FINAL REPORT – ADDENDUM II

Cold Spray Coatings for Cr and Ni Plating Replacement – Fatigue Testing Results

ESTCP Project WP19-5120

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14. ABSTRACT
This Addendum presents the Fatigue Testing Results for the WP19-5120 Project, "Cold Spray Coatings for Cr and Ni Plating Replacement".

15. SUBJECT TERMS
Cold Spray Coatings, Cr and Ni Plating Replacement, Corrosion and repair technologies, passivation, primers, topcoats, corrosion, coatings, manufacturing, surface preparation, repair, non-chrome, cold sprat

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1 Fatigue Testing Results

1.1.1 AXIAL FATIGUE

- Results indicate that both WIP-C1 and WIP-C2 can provide fatigue life performance equal to, or better than, the hard chrome coating.

The fatigue life was assessed at the stress levels shown in Table 1. All samples were tested at R=0.1 and were run either until failure or 10^7 cycles. The average fatigue life of all samples is found in **Table 1** and **Table 2,** and is shown as average cycle count and log average cycle count, respectively. Since fatigue data is log-normally distributed, standard deviation is also shown in **Table 2**. The full dataset is shown on an SN curve in **Figure 1**.

Cold Spray Coatings

Cold spray recipes can be found in Table 5 in the Test Design section of the Final Report, with Axial Fatigue Testing spray recipes further defined in Table 24 in the Axial Fatigue section of the Final Report. The nitrogen-deposited WIP-C1 and WIP-C2 coatings were tested at 90, 120, and 130 ksi. The helium-deposited coatings were tested at the same stress levels, plus 70 and 80 ksi.

In addition to the full dataset SN curve in **Figure 1,** the results for WIP-C1 and WIP-C2 are plotted in **Figure 2** and **Figure 3,** respectively, both with hard chrome test results plotted for a baseline comparison. This is done to better visualize the performance differences between cold spray coating samples and hard chrome.

Table 1. Test Results - Axial Fatigue.

Specimen Coating	Carrier Gas	Average Fatigue Life [cycles]				
		70 ksi	80 ksi	90 ksi	120 ksi	130 ksi
WIP-C1	N_2	--	--	6.6×10^4	2.5×10^4	2.0×10^4
	He	6.3×10^6	6.6×10^5	1.3×10^5	2.1×10^4	2.5×10^4
WIP-C2	N_2	--	--	3.1×10^5	3.6×10^4	2.2×10^4
	He	10^7	7.0×10^6	1.5×10^5	2.1×10^4	2.7×10^4
Hard Chrome		--	--	5.8×10^4	2.7×10^4	1.6×10^4

Table 2. Average Log Fatigue Life of sample tested.

Specimen Coating	Carrier Gas	Log Average Fatigue Life [cycles]				
		70 ksi	80 ksi	90 ksi	120 ksi	130 ksi
WIP-C1	N_2	--	--	4.81 ± 0.08	4.40 ± 0.03	4.29 ± 0.13
	He	6.68 ± 0.44	5.79 ± 0.24	5.11 ± 0.04	4.33 ± 0.04	4.40*
WIP-C2	N_2	--	--	5.48 ± 0.10	4.55 ± 0.12	4.25 ± 0.17
	He	7*	6.68 ± 0.55	5.16 ± 0.14	4.30 ± 0.18	4.37 ± 0.32
Hard Chrome		--	--	4.76 ± 0.02	4.43 ± 0.06	4.21 ± 0.10

*Only one specimen tested per condition

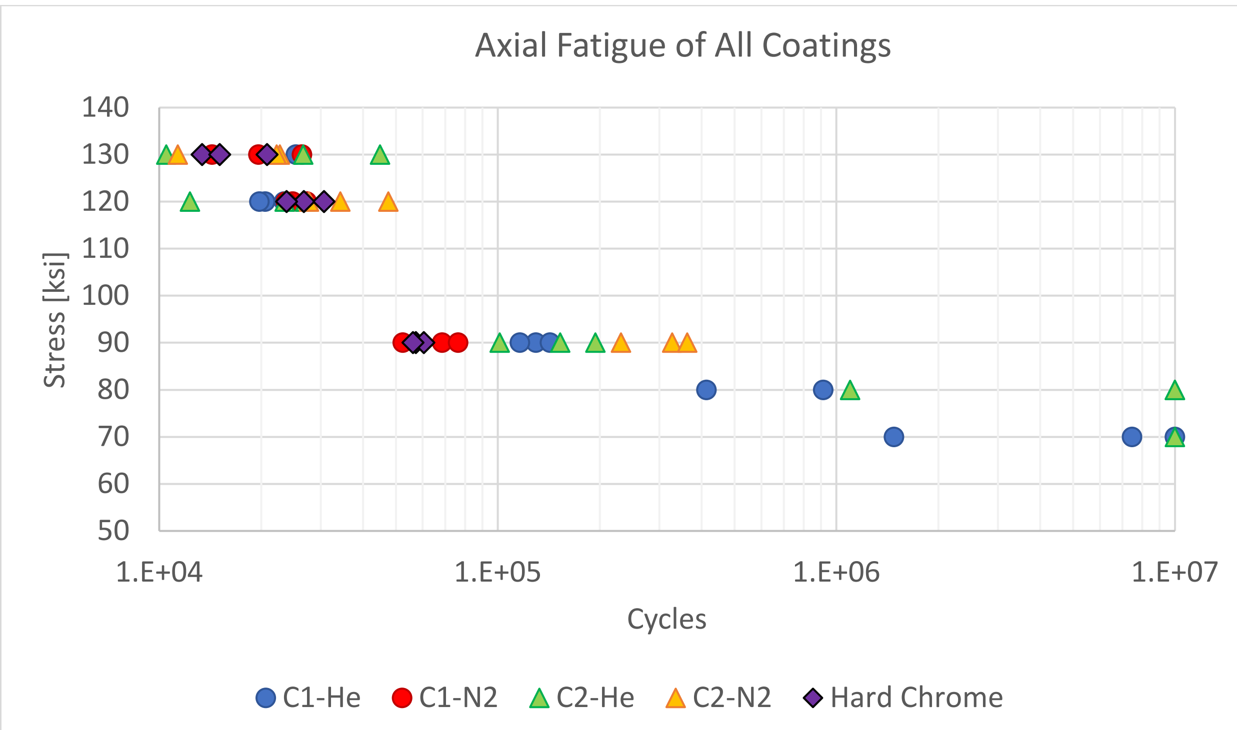

Figure 1. Test Results – Axial Fatigue Curves of all coatings.

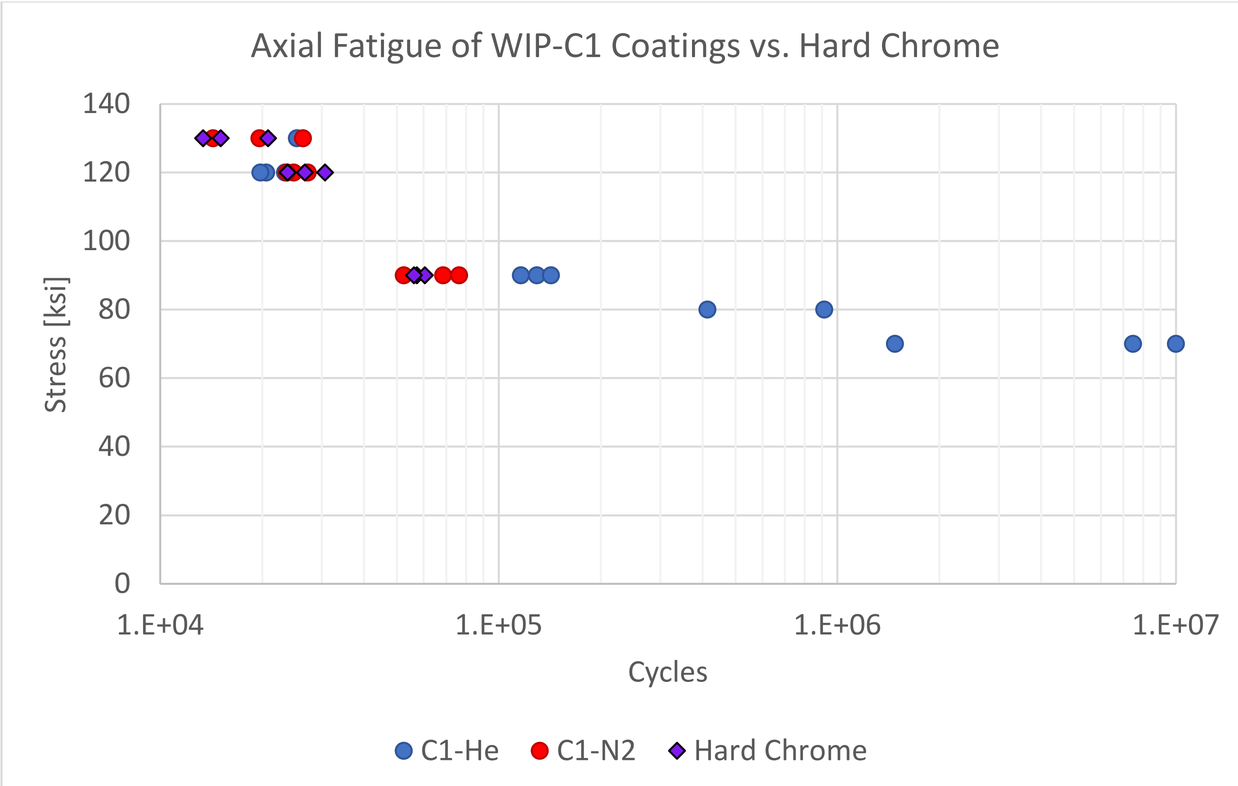

Figure 2. Test Results – Axial Fatigue Curves of WIP-C1 vs. Hard Chrome.

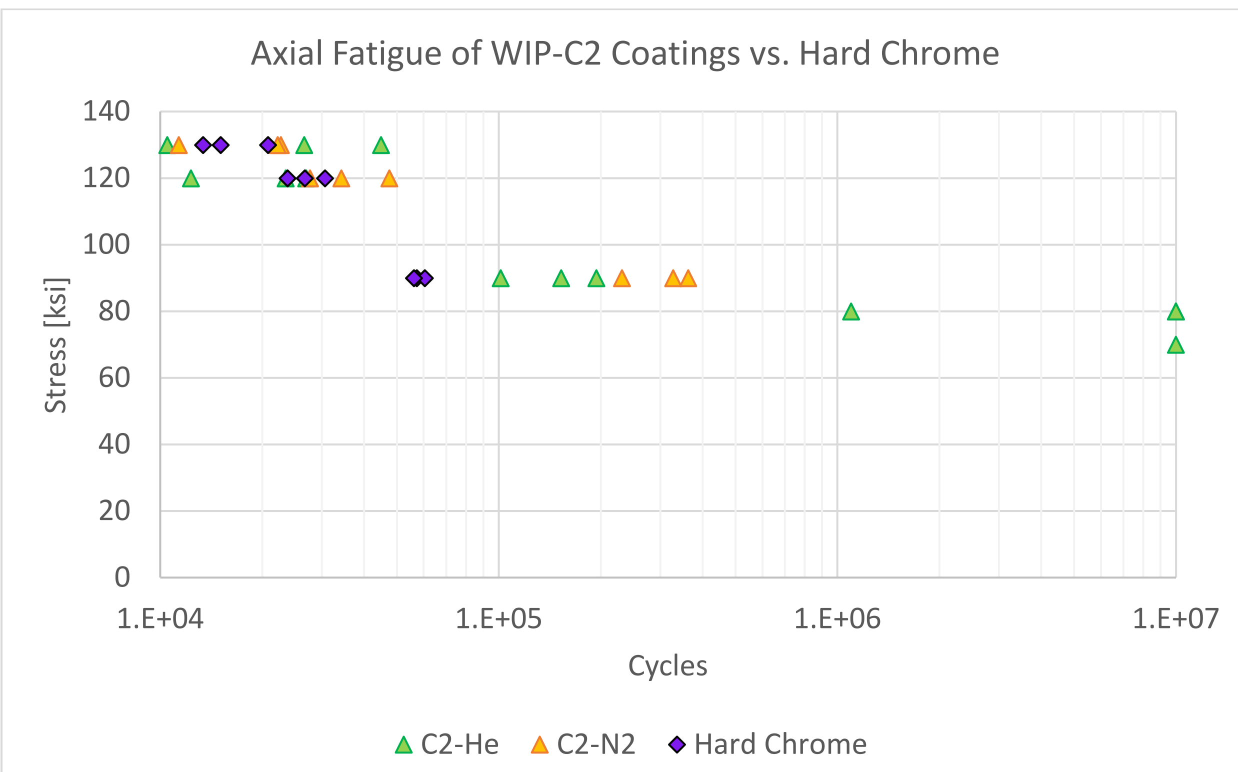

Figure 3. Test Results – Axial Fatigue Curves of WIP-C2 vs. Hard Chrome.

The statistical significance of fatigue life differences discussed in the following section were measured using the two-tailed, equal variance T-test method on log fatigue life values, with a 95% confidence interval ($p < 0.05$ for significance).

At high load-levels (120 ksi, 130 ksi) fatigue life differences between WIP-C1 and WIP-C2 were insignificant. Carrier gas choice also had an insignificant effect on fatigue life performance for both coatings. When compared to the hard chrome samples, all differences at this high-load level range were deemed insignificant.

Significant differences were observed at the 90 ksi load level. WIP-C1 sprayed in helium showed significantly longer fatigue life than WIP-C1 sprayed in nitrogen (p-value = 0.006). A significant difference was also observed in WIP-C2 between carrier gases, but the difference is not as stark (p-value = 0.03). With nitrogen as the carrier gas, WIP-C2 exhibited a significantly longer fatigue life than WIP-C1 (p-value = 0.001). In helium, no significant differences between WIP-C1 and WIP-C2 was observed. All cold spray coatings, with the exception of WIP-C1 in nitrogen, had significantly longer fatigue lives than the hard chrome coating at the 90 ksi load level, with WIP-C2 in nitrogen performing the best.

At lower load-levels (70 ksi, 80 ksi), only coatings produced with helium were tested until failure or until 10^7 cycles. At 80 ksi, we find the WIP-C2 sprayed in helium exhibits significantly longer fatigue life than WIP-C1 sprayed in helium.

Given these results, WIP-C1 and WIP-C2 provide equal or better fatigue life performance than the hard chrome coating, with WIP-C2 being the best performer at 90 ksi.

Previous testing outlined in the full report has shown that generally WIP-C1 and WIP-C2 materials deposited with helium exhibit better mechanical performance than materials deposited with nitrogen. However, that trend did not hold in this fatigue testing, as WIP-C2 in nitrogen was the best performing coating. If fatigue life dictates the performance of the coating, this data shows nitrogen could be used in place of helium without a significant debit to performance.

Hard Chrome Coating

Hard chrome samples were prepared using the electroplating process. Substrates of 40 HRC, 4340 steel were placed in an electro-chemical bath with a chromic acid solution and treated until a coating thickness in the range of 0.0001 – 0.0003 inches (2.5 – 7.6 microns) was reached. Both sides of the substrate were coated, and sample geometry and testing parameters were selected to replicate the testing performed on the cold spray coatings. It should be noted that the hard chrome substrates were not shot peened to better reflect cold spray substrate preparation.

The fatigue results in **Figure 1** show that the hard chrome coating performed within a similar range to the different cold spray coatings, with some significant differences. At 90 ksi, the fatigue life of WIP-C1 (sprayed with nitrogen) and hard chrome were comparable, while the other cold spray coatings performed significantly better. At higher stresses, all coatings performed similarly to one another. This shows that these cold spray coatings can be expected to perform equal to, or better than, the incumbent hard chrome coating under fatigue conditions.

Hard Chrome Data and Literature Comparison

To provide a baseline to compare our cold spray results against, the fatigue life of hard chrome was evaluated and has been presented in comparison against our results earlier in this addendum (**Table 1, Table 2, Figure 1, Figure 2, Figure 3**). In addition to testing hard chrome samples, a literature search was performed to evaluate the fatigue performance of hard chrome in similar test conditions. Two similar studies were found [1, 2]. The test conditions outlined in these studies use a stress ratio of R=0.1, matching our current testing. Fatigue life is determined at each stress levels 130, 120, 90, 80, and 70 ksi. All substrates are AISI 4340 steel heat treated to 40 HRC. **Figure 4** shows the resultant fatigue curves from these studies, as well as the hard chrome test results for this report. Hard chrome results from this report fall within the same range as values found in literature, supporting the accuracy of above comparisons to cold spray coatings.

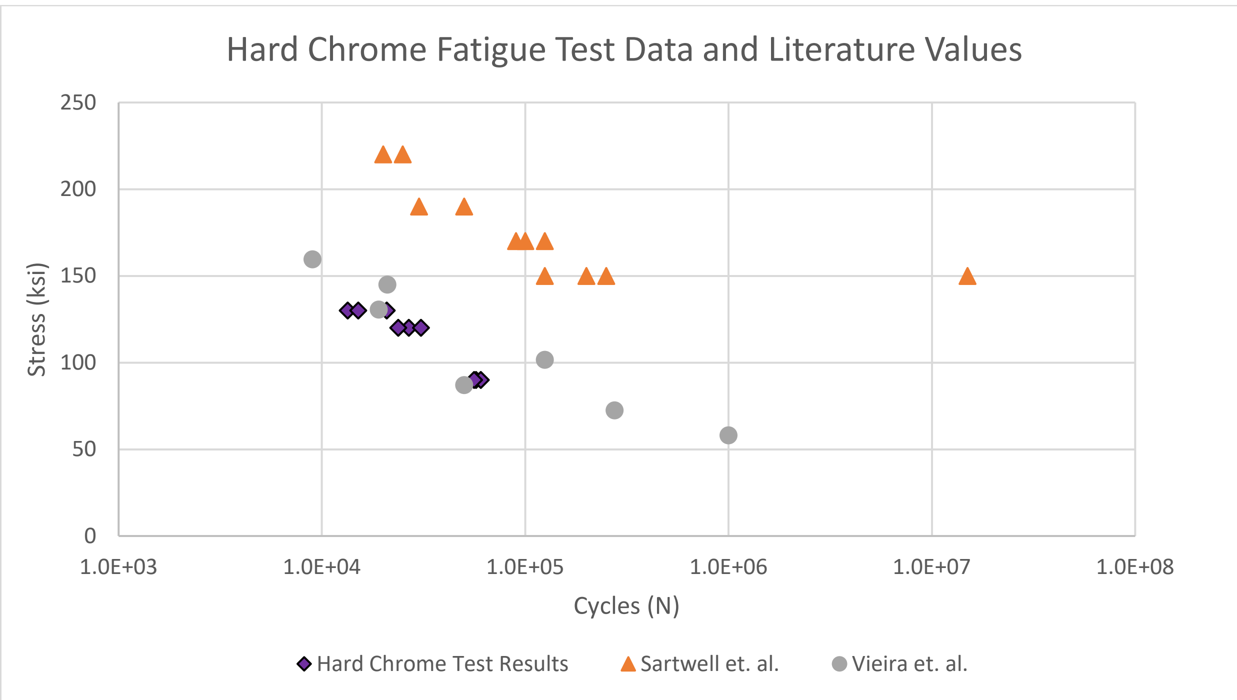

Figure 4. Hard Chrome data generated in this report compared against literature values [1, 2].

Vieira, Voorwald, and Cioffi [1] electroplated hard chrome onto 4340 steel substrates with a measured hardness of 52 HRC. Substrates were shot-peened prior to electroplating. Fatigue testing was performed with a stress ratio R = 0.1 and a frequency of 10 Hz at room temperature. The hard chrome coating was 250 µm (0.0098") thick. These fatigue results are represented by the gray circular data points. A stress lower than 50 ksi is required to runout the hard chrome to 10^7 cycles. A report from Sartwell, et al. [2] used similar fatigue testing methods to the testing outlined in the JTP. Hard chrome was electroplated onto 4340 substrates approximately 0.003" thick. A substrate hardness near 50HRC is inferred from stated UTS of 260-280ksi. The 4340 substrates were shot-peened prior to electroplating. The fatigue results are represented in by the orange triangle data points. Fatigue tests were not run below 150 ksi. At 150 ksi, the fatigue life of the hard chrome is approximately 200,000 cycles. Note that despite the lack of shot peening the hard chrome substrate, fatigue results from this report are still in line with literature values.

2 References

1. Vieira, L.F.S., Voorwald, H.J.C., Cioffi, M.O.H. Fatigue Performance of AISI 4340 Steel Ni-Cr-B-Si-Fe HVOF Thermal Spray Coated. Procedia Engineering, 606-612 (2015). doi: 10.1016/j.proeng.2015.08.111.
2. Sartwell, B.D., Legg, K.O., Schell, J., Sauer, J., Natishan, P. (2004). Validation of HVOF WC/Co Thermal Spray Coatings as a Replacement for Hard Chrome Plating on Aircraft Landing Gear. Naval Research Laboratory. Retrieved from: https://apps.dtic.mil/sti/pdfs/ADA422266.pdf.

3 Appendices

3.1 Appendix A: Points of Contact

Table 3. Points of Contact.

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
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3.2 Appendix B: Test Design

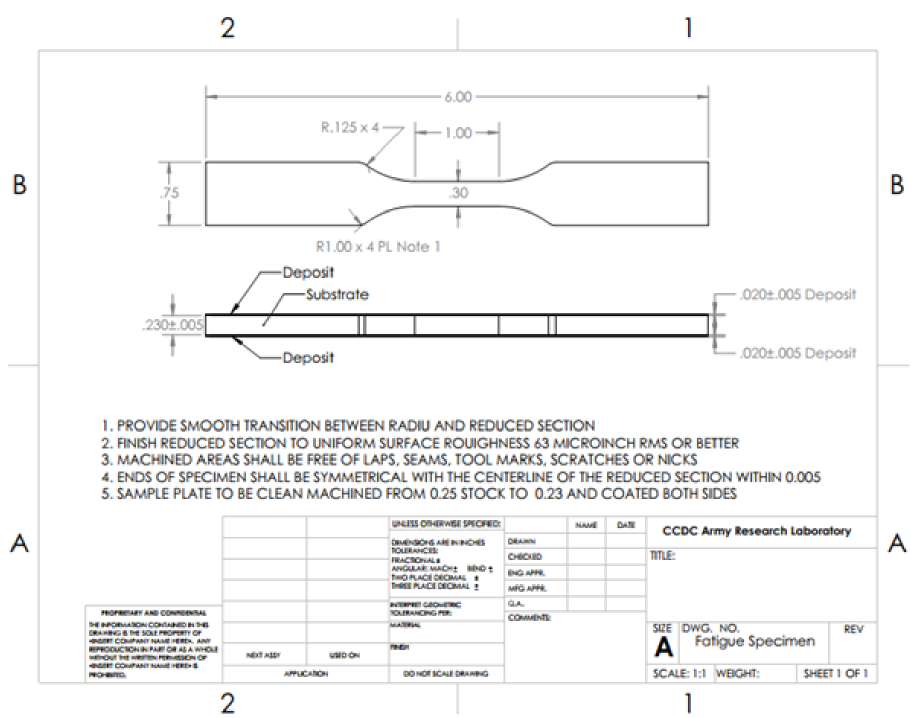

Figure 5. Axial fatigue specimen geometry.

Table 4. Test Description - Axial Fatigue.

Parameters	See Section 5.1.7 in ESTCP Project WP19-5120 for instructions; additional parameters at discretion of technician
Number and type of specimens per candidate alternative	15
Trials per specimen (if needed)	1
Experimental control specimens	15

3.3 Appendix C: Performance Assessment

Table 5. Test Results - Axial Fatigue.

Specimen Coating	Carrier Gas	Average Fatigue Life [cycles]				
		70 ksi	80 ksi	90 ksi	120 ksi	130 ksi
WIP-C1	N_2	--	--	65,718	25,230	20,114
	He	6,313,634	663,624	129,373	21,218	25,333
WIP-C2	N_2	--	--	307,167	36,464	22,473
	He	10,000,000	10,000,000	149,487	20,936	27,320

Table 6. Test Results for all specimens – Axial Fatigue

Specimen Coating	Carrier Gas	Fatigue Life [cycles]				
		70 ksi	80 ksi	90 ksi	120 ksi	130 ksi
WIP-C1	N_2	--	--	6.84E+04	2.48E+04	2.64E+04
		--	--	5.24E+04	2.72E+04	1.96E+04
		--	--	7.63E+04	2.37E+04	1.43E+04
WIP-C1	He	1.48E+06	9.14E+05	1.16E+05	2.05E+04	2.53E+04
		1.00E+07	4.13E+05	1.42E+05	2.34E+04	--
		7.46E+06	--	1.29E+05	1.98E+04	--
WIP-C2	N_2	--	--	6.84E+04	2.48E+04	2.64E+04
		--	--	5.24E+04	2.72E+04	1.96E+04
		--	--	7.63E+04	2.37E+04	1.43E+04
WIP-C2	He	--	1.00E+07	1.53E+05	2.35E+04	4.49E+04
		--	1.10E+06	1.01E+05	1.23E+04	2.66E+04
		--	1.00E+07	1.94E+05	2.70E+04	1.05E+04
Hard Chrome		--	--	5.7E+04	2.7E+04	1.3E+04
		--	--	6.0E+04	3.1E+04	2.1E+04
		--	--	5.6E+04	2.4E+04	1.5E+04

Table 7. Test Results for all specimens – Axial Fatigue (log)

Specimen Coating	Carrier Gas	Fatigue Life [log cycles]				
		70 ksi	80 ksi	90 ksi	120 ksi	130 ksi
WIP-C1	N2	--	--	4.84	4.39	4.42
		--	--	4.72	4.44	4.29
		--	--	4.88	4.37	4.16
WIP-C1	He	6.17	5.96	5.06	4.31	4.40
		7.00	5.62	5.15	4.37	--
		6.87	--	5.11	4.30	--
WIP-C2	N2	--	--	4.84	4.39	4.42
		--	--	4.72	4.44	4.29
		--	--	4.88	4.37	4.16
WIP-C2	He	--	7.00	5.18	4.37	4.65
		--	6.04	5.01	4.09	4.42
		--	7.00	5.29	4.43	4.02
Hard Chrome		--	--	4.76	4.43	4.13
		--	--	4.78	4.49	4.32
		--	--	4.75	4.38	4.18