast shutters are needed. A second possibility is to use low-coherence interferometry where interference is observed only when the path lengths of reference and object waves are matched to within the coherence length of the used light. In low-coherence holography [8] and optical coherence tomography [7] these methods are used to get a three-dimensional representation of the investigated object or to get cross-sectional tomographic images. Our aim is not to get absolute topographic information about the single layers we investigate but to measure their deformations. Of course one dominant presumption in all these methods is that the penetration depth of the light into the object and the backscattered light intensity are sufficiently high.

In Fig. 3 the set-up of the modified TV-holography system is shown. Here the laser light source is replaced by a superluminescence diode (SLD) with an output power of 8 mW, a central wavelength λ=840 nm and a FWHM of 20 nm. The coherence length is 34 µm which is the 1/e-value of contrast. Both reference and object light are coupled into single mode fibers. The angle between illumination and observation direction is again as small as possible to measure mainly out of-plane-deformations. The end of the fiber guiding the object beam and the collimating lens are mounted on a long range PZT translation stage. This enables us to control the path length of the object beam and to define a small volume of the object where the paths of the interfering beams are ideally matched. Of course multiple scattering has to be taken into account which can lead to a different optical path length.

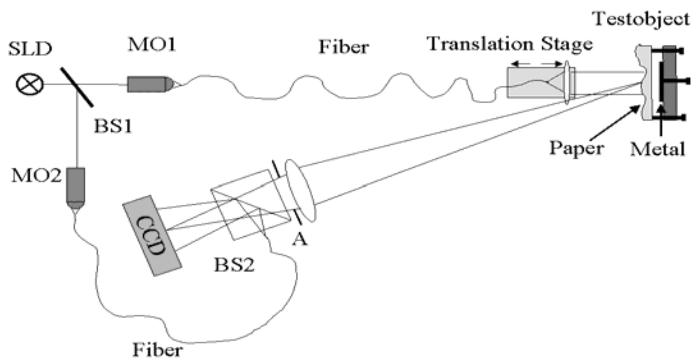

Fig. 3. Setup of short-coherence TV-holography

To evaluate the object phase we again use spatial phase shifting and the Fourier transform method. The advantage of this method is that only interfering light can build up the spatial carrier fringe pattern. By selecting the sidelobe we get rid of the unwanted incoherent light scattered, e.g., from the surface of the object. In some cases when the intensity of the object light and thus speckles are very bright as compared with the light in the reference beam the speckle halo in the middle of the Fourier transform will overlap with the sidelobes. This can lead to errors in the phase evaluation. To eliminate the speckle halo it is suitable to take a picture of the speckle pattern without the reference beam and subtract this from the interferogram. This leads to a pronounced enhancement in contrast.

5 Measurements on Artificial Layered Object

To demonstrate the capabilities of low-coherence TV-holography as compared with the unmodified system measurements were performed on a self designed test object. This test object consists of two layers, an ordinary piece of paper placed at a distance of approximately 2 mm in front of a white painted metal plate. The different layers can be displaced independently: the piece of paper can be tilted and the metal plate can be dent by a rear screw. Each measurement was carried out with two light sources, the SLD and a long-coherence laserdiode.

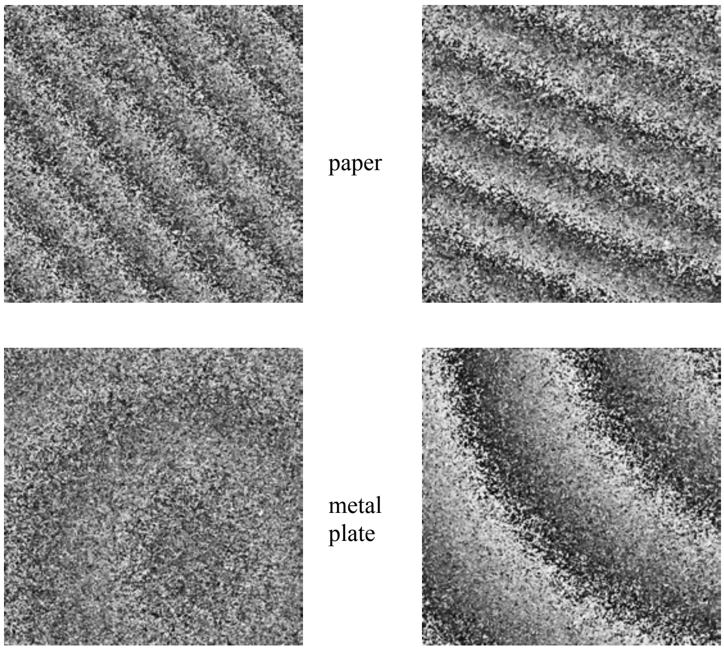

Fig. 4. Mod-2π phase maps representing deformation of test object due to tilting the paper (upper) and denting the metal plate (lower). Left: results with laser diode. Right: results with low-coherence SLD.

In Fig. 4 some results are shown in a mod-2π phase representation. The size of the investigated area is 4x4 mm^2. Two images obtained with the long-coherence laser diode in the left side of the figure are facing two respective results with the SLD on the right side. Both upper images of Fig. 4 result from a tilt of the paper layer, while the lower images are obtained after denting the metal plate.

Let us first discuss the upper phase maps, where the surface of the paper layer is observed. The contrast of the fringes obtained with the short-coherence SLD is only slightly better than the fringe system obtained with a laser diode. Both fringe systems are degraded possibly due to multiple scattering within the paper and due to humidity fluctuations. The fringes obtained with the laser diode suffer in addition from the coherent light scattered by the metal plate which is incoherent in the low-coherence case and thus less annoying.

More impressive are the effects if the second layer, the metal plate is observed (lower images in Fig. 4). With the laser diode the fringe pattern resulting from the dent are hardly visible (lower left) while the phase map from the SLD experiment shows up with a good contrast (lower right). In this case the scattered incoherent light from the paper does not degrade the fringe contrast. So the deformation pattern can easily be evaluated.

6 Conclusion

It is shown that the use of a microscopic TV-holography system is well suited to monitor humidity induced deformations of ancient colour layers. Valuable informations for the test and optimization of conservation agents and methods can be obtained long before a severe degradation of the surface occur. In a further modification it was shown that with the implementation of a short-coherence superluminescence diode depth selective deformation measurements in layered objects are possible.

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