OPTICAL AND LASER NDT: A RISING STAR

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Abstract: Productivity increase, consumer satisfaction and safety require that manufactured products or structures be thoroughly inspected or characterized during fabrication, after fabrication or in service. Characteristics that deserve evaluation are shape and thickness, material composition, material microstructure and surface and inner defects of various kinds that may affect product integrity (such as delaminations, cracks, porosity, disbonds). These requirements are satisfied by a broad panoply of light and laser-based techniques using technical approaches going far beyond visual inspection. These techniques are photogrammetry, laser triangulation, fringe projection, Moiré, D-Sight, Edge-of-light, Optical Coherence Tomography (OCT) for the evaluation of shape and surface profiles, Laser Induced Breakdown Spectroscopy for composition determination, holography, Electronic Speckle Pattern Interferometry and Shearography for the detection of flaws, laser-ultrasonics for the detection of flaws and microstructure characterization. OCT and another technique called Photon Density Waves can probe transparent or translucent materials. In this presentation, a broad overview of all optics or laser-based NDT/NDE techniques is presented, outlining their present industrial use and future perspectives.

Introduction: Light is certainly at the basis of the most widespread NDT technique: visual inspection. This technique is also likely to be the oldest one, dating back to prehistoric times when human beings started to fabricate rudimentary tools and objects. Presently, at the beginning of the third millennium, following the invention of the laser in 1960, the introduction of optical fibers for guiding light, solid state imaging detectors and computers for acquiring and processing complex data and images, light-based techniques occupy a much larger place in the spectrum of NDT or NDE techniques. Light can obviously be used for probing transparent materials but also completely opaque ones, either by measuring surface deformations that have their origin deep inside the probed part or using ultrasound generated and detected by lasers. In this presentation, NDE or NDT is defined broadly as encompassing all the inspection methods and techniques for finding out if materials, manufactured or in-fabrication objects and structures satisfy specifications, are defect-free and safe. Note that a flawed product can be defective in many aspects. First its shape, size or thickness may be out of specifications. Its composition may also be improper or the material may not have the desired microstructure. Its physical properties, particularly its mechanical properties may be insufficient for the intended purpose. Finally its flawed nature may be associated to cracks, disbonds, porosity either produced at fabrication or caused by a degradation process (fatigue, corrosion, erosion, creep…). Light-based techniques, of one kind or the other, are capable of detecting all these out-of-specification or defective features. A key characteristic of all light based techniques is the operation without contact and at a distance. As a consequence they can more easily probe materials and products on the production line when the material is at an intermediate state (e.g. hot) or in a raw state (e.g. molten) and products with complex or odd shapes. Note also that light based techniques can be classified as point techniques in which the object is probed at a single location and an image is obtained by scanning the object or the probe, and full-field techniques in which a whole area of the object is analyzed in parallel at once. Since this subject is very broad, the presented techniques will not be described in detail and essentially only the ones that are currently used in industry or have this potential will be mentioned, leaving aside techniques applicable essentially in the laboratory or used for mechanical engineering studies. Unlike previous reviews that covered sub-fields such as shape determination techniques or speckle techniques, this presentation is very broad and includes essentially all remote light-based techniques for inspection or characterization.

Visual inspection: this is the oldest NDT technique but still widely used [1]. It is used in the automobile industry where the visual aspect a car body is an important factor for sale. Specific approaches have been developed to measure in particular paint gloss, reflectance and surface roughness. Systems have also been developed to look at the surface conditions of metal strips (made of steel or aluminum) on a processing line. Visual inspection is also very important in the airline industry, and accounts for most of the inspection tasks in search for cracks and corrosion. Light guiding systems (boroscopes) have been developed for looking in areas where direct eye inspection is not possible. Present systems have benefited from the development of optical fibers technology and are very flexible. Direct eye vision is often advantageously replaced by artificial vision with a video camera using an imaging detector (such as a Charge Coupled Device or CCD).

Measuring shape and surface profile: they are many known techniques available for measuring the shape of an object [2]. One is based on photogrammetry (also called stereo vision imaging) and consists in reconstructing the shape from two or more pictures of the object. A point technique called laser triangulation is sketched in Fig.1. In laser triangulation, the surface is illuminated by a narrow beam of light and the image of the light spot on the surface through a lens is tracked by a linear detector. Knowledge of the parameters of the sensor and calibration allows finding the distance between the sensor and the illuminated spot on the surface. Full shape determination requires scanning of the sensor or the object. An extension of laser triangulation is the fringe projection technique (called also structured light). In this full field technique, sketched in Fig.2, a Ronchi grating is projected onto the object. The image of the object modulated by this fringe pattern is recorded by a CCD camera. The deformed fringe pattern provides a mapping of the object elevation in the direction of observation, so shape can be retrieved after analysis. Another technique uses an additional grating (the reference grating) to produce by combination (interference or beating) of these two gratings a Moiré pattern (see Fig.3) requiring less resolution of the camera. A variant of the technique uses the same grating at projection and analysis (shadow Moiré). Other known techniques are based on the measurement of the time-of-flight of short laser pulses, the enhancement of surface deformation by retroreflection (D-sight technique [3]) and the detection of shadow edge deflection by surface slope (Edge-of-light technique [4]).

Probing inside transparent or translucent materials: even if a discontinuity in a perfectly transparent material can rather easily be detected by looking through it, finding its depth is not straightforward. Such a capacity is obtained with a relatively novel technique called Optical Coherence Tomography (OCT). This technique is also applicable to translucent materials. OCT is in fact an interferometric technique that uses a broadband source (super luminescent diode) and is based on the principle of white light interferometry. As sketched in Fig. 4, which shows a modern version of this technique using fiber optics, an interference signal is obtained when the pathlengths (or delay times) along the path going to the sample and the reference path are equal. The length of this reference path being scanned, the depth of discontinuities inside the tested specimen can then be measured [5]. OCT is a point technique, so an image is obtained by scanning either the probe or the

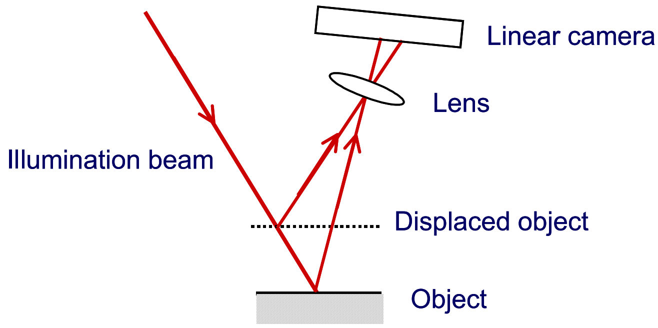

Figure 1: Principle of laser triangulation

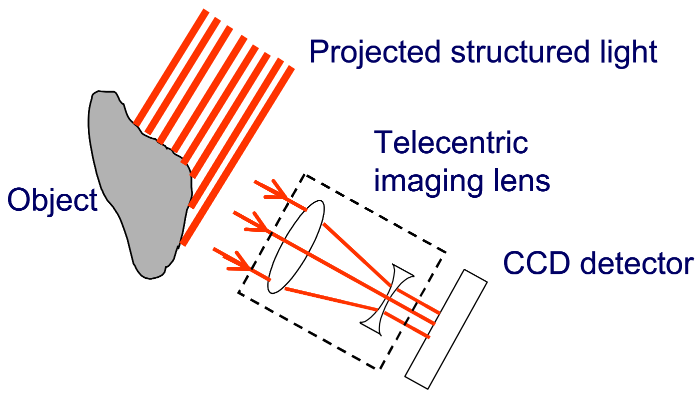

Figure 2: Projected fringes or structured light contouring technique. If there is 90° between the projected beam of spatial period *p* and the viewing direction, the fringes lines seen on the object correspond to height levels with increment equal to *p*.

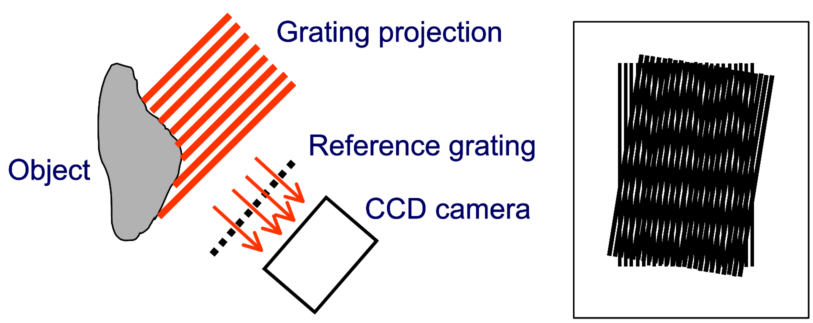

Figure 3: Projection Moiré technique; the insert at right shows a Moiré pattern resulting from the superposition of two gratings

tested object. OCT is being very actively developed for bio-diagnostic and medical applications, but applications to the industrial field are relatively new. OCT has obviously good potential for all polymer-based materials (except when reinforced with carbon fibers, carbon absorption being too large) and can be used for measuring the surface profile of opaque materials (such as measuring the surface roughness of a metallic part) [6]. Note that OCT uses only the fraction of light that stays coherent with excitation and has not been scattered.

Another technique that has been also developed for the medical field uses the scattered or diffuse light portion. This technique is implemented by modulating at high frequency (at MHz to hundreds of MHz) a beam of light sent into the translucent part. The injected photons are then scattered producing quasi-waves (the photon density waves) described by a diffusion equation (as thermal waves). On the opposite side of the specimen or at another location these waves are received by a detector after some delay. This technique can be used for imaging purposes and has found applications for medical diagnostic [7], but apparently none yet in the industrial field.

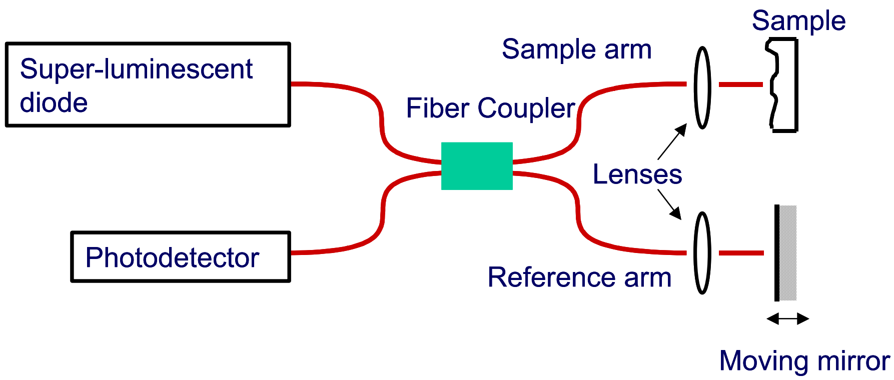

Figure 4: schematic of principle of all-fiber coupled OCT system.

Measuring composition: controlling chemical composition is very important for many industrial products, particularly metallic alloys. Many optical spectroscopic techniques based either on light emission, transmission or Raman scattering are used in the laboratory after suitable sample preparation, which often involves grinding or dissolving. Some of these techniques can also be used in a production environment if the material has proper transmission characteristics (e.g. infrared transmission spectroscopy of polymer sheets) or reflection characteristics (infrared reflectance spectroscopy to find a surface contaminant or diffuse reflectance spectroscopy of light scattering materials such as paper). In industry X-ray fluorescence is widely used for finding elemental composition of materials [8]. Elemental composition can also be found with less limitation regarding the detectable elements by using Laser Induced Breakdown Spectroscopy (LIBS) [9]. As shown in Fig. 5, LIBS consists in producing a plasma at the surface of the material and analyzing the spectra of the emitted light to identify the various elements. LIBS could be applied in very harsh environments, in particular on molten metals to find the composition of alloys. It could be used for sorting in recycling operations. By focusing the laser beam onto a small spot, analysis can be performed at the micron-scale, replacing advantageously X-ray dispersive analysis performed in Scanning Electron Microscopes. One drawback of LIBS is the mark or small crater left on the surface. However this can be turned into an advantage by providing composition depth profiling, the laser digging into the surface while analysis is performed.

Speckle techniques: these techniques include Holographic interferometry, Electronic Speckle Pattern Interferometry (ESPI, also called television holography, electronic, video or digital holography) and Shearography [10]. They are all full field interferometric techniques and require two sequential operations: a first recording of the object is followed by a second one after application of a stress to the object (e.g. by applying vacuum suction, pressurization or creating a thermal stress). After application of the stress, a surface displacement or strain is produced at the surface which reveals inner discontinuities or flaws in the material (such as delamination, disbond or crack). These techniques that have been in development since the early days of laser and holography have for a long time used photographic films for recording the speckles and optical

Fourier processing. Now, electronic recording (CCD camera) and computer processing is almost exclusively used. They have many variants, regarding either the detection of out-of-plane or in-plane displacements and fringe interpretation. Fig. 6 and 7 show schematics of principle of ESPI for out-of-plane measurement and shearography. ESPI is sensitive to vibrations and requires a stable environment or mounting the reference surface on the tested object (without stressing it). Shearography, which makes light from two adjacent points of the object surface to interfere on the imaging sensor measures surface strains. It is practically insensitive to vibrations and is gaining wide acceptance in industry, particularly in the aerospace industry for testing large parts [11,12].

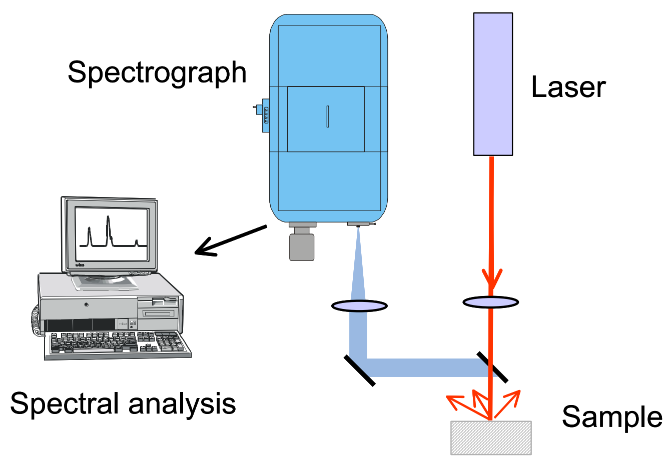

Figure 5: Schematic of principle a LIBS system.

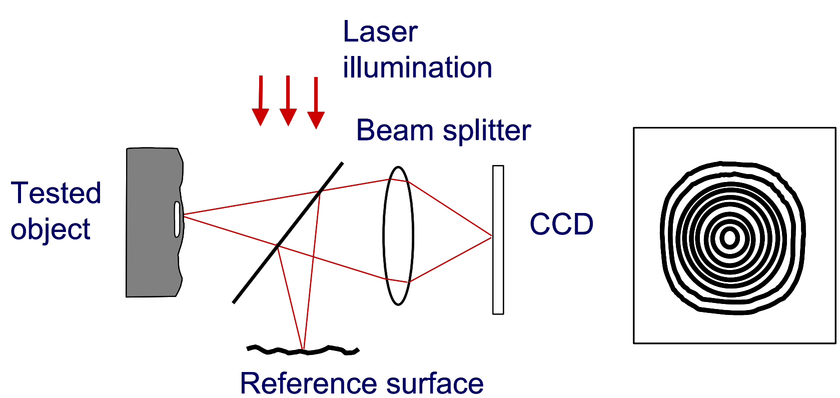

Figure 6: Schematic of principle of ESPI for measuring out-of-plane displacements on a sample with a delamination or disbond. The picture in the insert at right represent schematically (without the speckle noise background) the fringe pattern observed after electronic subtraction of the two speckle patterns (one before vacuum suction and one after). This pattern is related to the out-of-plane displacement produced by the budging of the surface above the defect (assumed to have square shape).

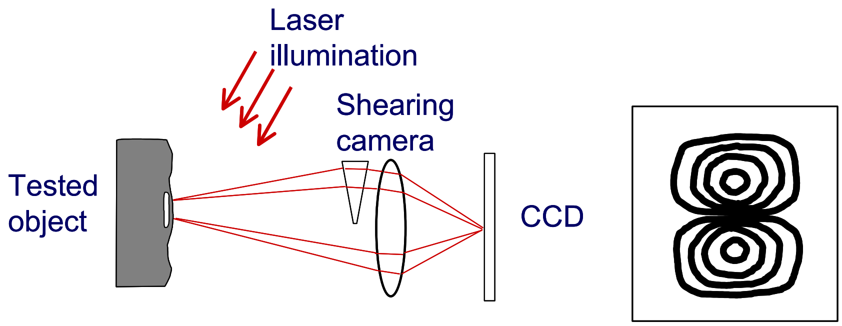

Figure 7: Schematic of principle of shearography on a sample with a delamination or disbond. The picture in the insert at right represent schematically (without the speckle noise background) the fringe pattern observed after electronic subtraction of the two speckle patterns (one before vacuum suction and one after). This pattern is related to the gradient or slope (along the vertical shearing direction) of the surface bulging above the defect (assumed to have square shape).

Laser-ultrasonics: laser-ultrasonics (also called laser-ultrasound, laser-based ultrasound) consists in "viewing" inside opaque materials by using ultrasound generated by a laser and detected by another laser coupled to an interferometer [13,14] (see Fig 8). In laser-ultrasonics the material surface is actually the emitting ultrasonic transducer. The ultrasonic source is produced either by a thermoelastic mechanism or material ablation. Detection is based on the Doppler effect that produces a frequency or phase modulation on the scattered light. Demodulation is performed by the interferometer that is preferably insensitive to speckle (confocal Fabry-Perot or photorefractive interferometer). The technique is particularly useful for finding flaws in parts with complex geometry and measurements on hot products. The technique has at the present time been commercially developed for three industrial applications. One is the inspection of aircraft parts and structures made of polymer-matrix composites. Fig. 9 show as example the mapping of the internal structure of the horizontal stabilizer of a F-18 fighter plane obtained by scanning the generation and detection laser beams. Fig. 10 shows a partial view of a system that is installed on the fabrication line of seamless steel tubes. The system measures the wall thickness and the eccentricity of these tubes that are at about 1000 °C and move while rotating at about 3 m/s. This example illustrates the ability of optics-based techniques to operate in severe environmental conditions by their remote operation nature. Obviously optical and laser equipment has to be properly protected, but this is facilitated by locating it away from the severe environment and using fiber optics coupling. Note that the same gauging system is also used to measure grain size [15]. This capability of laser-ultrasonics of measuring material microstructure is actually quite general and powerful. It is based on the stronger attenuation of ultrasound by a coarser microstructure (such as a larger grain size) and on the dependence of ultrasonic velocity on material elastic anisotropy [13]. The third industrial application is the thickness determination of microelectronic thin layers and is based on the generation of very high frequency ultrasonic waves with femtosecond lasers [13].

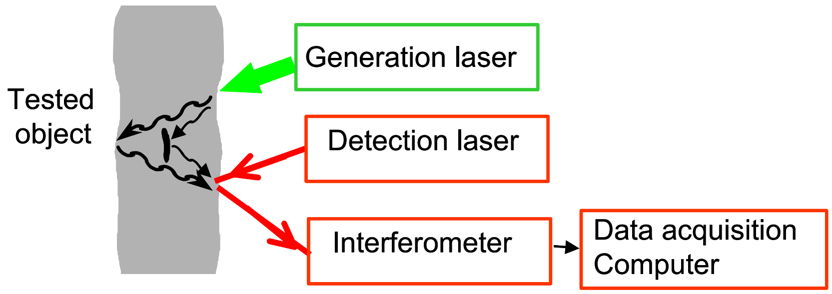

Figure 8. Sketch of the principle of laser-ultrasonics.

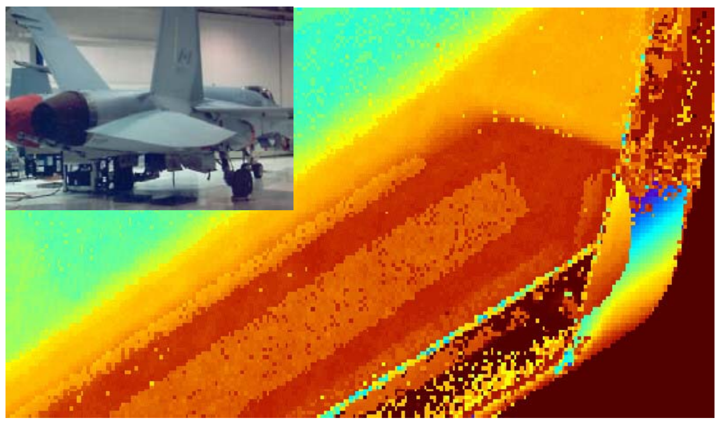

Figure 9. Internal mapping (ultrasonic C-scan) of the horizontal stabilizer of a Canadian F-18 airplane obtained by laser-ultrasonics. The plane (see insert) was in a maintenance hangar and in ready for take-off conditions.

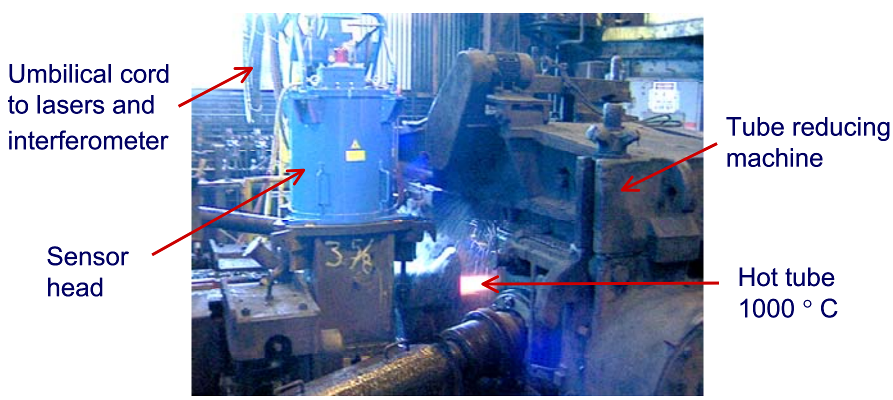

Figure 10. View of the inspection head of a laser-ultrasonic system installed on seamless tube fabrication line.

Conclusion: We have presented an overview of the various light or laser based techniques that can be used for probing objects, materials or structures. We have seen that these techniques encompass a wide spectrum of technical approaches, so all the information needed to evaluate thoroughly a product or a structure, such as shape, composition, microstructure, and defects can be provided. Being by essence non-contact and remote techniques, they could be used in conditions where other techniques will be difficult to apply, such as on hot or odd shape products and on a production line. These techniques could be either used individually or combined for providing a more thorough evaluation, such as shape and defect detection or composition and microstructure. With the need of increasing productivity and safety, of better controlling fabrication processes and finding flaws as soon they are produced, while benefiting of continuing advances in lasers, optical fibers, image sensors and computers, the importance of optical and laser techniques is due to increase, making them the rising star of NDT/NDE.

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