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Tyler Brockel
South Dakota State University

Ozan Ozdemir
South Dakota State University

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Authors: Tyler Brockel, Ozan Ozdemir
Faculty Advisors: Dr. Jikai Du, Dr. Fereidoon Delfanian
Department: Mechanical Engineering Department

ABSTRACT

The objective of this paper is to describe the process and results of a residual stress analysis done on a composite cannon barrel. A cross section of a full cannon barrel was cut off to be used in the analysis. The barrel cross section was composed of an inner steel layer that was wrapped in an outer composite layer.

The residual stress analysis was done using x-ray diffraction (XRD). The XRD machine uses different types of x-ray tubes based on what material it is analyzing. For this reason, the first portion of the experiment dealt with finding the exact material of the inner steel layer of the barrel. It was concluded that the majority of the barrel was composed of iron. This meant that a chromium x-ray tube had to be used in the XRD machine. Once the material composition was found, the next step was to determine how much the barrel needed to be polished down before accurate readings could be obtained. The reason this is necessary is because the cutting of the barrel would introduce stress into the system through the friction from the blade. By chemically eating away the metal, a depth in the material could be obtained where the residual stress level was not affected by the cutting. The results showed that at a depth of 200 microns or greater, accurate results were obtained. It was also observed that the inner portion of the barrel was in compression while the outer was in tension. Once the barrel was analyzed, the outer composite layer was cut off. It was predicted that the material in the inner steel layer would relax if the outer layer was removed. When placed in the XRD machine, the hypothesis was confirmed. The inner ring of the steel layer went from -396 MPa to -300 MPa, but the residual stress in the outer layer did not change.

INTRODUCTION

Residual stress is stress that remains in a material after the original cause of the stress has been removed. Common forms of this initial stress are usually from the manufacturing process-e.g. forging, extruding, plating, bending, and welding. Stress can also be introduced into a material from outside forces. It can be generated after plastic deformation caused by applied mechanical loads, thermals loads, or phase changes such as the material expanding or contracting due exposure to extreme heat or cold [1,2].

When a material has a positive residual stress, it means that it has a tensile residual stress. This means that the material is pulling apart. This could help to open a crack and increase crack propagation. When a material has a negative residual stress, it means that it has a compressive residual stress. The material is pressed together which in turn will help to close a crack and slow crack propagation.

It is important to monitor residual stress because it may help predict life expectancy of a part. By controlling the amount of residual stress in a material during the manufacturing process, it can help extend the part's life. This is why it is beneficial not only to control the amount of residual stress, but also to attempt to obtain a negative residual stress value during the manufacturing process [2].

Cannon barrels are subjected to extreme heat and pressure changes due to the rounds being fired through them. With each round, more stress is placed on the barrel and increases the amount of residual stress in the barrel material. Eventually, enough stress will cause surface defects or cracks along the inner surface of the barrel. This could potentially set off a round traveling through the cannon which could cause severe equipment damage and/or loss of life. Currently, the Department of Defense is replacing the barrels after a set number of rounds have been fired. By comparing the residual stress in a barrel to the amount of rounds that have been fired through it, the life expectancy can be more accurately predicted.

A cross section of a cannon barrel was analyzed for this project. The barrel consists of an inner steel layer that is wrapped in an outer carbon fiber composite outer layer. The goal of this project is to analyze the residual stress content of the barrel, and how the composite layer affects the inner steel layer.

DEVELOPMENT OF THEORY

Bragg's Law

Bragg's law explains why crystal lattices will reflect x-ray beams at certain angles of incidence. It is used to measure the distance between atomic layers in a crystal plane. This is called the d-spacing. Figure 1 shows an example of an x-ray hitting a crystal plane. The x-ray strikes the plane at a certain angle θ and reflects back at an angle of 2θ from the path that it was traveling [3]. Equation 1 relates the wavelength of an x-ray (λ) and the angle at which the x-ray hits the surface plane (θ) to the distance between the atomic layers [4].

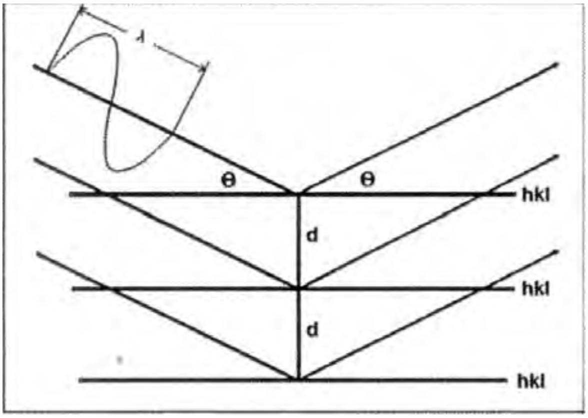

Figure 1. Complete Figure Definition of Bragg's Law [4].

$$\lambda = 2d_{hkl} \sin\theta \quad (1)$$

Where:

λ = *Wavelength of incident x-rays*
d_{hkl} = *distance between crystal plane*
θ = *angle of incidence*

X-Ray Diffraction (XRD) for Residual Stress Evaluation

X-ray diffraction was used to measure the residual stress in the cannon barrel. X-ray diffraction works by first bombarding a part's surface with an x-ray source. The x-rays are diffracted by the atoms arranged periodically in the crystal lattice of the material. The angles of the diffracted x-ray beams are related to the spacing of the atoms in the crystal structure through Bragg's Law. The lattice spacing is calculated from the diffraction angle. The larger change of the d-spacing means a larger strain component and therefore a larger residual stress value. If the d-spacing of a material is greater than the equilibrium spacing, the material is in tension. The same is vice versa. If the d-spacing is less than equilibrium, the atoms in the material are closer. This means that the material is in a state of compression [2,5].

As stated in the introduction, residual stress is stress that remains in a material after the original cause of the stress has been removed. Figure 2 shows a surface plane of a given material. X-ray penetration is very shallow, less than 10 microns. Equation 2 calculates the strain in the material by using the changes in the distance between crystalline planes. d_0 in equation 2 is the d-spacing that is assumed to have no residual stress. When the x-rays are bombarded perpendicular to the surface of the plane, the results obtained are assumed to be the original d-spacing of the material. This means this value is d_0. $d_{\phi\psi}$ is the d-spacing in relation to the angle that the x-rays hit the surface. The angled x-rays will hit the grain of the material differently and cause the strain readings to change. Equation 2 shows how the strain in the material is calculated using d_0 and $d_{\phi\psi}$. The strain component is directly related to the residual stress as a result of Poisson's ratio and the modulus of elasticity seen in equation 3 [5].

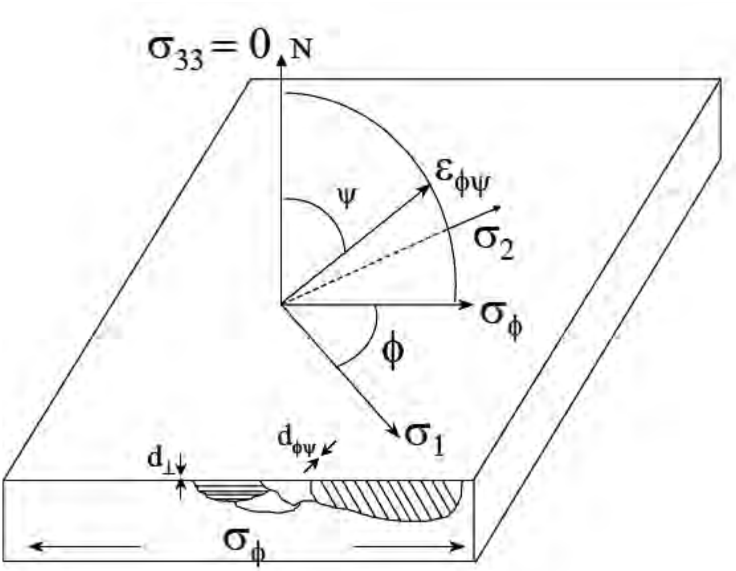

Figure 2. Plane Stresses Description for XRD Evaluation [5].

$$\varepsilon_\psi = \frac{d_{\psi\phi} - d_0}{d_0} \tag{2}$$

Where:

ε_ψ = *Strain in the material*
$d_{\Psi\phi}$ = *Distance between crystal planes at a particular angle*
d_0 = *Distance between crystal planes at* 0 *degree bombardment*

$$\sigma_\phi = \frac{E}{(1+v)sin^2(\psi)}\left(\frac{d_{\psi\phi} - d_0}{d_0}\right) \tag{3}$$

Where:

σ_ϕ = *Residual Stress in the material*
E = *Modulus of elasticity*
v = *Poisson'sRatio*
$d_{\Psi\phi}$ = *Distance between crystal planes at a particular angle*
d_0 = *Distance between crystal planes at* 0 *degree bombardment*

It is very beneficial to optimize the residual stress to some level. It is even better to manufacture the material so that it is in a state of compression. This is due to the fact that the total stress experienced on a material is the sum of the residual stress and any applied stresses. This means that if an outside force (applied mechanical load, heating, etc.) was placed on the material, the total stress could be high enough that if additional stress was added, it could cause the part to break if it is past the yielding stress. If the residual stress is negative, it could allow the part to withstand more loading placed on it [2].

EXPERIMENTAL APPARATUS AND PROCEDURE

Determining Material Composition

The first step was to determine what material the inner steel layer of the barrel was. A Niton Alloy Analyzer from Thermo Scientific was used. This tool utilizes an x-ray fluorescence technique (XRF) to determine the element composition of what it is testing. It was predicted that the inner diameter of the barrel may have had some type of plating treatment done to it. For this reason, the inner diameter surface and the cross section of the barrel will both be tested.

Determining Proper Depth for Accurate Residual Stress Readings

A cross-section of the barrel had to be cut off for the piece to be able to fit into the XRD machine. During the cutting process, heat was introduced into the part. Due to the friction, the residual stress readings could be affected. If the part was heated, it could cause a compressive force to release slightly. If there was a tensile residual stress, the additional heat could cause it to increase. To ensure accurate readings, a depth in the material would have to be found where the cutting had no effect. The barrel would have to be chemically eaten away through the use of a micro-polisher. A micro-polisher uses an electrolyte solution with a current running through it to chemically eat away the metal. This process would not introduce any stress into the system that could throw off the readings from the XRD machine. Accurate readings were determined when the amount of polishing had no effect on the residual stress. This means that once the data became consistent regardless of depth, the polishing was complete. The readings taken were the residual stresses at the inner and outer rings of the inner steel layer with the composite layer on the barrel.

Residual Stress Analysis of Cross Section without the Composite Layer

Once the proper depth had been determined, the residual stress at the inner and outer rings on the cross section was recorded. The next step was to determine how the outer composite layer was affecting the inner steel layer. The outer layer had to be removed and the barrel had to be analyzed again.

EXPERIMENTAL RESULTS AND INTERPRETATION

Determining Material Composition

The results from the Niton Alloy Analyzer from the inner diameter of the barrel can be seen in table 1.

Table 1: Inner Diameter Material Composition

Fe (%)	Fe % Error	Cr (%)	Cr % Error	V (%)	V % Error	Ni (%)	Ni % Error	Pb (%)	Pb % Error	Mo (%)	Mo % Error
0.176	0.025	99.519	0.078	< LOD	0.046	< LOD	0.021	0.004	0.002	0.017	0.001
0.31	0.032	99.406	0.088	< LOD	0.051	< LOD	0.026	0.004	0.002	0.029	0.002
0.743	0.045	98.901	0.097	< LOD	0.054	< LOD	0.028	0.005	0.002	0.037	0.002
0.363	0.029	99.314	0.076	< LOD	0.044	< LOD	0.019	0.003	0.002	0.032	0.001
0.27	0.028	99.469	0.081	< LOD	0.047	< LOD	0.023	0.004	0.002	0.019	0.001

The results show that the material at the inner diameter of the barrel is almost entirely composed of chromium at 99.5%. It can be concluded from this that the barrel has a coating on it to eliminate corrosion. The barrel needed to be cut so the cross section side wall could be analyzed.

Table 2 shows the results from the Niton Alloy Analyzer when the barrel's cross section side wall was analyzed. It shows that the material in the barrel is comprised of about 92.5% Iron, 3.75% Nickel, 1.5% Chromium, 1% Mo, and 1.25% other. From this data, it was concluded that a Chromium x-ray tube was needed in the LXRD machine since the majority of the barrel material was Iron.

Table 2: Barrel Cross Section Material Composition

Fe (%)	Fe % Error	Cr (%)	Cr % Error	V (%)	V % Error	Ni (%)	Ni % Error	Pb (%)	Pb % Error	Mo (%)	Mo % Error
92.857	0.37	1.629	0.035	0.272	0.019	3.685	0.117	< LOD	0.032	0.955	0.017
92.41	0.429	1.644	0.036	0.265	0.019	3.689	0.133	< LOD	0.038	0.944	0.02
92.26	0.41	1.703	0.036	0.265	0.018	3.728	0.131	< LOD	0.035	0.938	0.019
92.71	0.425	1.774	0.034	0.265	0.017	3.819	0.139	< LOD	0.036	0.94	0.02
92.902	0.419	1.624	0.021	0.255	0.01	3.705	0.137	< LOD	0.037	0.964	0.02

Residual Stress Measurement (Machine Calibration)

When the powder sample (0 MPa residual stress) was placed in the LXRD machine for calibration, the results showed that it had a residual stress level of 11.7 Mpa. Figure 3 shows the linear dependence of the d-spacing vs. $sin^2\psi$. A horizontal line was produced because the d-spacing did not change in relation to the incident x-rays. This means that that there was little to no residual stress in the calibration sample. A residual stress of 11.7 MPa was recorded, but this was within the standard deviation of the machine so it is an acceptable value for the 0 MPa stress sample.

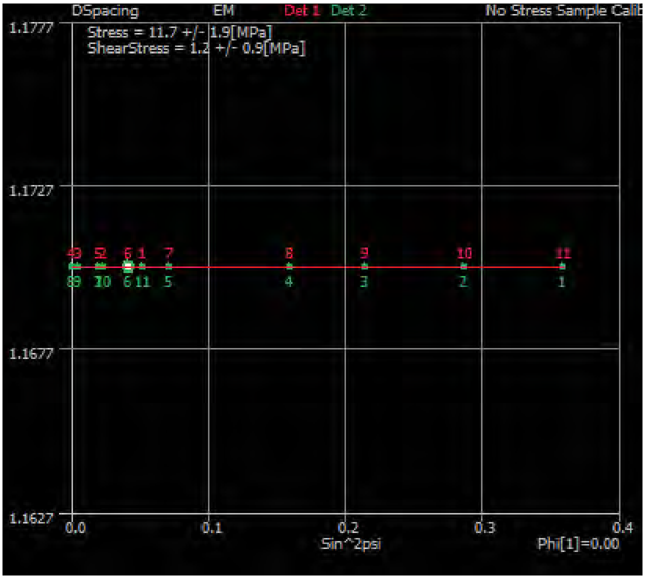

Figure 3. Calibration Results from Powder Sample

Figure 4 shows the linear dependence of the d-spacing vs. $sin^2\psi$ in the -526 MPa calibration sample. The graph shows that as the orientation of the grain change increases, the d-spacing in the crystal lattice of the material decreases. This is accurate since it is known that this sample is in compression. The results of the test showed that it had a residual stress of -510.1 MPa. This was within an acceptable range of deviation for the sample so it was determined that the machine was calibrated.

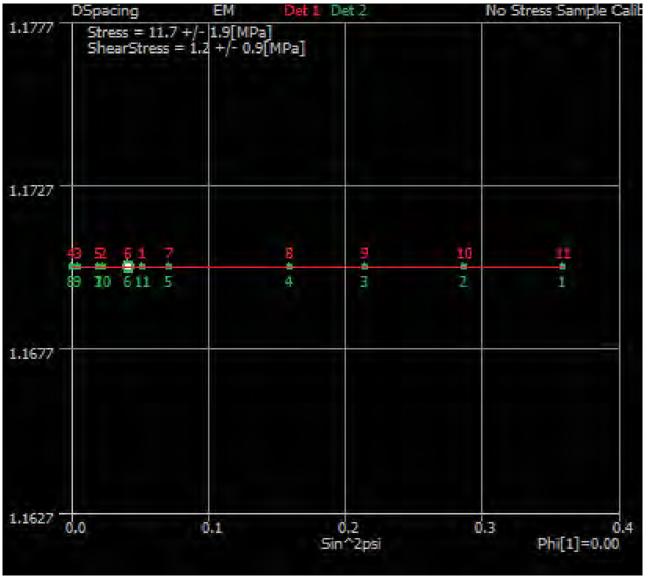

Figure 4. Calibration Results -526 MPa Sample

Determining Proper Depth for Accurate Residual Stress Readings

The locations on the outer and inner rings were done simultaneously. Figure 5 shows the location of the outer and inner holes that were polished.

Figure 5. Schematic of Polished Locations

Figure 6 shows how the hoop residual stress readings changed as the depth in the material increased. At a depth of 0 microns, there is virtually no residual stress. This is due to the cutting of the cross section relaxing the material. As the depth increased, so did the amount of residual stress. At 200 microns, the residual stress starts to even out. A depth of 220 microns was attained and the results at this depth were similar to the results that were obtained at 200 microns. This shows that the outer ring on the barrel has a residual stress of 200 MPa, which means that the outer portion of the steel layer is in a state of tension.

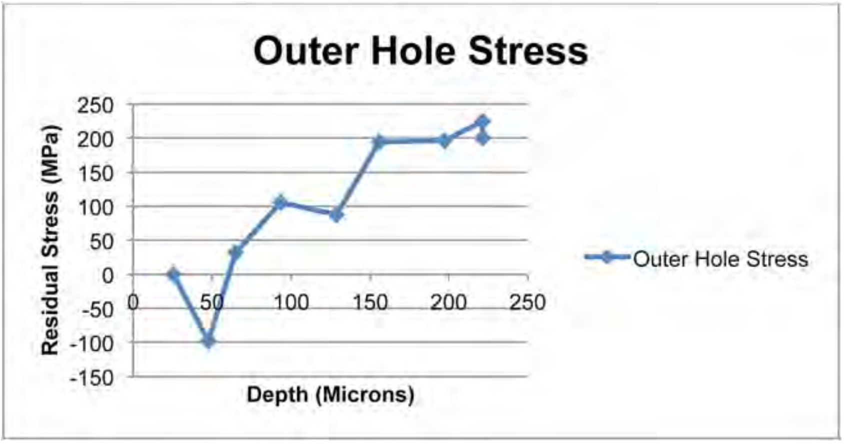

Figure 6. Outer Ring Hoop Residual Stress vs. Depth

Figure 7 shows the hoop shear stress on the outer ring of the steel layer. It initially has a shear stress of -60 MPa. As the depth increases, the shear stress begins to increase. At the 200 micron depth, the average shear stress is -2 MPa. This is a very small value which means there is no hoop shear stress in the barrel.

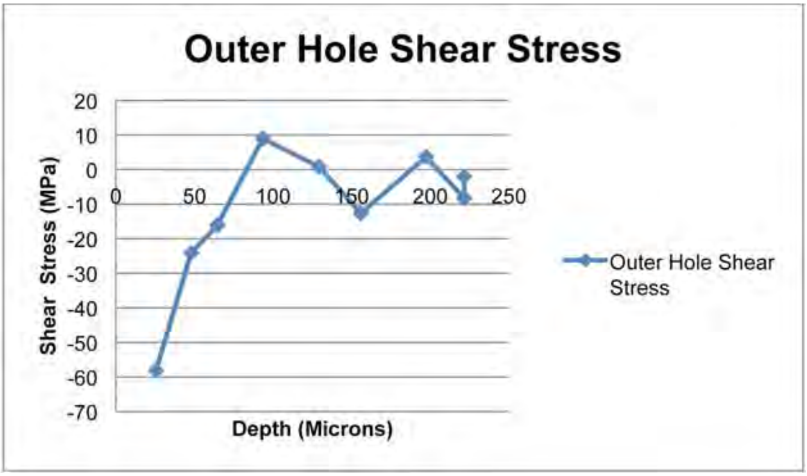

Figure 7. Outer Ring Hoop Shear Stress vs. Depth

Figure 8 shows how the hoop residual stress readings changed as the depth in the material increased on the hole in the inner ring of the steel layer. Before any material was polished away, the residual stress was about 0 MPa. As the barrel was polished down, the residual stress decreased. The residual stress values for this portion of the barrel were all negative. This means that the inner portion of the barrel was in a state of compression. Around 200 microns, the residual stress values began to level off. The residual stress level after this depth was about -396.64 MPa.

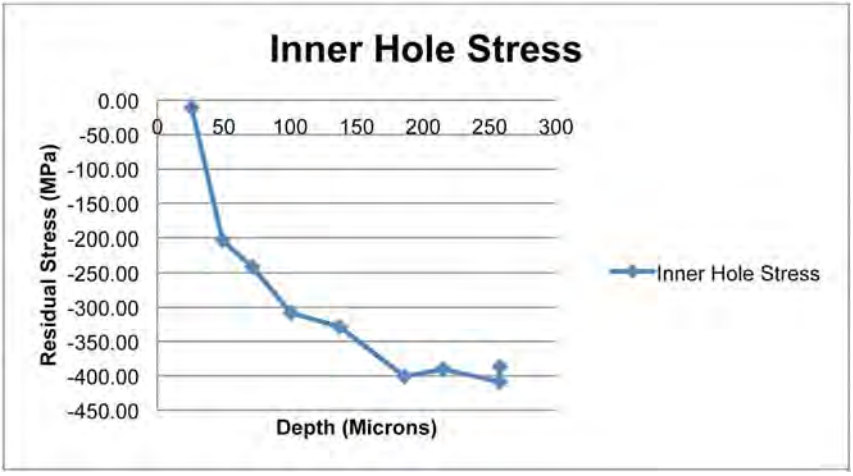

Figure 8. Inner Ring Hoop Residual Stress vs. Depth

Figure 9 shows the shear stress on the inner ring of the steel layer. It initially has a shear stress of -70 MPa. As the depth increases, the shear stress begins to increase. At the 200 micron depth, the average shear stress is -14 MPa. This is a very small value which means that there is no hoop shear stress in the barrel.

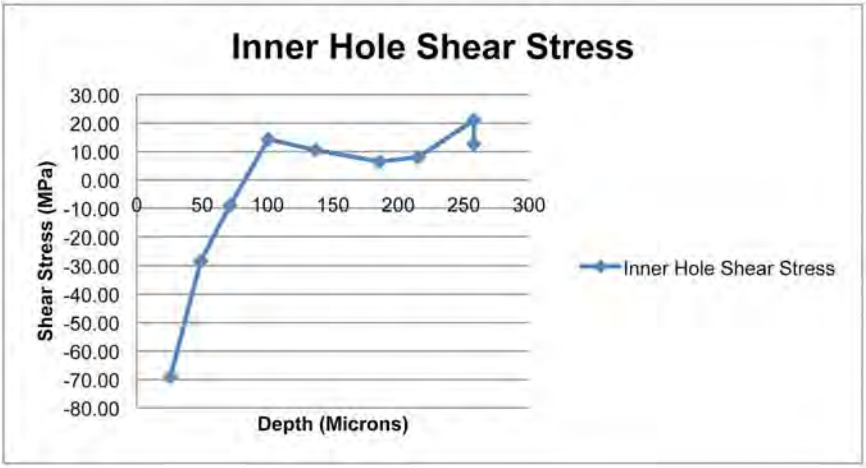

Figure 9. Inner Ring Hoop Shear Stress vs. Depth

Figure 10 shows a schematic of the vector stress distribution in the barrel. As shown by these results, the inner portion of the barrel was in compression with the maximum value being at the inner diameter of the bore. The stress increased with a larger radius until it hit its peak value at the outer diameter of the barrel.

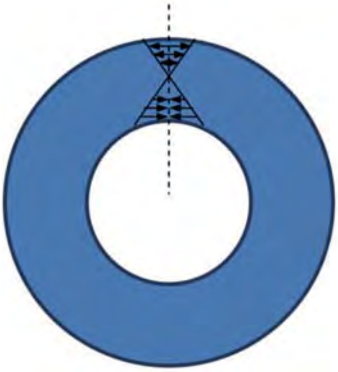

Figure 10. Schematic of Barrel Stress Vectors

Residual Stress Analysis of Cross Section without the Composite Layer

Once the residual stress was taken on the cross section, the outer composite layer was removed. Table 3 shows the data taken on the inner ring of the barrel with the composite layer removed.

Table 3. Inner Hole with No Composite Layer

Inner Hole	Normal Stress (MPa)	Standard Deviation	Shear Stress (MPa)	Standard Deviation
Hoop 1	-321.36	±8.95	8.51	±4.03
Hoop 2	-301.11	±12.92	-1.91	±5.82
Average	-311.24	Average	3.3	
Radial 1	103.65	±9.55	2.72	±4.30
Radial 2	84.16	±10.13	7.53	±4.56
Average	93.905	Average	5.125	

The average residual stress in the hoop direction is -311.24 MPa. The inner portion of the barrel is still in compression, but the material relaxed about 85 MPa from when the composite layer was on. The shear stress is about 3 MPa. With the standard deviation of the machine, anything within the range or positive or negative 14 MPa is considered to have no residual stress. Table 4 shows the data taken on the outer ring of the cannon barrel with the composite layer removed.

Table 4: Outer Hole with No Composite Layer

Outer Hole	Normal Stress (MPa)	Standard Deviation	Shear Stress (MPa)	Standard Deviation
Hoop 1	221.75	±13.94	12.26	±6.28
Hoop 2	223.61	±10.44	15.6	±4.70
Average	222.68	Average	13.93	
Radial 1	-47.54	±16.36	13.18	±7.37
Radial 2	-48.04	±14.65	8.95	±6.60
Average	-47.79	Average	11.065	

The outer layer is still in tension. It had an average residual stress of 222.68 MPa. This only increased by about 20 MPa. The results show that there is still no shear stress in the material.

Since the composite layer was removed, the surface on the outer diameter of the steel layer could be analyzed. A hole polished down to almost 400 microns. Table 5 shows the results of the top hole.

Table 5: Outer Surface Results

Top Hole	Normal Stress (MPa)	Standard Deviation	Shear Stress (MPa)	Standard Deviation
Hoop Deeper	222.16	±12.75	7.64	±5.74
Hoop 1	244.23	±18.25	-8.26	8.22
Hoop 2	215.42	±12.41	-3.57	±5.59
Average	229.825	Average	-5.915	

The results from this surface were very similar to the ones from the outer ring on the cross sectional side wall. The outer surface is in a state of tension with an average residual stress of 229.825 MPa and an average shear stress of -5.915 MPa, which means that there is still no shear stress.

CONCLUSION

It can be seen from the alloy analyzer results that the composition of the barrel is primarily iron with a bit of nickel, chromium, and some other miscellaneous metals. It was also observed that the inner diameter of the barrel has chromium plating on it to help reduce corrosion and wear.

Once the machine was calibrated, the first step in measuring the residual stress on the barrel was to determine at what depth the machine would yield accurate results. Eight different depths were scanned and it was determined that at 200 microns, the residual stress measurement that was produced was not affected by the stress induced by the cutting of the barrel. This depth was to be used for all future residual stress measurements on this barrel cross section.

Once an accurate depth was determined and results were recorded for the inner and outer rings on the cross section, the outer composite layer was removed. The results showed that the material in the inner steel layer “relaxed” slightly. This means that the stress in the material became more positive due to it being in compression. The inner ring of the barrel increased its residual stress level by about 85 MPa while the outer layer does not change much.

From all of this, it can be seen that the barrel was manufactured to be in a state of compression to help combat the extreme pressure and temperatures it would experience during the firing of a shell. This would ultimately help to increase barrel life. The inner most portion of the barrel had a compressive residual stress. As you move outward on the barrel, the material starts moving toward a higher value of tensile residual stress. The results showed that the carbon fiber composite layer was helping to hold the entire barrel in a state of compression.

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