EXPERIMENTAL ANALYSIS OF RESIDUAL STRESSES BY ESPI

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Optical Techniques

Introduction

Optical techniques have one thing in common: the person making the measurement is light, or rather light radiation. Optical techniques measure displacement fields. Displacement fields can be transformed into strain fields. Strain fields can be transformed into stress fields. Specifically we will see three possibilities:

- *Speckle interferometry;*
- *Moire methods;*
- *Digital image correlation (DIC).*

Optical techniques do not include X-ray diffractometry. What characterizes diffractometry is having a very low wavelength or a very high frequency and the phenomenon of diffraction occurs at high energies (as in the case of x-rays)but it can also happen at low energies. These phenomena can also occur in the visible.

An optical method is considered when working in the **visible**.

These are the characteristics of optical methods:

- *High sensitivity: on the order of a few hundred nm (wavelength between 450-750 nm)*;
- *Entire field: with such approach, I illuminate the component and recording the answer I appraise the total behavior of the answer. Allows you to store a lot of information in a short time*;
- *High resolution: the distance between a point of which we know the information in terms of deformation and the nearest point, can be kept very low*;
- *Non-destructive and non-contact measurement: This technology itself is non-destructive, but when combined with other processes it can become semi-destructive or destructive*.

The measuring instrument is light radiation (light). There are two types of radiation:

- Coherent radiation source (laser);
- Non-coherent radiation source (diffuse light).

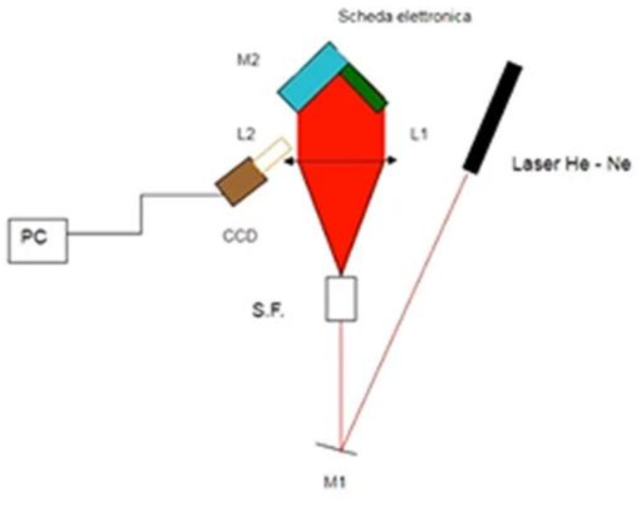
Consistent light differs from diffuse light by the following characteristics:

- *Monochromatic: has only one specific wavelength λ (e.g.: green = 632nm) with tolerances* $\Delta\lambda$ very low;
- *Directionality: diffused light propagates with very wide opening cones, in laser beams the light beams propagate parallel to each other*;
- *High brightness: it is nothing but the power density, the laser concentrates a high power in very small areas (just think of the laser welding)*;
- *Coherence: the electromagnetic field can be represented by a simple sine wave in time and space. Lasers have a high consistency space is spoken from a few meters to 1km*.

ESPI – Electronic Speckle Pattern Interferometry

Setup description

The typical setup of this technique is as follows:

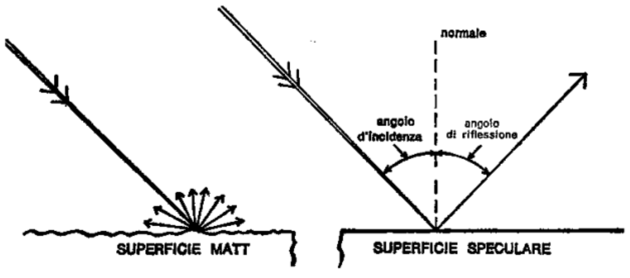


Lay-out schematico del sistema

First the laser meets the M1 mirror with a surface roughness of λ/10 to give rise to mirror reflection.

Reflection physical principle

When an electromagnetic wave meets a surface from place to reflection, this can be described by two models: diffuse reflection and specular reflection.



In general these two phenomena always coexist, one prevails over the other depending on the roughness of the surface:

$$\begin{cases} Se\ R_u > \lambda \rightarrow prevale\ la\ diffusione \\ Se\ R_u < \lambda \rightarrow prevale\ laspeculare \end{cases}$$

The mirrors supplied for the optical instrumentation have a roughness equal to λ/10 to make the mirror reflection prevail.

Back to the setup …

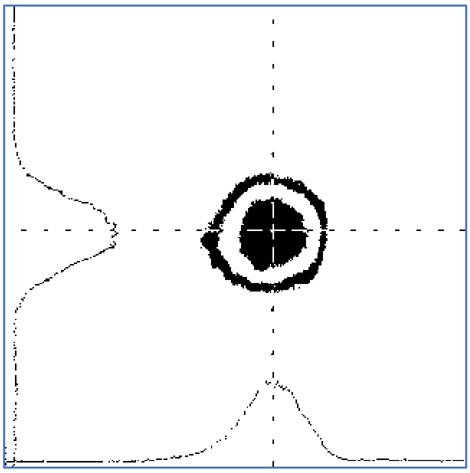
We could avoid putting the M1 mirror but this makes the installation more compact than the fully inline one.

After diverting the beam we have a space filter (S.F.) that has the ability to preserve the low-frequency component of the electromagnetic radiation of the laser with emission $TEM_{0,0}$.

Laser physical principle

A laser has emission only according to some atomic vibrating modes (wavelength) also called TEM modes, who are classified with two pedixs "n" and "m". What does it mean in practice? If we consider the electromagnetic distributions inside the laser cavity, that is if we analyze the electromagnetic radiation that slams from one mirror to another, only some solutions of the Maxwell equation are possible and these solutions are the TEM modes.

Generally, commonly used lasers are $TEM_{0,0}$ that emit long luminous intensity x and y with Gaussian pattern:



Actually the signal will not be a perfect Gaussian but will be the sum of a high frequency component (noise) and a low frequency. A filter has the ability to preserve the low-frequency component of electromagnetic radiation.

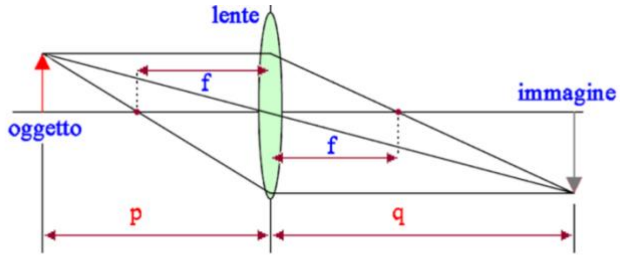
Back to the setup …

S.F. exploits a property of the lenses (not mirrors), that is to divert the beam in a single point called fire according to the law of thin lenses:

The lens deviates the light beam depending on the height at which the light beam affects:

$$\frac{1}{\rho}+\frac{1}{q}=\frac{1}{f}$$

The lens will reconstruct the image at a certain distance q, the focal distance f depends on the type of lens and may not coincide with q. The lens object distance is the p.



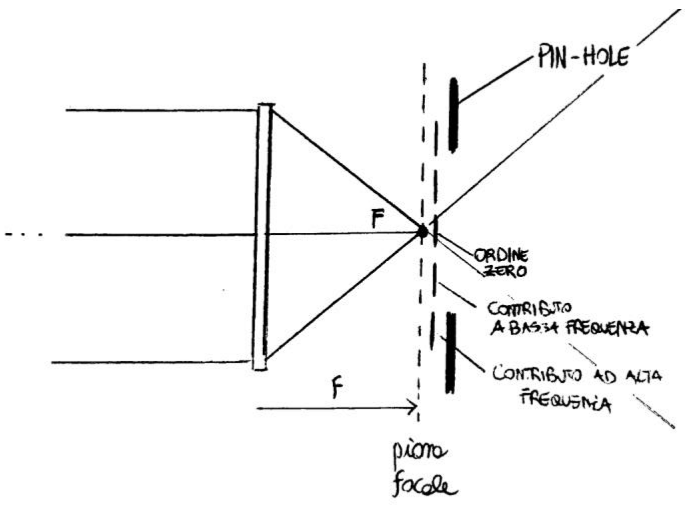
In our case $\rho \rightarrow \infty$ because the beams affect all parallel on the lens at distance q:

$$q = f$$

The result indicates that the focus point coincides precisely with the image.

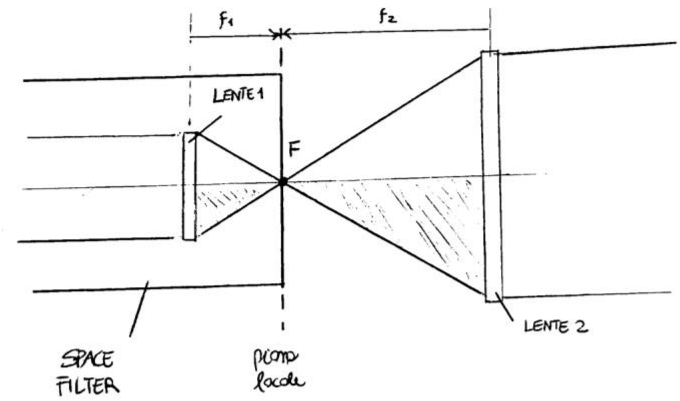
If on the lens there is an intensity I(x,y), on the focal plane, the lens will automatically carry out the Fourier transform of I(x,y), that is I can separate the various contributions in frequency.

S.F. is equipped with a plate with very small holes (Pin Hole) in the order of 10 15 μm that prevents high frequency contributions from propagating in the focal plane.



The S.F. works as much better as I can bring the focal plane closer to the lens, f small means to be able to separate the various contributions in frequency.

After the S.F. the beam diverges, but the spot is too small to make field measurements; therefore, the beam needs to be straightened:



The law is always the same; for the second lens we have:

$$\frac{1}{\rho}+\frac{1}{q}=\frac{1}{f_2}\rightarrow but\ \rho=f_2\rightarrow q\rightarrow\ \infty$$

This means that after the lens two we have a beam collimated.

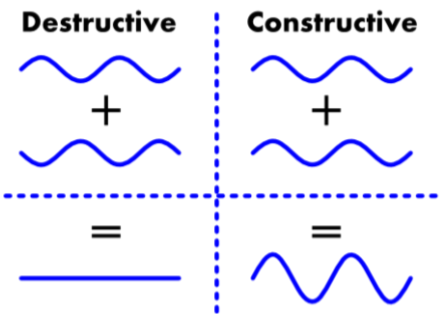
Using the symmetry of the triangles it is possible to define the magnification ratio, which can be modified by playing with f_2/f_1, from the similarity of the triangles:

$$\frac{D_2}{D_1}=f_2/f_1$$

There is another optical element, a second mirror alongside the component under examination after the beam expander. This configuration is called Lender configuration. So you have a reference beam that does not change and a measurement beam. The interference of these two will give rise to the pattern speckle pre- and post-load.

Physical principle interference

Interferometry is used when the property of the electromagnetic waves that interact with each other, or interference, can be constructive or destructive:

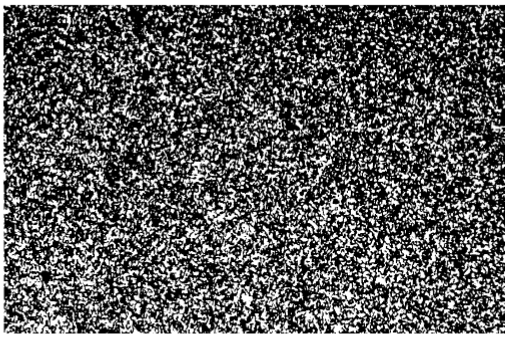


Of course, in order to combine sinusoids, you have to make sure that they are of the same type: that's why you use laser.

Consider a surface of a material affected by the laser beam previously treated. Obviously each material will have a certain roughness. For diffuse reflection, these beams will be reflected in other directions.

The waves that make up the reference beam and those of the measuring beam will interfere with each other due to the diffused reflection generating on each pixel of the photodetector a point of different color and overall a pattern speckle with zones:

- White: constructive interference sign;
- Black: sign of destructive interference;
- Gray: interference sign not completely neither constructive nor destructive, intensity levels depend on the BIT of the photodetector.



Therefore, being the speckle pattern dependent on the morphology of the surface, it is possible to deform the surface and acquire a new pattern, by comparing the two patterns and measuring the deformations.

The roughness is like the fingerprint of the piece and "follows" the piece in its deformation.

Measures by change in phase

The mathematical operation behind this pattern comparison is the subtraction of images where each image is a matrix of points of different intensity.

During the structure acquisition download the field E_{T1} at the CCD of the camera is the sum of the field $E_0^{discharged}$ object and field E_r reference:

$$E_{T1} = E_0^d + E_r = A_0 e^{i\phi_0^d} + A_r e^{i\phi_r}$$

The intensity of this field is:

$$I_1 = I_0 + I_r + 2A_0 A_r \cos\left(\phi_0^d - \phi_r\right)$$

Similarly for the loaded structure there will be the two fields $E_0^{charged}$ and E_r, that will produce:

$$I_1 = I_0 + I_r + 2A_0A_r\cos\left(\phi_0^c - \phi_r\right)$$

The difference matrix between test-piece loading and unloading can be written compactly as:

$$I_1 - I_2 = 2A_0A_r(\cos(\phi_0^s - \phi_r) - \cos(\phi_0^c - \phi_r)) = 2A_0A_1(\cos(\psi) - \cos(\psi + \Delta\psi)) =$$

$$= I(x,y) = I_b(x,y) + \gamma(x,y)\cos\left(\Delta\psi(x,y)\right)$$

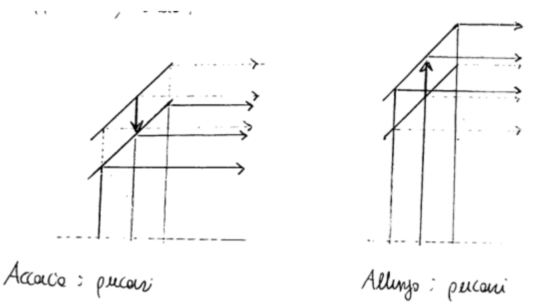
With x,y matrix indices. Analyzing the various terms:

- I_b = *background intensity: that is the one that refers to the ambient noise (light from the windows) or to the noise inside the room*;
- γ = *Contrast term: indicates how clearly you see the pattern and is linked to the quality of the setup and reflectivity of the object to measure*;
- $\Delta\psi$ = *phase variation: it is the term we are interested in and it is proportional to the displacement field*.

For each pattern there are two beams that must give interference, one spread from the surface and one reference!

We can see that the problem is badly placed as I have an equation in three unknowns: $I_b, \gamma, \Delta\psi$ because from the measure we obtain only $I(x,y)$.

To solve this problem it is necessary to move the mirror M_2 making it move back and forth and therefore the intensity of the difference matrix will vary:



If I move the mirror and repeat the difference between matrices, I get phase shifts Δq that no longer depends on (x,y) because we decide how much to move the mirror, according to the acquisitions we will get a system like:

$$\begin{cases} I_1(x,y) = I_{b1}(x,y) + \gamma_1(x,y)\cos\left(\Delta\psi_1(x,y)\right) \\ \dots \\ I_i(x,y) = I_{bi}(x,y) + \gamma_i(x,y)\cos\left(\Delta\psi_i(x,y) + \Delta q_i\right) \end{cases}$$

The system is characterized in the following way:

- If you are in the same environmental conditions, it is safe to assume: $I_b = I_{bi}$;
- If the setup does not change, you can assume $\gamma_1 = \gamma_i$;

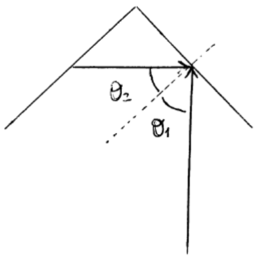
- If the component is in the same condition, ψ being proportional to the displacement field, it is permissible to assume $\Delta\psi_1 = \Delta\psi_i$.

I would need **three equations** to solve the system, such an approach is called *Temporal Phase Stepping*. It is essential to know the phase shift introduced by moving the mirror, and this can only be guaranteed in part by using a piezoelectric crystal to move the mirror in a controlled way. Typically we resort to a redundant system of measures type with 5 steps of 2π so we have:

$$\Delta s \propto \Delta\psi = \tan^{-1}\left(\frac{2(I_2 - I_4)}{2I_3 - I_5 - I_1}\right)$$

Lender setup

In the case of the Lender configuration, the two beams (reference and object) are made to reach the surface of the workpiece with the same inclination $\theta_1 = \theta_2$:



We have always said that the shift is proportional to the change in phase:

$$\Delta s \propto \Delta\psi \rightarrow \Delta s = \alpha\Delta\psi$$

For this configuration the proportionality factor applies:

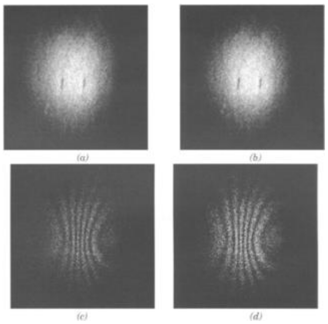
$$\alpha = \frac{\lambda}{2\sin(\theta)}$$

therefore we have:

$$\Delta s = \frac{\lambda}{2\sin(\theta)}\frac{\Delta\psi}{2\pi}$$

Output of the technique

The subtraction between the deformed and the indeformed matrix produces a difference matrix, which visually represents fringes (modulated by the term cosine = light and dark parts) or the place of the points at constant displacement with respect to the direction of sensitivity:



The fringes are modulated according to the cosine, this means that you pass from one fringe to another or two maxima of the cosine function every 2π or passing from $\Delta\psi \rightarrow \Delta\psi + 2\pi$:

$$\Delta s' = \frac{\lambda}{2\sin(\theta)}\frac{\Delta\psi + 2\pi}{2\pi} = \Delta s + \frac{\lambda}{2\sin(\theta)} = \Delta s + \alpha$$

The shift between one fringe and another is precisely the constant of proportionality of Lender and represents if we want the sensitivity of the interferometric system, it follows that:

the displacement must be small in relation to the size of the speckle (because of the term at the denominator of α).

Sensitivity of the method

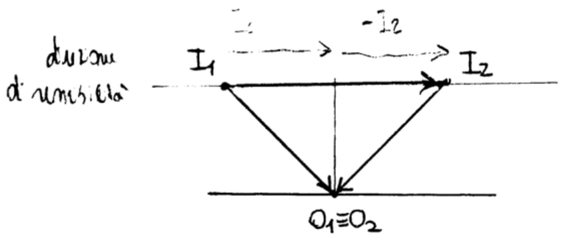
To vary the sensitivity of the method it is customary to vary the setup because the term of proportionality depends on the laser and the angles of incidence and observation:

$$\alpha = \lambda f(\theta_i, \theta_o)$$

Increasing sensitivity at the same time reduces the full scale, that is, the maximum measurable displacement. This could cause the pattern to decorate, meaning that the light beams no longer affect the same pixel between one matrix and the other.

Direction of sensitivity of the method

It depends on the optical configuration used and generally coincides with the difference of the vector of illumination and that of observation. In the case of the configuration of Lender I have only one direction of illumination and one observation, incident symmetrically by the way, so:



$$(I_1 - O_1) - (I_2 - O_2) = I_1 - I_2$$

That is, in the case of the Lender configuration the system is sensitive to the displacement component in the plane along the horizontal direction.

To measure other components I could: use the same configuration by rotating the piece or use other beams of illumination so as to have different vector sum.

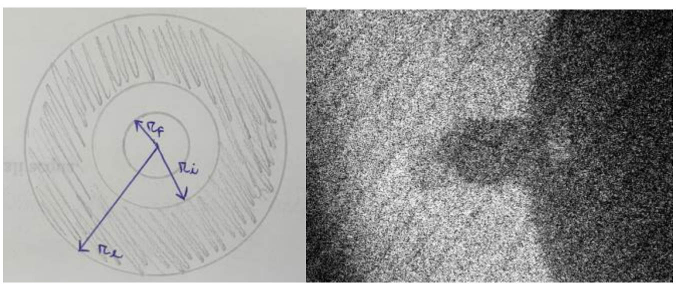
Hole drilling + ESPI

Compared to rosettes more expensive than a simple ER and not reusable, the ESPI allows to have various advantages, including the correction of the centering of the hole in the rosette because an eccentricity of the latter can be corrected by software and also you can study smaller components given the absence of ER.

With this technique we proceed as follows:

- It captures a reference pattern before making the hole;
- The multi-step drilling operation is carried out;
- Acquires a new speckle pattern with relaxed deformations;
- The luminous intensity matrices sampled by the pixel are compared;
- This procedure is repeated for each step.

Of all the image we will be interested in a specific area identified by a circular circle of rays:

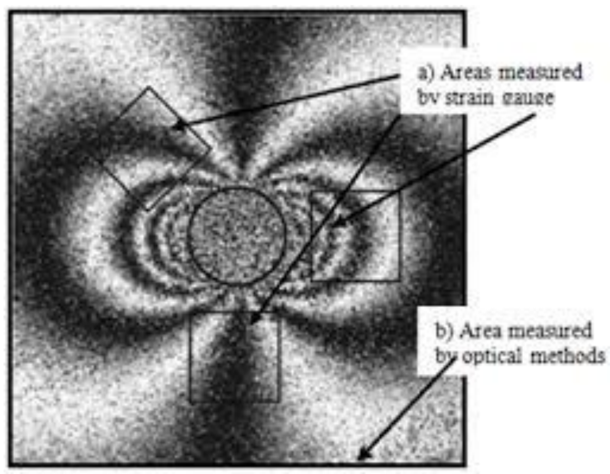


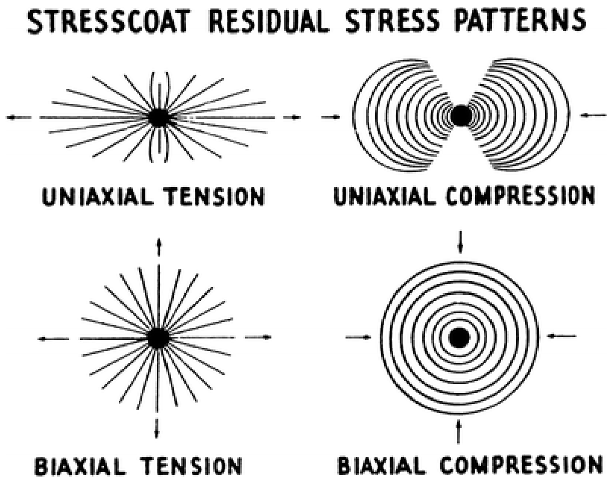
$$\begin{cases} r_e = 4r_{hole} \\ r_i = 2r_{hole} \end{cases}$$

The area roughly coincides with the area where the strain gauges are mounted and serves to move away from the area of the hole where there may be edge effects. Before the test you can see the shadow of the drill.

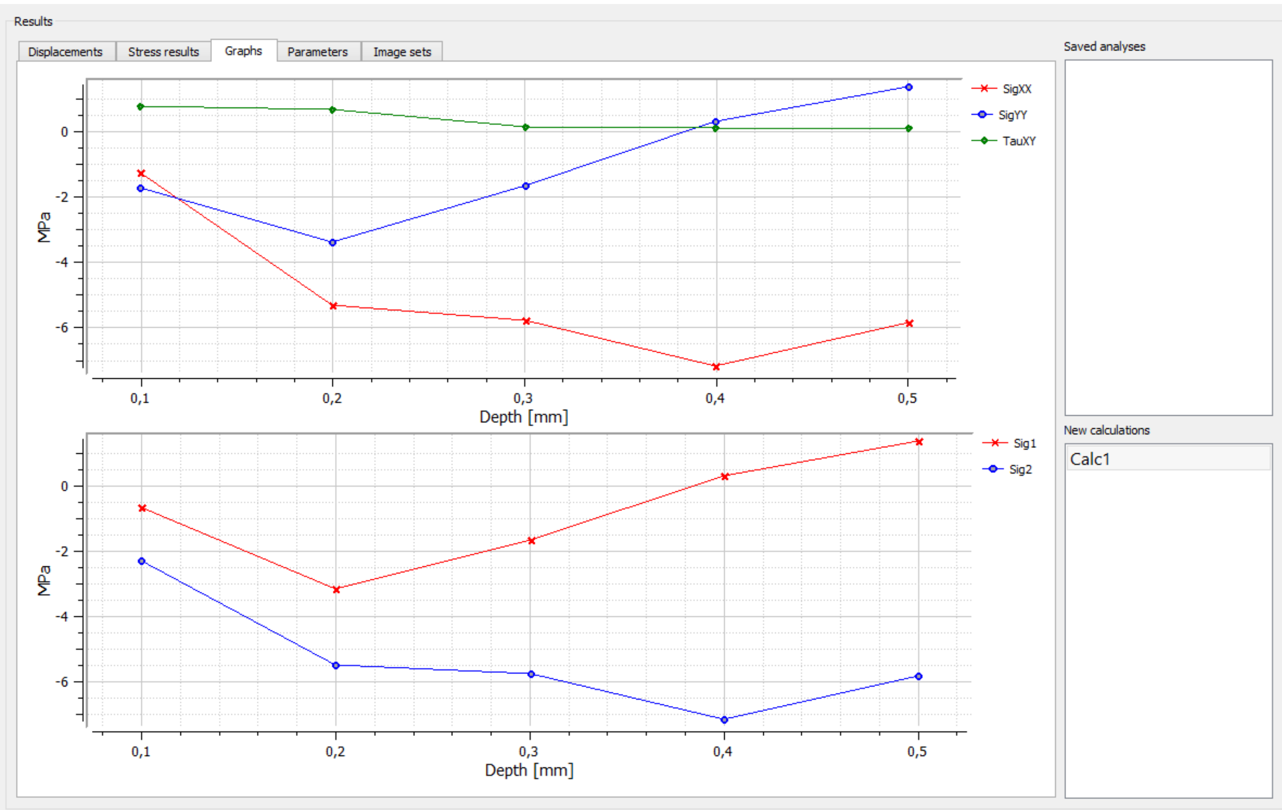
Test output

The speckle patterns obtained generally resemble the following:





Instead in terms of Residual Stresses you get quite smooth trends because you adopt the incremental method; I do not compare the pattern at each step with the surface but with the previous step. As follow in the case of a **test sample 3D printed**.



EXPERIMENTAL ANALYSIS OF RESIDUAL STRESSES BY X-RAY DIFFRATOMETRY

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Date: 20/02/2022

X-Ray Diffraction

Introduction

It is a non-destructive technique that allows to measure the residual stresses on the "surface" of materials that have a crystalline lattice for which: metal and ceramic. The principle of operation is based on the measurement of lattice distortion to solve deformations and stresses.

The advantages of diffractometry are:

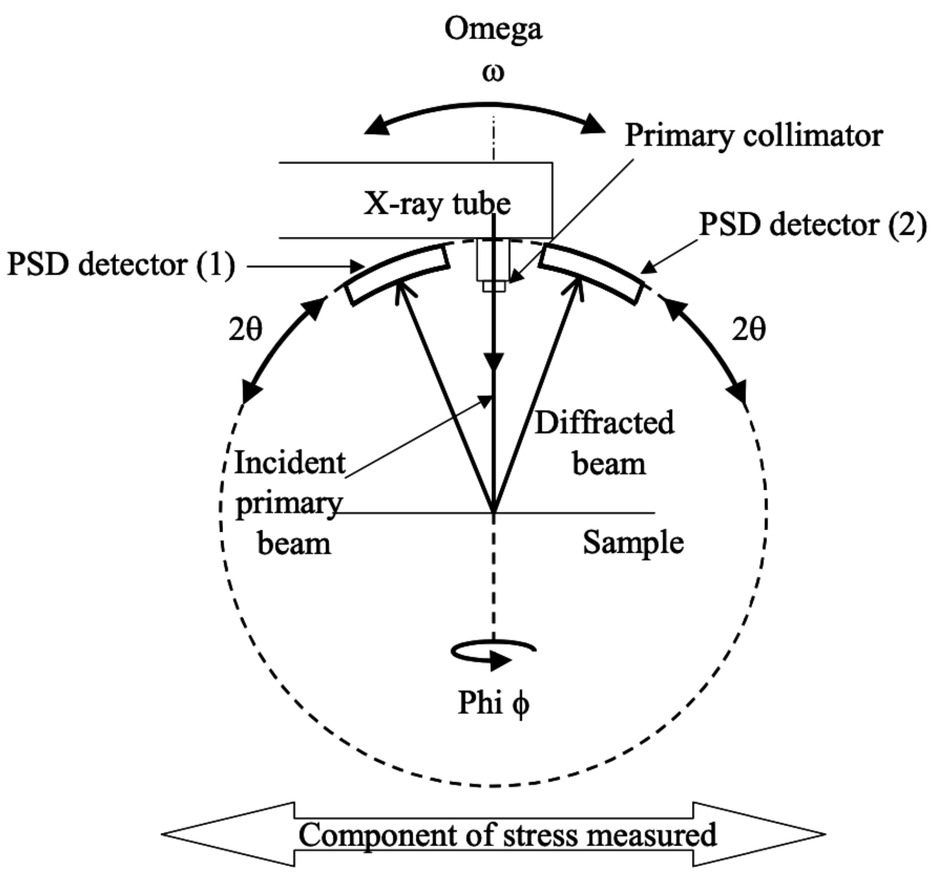
- Non-destructive measurement;
- Measurement of non contact;
- Non-field measurement: I can get the voltage state at a point;
- The surface does not need any preparation;
- Can be combined with electropolishing but becoming a destructive method;

the disadvantages are:

- No field measurements carried out;
- Limited to crystalline materials;
- Needs X-ray source

Experimental Setup

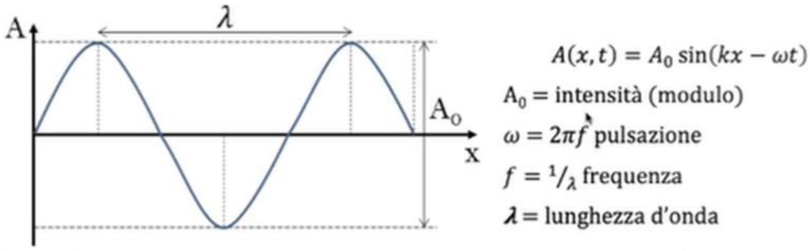
The measuring system consists of an omega headband with photodetector and a collimator that directs X-rays on the surface of the materials under consideration.



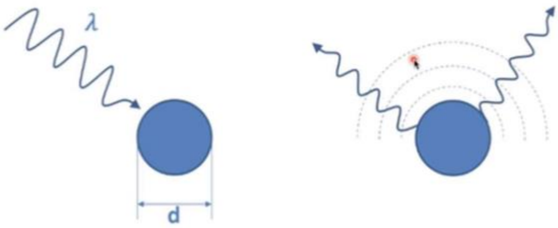
The entire arch is mounted on a mechanical arm that can lift and lower, the bow instead can rotate clockwise and counterclockwise, later you will see the usefulness of such features.

Physical Principle Diffraction

We introduce some physical quantities of electromagnetic waves, this can be indicated as:

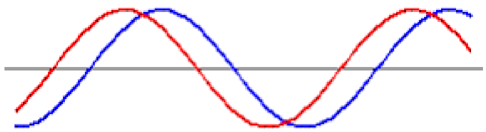


Suppose we have a spherical body of diameter d, and it is hit by a wave of wavelength λ, it will become a secondary emitter and will emit waves at the same λ.



Two waves with the same wavelength can interfere with each other, the laser swords of different color of star wars that interfere are a fiction.

Therefore, suppose we have two waves with the same wavelength but spaced between them by a temporal δ amount:



they will be:

$$A_1(t) = A_0 \sin(kx - \omega t)$$

$$A_2(t) = A_0 \sin(kx - \omega t + \delta)$$

The intensity resulting from the interference:

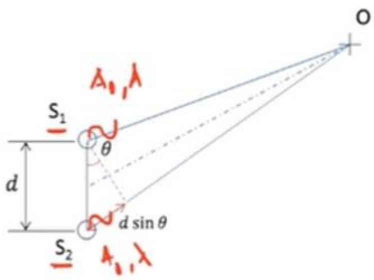
$$A_{tot}(t) = 2A_0 \cos(\delta /2)$$

Depending on the δ I can have:

$$\begin{cases} \delta = 2n\pi \rightarrow interferenza\ costruttiva \rightarrow A_{tot} = 2A_0 \\ \delta = 2n\pi \rightarrow interferenza\ distruttiva \rightarrow A_{tot} = 0 \end{cases}$$

Simple Ideal Lattice

Consider two spherical sources S_1,S_2 and an observer O. The two sources are located at a distance from each other and emit waves of the same wavelength, but the path to A_1 to reach O will be different from the path to be covered by A_2, which will therefore be delayed by δ:



$$S_1O = path\ of A_1$$

$$S_2O \cong S_1O + d * \sin(\theta) = path\ of\ A_2$$

therefore $\delta \propto dsin(\theta)$ in fact:

$$\omega{:}\,\delta = c{:}\,dsin(\theta)$$

$$c = wave\ propagation\ velocity$$

from which we get:

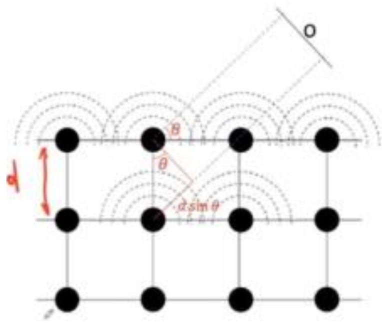
$$\delta = \frac{\omega}{c}\,dsin(\theta) = \frac{2\pi f}{c}dsin(\theta) = \frac{2\pi}{\lambda}dsin(\theta)$$

The type of interference, fixed λ (depending on the X-ray tube), depends on sin (θ):

$$\delta = \frac{2\pi}{\lambda}d\sin(\theta)$$

Ideal Crystal Lattice

Now consider a crystalline lattice of a material, in the absence of loads, TR and microstructural defects something of the following type happens, where, each atom is spaced by d_0 from the other and will act as emitter:

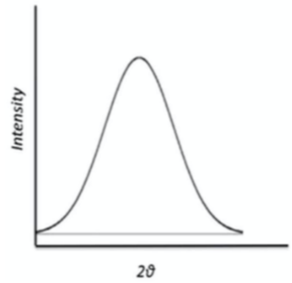


The δ required for a reading of the instrument is that which produces me constructive interference, and therefore the maximum intensity perceptible:

$$\begin{cases}\delta = \dfrac{2\pi d}{\lambda}d\sin(\theta) \\ \delta = 2n\pi\end{cases} \rightarrow n\lambda = d\sin(\theta)$$

This is the Law of Bragg or Fundamental Law of Diffractometry.

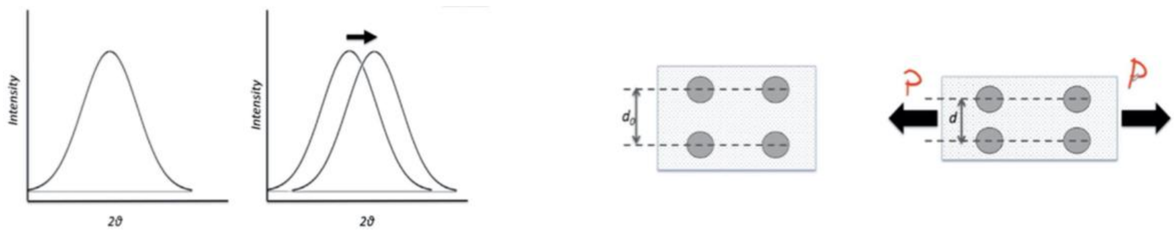
The signal detected by the photodetectors, distributed along the head of the measuring head, will be of the following shape; This is because each secondary emitter emits spherical waves that interfere with each other and there is a direction θ such that the intensity is maximum and is characteristic of each material:



Ideal Crystalline Lattice Loaded

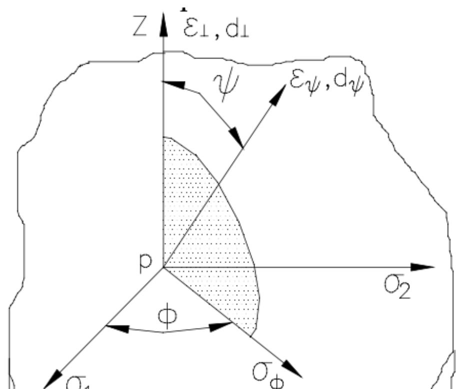
But if I load the sample, for example, I strain it, the atoms move away in the direction of stress, but they approach the surface in the normal direction because the cross section is reduced:

$$d \downarrow \rightarrow since\ n\lambda = cost \rightarrow \theta\ must\ increase \rightarrow SHIFT\ of\ the\ signal$$



Strain

Let’s take a reference system attached to the surface:



Suppose we want to measure the deformation along the z-axis normal to the surface of the piece, we define ϵ_z as a variation of the interatomic distance:

$$\epsilon_z = \frac{d_z - d_0}{d_0}$$

X-rays are used because they have a wavelength that can interfere with the interatomic distances of crystalline materials

The tension then in case of **plane stress**:

$$\epsilon_z = \sigma_z - \frac{\upsilon}{E}\left(\sigma_x + \sigma_y\right), \sigma_z = 0$$

$$\frac{d_z - d_0}{d_0} = -\frac{\upsilon}{E}(\sigma_x + \sigma_y)$$

Knowing the properties of the material (υ,E), I measure d_n with diffractometry. The only unknowns are σ_x, σ_y e d_0.

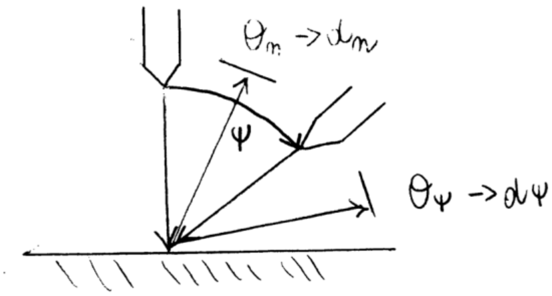
the problem is that d_0 of an alloy with random grain arrangement is not known a priori, also there is no material that is TR free against a processing. Also, I need at least two measures to discriminate separately σ_x e σ_y.

Usually we don't deal with **monoscristalline** structures, and each crystal can have different directions of growth, I can use a more general reference system where each crystalline grain will contribute according to its own direction of growth:

$$\epsilon_{\phi,\psi} = \frac{d_{\phi,\psi} - d_n}{d_n}$$

What is actually done is to place the nominal collimator on the surface and measure for θn from which I derive d_n; I then rotate the collimator ψ and gain $\theta_\psi$and d_ψ; therefore, with the **Law of Bragg**:

$$\begin{cases} \psi = 0 \rightarrow \max \theta_n \rightarrow \theta_n \rightarrow n\lambda = d_n \sin(\theta_n) \rightarrow d_n \\ \psi \neq 0 \rightarrow \max \theta_\psi \rightarrow \theta_\psi \rightarrow n\lambda = d_\psi \sin\left(\theta_\psi\right) \rightarrow d_\psi \end{cases}$$

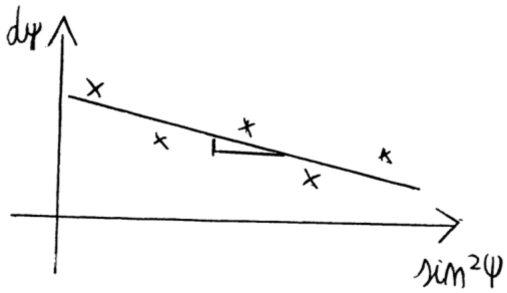


And you can thus calculate the voltage with the following:

$$\sigma_\psi = \frac{E}{(1+\upsilon)\sin^2(\psi)} \frac{d_\psi - d_n}{d}$$

From the theoretical point of view, only two measures are enough, from the practical point of view instead: up to five measures are made with ψ_i different because with only two measures could be measured surface tensions altered by an inclusion "close" to the surface.

A linear regression line of the results is then made and the voltage expressed as a function of this line:

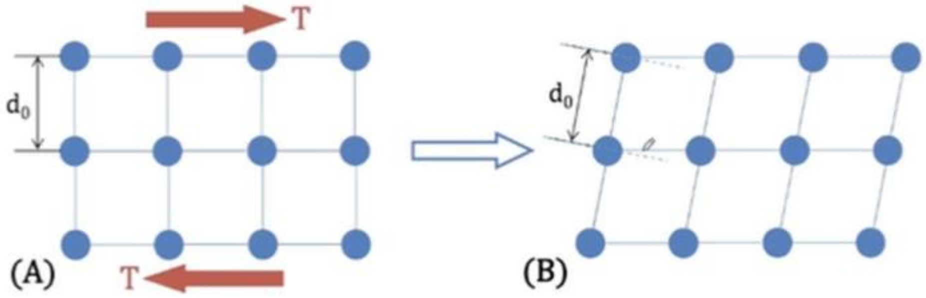


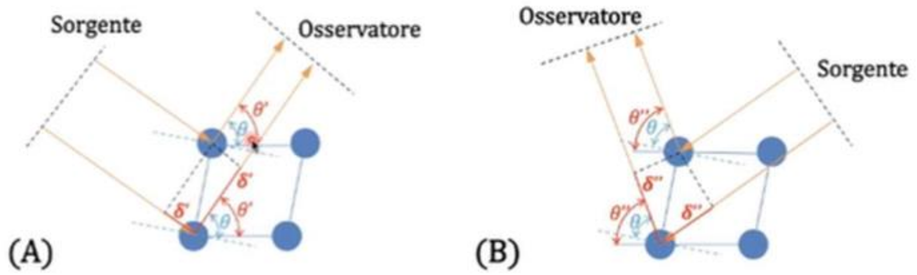
And it is calculated:

$$\sigma_\psi = \frac{E}{(1+v)\sin^2(\psi)}\frac{d_\psi - d_n}{d_n} = \sigma_\psi = \frac{E}{(1+v)}\frac{d\psi}{\sin^2(\psi)} = \frac{E}{(1+v)}m$$

Effetto del taglio plastico

Imagine having a TR-free material and applying a cutting load to it that causes plastic shear deformation. Such deformation would lead to a shift of the crystalline planes but the distance between them would remain unchanged. What happens is that based on how I position the collimator, I get residual **apparent** tensile or compressive stresses:

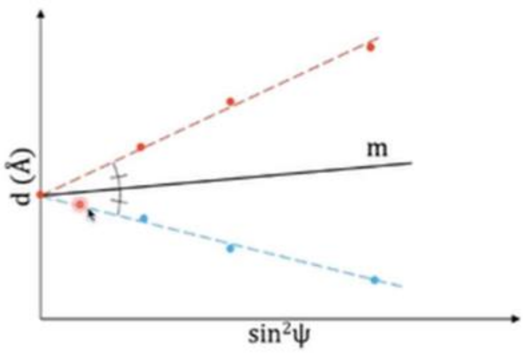




If I place the collimator on the left, $\theta' < \theta \rightarrow if\ \theta \downarrow then\ d \uparrow \rightarrow$ *TR apparent traction.*

If I place the collimator on the right, $\theta' > \theta \rightarrow if\ \theta \uparrow then\ d \downarrow \rightarrow$ *TR apparent compression.*

To overcome this problem I tilt the collimator to the right and left of the same angles, I find the bisector between the two linear regressions (regression of the right angles and regression of the left corners):



I use the bisector to characterize the stress:

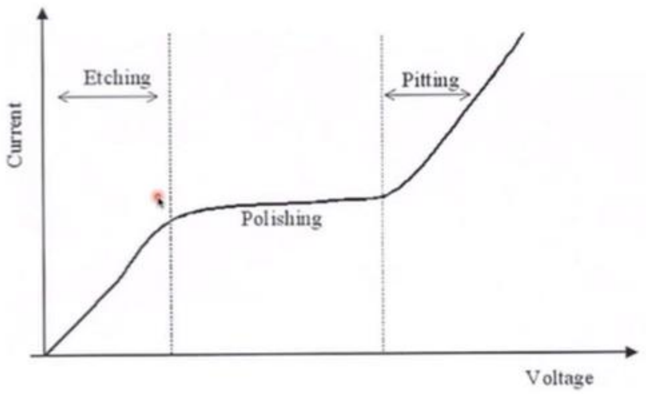
$$\sigma_\psi = \frac{E}{(1+\upsilon)} m$$

Diffractometry + Elettropolishing

I can combine what was previously seen with the EDM that does **not introduce** Resisal Stresses to study the tensional state in depth, i.e.:

- I perform the measurements;
- Remove a certain amount of material;
- Repeat measurements on new surface;
- I repeat the previous steps.

We have three possible areas of work in the electrolytic removal and the amount of material removed is proportional to the current, that is:



In a first zone there is **Etching** (this phase is generally used for polishing). The second phase is that of our interest, the reason is linked to the fact that you can remove in a controlled manner. In the third one you have discharges, you don’t work in this area.

Advantages over the hole method:

- Theoretically I have no drilling limits. Remember that in hole drilling you get up to a maximum value of 1-2 mm. The limit is that rosettes are not sensitive beyond a certain value;
- I can vary the steps, this is useful for example in the case of shot peening. In the case of shot peening, there are very high gradients.

Measurement Errors

- Errors related to instrumentation;
- Errors due to the imperfection of the specimen: the surfaces of the specimen can either plant or have a curvature. In case these have curvature, this must be limited, as if it were not, I would be inaccurate. What happens is that the radius of curvature must be at most 2 times the diameter of the collimator.
- Errors due to peak-fitting: that is, the signals, do not have an ideal Gaussian pattern but have a noise;