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THE ROLE AND THE DETECTION OF RESIDUAL STRESS IN HELICOPTER AND AIRCRAFT COMPONENTS

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THE ROLE AND THE DETECTION OF RESIDUAL STRESS IN HELICOPTER AND AIRCRAFT COMPONENTS.

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ABSTRACT

A brief illustration will be given on the argument of residual stresses and on their importance in determining the reliability of modern mechanical components.

The well-assessed X-ray diffraction measuring technique(XRD) will be briefly described along with its limits and possibilities. It will be pointed out that,as far as only surface information is required,XRD can be a powerful non-destructive quality control tool especially in the aeronautical industry.

Some practical cases dealing with typical aeronautical steels such as quenched and tempered AISI 4340 ESR and case carburized AISI 9310 ESR will be illustrated and particular emphasis will be given to the fact that,just because of the shallow penetration of X-rays in matter, an accurate and localized description of the state of the material can be given and this feature is particularly useful when either surface residual stress gradients,such as those produced by Electron Beam welding or in-depth gradients such as those created by surface hardening treatments are to be evaluated.

In this case,XRD represents one of the few industrial techniques capable of detecting even little changes in the metallurgical and mechanical state of the material.

At present,residual stresses are being considered as one of the most important factors affecting the structural integrity of a mechanical component.

These stresses are introduced into the material by means of different processes (heat treating,machining,forming,welding etc.) which impart their own characteristic stress pattern to the piece.

The effects of residual stresses are often not evident until the part is subjected to external loads or exposed to adverse environments. Tensile residual stresses are usually detrimental in as much as they increase the susceptibility to fatigue damage,stress corrosion and fracture,since they algebraically add to the externally applied forces, increasing the actual stress acting on the part.
On the other hand,compressive residual stresses are usually beneficial since they tend to reduce the above mentioned susceptibilities by decreasing the actual stress.
However,residual stresses of any kind can affect dimensional stability (i.e warpage due to welding).

Since residual stresses depend on many factors,it is quite difficult to perform numerical evaluation and prediction. The most widely used experimental methods can be subdivided into 4 groups:

1) Non-destructive : X-Ray Diffraction (XRD)
2) Non-destructive : Magnetic and ultrasonic methods.
3) Semi-destructive: Blind-hole and core-ring methods.
4) Destructive: Slicing,layer removal and boring out methods.

The semi-destructive methods are so called because a hole is usually drilled in the test piece,thus leaving a defect which sometimes can be acceptable,especially on large statically loaded constructions. They also apply to composite materials,where some non-destructive methods fail.

Both the semi-destructive and destructive methods are based on the stress relaxation and on the new residual stress pattern which ensues after a constraint (namely a portion of material) has been removed from the piece.

Material relaxation can be recorded in many ways:
a) electrically (strain-guages)
b) optically (brittle paints,interferometric fringes)
c) mechanically (dial guages)

The non-destructive methods are based on some strain-sensitive property of the material:
a) distance between atomic planes : XRD
b) magnetic permeability : Magnetic method
c) sound wave propagation velocity: Ultrasonic method

Though b) and c) are under continuous development,they still make it difficult to correlate the measured quantity to the residual stress state of the material,since many factors,mainly preferred orientation, can affect the result.

Another difficulty associated to the former methods is that the part of material being analyzed is not well defined so we can only obtain mean values over large volumes compared to those examined by XRD.

On the other hand,XRD has resolved quite well the problem of preferred orientation,but it is still difficult to apply on large grained structures.(Al,Mg castings,Ti alloys,etc.)

As regards the application of residual stress measuring methods to the aircraft domain,XRD is the most widely used for the following advantages:

i the inherent non-destructive nature of XRD as far as surface stress alone is concerned
ii the possibility of measuring steep surface stress gradients i.e stresses due to Electron Beam Welding).
iii the shallow penetration of X-rays in the metallic material.By means of in-depth examination,one can have an exact knowledge of the overall residual stress pattern of the piece. In this case, even if the technique is no longer non-destructive,it is the most accurate due its highly localized nature.

ORIGIN OF RESIDUAL STRESSES

Residual stresses are generated whenever a non-homogeneous elasto-plastic deformation takes place in a body.
3 fundamental causes have been envisaged that can lead to the for= mation of residual stresses.

a) Thermal
b) Structural
c) Mechanical

THERMAL CAUSES:

In order to simplify the example ,let us take into consideration a steel sample at high temperature during the phase of cooling.
No account will be taken for any strucural transformation.

During cooling,the surface contracts more than the core due to its faster cooling rate. However the surface cannot contract freely since the hotter core contrasts its shrinkage.Due to this reaction,the core undergoes compressive yield at high temperature,whereas the surface is in tension.
When the core starts to contract due to cooling,its contraction is impeded by the colder surface.So the final result is compression on the surface and tension in the core.
If the cooling rate is very high,cracks on cooling can occur in the surface since the tension exerted on it by the core can ex= ceed the U.T.S.,the value of which decreases at increasing tempe= rature.

STRUCTURAL CAUSES:
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2 common industrial processes which introduce residual stresses by means of structural transformation will be shortly viewed:

Direct quenching.
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Referring to same steel sample as before,during cooling,the Austenite -> Martensite reaction first starts in the surface.Since the specific volume of the Fe martensite (b.c.t) cell is greater than that of Fe austenite (f.c.c) by about 4%,the surface tends to expand during the transformation. However,like before,this expansion is contrasted by the not yet transformed core,so during this phase the result is compression on the surface,tension in the core.
When the core undergoes transformation,its expansion is partially impeded by the already hard martenistic surface.
Thus the final result is tension on the surface and compression in the core.
Quench cracks in the surface often occur during this phase.

Case carburizing.
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Among the other beneficial effects of this heat treatment(increase of surface hardness and mechanical resistance), it also improves fatigue resistance by introducing compressive residual stresses to an extent of about 1mm. in the bulk. The origin of these stresses can be briefly explained as follows.
It is well known that during this treatment,the surface becomes richer in Carbon than the bulk and that the temperature (Ms) at which the A->M transformation starts decreases as the content of free Carbon increases.
Thus during quenching,the less Carbon rich parts transform before the surface. Since the A->M increase of volume is directly proportional to the % of Carbon,the partially bulk impeded surface expansion induces a high level of compressive stress in the surface itself,whereas the bulk is put into tension.

MECHANICAL CAUSES:

Let us consider a simple flat beam subjected to a bending moment which produces tension yielding on one surface.
After the external moment is removed,all the beam tends to return to its initial shape. However,due to the permanent deformation which took place in the surface,the parts which underwent only elastic deformation cannot resume their initial length,so the final result is compression on the surface and tension underneath.
Had the surface yielded under compression,the final result would have been tension on the surface and compression underneath.
Many cold-work inducing processes (i.e peening,rolling,coining etc.) exploit this mechanism.

A very important example of how the 3 above basic mechanisms can lead to different results,according to the most predominant one is machining.

During machining,the friction between the tool and metal produces a temperature increase and plastic deformation of the surface of the workpiece.The greatest part of heat is removed by the chips however the increase of temperature of the piece depends on many factors,the most important of which are:
a) heat conductivity of the material
b) coolant supply and quality
c) tool sharpness and relative velocity with respect to the piece.

If thermal factors are important(frequent on high alloyed materials), tensile residual stresses are more likely to occur since,as the tool works,the expansion due to heating of the underlying surface layer is partially impeded by the colder parts. So this layer will undergo compressive yielding. On cooling,the surface cannot resume its initial length and remains in a permanently stretched state.

If plastic deformation is predominant,compressive residual stresses occur for the following reason.
As the tool works,tensile yielding of a layer of metal surrounding the tool tip occurs.
After the tool has passed,due to elastic relaxation,the plastically tensile deformed layer,is put into compression by the other parts which were only elastically tensile loaded by the tool.

RESIDUAL STRESS MEASUREMENT BY X-RAY DIFFRACTION

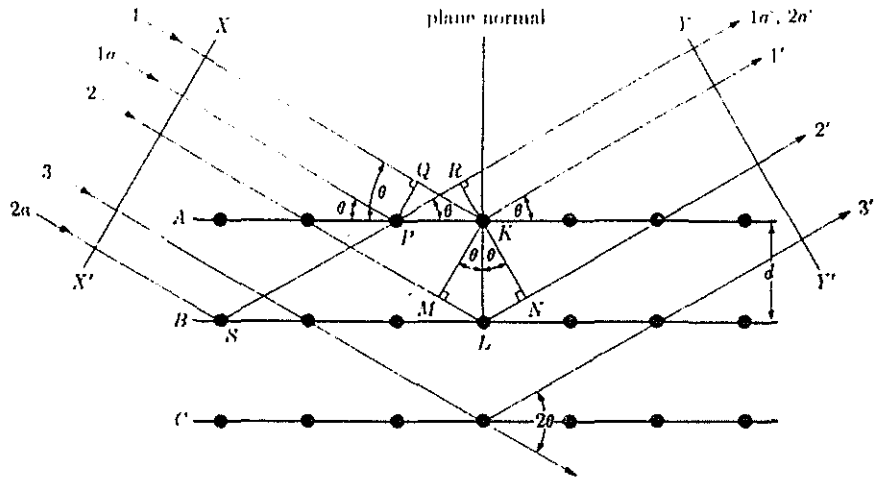
Before illustrating this technique,it is important to perform a finer subdivision of what is generally referred to as residual stress.
Residual stresses are generally divided into 3 orders according to the volume of material of interest.

Residual stresses of the 3rd order are generated around dislocations, slip lines,sub-grain boundaries and,in general,around defects within a grain.

Residual stresses of the 2nd order are an average of the previous ones and are improperly called "micro-stresses".They are often correlated to the micro-hardness of the material as will be better described further on.

Residual stresses of the 1st order are uniform over a large number of grains and represent an average of the previous ones over this distance.
These are called "macro-stresses" and represent the engineering residual stresses.
Therefore,by means of XRD,one always measures stresses of the 1st order which are superimposed,but distinguishable,from the 2nd order ones.

In order to understand this method,some fundamentals of the theory of diffraction will be illustrated.
Let us consider a set of evenly spaced atomic planes at a distance d,irradiated by an incident beam of monochromatic X-Rays.



Let XX' be the wavefront of the incident beam and K and L 2 atoms belonging to the crystal planes A and B. According to the classical wave theory,there exist certain directions in the space in which the intensities of the beams diffused by K and L increase and these directions are such that the path length difference between beam 1 and 2,i.e. ML+LN,is an integer multiple of wavelengths. This fact is translated into the following equation (Bragg's law):

$$\eta\lambda = 2d \sin\theta \qquad (1)$$

where:

η = Integer
λ = Wavelength of x-ray beam
d = Spacing between reflecting planes
θ = Angle of incidence of the beam with these atomic planes

Eq.(1) represents one of the fundamental relationships employed in XRD and will be commented in order to extract the maximum amount of information from it.

By differentiating (1) ,at constant λ ,we obtain:

$$\frac{\Delta d}{d} = -\cot\theta \times \Delta\theta \qquad (2)$$

Eq. (2) can have 2 interpretations according to the meaning of Δd If we consider this quantity as a distribution of d values around a mean value, a distribution of θ values will occur around a mean value θ .This means that the greater the degree of permanent deformation (strains of the 2nd order) the broader the peak will be.

A typical plot of the peak broadening,measured by means of the Full Width at Half Maximum,as a function of plastic deformation is shown in fig.1 a,b,c.

Fig. 1a

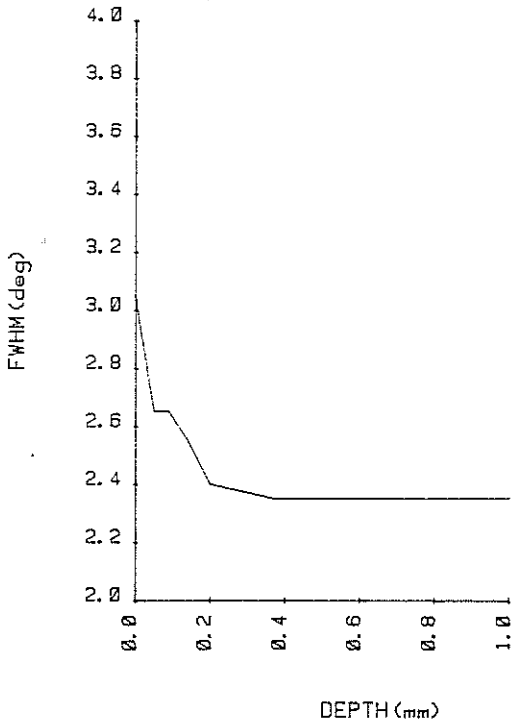


Fig. 1b

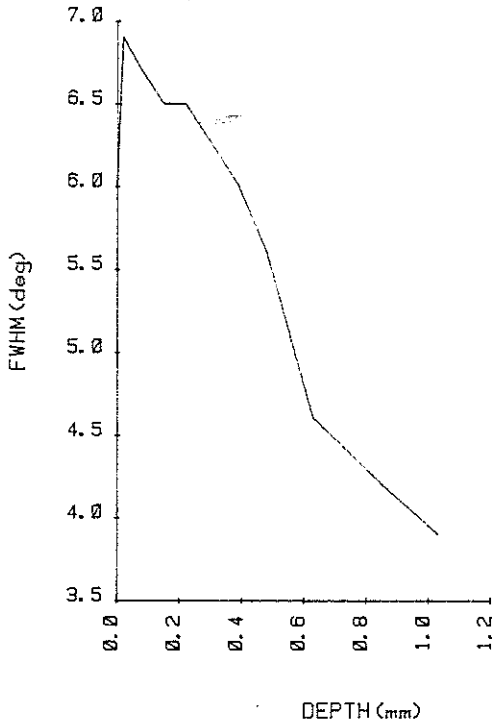


Fig. 1c

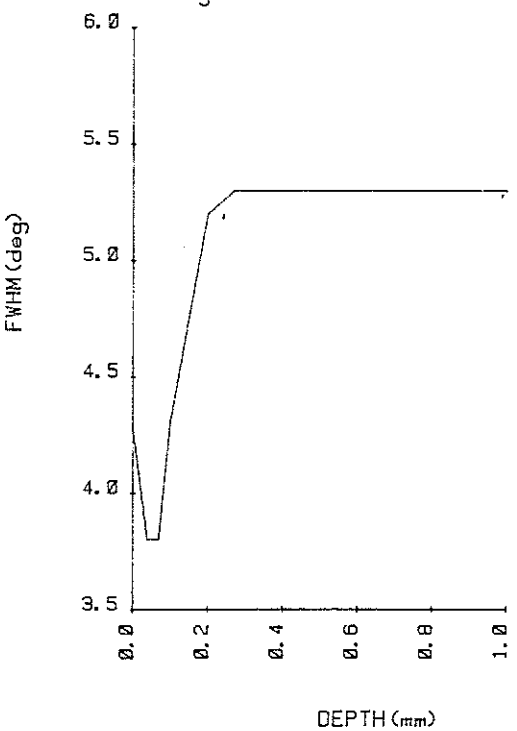


Fig.1 a is relative to the plastic deformation induced by shot peening on an Almen soft steel strip as a function of depth.

Fig.1 b is relative to the different hardness levels induced by case-carburizing as a function of depth.

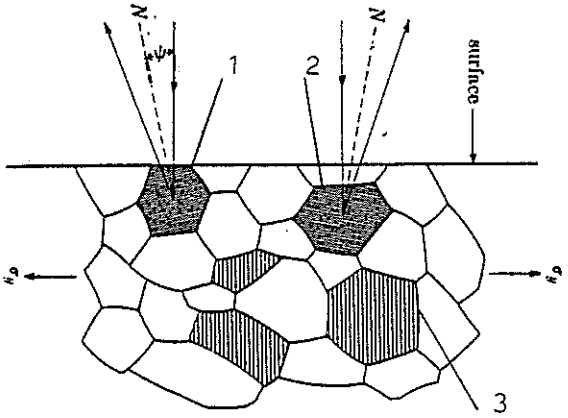
As it can be seen,in both cases,the FWHM decreases as the degree of micro-strain induced by cold-working or structural transformation decreases.
Fig.1 c shows the plot of the FWHM as a function of depth of a shot-peened 52HRc steel .

As it can be seen,the degree of micro-strain is lower on the shot peened part than in the bulk. This can be explained as follows. The externally supplied dislocations by means of shot-peening encounter an already dislocation-rich martensitic structure which is in a some sort of "saturated" state. So the incoming dislocations react negatively with the already existing ones,reducing the degree of micro-strain.
The opposite effect occurs when cold-working soft materials(cfr.fig 1 a).
An empirical relationship has been derived between FWHM and the micro-hardness converted to HRc scale:

$$FWHM(deg) = 0.001*HRc\ **2.16 \qquad (3)$$

which has proved to be useful in performing non-destructive measurement of hardness on steels.

The 2nd interpretation which can be given to Δd in eq.(2) is to consider this quantity as a net difference between 2 mean values of d,which will yield a net difference in the peak angular position (peak displacement). This is the effect of residual stresses of the 1st order.
In order to gain a better understanding of the role XRD has in determining residual stresses let us refer to fig.2.



1,2,3 etc. are different grains,showing the same set of atomic planes with a different orientation, ψ , with respect to the sample's surface.

For simplicity,it is assumed that the condition of plain stress which exists on the very surface of the sample is valid throughout the shallow depth (1-20 microns in Fe based materials) X-rays can attain. The above assumption is valid except for the case where tangential forces (i.e machining) are acting on the piece. In this case a more complex formulation is required.
However,apart from machining,the residual stress state induced by other processes is fairly well bi-axial.

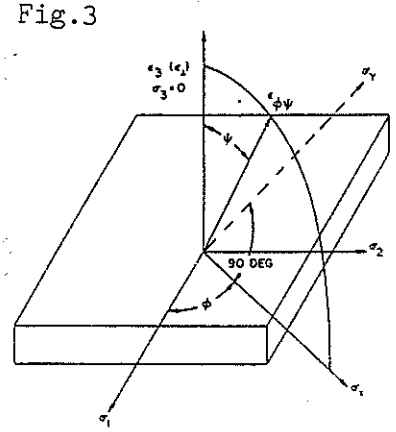
According to the orientation of the atomic planes with respect to the direction of stress,with reference to an ideal unstressed value d_o ,we will have different values of strain $\epsilon_{\phi\psi} = \frac{d_\psi - d_o}{d_o}$

Referring to fig.3,the theory of elasticity yields the following relationship between $\epsilon_{\phi\psi}$, ψ , σ_ϕ :

$$\epsilon_{\phi\psi} = \left(\frac{1+\nu}{E}\right)\sigma_\phi \sin^2\psi - \frac{\nu}{E}(\sigma_1 + \sigma_2) \qquad (4)$$

where: $\sigma_\phi = \sigma_1 \cos^2\phi + \sigma_2 \sin^2\phi$.

Fig.3



Before applying straightforwardly eq.(4) to the XRD technique it must be pointed out that the theory of elasticity assumes that the material be isotropic and homogeneous.

The request for homogeneity is rather easy to fulfill especially on fine grained structures,where the number of irradiated grains is very large,approximating a "continuum".
In large grained structures however,this problem is sometimes difficult to resolve.

The more important fact is isotropy.We must bear in mind that in XRD residual stress analysis,one measures the strain in a direction normal to a certain set of atomic planes,which,in principle,may have a different response to stress than others.
Differently speaking,it is not,a priori,correct to employ the bulk values of E and ν (which are an average value over all the crystallographic directions) when correlating $\epsilon_{\phi\psi}$ to σ_ϕ .

In this case,one should write eq.(3) as:

$$\epsilon_{\phi\psi} = \frac{1+\nu}{E}_{rx}(\sigma_\phi \sin^2\psi) - \frac{\nu}{E}(\sigma_1 + \sigma_2) \qquad (5)$$

where $\frac{1+\nu}{E}_{rx}$ is a value which should be determined experimentally by recording $\epsilon_{\phi\psi}$ as a function of an externally applied known stress.
Fortunately this procedure is not always necessary,especially on steels using Cr radiation.

As eq.(5) shows,there exists a linear relationship between $\epsilon_{\phi\psi}$ and $\sin^2\psi$ .The measurement consists in determining $\epsilon_{\phi\psi}$ at various values of $\sin^2\psi$ and by calculating the slope m of the least squares fitted straight line ,from which:

$$\sigma_\phi = \frac{m\,E}{1+\nu}$$

Eq.(5) can be written as:

$$\epsilon_{\phi\psi} = \left(\frac{1+\nu}{E}\right)\sigma_\phi \sin^2\psi + \epsilon_\perp$$

$$\epsilon_\perp = -\frac{\nu}{E}(\sigma_1 + \sigma_2)$$

where the suffix $\perp$ indicates the normal direction to the surface of the sample.
By approximating,with a slight error,$d_\perp$ for d_o,we obtain the final equation:

$$(\epsilon_{\phi\psi} - \epsilon_\perp) = \frac{d_\psi - d_\perp}{d_\perp} \qquad (6)$$

The use of eq.(6) makes it unnecessary to known the value of d in an unstressed sample,which sometimes is impossible such as for a martensitic structure.
So far only the underlying principles have been described.However in order to make the measurement practicable some other important considerations must be done,namely:
a) sensitivity of the technique
b) radiation to be used
c) factors affecting the accuracy and reproducibility of the determination of the peak position.

By considering eq.(2) : $\frac{\Delta d}{d} = -\cot\theta \times \Delta\theta$

it can be seen that at high diffraction angles ($0< \theta <90$),even very small strains are amplified by a very large factor ($\tan\theta$) yielding appreciable values of $\Delta\theta$ (0.2-1.5 deg). So,in order to maximize the sensitivity of the technique,reducing other factors which themselves yield a shift in 2θ ,even in the absence of stress (instrumental factors),it is necessary to be able to work with a diffraction peak such that 2θ >130deg.
The radiation to be used directly derives from the above requirement.
In tab.5(cfr.1) are reported the most common combinations of material and radiation as well as the maximum depth of penetration,X,of that radiation.

Tab.5

Material	Radiation	2θ	X(mm)
Ferritic steel	Co	161.8	0.030
	Cr	156.2	0.016
Austenitic steel	Cu	149.8	0.006
Al+alloys	Cu	137.5	0.106
	Cu	162.5	0.112
	Co	148.9	0.073
	Co	162.6	0.075
	Cr	139.5	0.035
	Cr	156.9	0.036
Cu	Co	163.9	0.021
Cr	Co	157.8	0.005
	Cr	152.8	0.022
Ti+alloys	Co	154.6	0.011
	Co	139.4	0.010
	Cr	157.0	0.005

As it can be seen,for the same material different radiations can be employed.
Often,the factor which decides for the choice is the gradient of stress in the depth of the material compared to the penetration depth of that radiation.
Steep gradients are obviously better analyzed by means of more shallow penetrating radiations.
For instance in the case of Al shot-peened alloys,in which the depth of the plastically deformed layer is about 0.1-0.2 mm, the best choice would be Cr. (3)

The final consideration regards the factors that can affect the the "goodness" of the results.
The most important ones are:
1) the statistical nature of the process by which a peak is detec= ted.
2) the accuracy and insensitivity of the algorithm employed for determining the peak position with respect to factor 1).

A few words dealing with the process of peak detection will be helpful in order to better understand these factors.
In conventional diffraction,a peak is scanned from one side to the other,either in a continuous or step-wise manner.
In both cases a detector collects the diffracted X-rays and transforms their energy in voltage pulses.Each pulse which is associated to a single photon is called a count.
The diffraction peak represents the "ensemble" of the different total counts acquired in the same amount of time at varying 2θ values.
The total number of counts,N,is a statistical variable the standard deviation of which is however proportional to $N^{1/2}$

This leads to the result that the relative statistical error of N decreases as N increases.
High intensities may be obtained either by increasing the X-ray source or by waiting more time for collecting counts.
However,due to the limited maximum power of X-ray tubes,normally counting time is optimized.

In the following table are shown 4 repeated determinations of residual compressive stress on a steel sample by means of 2 common algorithms. As it can be seen,the middle of the chord method (*) yields more reproducible results than the centroid method (**),and each single determination by the middle of the chord is better defined than by the centroid.

Counting time (secs)	Stress(Kg/mm2) Centroid	Stress(Kg/mm2) Middle of the chord
40	-21 +/- 5	-33 +/- 5
40	-25 +/- 5	-35 +/- 2
40	-19 +/- 6	-31 +/- 3
40	-39 +/- 4	-32 +/- 1

(*) In the middle of the chord method,the peak's position is taken as the position of the middle of the chord at half maximum intensity above the peak's background.

(**) In the centroid method,the peak's position is taken as the position of the centre of gravity of the peak above the peak's background.

However the results obtained by the centroid method improve as the statistical fluctuations decrease (i.e longer counting times).

After a brief introduction to the general argument of residual stress and to the X-ray diffraction measuring technique,a few pratical cases will be reported with a brief discussion of each.

CASE 1): AISI 4340 E.S.R quenched and tempered (52 HRc)
PURPOSE: To investigate the residual stress pattern imparted by each stage of preparation,prior to use,of the piece,in order to detect the critical operations.(cfr.Fig 4a,4b)

Fig.4 a

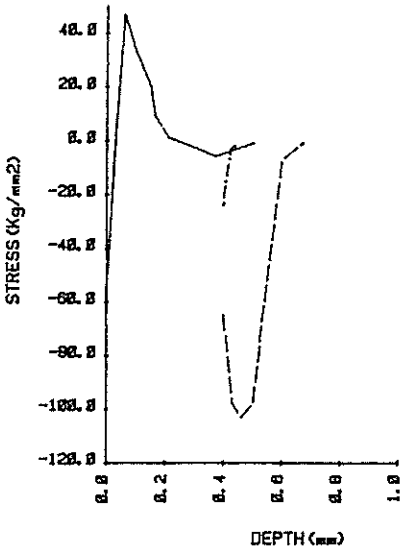
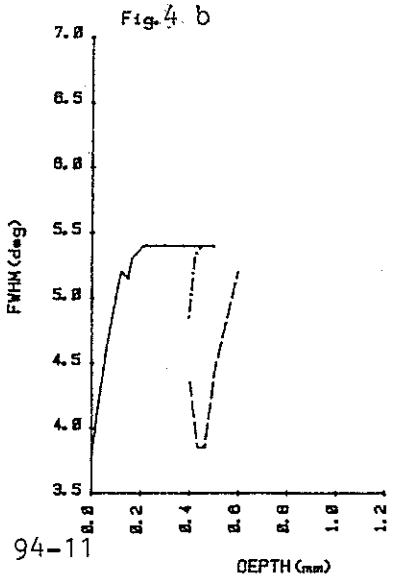


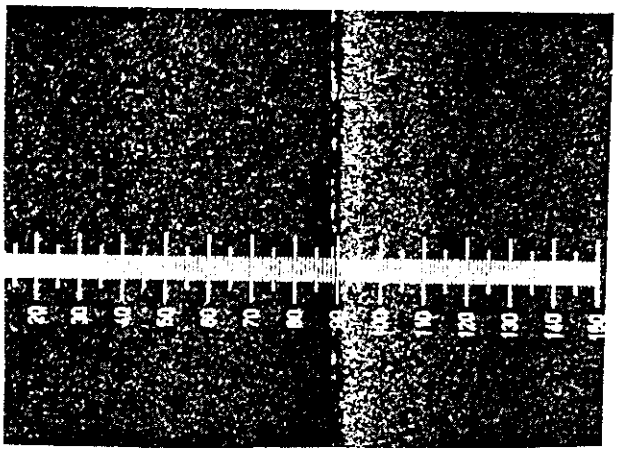
Fig.4 b



1) HEAT TREATMENT: The piece was homogeneously austenized in a salt bath,oil quenched and tempered to the final hardness. According to eq.(3) the bulk values of FWHM correspond to the bulk values of hardness.

2) SAND BLASTING: solid line After the heat treatment,the piece is sand blasted on order to remove scale and oxides from from the previous operation.
As it can be seen,sand blasting introduces a significant but shallow compressive stress. The tensile stress which follows is due to the de= carburization of the sample (see photo 1.)

Photo 1. 1 subdivison = 8 microns: Picral etch



In fact,during austenizing the carbon content of the surface decreases due to the reaction with the external environment(salt bath,moisture) so the surface Ms becomes higher than the bulk's one .During quenching,the A -> M reaction takes first place in the surface,so the final result is tension in the surface and compression beneath.

3) GRINDING: dash and dot line Normally the decarburized layer is removed due to its negative effects (minor hardness,tensile residual stress). Grinding introduces a slight and shallow compressive stress and heating (decrease in FWHM) on the surface.

4) SHOT PEENING : dashed line This procedure is one of the most common ways of introducing beneficial compressive stresses in a material.
In spite of the base metal hardness,shot peening introduces very high compressive residual stress to a depth ranging between 0.1-0.2mm
The variation of FWHM has already been discussed Fig.1 c.

5) TEMPERING: not indicated The final operation performed on the sample was a high temperature (160 C x 3 h) application of a solid lubricant.The exposure at this tempera= ture (tempering) doesn't significantly affect the shot peening compression.

CASE 2: AISI 9310 CASE-CARBURIZED GEAR TOOTH
PURPOSE: Comparison between a damaged and undamaged gear tooth.

Fig. 5 a'

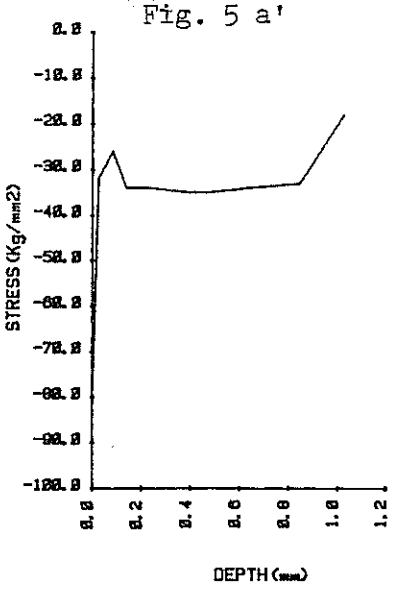


Fig. 5 b'

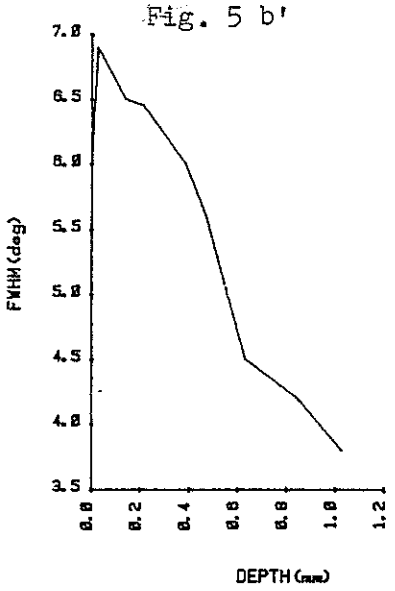


Fig. 5 a''

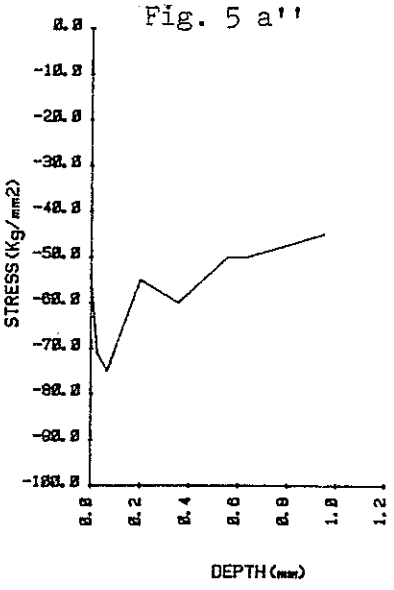


Fig. 5 b''

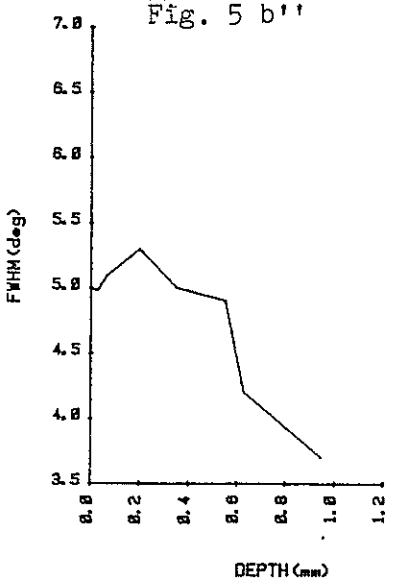


Fig. 5a' and 5b' show the residual stress and FWHM in-depth pattern on an undamaged gear tooth whereas fig.5a'' and 5b'' show the same quantities for the damaged one.
The latter presented severe surface wear due to an excessive compressive action between 2 coupling teeth.This action is responsible for plastic deformation of the surface which in turn leads to the formation of compressive residual stress (peening action) and a decrease in FWHM.

CASE 3): AISI 9310 SHOT-PEENED CASE-CARBURIZED GEAR TOOTH
PURPOSE: To evaluate the effect of shot-peening on a very hard (> 60 Hrc) surface as a means of further increasing fatigue resistance of gears.(2)

Fig. 6 a

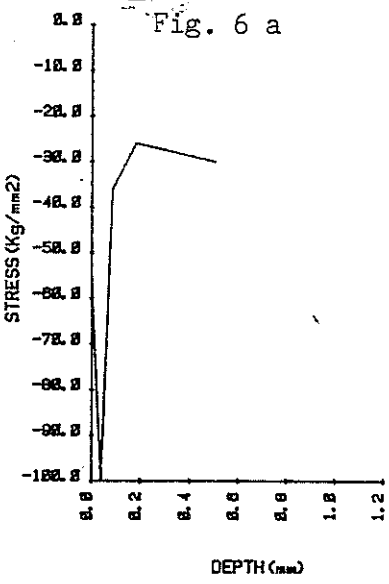
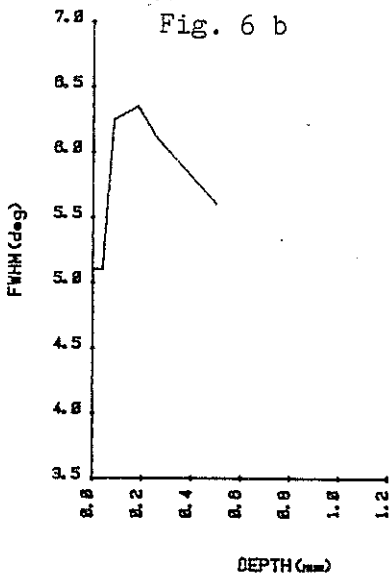


Fig. 6 b



In spite of the surface hardness,as Fig.6a shows,shot-peening introduces high compressive stress the beneficial effect of which in increasing fatigue performance in case-carburized steels is being exploited in order to boost the intrinsic fatigue resistance of these steels.(2)

CASE 4): AISI 4340 (50 HRc) E.B.W steel.
PURPOSE: To perform preliminary investigation of residual stresses induced by Electron Beam Welding on an ultra high strength aeronautical steel.

Fig. 7 a

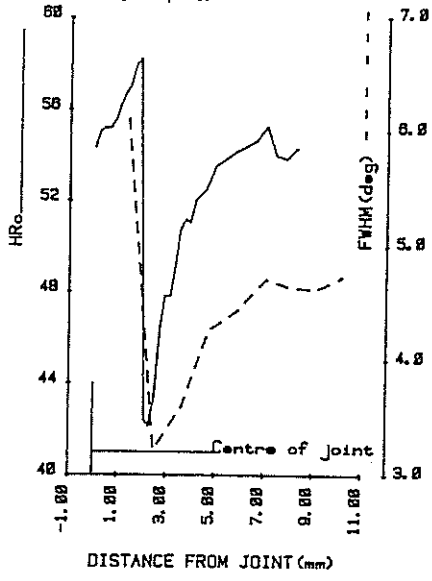


Fig. 7 b

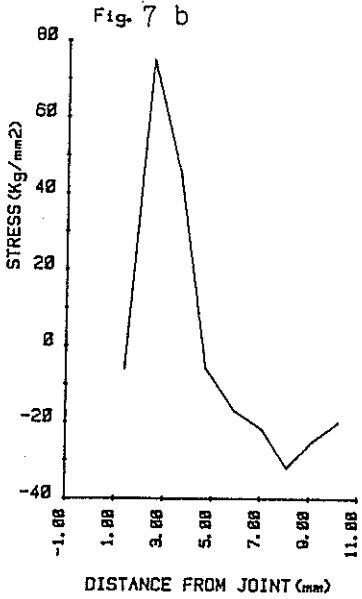


Fig.7a shows a comparative plot of FWHM and Vickers micro-hardness - converted to the Rockwell C scale as a function of the distance from the centre of the welded joint. The hardness measurement was performed on a tranverse metallographic section whereas the FWHM measurements were performed on the surface of the sample consisting of 2 ground flat strips welded together.
As it can be seen,both the FWHM and micro-hardness curves have the same shape,suggesting a correlation between these 2 quantities as given in eq.3.
The XRD measurement requires special attention in defining the measu= ring area,since due to rapid structural changes,it is very easy to obtain sensless results,if the chosen area is too large.A good check that the part under analysis is satisfactorily homogeneous from a structural point of view is given by analyzing FWHM values,a large dispersion of which,indicates structural inhomogeneity.

An explanation of the residual stress diagram (direction parallel the joint) can be given if combined with the FWHM (Micro-hardness) curve.
During welding,some parts melt,others are austenized and others are tempered.The FWHM diagram represents the thermal history of the piece. Starting from the centre of the joint,we have high values of FWHM due to the rapid cooling of the melted and austenized parts.Subsequently we have low values of FWHM due to the tempering of the material,and finally the bulk values of the heat unaffected parts are attained.

As shown,in this particular case,the maximum of tensile stress lies in the proximity of the minimum in FWHM.
In fact,during quenching,the A -> M volume increase is partially impeded by the untransformed tempered parts(low values of FWHM) so the former are put into compression,whereas the latter into tension.
The compressive values far away from the joint are due to the grinding operation.

CONCLUSION

From the discussion of the previous results it appears how XRD yields important information on the metallurgical state of a material (residual stress state ,degree of plastic deformation and micro-hardness) and,just because of its surface nature ,it is capable of detecting rapidly in-depth or surface varying phenomena with a good degree of accuracy giving a fundamental contribution to the understanding of the onset of material "weakening" processes (crack initiation and propagation) and a means of verifying the fitness of certain compressive-stress inducing treatments which can delay fracture.

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