Residual stress measurement by ESPI hole drilling and XRD – a comparison of the methods using measurements on shot-peened titanium alloys

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Introduction

A full assessment of the residual stress state in a shot-peened part requires measuring a residual stress depth profile. The most common methods for stress measurements are X-ray diffraction (XRD) and hole drilling. Such measurements may be used for testing and fine tuning of the shot peening process or for verifying the stress state in specific or representative parts. The XRD technique is highly regarded, but doesn't work equally well in all materials and can be slow. The traditional hole drilling technique requires the proper attachment of strain gages, which requires expertise and extra time. A newer variation of the technique combines hole drilling with an optical measurement, Electronic Speckle Pattern Interferometry (ESPI). This reduces the setup time substantially while maintaining fast measurement times.

Objectives

Residual stress measurement is often viewed as complicated and the variety of methods offered can be confusing. The reason why several techniques exist is that they all have their specific range of application where they excel. Some of the factors distinguishing the application range of XRD and ESPI hole drilling will be discussed using the example of shot-peened titanium.

Methodology

The samples were taken from commercially available, 3mm thick titanium plates of Grade 2 (commercially pure) and Grade 5 (Ti6Al4V, α-ß alloy). Both alloys are mainly composed of α phase (hexagonal); Grade 5 may have up to 10% ß phase (cubic) dependent on manufacturing history. In-house shot peening was performed on some of the samples.

The commercial X-ray diffraction instrument used is built specifically for residual stress measurement. Thus all the movements required to take measurements from different angles against the sample surface are made by the instrument while the sample remains in place. This removes most restrictions on sample size and shape and reduces sample preparation time. Only measurements on the α phase were made. Measurements on a minority phase of 10% would be much slower and significantly less accurate. They would also be more sensitive to microstructural parameters. The stress measurements themselves are fully automated. Yet measurements at depth require the removal of material, which has to be done with minimal effect on the residual stresses in the remaining part. Manual electro-polishing is common practice and was used here. Depth measurement also was performed manually, using a dial indicator.

The XRD measurements shown here were part of a separate study that included the measurement of the material parameters on the sample materials [1]. The X-ray elastic constants were determined as $10.4\cdot / 10.7\cdot 10^{-6}$ MPa^{-1} for Grade 2 / Grade 5 and Cu radiation ((213) peak), and $11.1\cdot / 8.7\cdot 10^{-6}$ MPa^{-1} for Grade 2 / Grade 5 and Ti radiation ((110) peak).

The ESPI hole drilling system used is also commercial. Yet the technique is relatively new and not so well known. The hole drilling part is basically the same as for strain gage hole drilling. The drill used is electric and allows rotation speeds from 5,000 to 50,000 rpms. 30,000 rpm was used. For most measurements the drill was in an orbiting motion during drilling. This is a common practice since it is known to be beneficial for difficult to drill materials [2]. The tools for all orbital drilling measurements had a nominal diameter of 0.015" (0.38 mm; TiN coated, square-end end mill) and the orbiting offset was ±0.18 mm. One additional measurement was made for comparison without the orbiting motion. It used a 1/32" (0.79mm) diameter tool of the same type. The hole sizes were thus comparable. The ESPI hole drilling stresses were calculated with the elastic moduli of 103 / 114 GPa for Grade 2 / Grade 5 and a Poisson's ratio of 0.32 (published values, obtained for [1]).

Hole drilling measurements determine the effect that the removal of a known amount of material and the stresses it contains has on the surface of the part. The stresses in the surrounding material find a new equilibrium, which changes the surface shape slightly. Strain gages measure electrical resistance changes / strains; ESPI measures surface displacements. The latter is based on images taken of the surface before and after every drilling increment using laser light [3-5]. The measurement area was painted to improve the optical properties of the surface. The pixels used in the analysis lie on a ring around the hole. Stresses are calculated using the Integral Method and coefficients that describe the relationship between surface displacements and stresses. The coefficients are generated in computer simulations.

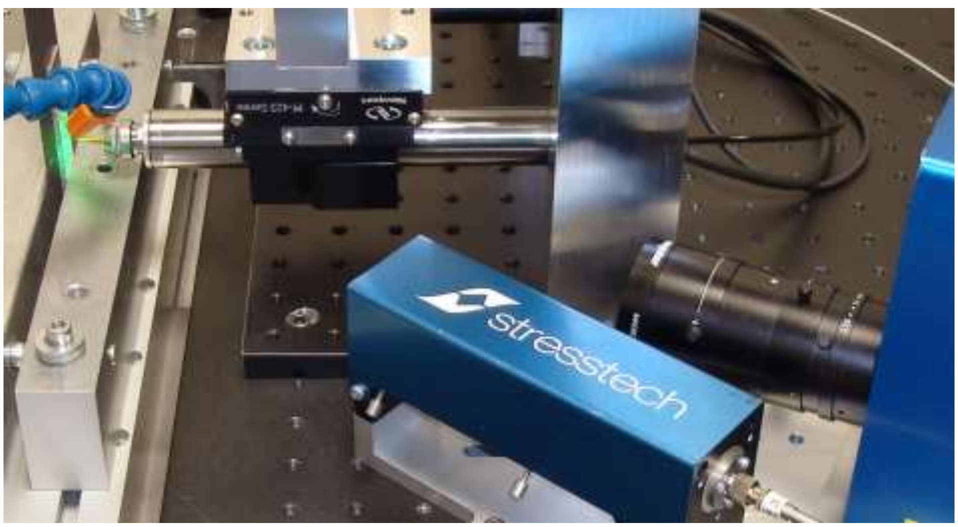

Figure 1 Example of the measurement setup of the ESPI system, left to right: illuminated sample, electric drill on orbiting device, illumination stand, camera.

Results and analysis

The XRD measurements were performed as part of a separate study comparing measurement quality when using Ti-and Cu-radiation [1]. The measurements on the samples without shot peening were not successful. The method requires that the diffracted X-rays measured are from a variety of grains with different orientations. But the poor diffraction peak shapes observed suggest coarse microstructures (too few grains). The measurements on shot peened samples were better, yet the Grade 2 results still have poorer statistics (Fig. 2). The error bars in the graphs are the deviations for the linear $\sin^2\chi$ fits, a large portion of the measurement uncertainty. The deviations are greater at greater depths where the shot peening process produced less deformation. The plastically deformed microstructure in the surface zone provides better measurement conditions for XRD because the diffraction peaks are broader [6]. The two radiations used produced similar stress depth profiles.

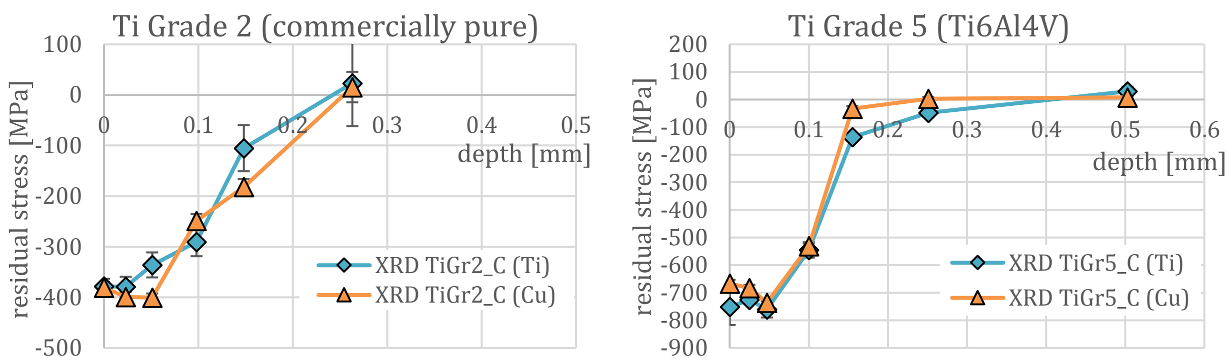

Figure 2: Residual stress depth profiles measured by XRD on shot peened samples using Ti- and Cu-radiation. Note the different stress scales in the two graphs.

Stress depth profiles were obtained from non-shot peened samples using ESPI hole drilling (M1 & M4 in Fig. 3). Besides relatively small tensile stresses at the immediate surface (<0.05 mm) there are only negligible stresses. All measurements on shot peened samples show typical stress profiles with the highest compressive stresses close to the surface, followed by a steep gradient and smaller tensile stresses at greater depths. Two Grade 2 samples were measured with very similar results (M2 & M3). For Grade 5, one sample was measured repeatedly. The results show some variability especially near the surface (M5 thru M8).

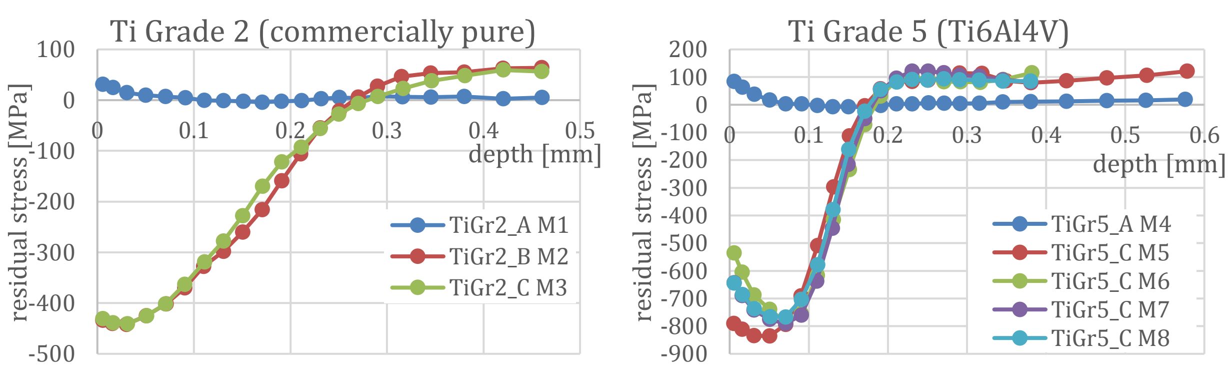

Figure 3: Residual stress depth profiles measured by ESPI hole drilling on samples without (M1, M4) and with shot peening (all others); M2 and M3 (left) were on different samples; M5 thru M8 (right) were on the same sample and with the same measurement parameters.

The variability of the stress profiles near the surface could in principle be due to measurement variability or differences in the sample. Though, results on commercially shot peened aluminum showed clearly better measurement repeatability for ESPI hole drilling with orbiting motion [7]. Thus, the variation observed may be caused by a less well controlled shot peening process or microstructural factors.

The results from both methods on the shot-peened samples are compared in Figure 4. The agreement is poorer for Grade 2 where the XRD method has problems with the microstructure. Note that the graphs in Figure 4 use discrete data points for the XRD data and continuous lines for the hole drilling data. This is meant to indicate that XRD depth profiles consist of fully independent measurements. Each value represents the stresses in a layer with a thickness of only a few microns. The penetration depth (depth of the surface zone from which 63% of the detected X-rays originate) is ~7 µm for Ti radiation and ~4 µm for Cu radiation [8]. One can drill holes in similarly small depth increments of for instance ~10 µm. But the calculated stress values are not independent of each other. The stress calculation for every depth increment has to include all the stresses from above. Small increments also have poorer measurement statistics, requiring more smoothing of the depth profile. Tikhonov regularization is used here, as suggested in the ASTM standard for strain gage hole drilling [9].

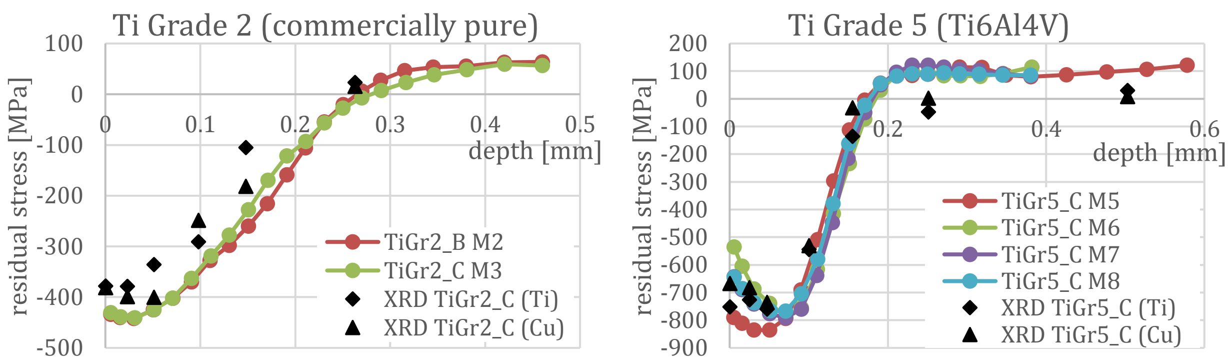

Figure 4: Comparison of the XRD and ESPI hole drilling results on the shot peened samples.

It is important to remember that the calculated stress quantities are directly dependent on the material parameters used and that the two methods used different parameters. The range of X-ray elastic constants measured in the x-ray study and from literature [1] is greater than 10%, which likely is related to variability in microstructure and the relatively large anisotropy of titanium alloys.

Like XRD, the hole drilling method has microstructure sensitivity because it is caused by anisotropic (direction dependent) material behavior while both methods assume isotropy. The problem for XRD is that data acquisition is affected while the hole drilling method can always generate a result.

As mentioned, Grade 5 titanium is a two-phase material and only the α phase is measured by XRD. The stress profiles determined by ESPI hole drilling are still very similar. The volume fraction of the ß phase may simply be too small to affect the overall stresses significantly.

Figure 5 compares the average stress profile of the four orbital drilling measurements (M5 thru M8) with that from the one measurement made by plunge drilling (M9). The agreement is excellent. The orbital drilling option had been used as a precaution since not all materials can be drilled well by plunge drilling. This doesn't seem to be an issue here.

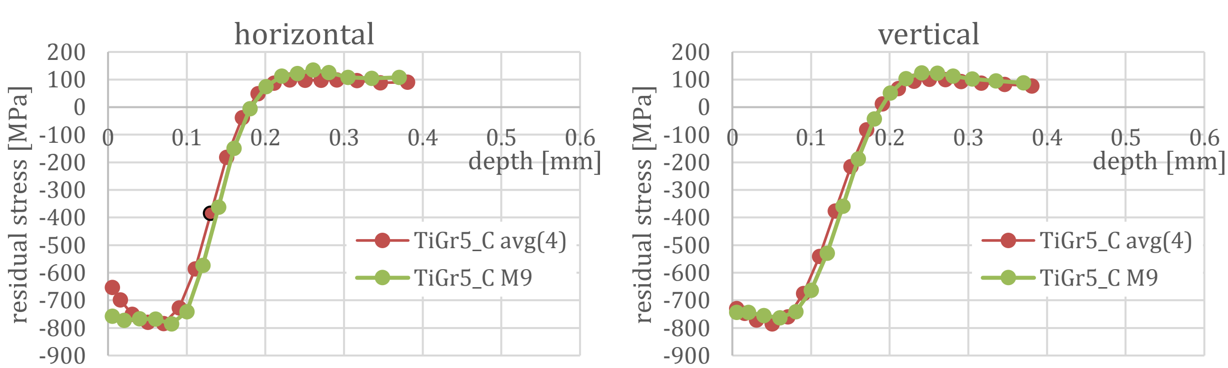

Figure 5: Comparison of stress profiles in horizontal and vertical directions, for the average of four measurements using orbital drilling (M5 thru M8) and one plunge drilling measurement (M9)

The figure also compares stress results in horizontal and vertical directions. The ESPI system actually measures displacements only in one direction, the sample horizontal. Stresses in vertical direction affect the displacement in measurement direction only through the Poisson's effect. Thus, measurement sensitivity for that direction is reduced by the Poisson's ratio. The results in Figure 5 therefore suggest good measurement sensitivity.

Measurement times can be an important feature for selecting a measurement method. Since most shot peening is probably used to produce the same properties in all surface directions, measurements in multiple directions may often be unnecessary and the disadvantage of the directionality of the XRD measurements immaterial. Measurement times with XRD then depend more on the signal to noise ratio of the diffraction peaks, which determines the required exposure times and is largely material dependent. The electro-polishing process is comparatively slow, though, and the amount of material to be removed can increase total measurement times a lot. In comparison, ESPI hole drilling measurement times do not increase as much with increasing final depth. Practical experience shows that single-direction XRD measurements on carbon steels for relatively shallow depths may be nearly as fast as ESPI hole drilling; yet aluminum alloys and particularly titanium alloys generally take significantly longer.

Shot peening stress depth profiles have two main characteristics: the maximum compressive stress and the depth of the compressive zone (Fig. 6). In that regard the XRD and hole drilling results are quite similar. One might also want to control the level of tensile stresses at greater depths. It is related to the other characteristics since the tensile stresses at greater depths balance the compressive stresses near the surface. The tensile stress level should be expected to increase when the part thickness decreases while the compressive stress zone remains similar.

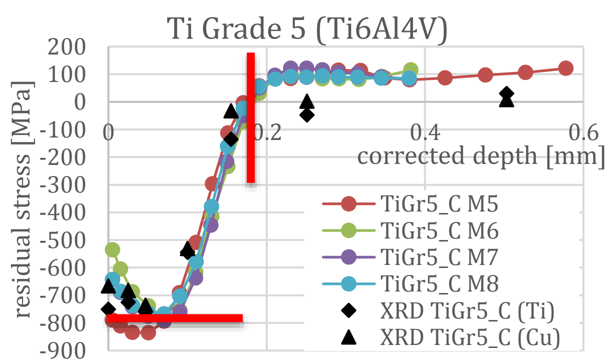

Figure 6:
Characteristic parameters of shot peening stress profiles: maximum compressive stress and depth of compressive stress zone

The stress profiles measured by XRD do not show tensile stresses at greater depths as clearly even though the surface compressive stresses have to be balanced by tensile stresses at greater depths. This may be an effect of the material removal, which causes stress relaxation. The material removal here was of a near cylindrical volume in the measurement location. The commonly available correction formulas are for simpler geometries. No correction was applied.

These measurements were made on samples similar in size to Almen strips, which could also be used. But Almen strips are much more efficient for process control purposes. Both stress measurement methods described may be useful for the development of a process or for determining whether various locations of a part are peened equally well. Both are similar in the relatively small area that they cover – typically less than 1 cm^2.

Table 1: Comparison of the two methods.

X-ray Diffraction	ESPI Hole Drilling
measures surface stress and stress depth profiles	measures stress depth profiles
local measurement	local measurement
measures single direction stresses	measures single direction but uses Poisson's effect for other directions (lower sensitivity)
measures stresses in layer penetrated by x-rays (microns)	measures surface displacements as function of volume removed in each increment
requires crystallinity	limited by ability to drill good-quality hole
limited by grain size and texture	grain size and texture affect results moderately
manual electro-polishing	integrated material removal
manual depth measurement	integrated depth measurement
fully independent measurements	stress calculation has to consider all increments; profile is smoothed
may be as fast for steels	generally faster for titanium and aluminum

Conclusions

- The stress depth profile obtained by the two measurement methods agree reasonably well. The basic characteristics are the same for both alloys.
- The percentage of ß phase in Grade 5 may be too small to affect the overall stresses significantly and cause different results for the two methods.
- Measuring titanium alloys by XRD can be complicated by a coarse microstructure that doesn't significantly affect hole drilling measurements.
- ESPI hole drilling with and without orbiting motion was equally successful.

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