Non-destructive testing of the residual stress profile after shot peening by multifrequency-eddy-current analysis

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Introduction

Residual stress (RS) testing after shot peening (SP) is an issue of high industrial interest. A reliable test has to quantify the imparted residual stress: superficial RS, subsurface maximal RS and total affected depth by SP. The most common testing methods are: incremental X-ray diffraction (XRD) with material layer removal, and incremental strain gage hole drilling. Both are destructive and usually implemented as off-line test because of long time measurement (one hour to one day). For non-destructive testing (NDT) of RS, the opportunity to apply conventional ultrasonic or magnetic methods was identified. For instance, multi-frequency eddy current (EC) testing appears as a promising tool since the penetration depth is dependent to the applied test frequency, and the residual stress can be correlated to EC test results (measured coil electrical impedance or calculated apparent conductivity of the material under investigation) [1][2].

Objectives

The goal of this research is to describe how a commercial multifrequency EC testing system can be used as high speed, non-destructive RS testing solutions after SP on industrial materials.
This study shows how to easily process the EC response to find a quasi linear relation to the imparted residual stress previously characterized by conventional XRD measurement. The method is detailed for structural steel and also illustrated for Ti alloy, Ni-based alloy and Al alloy.

Methodology

Four industrial materials (C22 steel, Ti-6Al-4V, Inconel718, and AA7075) are studied. After cutting and polishing with '1200' grain size SiC paper, samples were shot peened by ultrasonic shot peening [3] (USP) at various intensity as summarized in the Table 1.

Table 1: USP parameters. Other process parameters are as follows. Frequency 20 kHz. Ball material: hardened 800HV1 Cr-alloyed steel. Duration 20 s. Coverage > 125 %. Sonotrode and chamber diameter 50 mm.

Reference	Sonotrode amplitude [µm]	Ball diameter [mm]	Total ball weight [g]	Approximate Almen intensity
'low'	60	1.0	3.0	0.15mmA / 6A
'intermediate'	80	2.0	6.0	0.40mmA / 16A
'high'	100	5.0	14.0	0.25mmC / 10C

In-plane RS are characterized by XRD using the common $\sin^2\Psi$ method with a Stresstech X3000 G2R diffractometer, with acquisition parameters as proposed in [4]. Localized material layer removal on 10 mm diameter area was carried out with saturated NH_4Cl solution under 2 $A.cm^{-2}$. After each removal step, depth is measured with a TaylorHobson contact profilometer. RS and averaged full-width at half maximum (FWHM) profiles are displayed in Figure 1. These are 'raw' XRD results for RS since the effect of stress relaxation caused by material removal is not corrected. FWHM is directly related to cold work. Table 2 summarizes XRD residual stress profile characteristics and roughness. The total imparted RS is defined as the area under the stress-depth curve.

Table 2: RS profile characteristics and roughness after SP

Material	SP intensity	Superficial RS [MPa]	Maximal RS [MPa]	Affected depth [µm]	Total imparted RS [MPa.µm]	Roughness Ra [µm]
C22	'unpeened'	-210	-210	15	2 000	0.2
C22	'low'	-400	-400	190	40 000	1.4
C22	'intermediate'	-360	-360	450	79 000	3.1
C22	'high'	-330	-330	1 300	129 000	8.4
AA7075	'unpeened'	-100	-100	10	6 000	0.2
AA7075	'low'	-260	-340	180	46 000	1.5
AA7075	'intermediate'	-230	-360	490	125 000	3.5
AA7075	'high'	-210	-560	1 400	437 000	8.4
In718	'unpeened'	-310	-310	20	400	0.1
In718	'low'	-740	-740	180	80 000	0.9
In718	'intermediate'	-710	-800	440	207 000	1.5
In718	'high'	-760	-790	1 400	684 000	3.4
Ti6Al4V	'unpeened'	-260	-260	20	7 000	0.1
Ti6Al4V	'low'	-780	-780	110	58 000	0.6
Ti6Al4V	'intermediate'	-650	-800	290	206 000	1.4
Ti6Al4V	'high'	-610	-890	1 000	652 000	4.8

A commercial multi-frequency EC testing device dedicated to industrial quality control of metal part was used without any particular configuration. The instrument operates on a differential mode. The 10 mm diameter probe with the first coil is put in direct contact, perpendicular to the shot peened surface. Lift-off is assumed to be zero. The second coil acts as a reference. Assuming that the reference coil is loaded by air at the same temperature (ambient) as the measuring coil, potential influence of temperature variation is reduced. Eight frequencies from 2.5 kHz to 250 kHz are tested. A single test duration is less than 0.2 s. Test result is the differential complex impedance Z of the measuring coil for each tested frequency f. This paper particularly describes its magnitude $|Z|$.

EC test result is correlated to material conductivity which is changed by an applied stress. This assumption is the fundamental basis for the opportunity to test residual stress with EC. Trying to get an absolute measurement of stress from EC test, one need to conduct long fundamental and experimental research (i) to calculate the apparent and true electrical conductivity from EC coil impedance, (ii) to determine coefficient of the piezoresistivity tensor, and (iii) to rigorously quantify cold work and roughness effects. In the present study, coil impedance for shot peened materials is normalized to the unpeened sample considered as a 0 MPa reference sample. It is supposed that direct correlation between change $\Delta|Z|$ in magnitude of the impedance and residual stress can be made. Additional tests described in the present paper quantify the effect of roughness on steel. The way to consider cold work and residual stress in the particular case of shot peening is also discussed.

Penetration depth for each frequency is proportional to $f^{-0.5}$, the inverse of the square root of the frequency. Knowing electrical and magnetic properties of the material, one could calculate the 'skin depth' or 'standard depth of penetration'. Based on existing general material database for electrical conductivity and magnetic permeability, the present tested frequency range corresponds basically to the following depth ranges: carbon steel 100-1200 µm, AA7000 600-7000 µm, Inconel 3000-30000 µm, Ti6Al4V 4000-40000 µm. These values show that the frequency is a priori too low to characterize the RS profiles for Inconel and titanium alloys with the same resolution as C22 and AA7075. Electrical conductivity and magnetic permeability for the materials under investigation have not been characterized. Effective penetration depth may also deviate from standard penetration depth under the influence of several experimental parameters. That is why further EC results are displayed as a function of $f^{-0.5}$ and not as a function of absolute depth values.

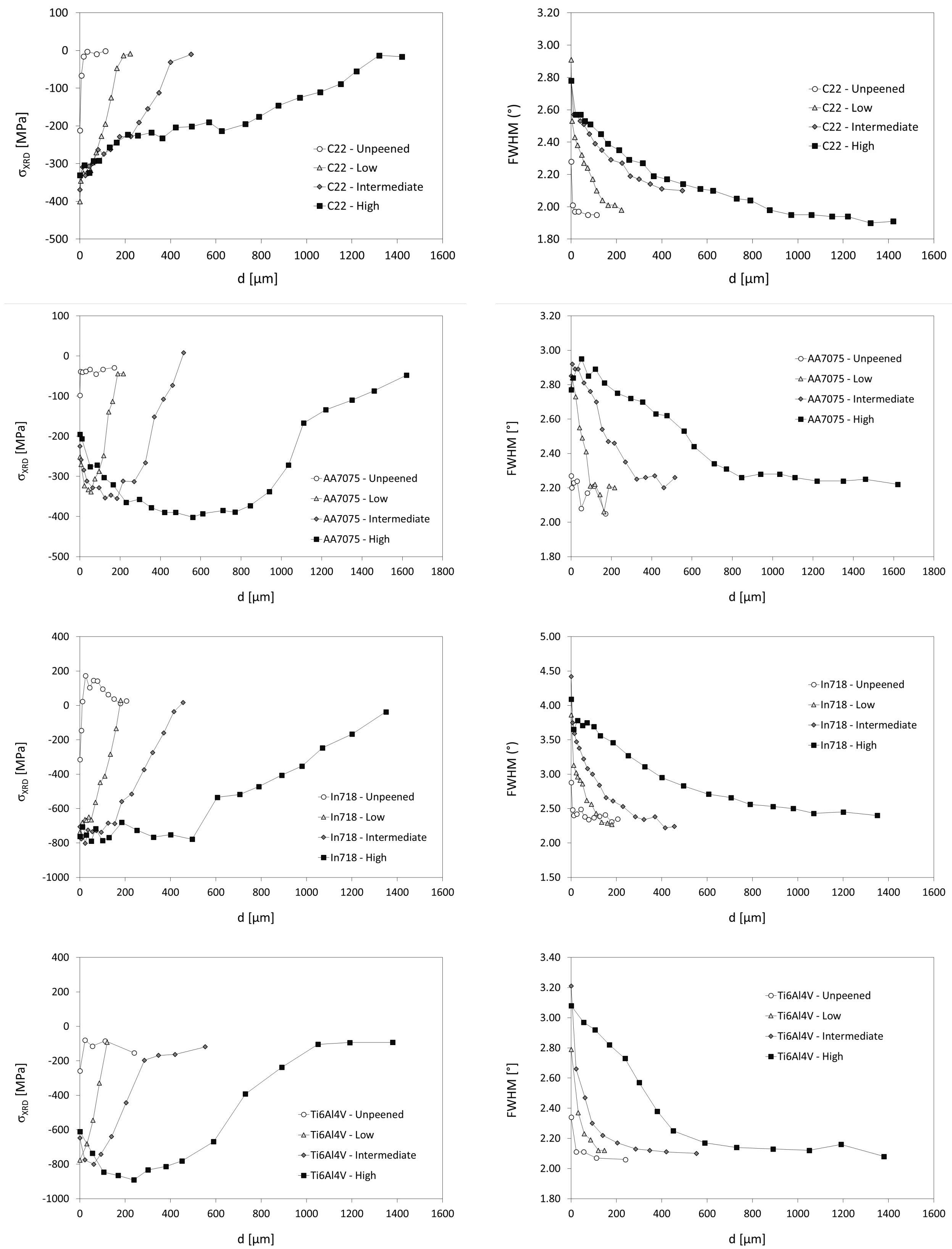

Figure 1: Incremental XRD characterization after SP. Left: residual stress, right: FWHM. From top to bottom: C22, AA7075, In718, Ti6Al4V.

Results and analysis

Figure 2a shows the EC results on the complex plane reactance X *vs.* resistance R of the coil when testing the C22 steel samples. Differences between the four locus curves can be seen. Magnitude */Z/* is displayed as a function of frequency on Figure 2b. As mentioned above, the last data are processed to display $\Delta|Z|$ *vs.* $f^{0.5}$ in Figure 3 for C22 steel and AA7075 samples (left graphs). This process is an adaptation of the simple inversion method described in [1]. For both materials */Z/* is reduced after SP and the effect of SP intensity is clearly visible. Percentage values are greater for steel than for Al. This is in agreement with the fact that stress and cold work after SP may induce change in electrical conductivity and magnetic permeability for ferromagnetic C22 steel, but only change in electrical conductivity for paramagnetic AA7075. For AA7075, decrease in the resistance R of the coil, and consequently of the magnitude of the impedance */Z/*, is consistent with an increase in electrical conductivity of the material after SP under the influence of compressive residual stress. For C22 steel, an increase for */Z]* is observed for the highest frequency and so the smallest penetration depth. It is probable that the effect of stress and above all of cold work on magnetic permeability may overshadow the effect on conductivity. This fact is known in basic industrial conductivity control of material by EC which is not applied on magnetic material, but only on non-magnetic material.

Figure 3 (right side graphs) also shows that the area under the $\Delta|Z|$ *vs.* $f^{0.5}$ – named 'processed EC response' – is well correlated to the area under the stress-depth curve from XRD characterization (Figure 2), namely the imparted residual stress. Indeed a very simple quasi-linear relation exists. This figure is the most important result and shows that basic calibration could probably be carry out to quantify RS with such an EC test.

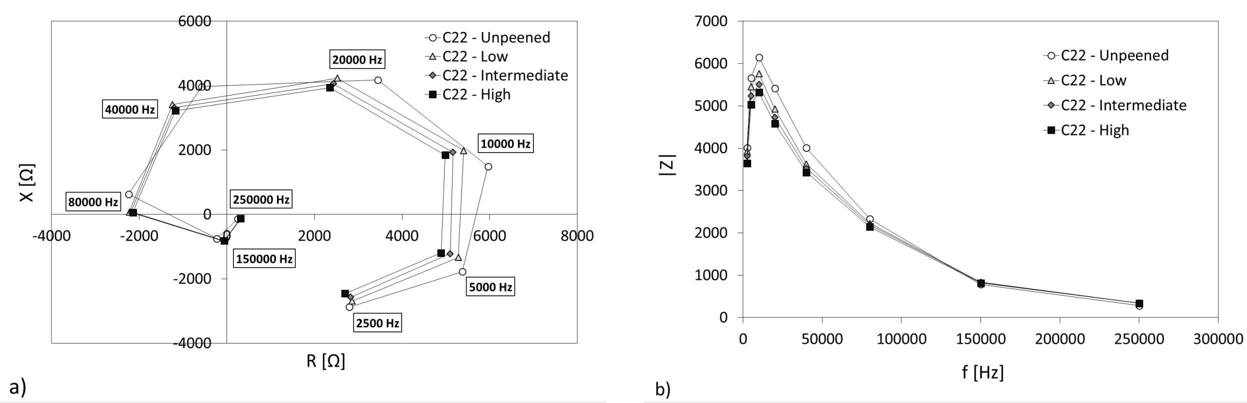

Figure 2: Coil impedance *Z* on the complex plane (a) and magnitude of the impedance */Z/ vs.* frequency *f* (b) for C22 steel samples

Effect of roughness is assessed by repeating EC tests on shot peened specimens after light polishing (P) with 1200 SiC paper until the shot peening roughness is eliminated. The results displayed in Figure 4a are very close to those found before polishing (Figure 3, top left graph). The effect of roughness is quantified on Figure 4b with a significant deviation of the correlation with XRD results – for RS before polishing – for high intensity peening with initial high roughness. Nevertheless, this experiment shows that change in */Z/* values was not due to a roughness effect, and that the EC test is able to adequately quantify SP intensity and RS even for rigorously identical surface roughness.

Figure 5 shows the same results for the In718 and Ti6Al4V samples. Interpretation of the results is difficult and the relation to the imparted residual stress is not as direct as for AA7075 and C22 steels. As mentioned above, it is probable that the penetration depth is too high because of too low testing frequencies. Nevertheless these preliminary results show that the test is able to classify SP intensities. This is encouraging results indicating that the present methodology is valid on these materials.

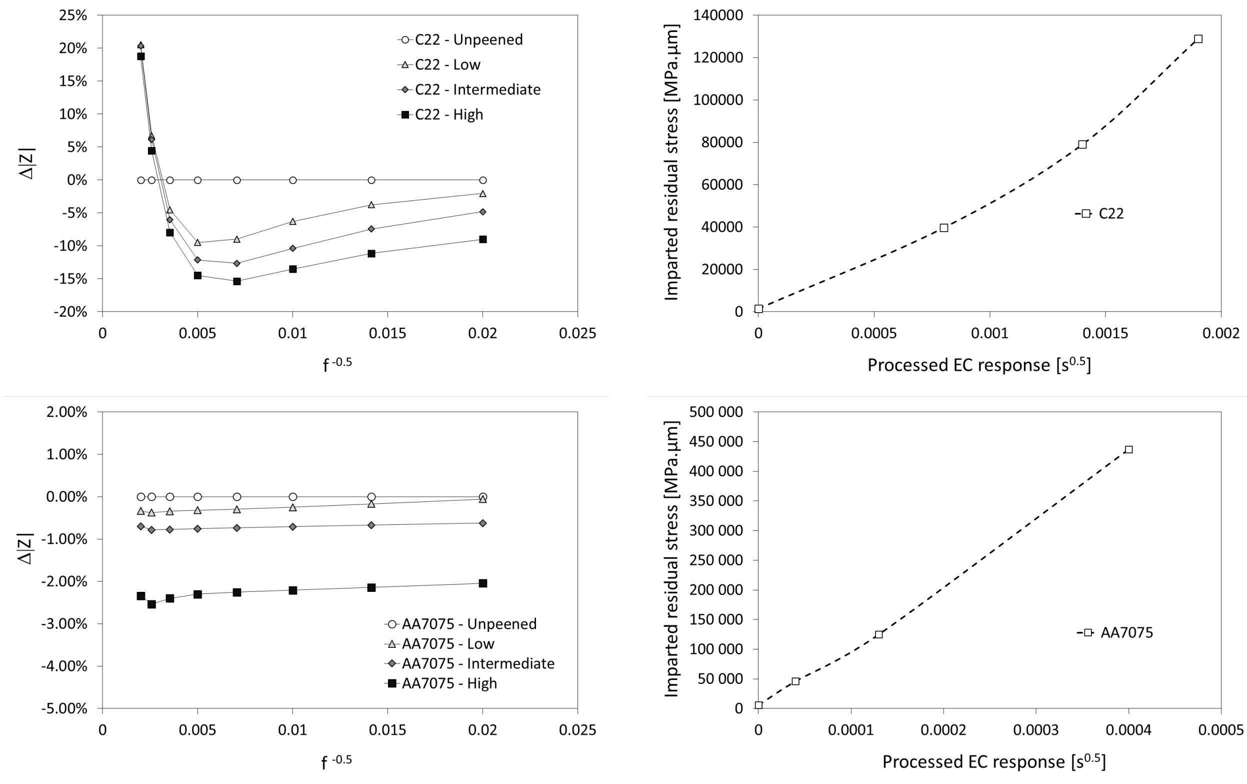

Figure 3: Change in the magnitude of the impedance caused by shot peening (left), and correlation between the multifrequency EC test response as processed in the present paper and the XRD residual stress profile surface area, namely imparted residual stress (right). Results for C22 (top) and AA7075 (bottom).

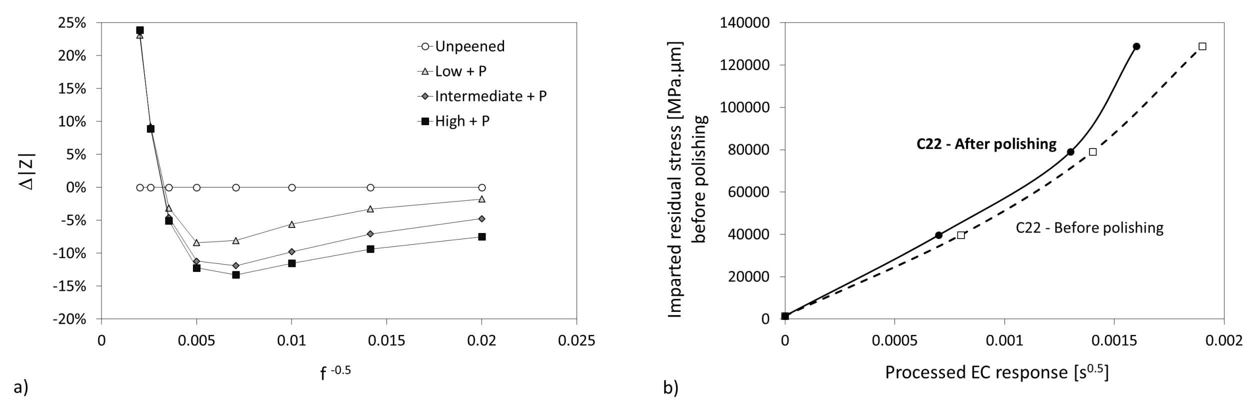

Figure 4: Effect of polishing the SP-induced roughness on EC response

The effect of cold work is certainly not negligible, regardless of the material to be tested. Change in coil impedance captures both the RS and the cold work induced by SP. But cold work and RS in SP are not independent variables. Indeed the principle of RS introduction by SP is plastic deformation, namely cold work. Finally, knowing cold work effect on EC response is interesting for comprehension but is unlikely to give any opportunity to optimize the capability of the present testing system and methodology.

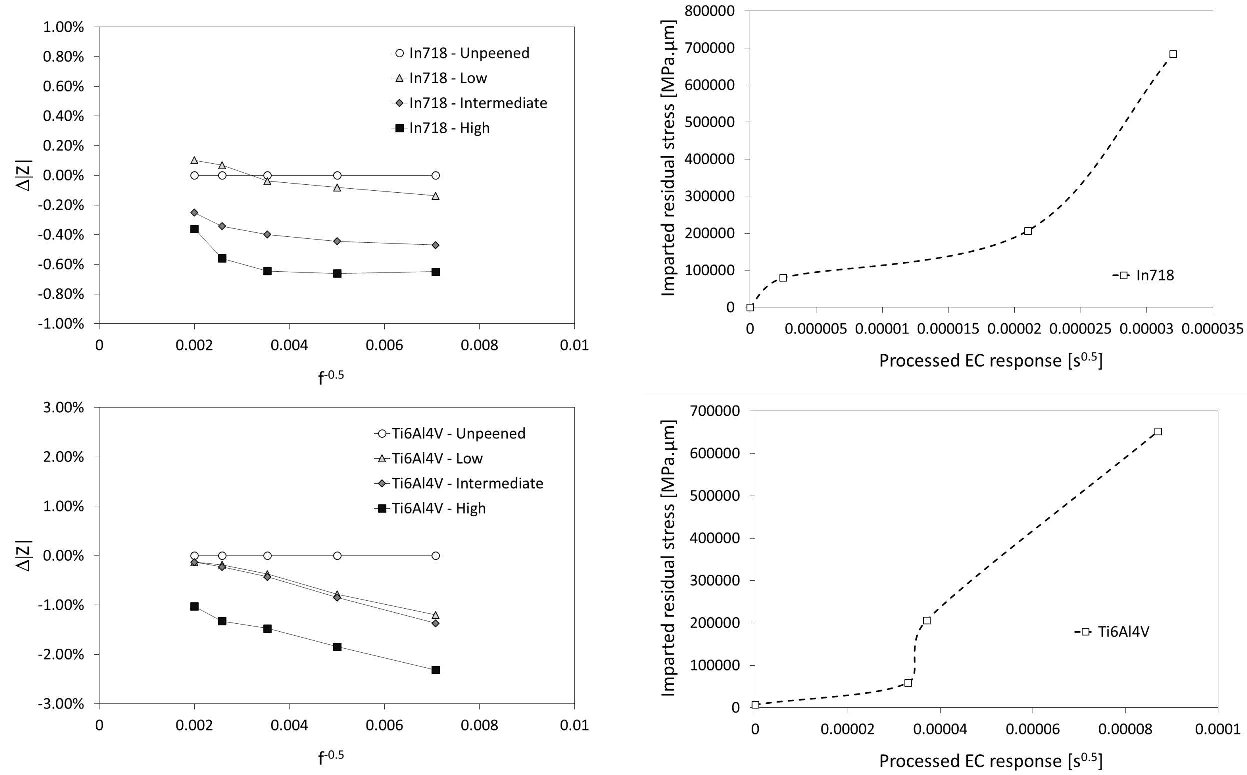

Figure 5: Change in the magnitude of the impedance caused by shot peening (left), and correlation between the multifrequency EC test response as processed in the present paper and the XRD residual stress profile surface area, namely imparted residual stress (right). Results for C22 and AA7075

Conclusions

Even if this study is far from identifying the fundamental effect of cold work, residual stress or other unexpected interactions on observed magnetic phenomena, these experiments show that multifrequency EC systems can be used as high speed, non-destructive testing solutions for the RS profile after SP on ferritic steels and aluminum alloys. A calibration curve can easily be found. This would of course be valid only for one particular testing configuration with constant material, shot peening process, and part geometry. This method has nevertheless high industrial potential. Further experiments on steels and aluminum alloys will be conducted to apply the methodology to industrials cases with typical SP specifications on acceptable range of intensity and RS criteria. The present configuration is not optimized for Ni-based alloys and titanium alloys. Further experiments need to be carried out at higher test frequencies.

References

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