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Technical Report ARWSB-TR-09004

Candidate M4 Barrel Characterization

Stephen B. Smith
Christopher Rickard

February 2009

ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
xx-02-2009	Final	2008

4. TITLE AND SUBTITLE
Candidate M4 Barrel Characterization

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Smith, Stephen B. ; Rickard, Christopher

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC, WSEC
Benét Laboratories, AMSRD-AAR-WSB, B. 40
1 Buffington Street
Watervliet Arsenal, NY 12189-4000

8. PERFORMING ORGANIZATION REPORT NUMBER
ARWSB-09004

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC, WSEC
Benét Laboratories, AMSRD-AAR-WSB, B. 40
1 Buffington Street
Watervliet Arsenal, NY 12189-4000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution limited to US Government Agencies only, Proprietary information, 2009. All other requests for this document shall be referred to US Army Benét Laboratories, AMSRD-AAR-WSB, Watervliet Arsenal, NY 12189-4000

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Four 5.56mm M4 barrels, with unique rifling profiles, were sectioned and analyzed according to the protocol established in previous investigations. Each barrel was examined at four locations: the chamber, the forcing cone, 3" forward of the breech face, and 5" rearward of the muzzle face. Each location was metallographically prepared and subsequently analyzed, with particular attention paid to the condition of the high contractile (HC) chromium bore coating.
The investigation noted rough chromium bore coatings, variation in coating thickness, and extensive cracking in the substrate steel.

15. SUBJECT TERMS
M4 gun barrels, 5.56mm guns, materials characterization

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(Include area code)*
U/L	U	U	U	26	

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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5d. PROJECT NUMBER. Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

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5f. WORK UNIT NUMBER. Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

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Candidate M4 Barrel Characterization

S.B. Smith and C. Rickard

29 October 2008

1. Abstract

Four 5.56mm M4 barrels, with unique rifling profiles, were sectioned and analyzed according to the protocol established in previous investigations. Each barrel was examined at four locations: the chamber, the forcing cone, 3" forward of the breech face, and 5" rearward of the muzzle face. Each location was metallographically prepared and subsequently analyzed, with particular attention paid to the condition of the high contractile (HC) chromium bore coating.

The investigation noted rough chromium bore coatings, variation in coating thickness, and extensive cracking in the substrate steel.

2. Background

Four 5.56mm M4 barrels, identified as 1-1, 2-1, 3-1, and 4-1, were received from A. Fultz, AMSRD-AAR-AEW-M(D), in July 2008. These barrels were to undergo a complete characterization in accordance with the small caliber coating characterization protocol established in previous analyses. [Mulligan, et al. "Comparison of electroplated chromium coatings applied to M4 and M16 barrels."

(January 2007). US Army-ARDEC. and Smith, et al. "Characterization of HC Chromium Plated M16 Barrels from Two Manufacturers." (March 2008). US Army-ARDEC.]

3. Procedure:

The specimens provided were subjected to a characterization procedure based upon ARDEC-Benét Laboratory's established protocol for protective coatings. The specific characterization tests performed on these specimens include:

- Macroscopic examination and sectioning. The sample will be cut into small segments in order to access areas for further investigation. The sample will be photographed as-received and during the sectioning procedure.
- Coating thickness measurement. Metallographic specimens will be prepared of the sample in cross-section. The coating thickness will be measured with a measuring optical microscope.
- Microstructural analysis. Metallographic specimens will be prepared of the sample and etched for microstructure.
- Microhardness testing. Metallographic specimens will be prepared of the sample in cross-section. Microhardness measurements will be taken through the thickness of the coating and substrate.
- Surface analysis. The surface of sample sections will be investigated with optical and electron microscopes.
- Adhesion testing. Groove testing and subsequent microscopic examination will be performed on a chamber section.

The results of these tests are described below.

4. Data/Observations

4.1. Macroscopic examination and sectioning

All barrels appeared new upon receipt with the observable chromium plating looking bright and shiny.

The barrels were sectioned to facilitate analysis by the following process. Four sections were identified, mirroring the locations used by Mulligan (2007). These locations for analysis are:

- Location 1 (Loc1) – chamber – ¼" ring section
- Location 2 (Loc2) – forcing cone – ½" longitudinal section
- Location 3 (Loc3) – 3" forward of the breech face – ¼" ring section
- Location 4 (Loc4) – 5" rear of the muzzle face – ¼" ring section

See Figure 1.

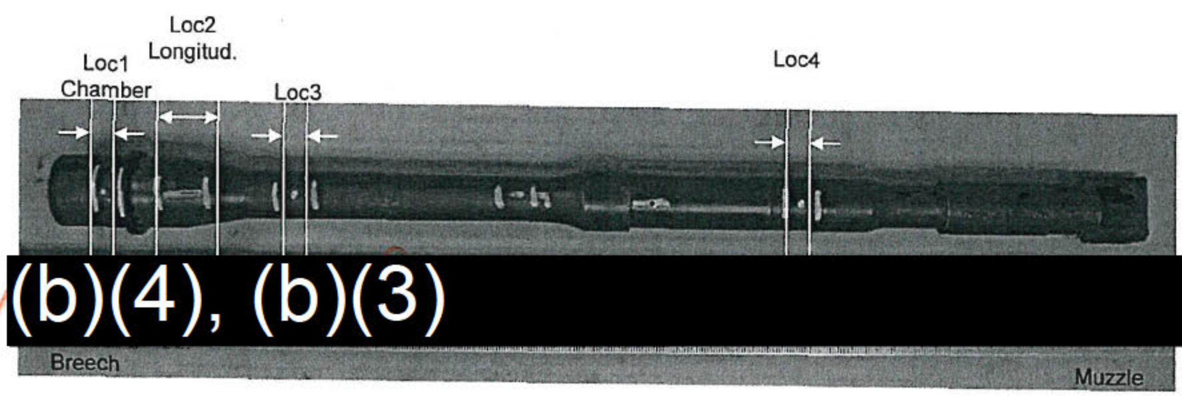


Figure 1: M4 Barrel Cut Plan

4.2. Coating thickness measurement

The samples were metallographically mounted in cross-section, polished to a mirror finish, and etched lightly with Nital. The chromium coating thickness of the barrels was measured as a function of clock position at Locations 1, 3, and 4 using an inverted metallograph with a measuring eye-piece. See Figure 2.

ID#	12 o'clock (microns)	3 o'clock (microns)	6 o'clock (microns)	9 o'clock (microns)
1-1 Loc1	[redacted]	[redacted]	[redacted]	[redacted]
1-1 Loc3	[redacted]	[redacted]	[redacted]	[redacted]
1-1 Loc4	[redacted]	[redacted]	[redacted]	[redacted]
2-1 Loc1	[redacted]	[redacted]	[redacted]	[redacted]
2-1 Loc3	[redacted]	[redacted]	[redacted]	[redacted]
2-1 Loc4	[redacted]	[redacted]	[redacted]	[redacted]
3-1 Loc1	[redacted]	[redacted]	[redacted]	[redacted]
3-1 Loc3	[redacted]	[redacted]	[redacted]	[redacted]
3-1 Loc4	[redacted]	[redacted]	[redacted]	[redacted]
4-1 Loc1	[redacted]	[redacted]	[redacted]	[redacted]
4-1 Loc3	[redacted]	[redacted]	[redacted]	[redacted]
4-1 Loc4	[redacted]	[redacted]	[redacted]	[redacted]

Figure 2: Chromium Thickness

The chromium plating on all barrels is relatively rough. The plating roughness exaggerates the surface contours of the steel substrate. This roughness is particularly evident in the *4.5 Surface analysis* images.

US Army-ARDEC drawing #9349054 Barrel and Barrel Extension Assembly for the M16 barrel specifies in Note #21 that the thickness of electroplated chromium in the chamber should be between [redacted]. The chamber of barrel 1-1 failed to meet this criterion entirely. The chambers of barrels 2-1, 3-1, and 4-1 met this criterion on average, but all included localized areas that were below limit.

Note #21 also states that the chromium thickness in the rifled section of the barrel should be greater than (b)(4), (b)(3) The bores of all barrels met this criterion on average but all included localized areas that were below limit.

4.3. Microstructural analysis

The metallographic specimens used to measure the coating thickness were also analyzed to discern microstructure information about the barrel steel and the chromium coating. See Figures 3 to 14. Observations of note include:

1. The rifling profile is not consistent between barrels. Barrels 1-1 and 4-1 have a traditional near-90° land profile, while barrels 2-1 and 3-1 have a shallower land profile.
2. The chromium coating is relatively rough. This is noted in both cross-section (*4.2 Coating thickness measurement*) and surface analysis (*4.5 Surface analysis*).
3. Cracking is occurring in the chromium coating. The crack density appears similar to Colt manufactured barrels previous analyzed by Mulligan and Smith. This cracking is inherent to the traditional electro-deposited chromium process.
4. Cracking is occurring in the steel. Cracking is noted in barrels 2-1 Loc3, 3-1 Loc3, 4-1 Loc3, and 4-1 Loc4. The cracks in barrels 2-1 and 3-1 extend from the land and groove surfaces, while the cracks in barrel 4-1 extend from the root of the land. Chromium has been plated into the crack mouths suggesting cracking has occurred prior to plating. The steel cracks extend through

the chromium coating in all cases. The cracks are intergranular, suggesting environmental cracking, such as quench cracking, hydrogen embrittlement, et al. More information on the production methods in necessary to fully identify the root cause of the steel cracking.

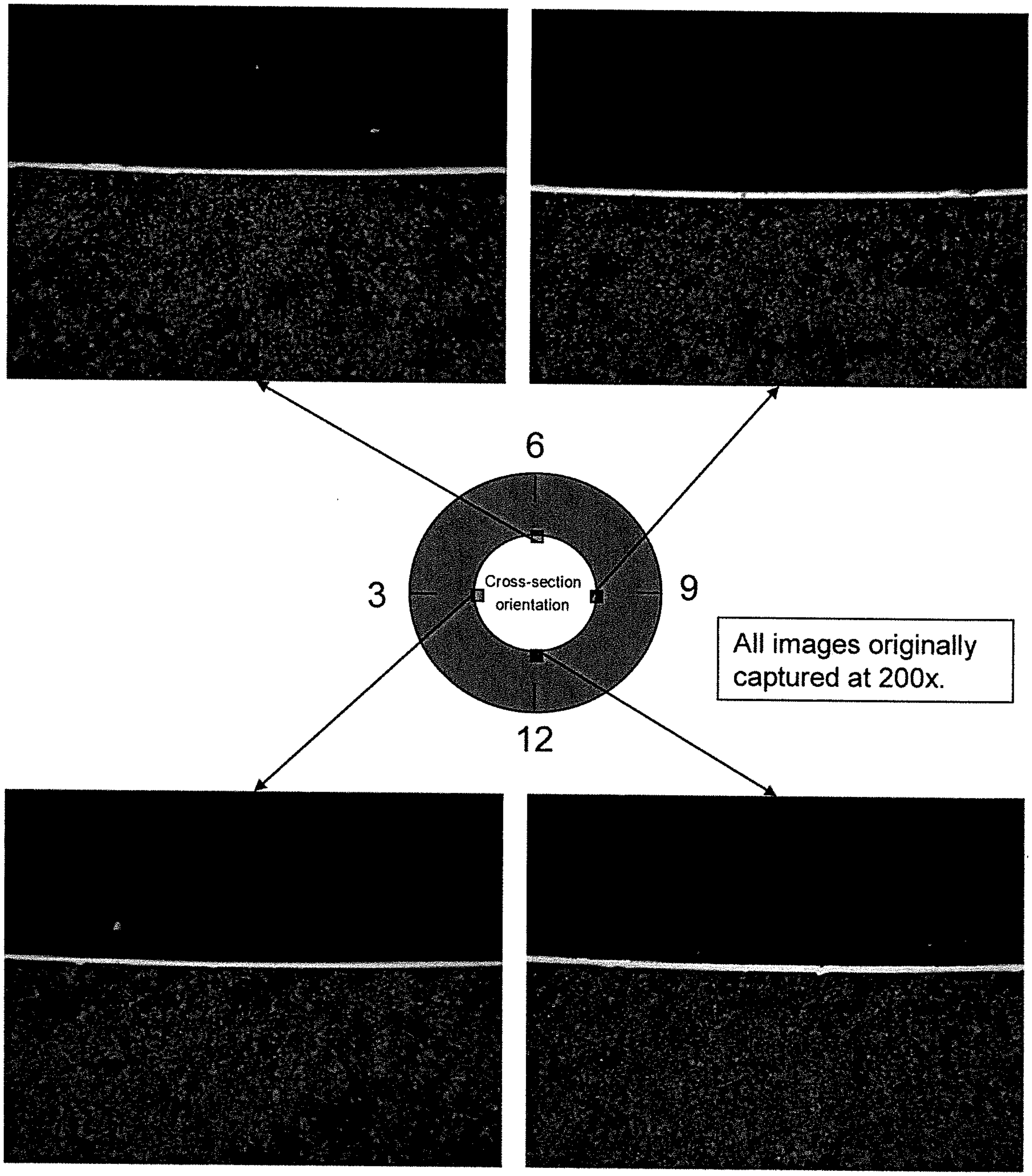


Figure 3: Tube 1-1, Location 1/Chamber

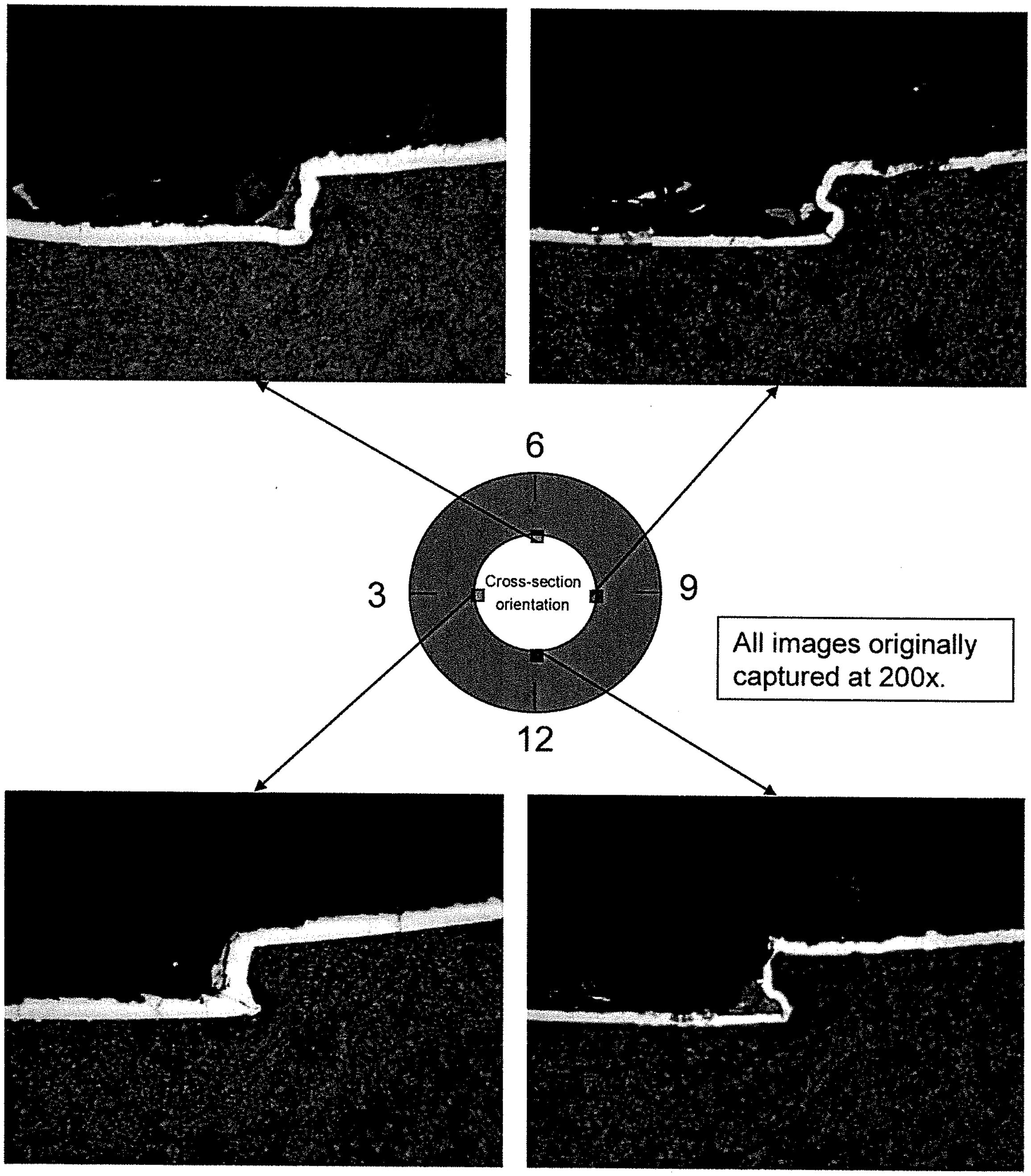


Figure 4: Tube 1-1, Location 3

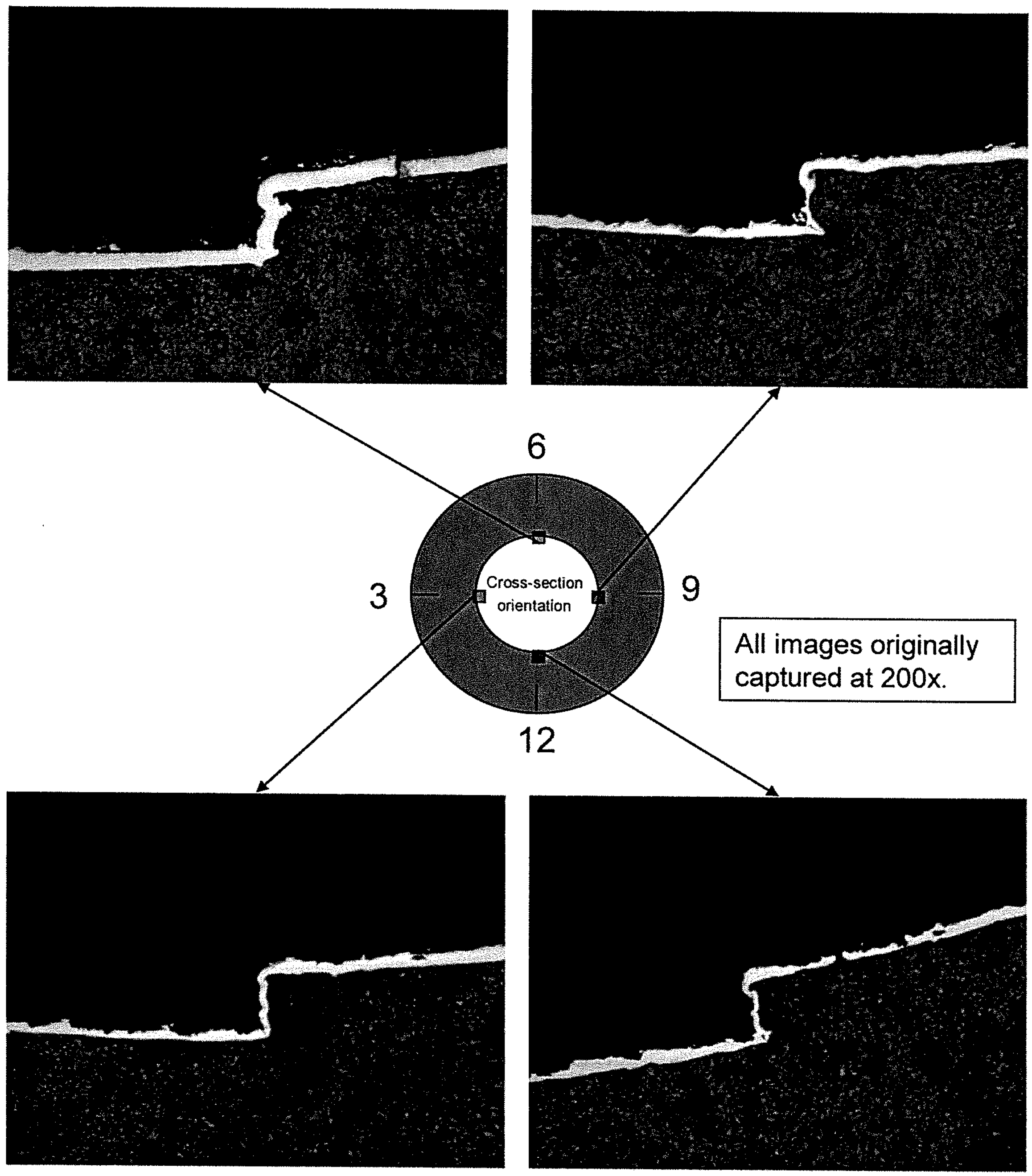


Figure 5: Tube 1-1, Location 4

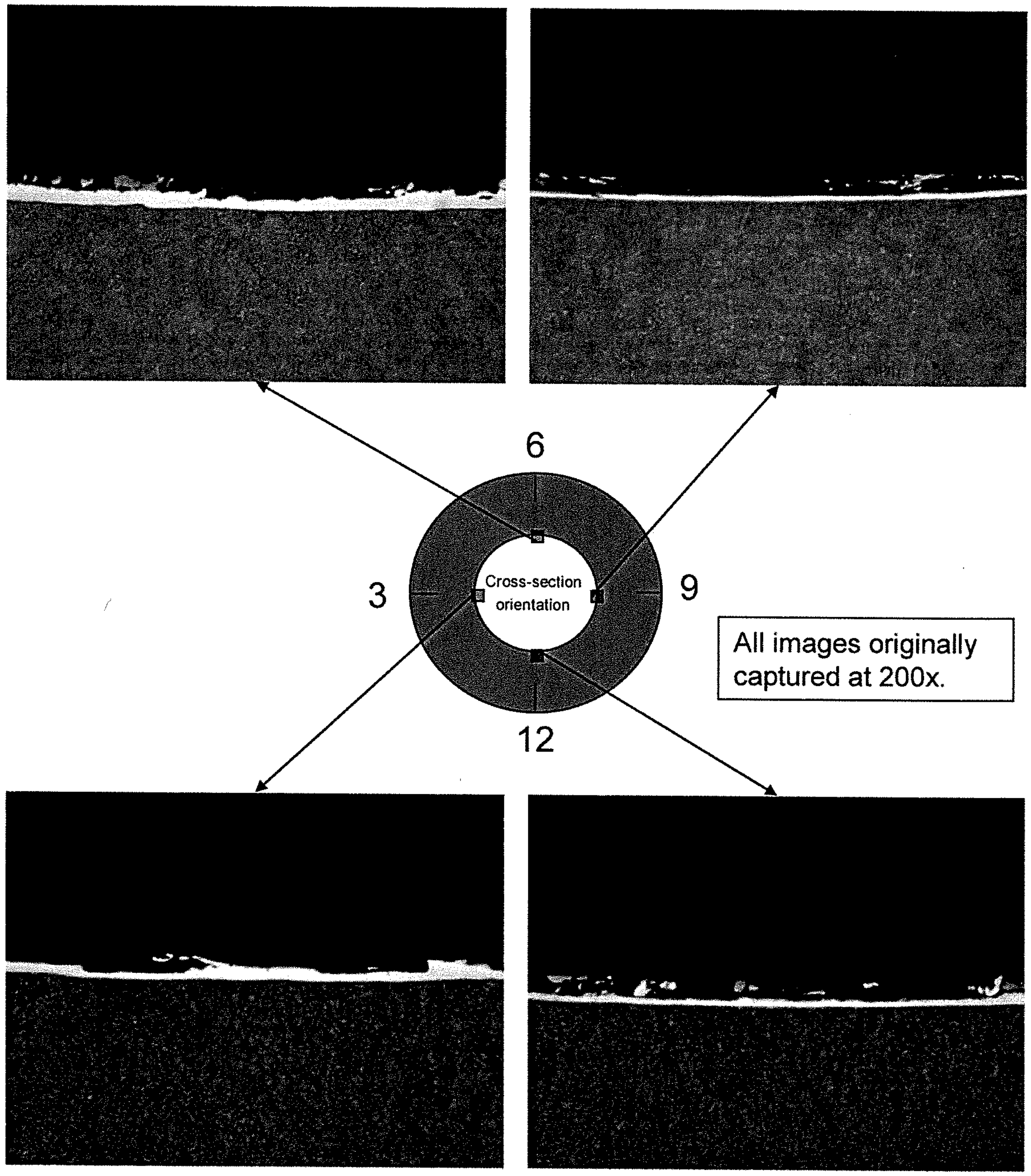


Figure 6: Tube 2-1, Location 1/Chamber

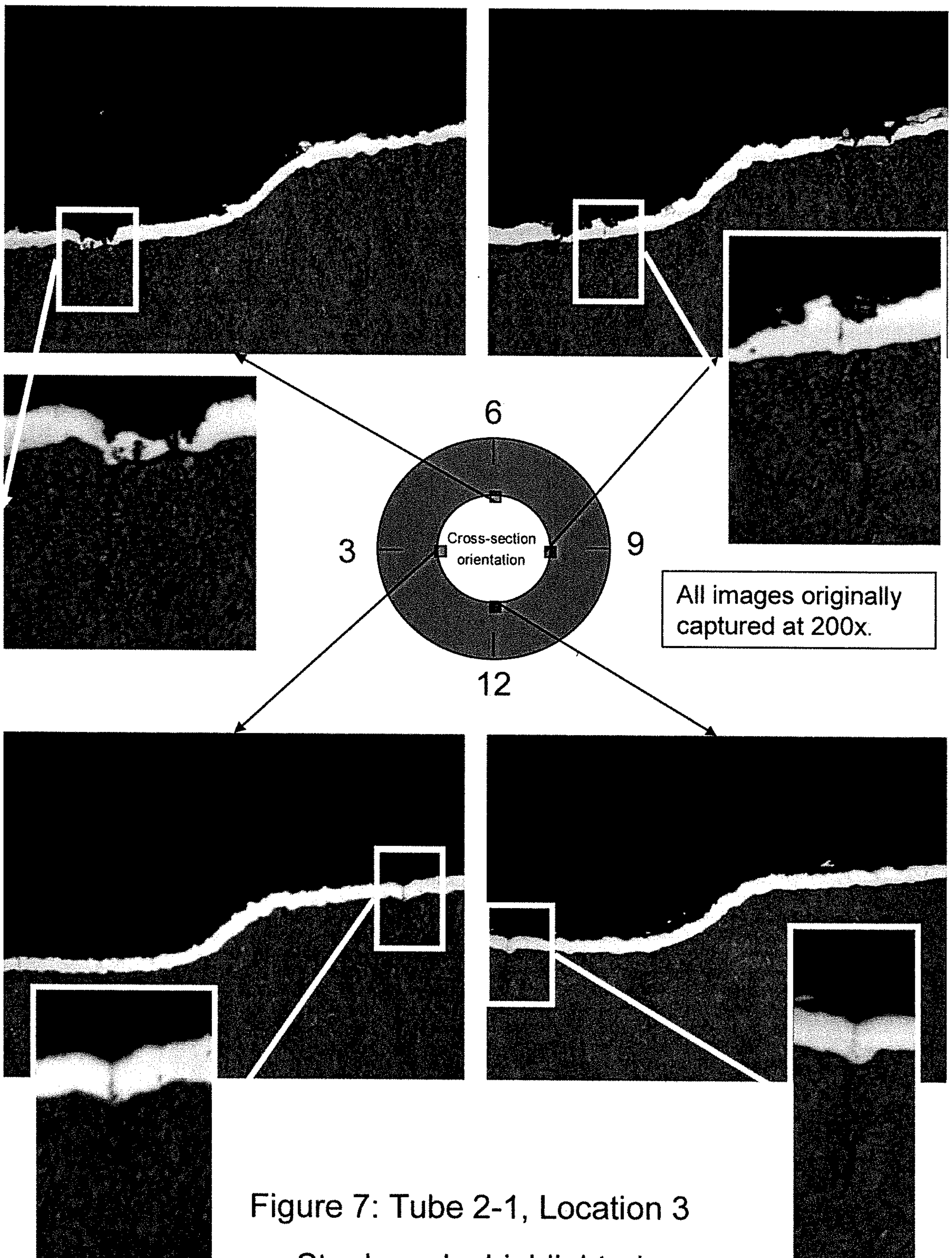


Figure 7: Tube 2-1, Location 3

Steel cracks highlighted

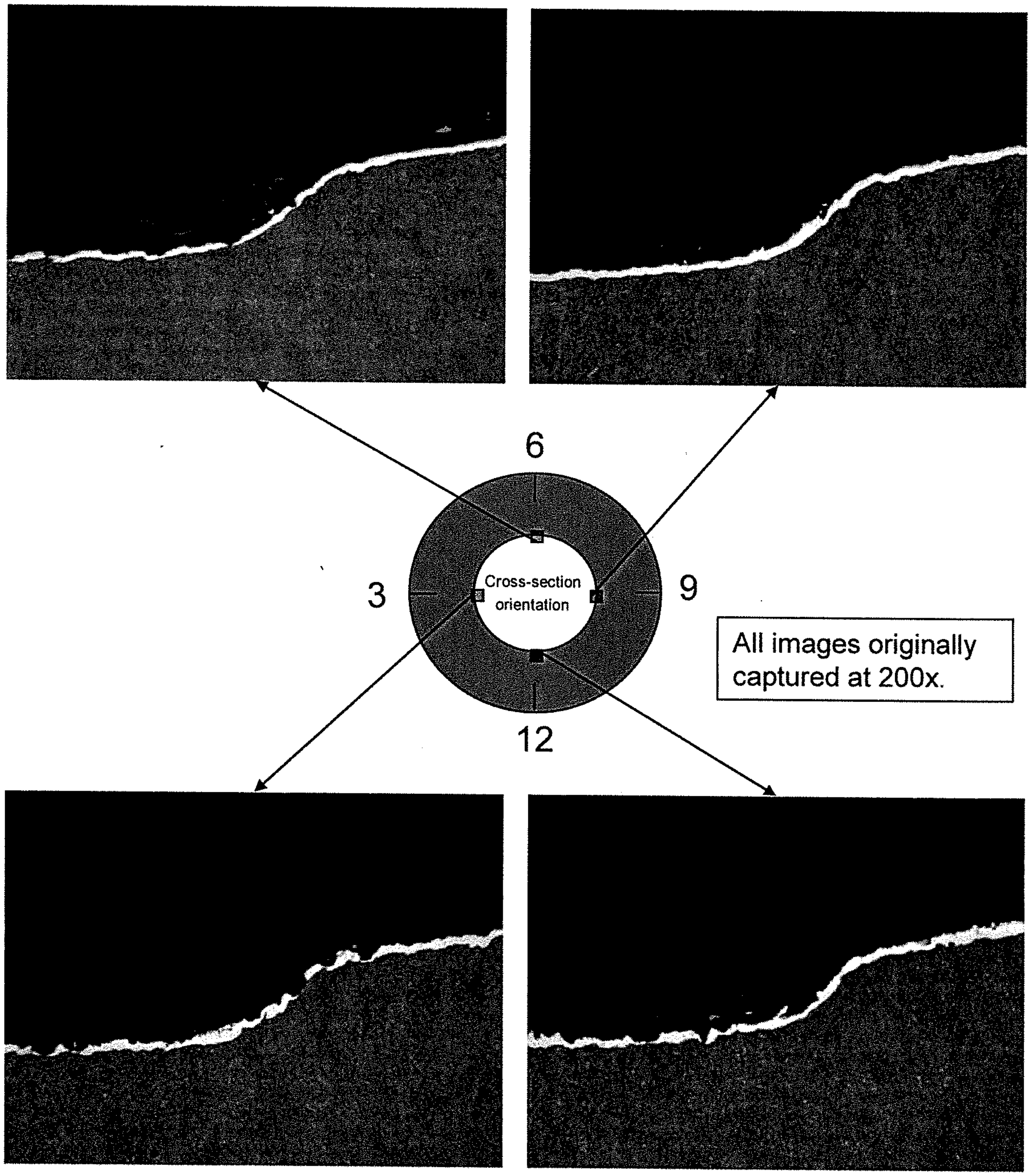


Figure 8: Tube 2-1, Location 4

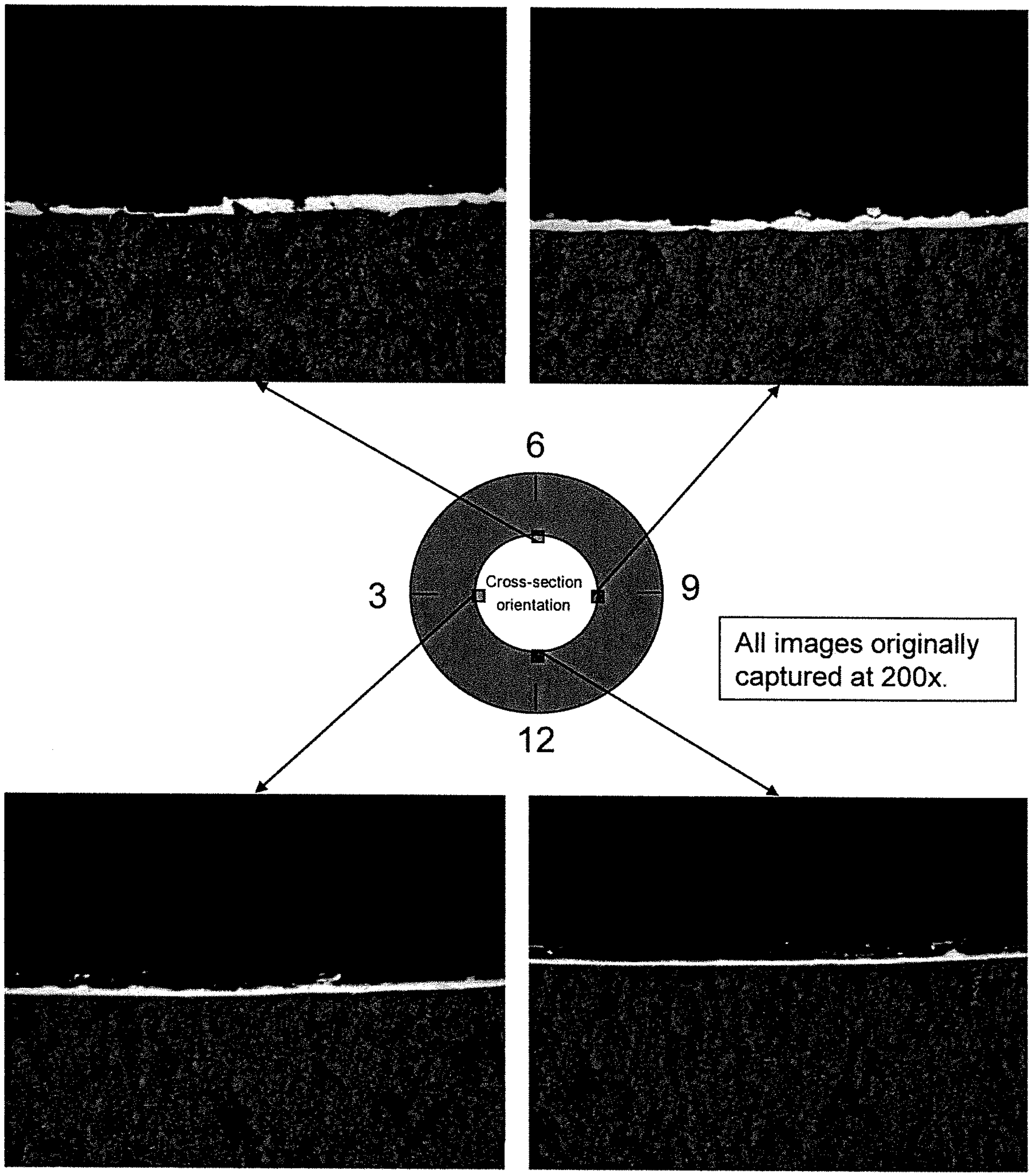


Figure 9: Tube 3-1, Location 1/Chamber

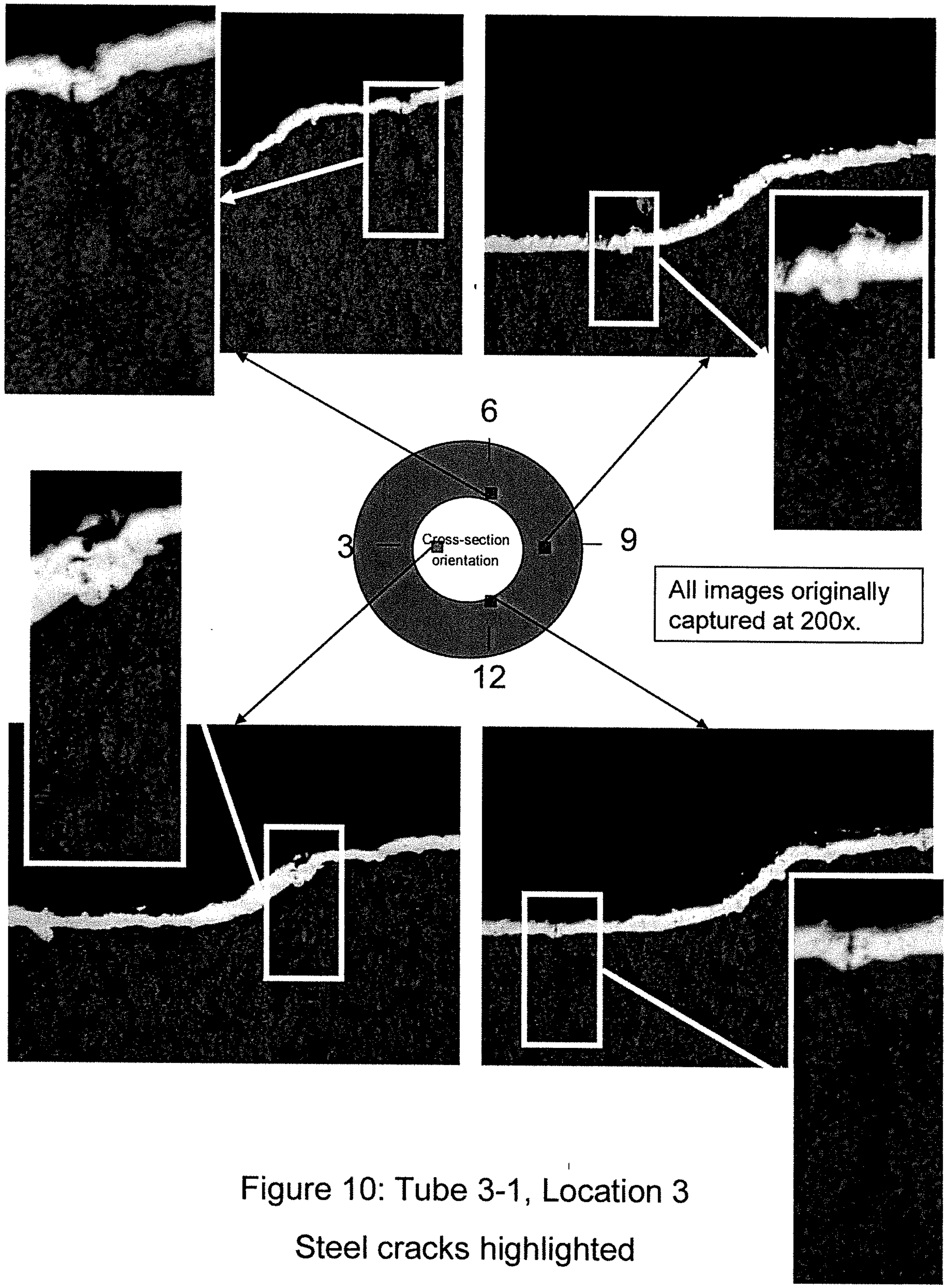


Figure 10: Tube 3-1, Location 3

Steel cracks highlighted

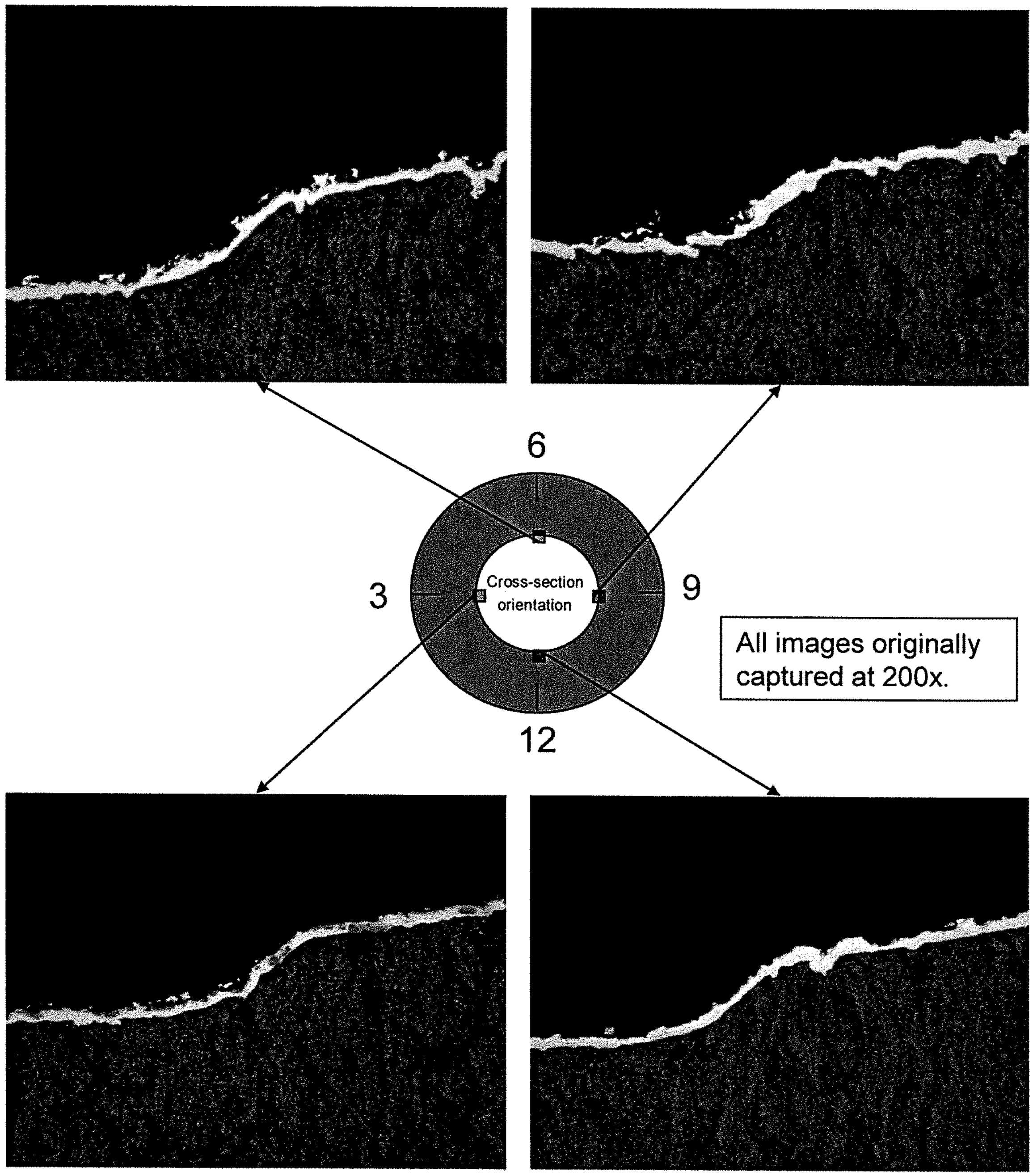


Figure 11: Tube 3-1, Location 4

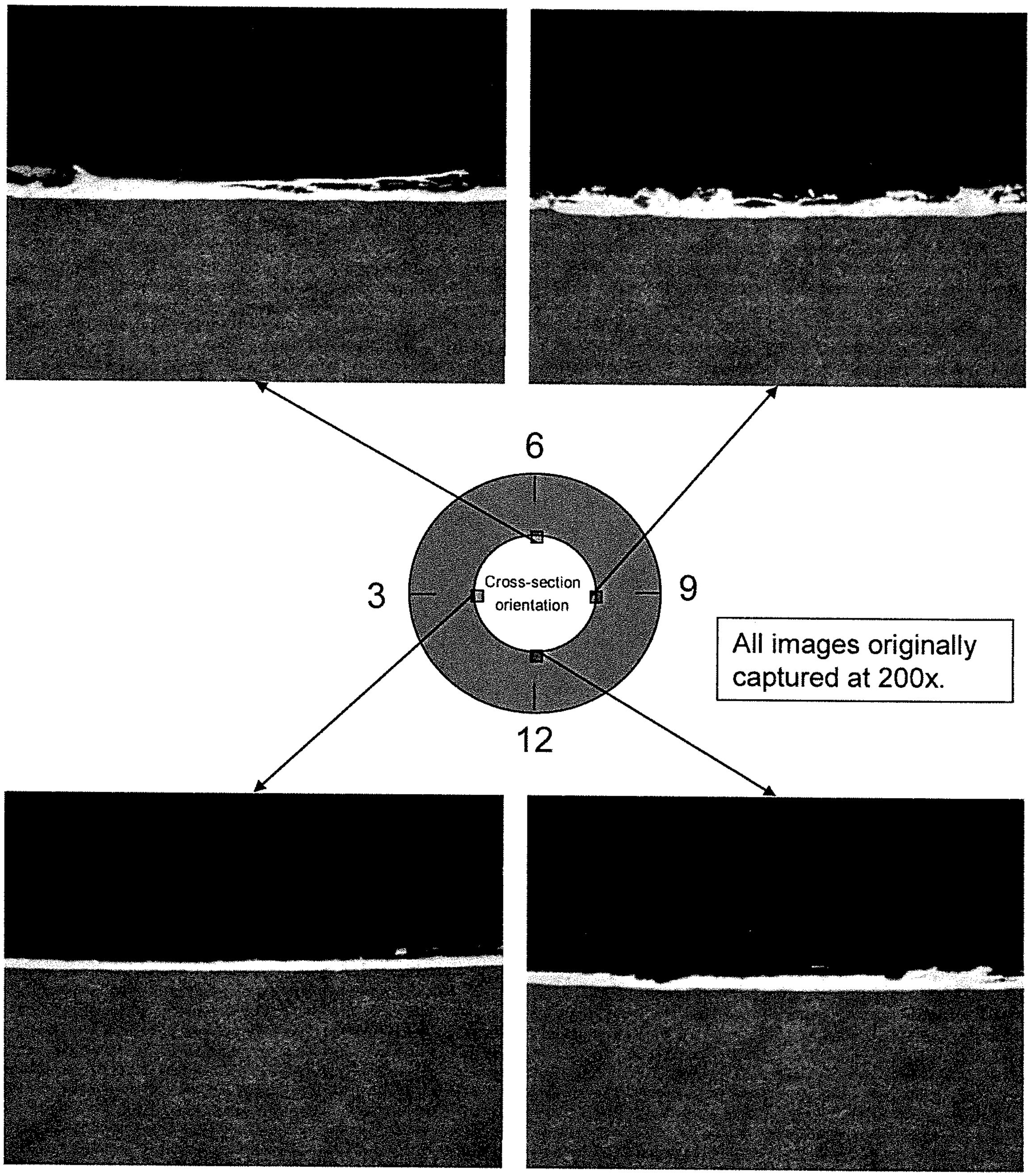


Figure 12: Tube 4-1, Location 1/Chamber

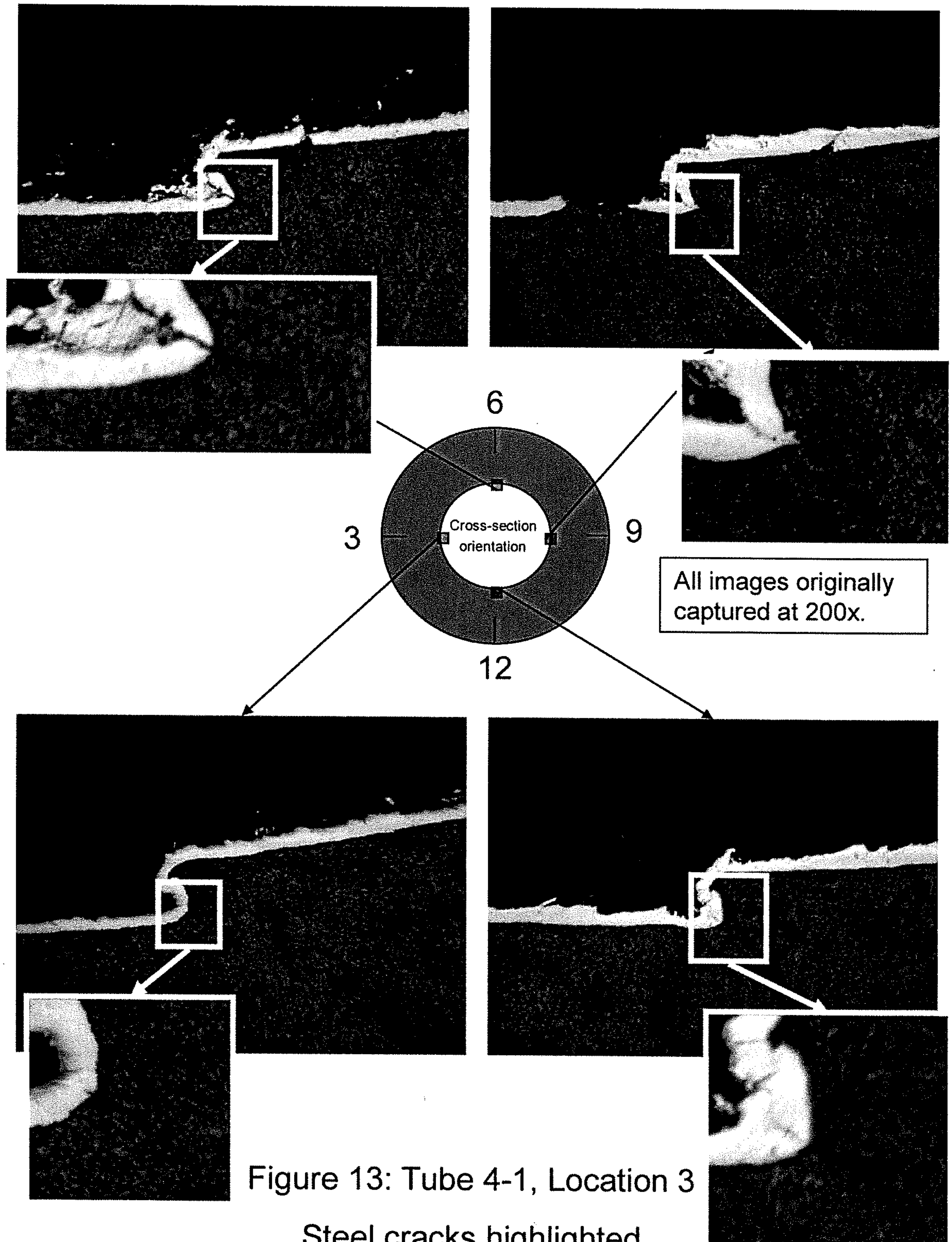


Figure 13: Tube 4-1, Location 3

Steel cracks highlighted

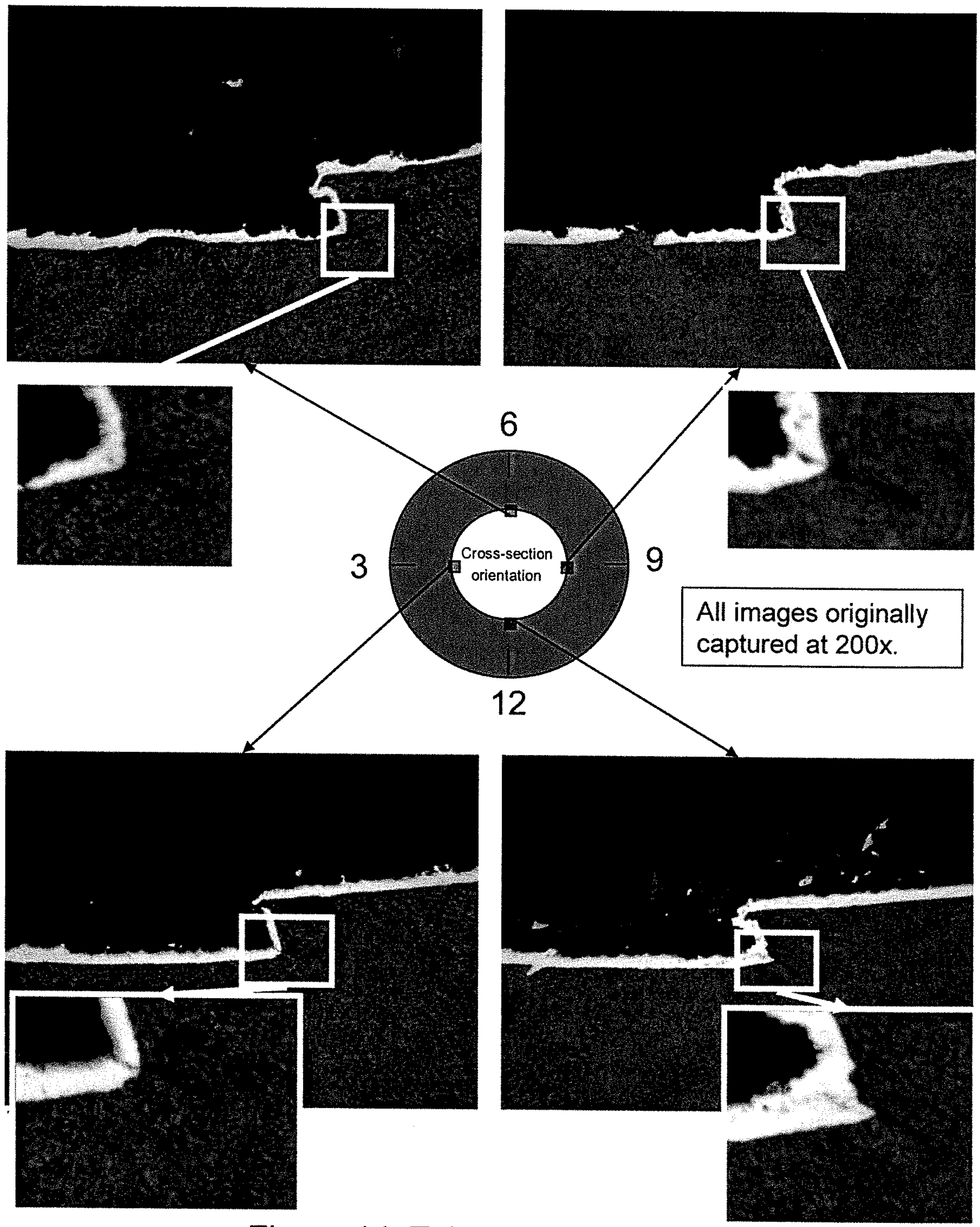


Figure 14: Tube 4-1, Location 4

Steel cracks highlighted

4.4. Microhardness testing

Microhardness measurements for the chromium coating were nearly identical for all barrels. Microhardness measurements averaged from 400 to 500 HK (40 to 47 HRc). See Figure 15.

ID#	HRc	HK (converted)
1-1 Loc3	40-47	409-495
2-1 Loc3	40-45	409-468
3-1 Loc3	43-47	443-495
4-1 Loc3	43-47	443-495

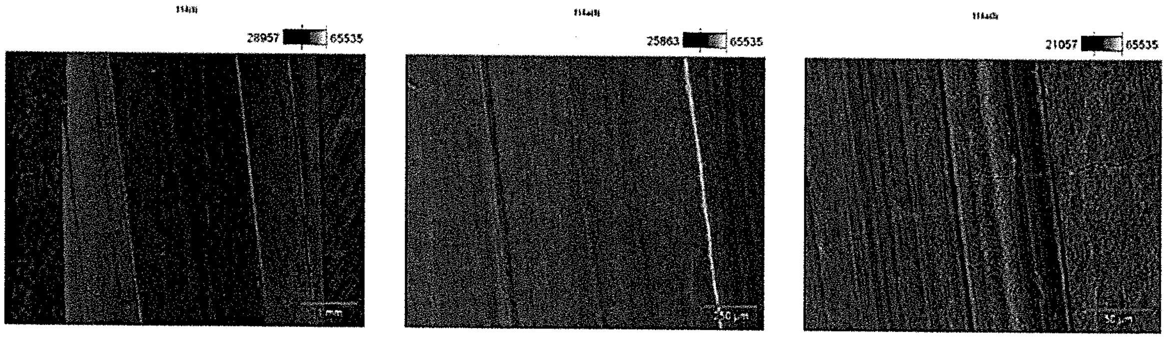
Figure 15: Microhardness

4.5. Surface analysis

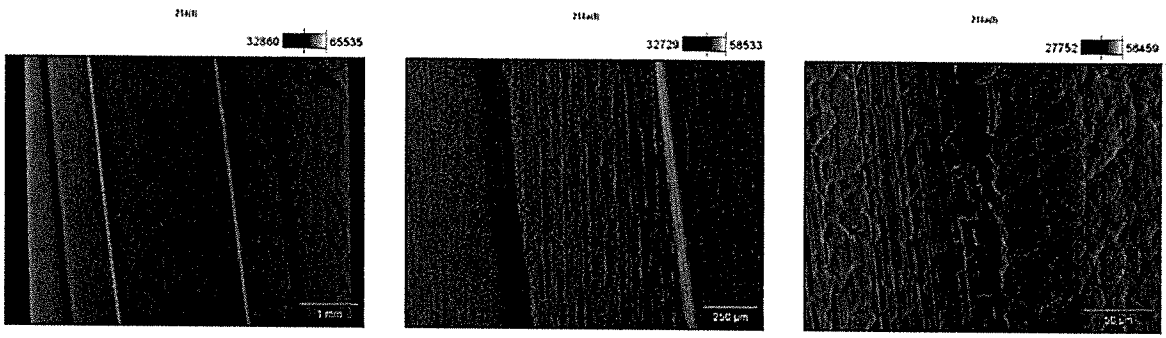
The surface of the bore showed a relatively rough and nodular surface, particularly barrels 2-1 and 3-1. Surface machining marks, noted on previous analysis by Mulligan and Smith, were not present. See Figure 16.

4.6. Adhesion testing

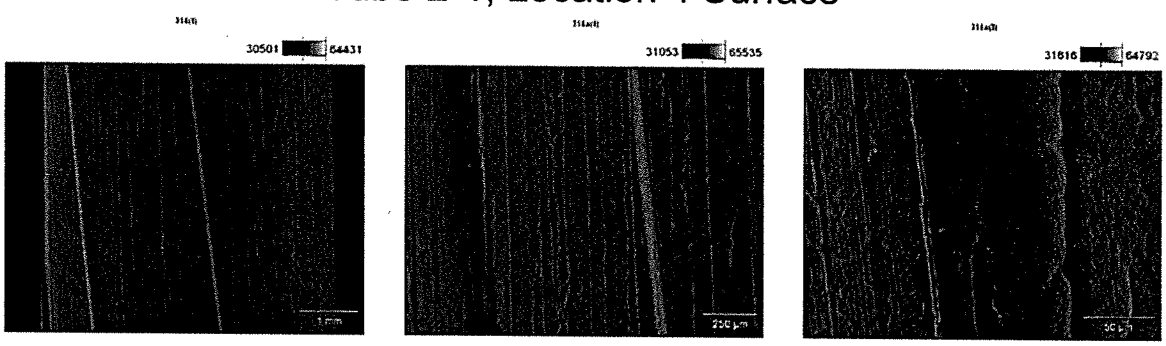
Groove testing was performed on Location 2 of all barrels. The coating survived testing in all tubes. See Figure 17.



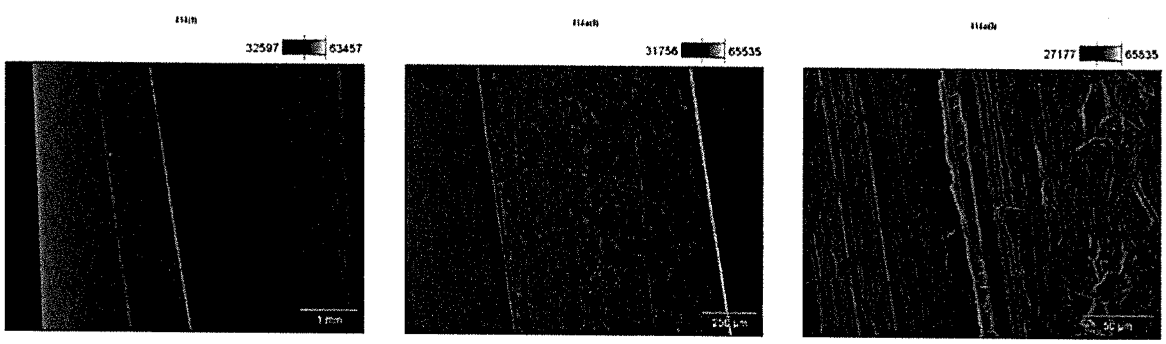
Tube 1-1, Location 4 Surface



Tube 2-1, Location 4 Surface

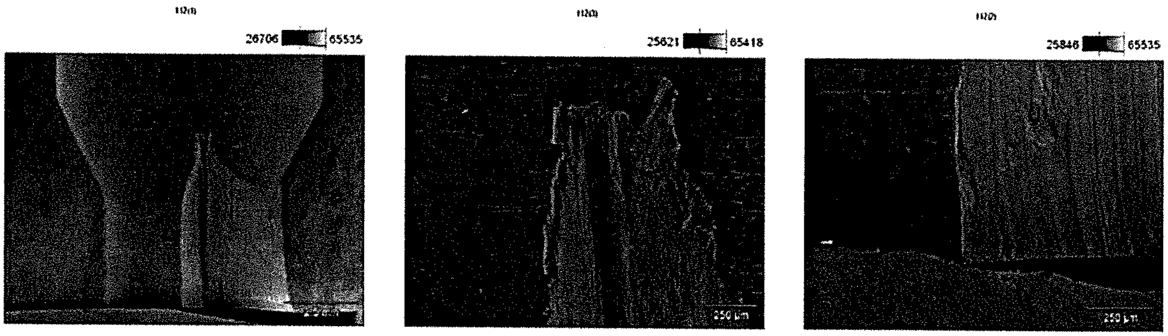


Tube 3-1, Location 4 Surface

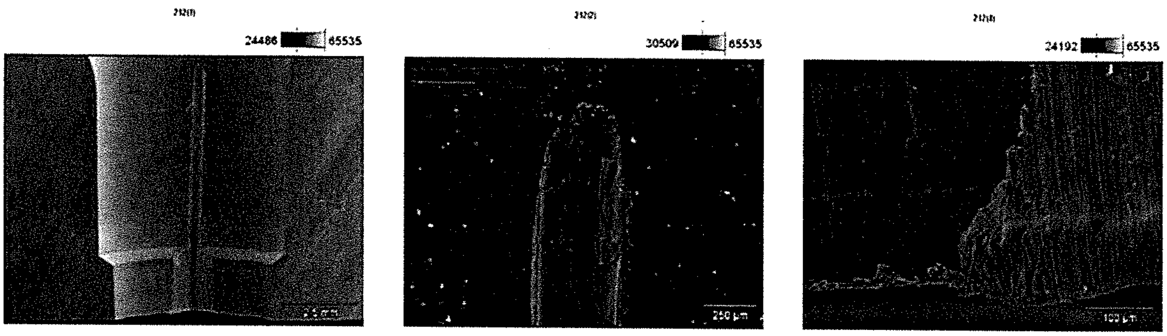


Tube 4-1, Location 4 Surface

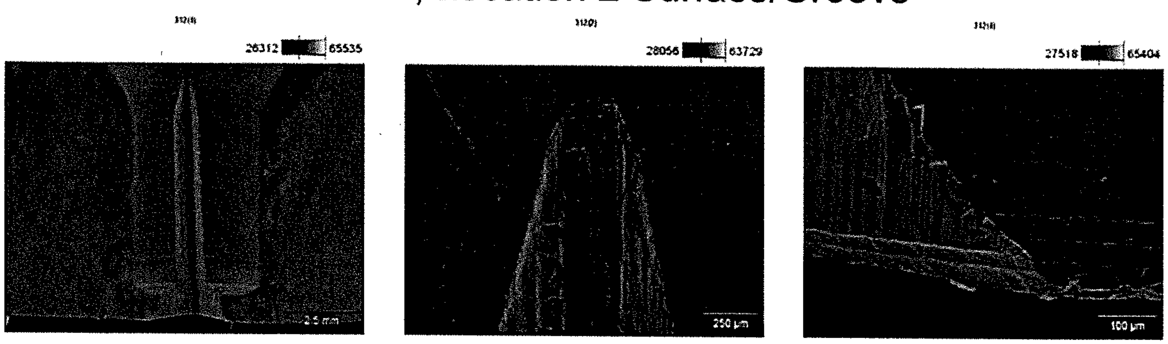
Figure 16: Surface Images



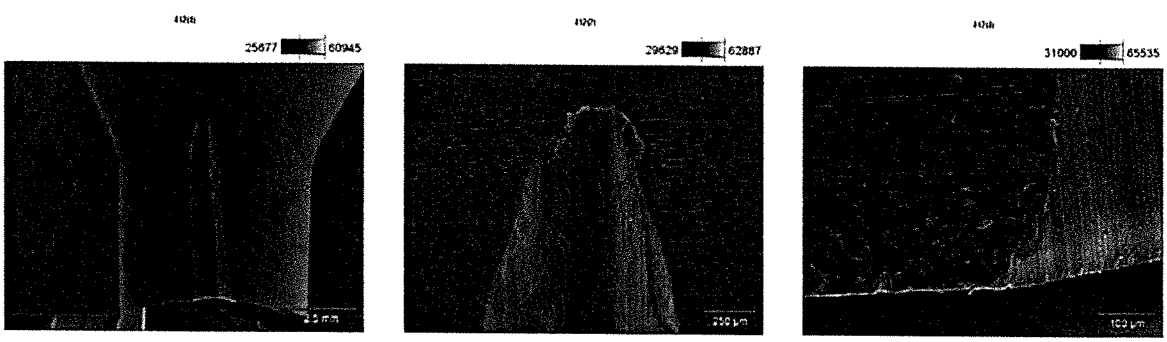
Tube 1-1, Location 2 Surface/Groove



Tube 2-1, Location 2 Surface/Groove



Tube 3-1, Location 2 Surface/Groove



Tube 4-1, Location 2 Surface/Groove

Figure 17: Forcing Cone Surface Groove Images

5. Summary/Recommendations

The chromium plating surface appears unfinished when compared to previously analyzed barrels. The surface exhibits the traditional nodular structure of an as-plated barrel and finish machining marks are not present.

Chromium thickness and thickness uniformity continue to be an issue. While the extreme non-uniformity noted during a previous investigation [Smith 2008] is not present, specific areas of the bore have thinner chromium platting than the drawing requirement. The thickness of the chamber plating continues to be below requirement.

Observed cracking in the steel if of great concern. The frequency and extreme depth of these cracks compromise the mechanical integrity of the barrels. Further investigation is strongly advised to determine the cause of barrel cracking prior to chromium plating. If the manufacturing process used to produce these barrels is to proceed to full production, either the cracking must be eliminated, or quality assurance must improve to the point that all cracked barrels are scrapped before platting.

AD

Technical Report ARAEW-TR-07016

COMPARISON OF ELECTROPLATED CHROMIUM COATINGS APPLIED TO M4 AND M16 BARRELS

C.P. Mulligan, C. Rickard, A. Welty, S.L. Lee

June 2007

ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
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Weapon Systems & Technology

REPORT DOCUMENTATION PAGE	*Form Approved* **OMB No. 0704-0188**

1. REPORT DATE *(DD-MM-YYYY)*
04/06/2007

2. REPORT TYPE
Technical

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
COMPARISON OF ELECTROPLATED CHROMIUM COATINGS APPLIED TO M4 AND M16 BARRELS

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
C.P. Mulligan, C. Rickard, A. Welty, S.L. Lee

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Benet Laboratories, RDAR-WSB
Watervliet, NY 12189-4000

8. PERFORMING ORGANIZATION REPORT NUMBER
ARAEW-TR-07016

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Benet Laboratories, RDAR-WSB
Watervliet, NY 12189-4000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
Characterization analyses were conducted on sections taken from two 5.56 mm gun barrels. The first was manufactured by Colt and is designated for an M4 and the 2nd barrel was manufactured by Fabrique Nationale and is designated for an M16. Both barrels were received new from the manufacturer and had an electrodeposited Cr coating of nominal [redacted] thickness. Characterization work included macroscopic examination, coating thickness measurements, microstructural analysis, microhardness testing, adhesion testing, scanning electron microscopy, energy dispersive spectroscopy, and X-ray diffraction with stress measurement. Characterization results indicated differences in the quality of the Cr coatings as applied to each barrel. Overall, the M4 Cr coating possesses superior quality in terms of ductility, micro-cracking, flaw density, and coating thickness uniformity. In actual firing of these test assets it is predicted that the erosion life of the M4 barrel would be much improved over that of M16 barrel undergoing identical firing scenarios.

15. SUBJECT TERMS
Characterization analyses, 5.56mm gun barrel, CR coating, adhesion testing, macroscopic examination, coating thickness measurements, microstructural analysis, microhardness testing, scanning electron microscopy, energy dispersive spectroscopy, X-ray diffraction with stress measurement

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	L	29	C. P. Mulligan
U/L	U/L	U/U			**19b. TELEPONE NUMBER (*Include area code*)** 518-266-5415

INSTRUCTIONS FOR COMPLETING SF 298

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5f. WORK UNIT NUMBER. Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

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ABSTRACT

Characterization analyses were conducted on sections taken from two 5.56 mm gun barrels. The 1st barrel was manufactured by Colt and is designated for an M4 and the 2nd barrel was manufactured by Fabrique Nationale and is designated for an M16. Both barrels were received new from the manufacturer and had an electrodeposited Cr coating of nominal [redacted] thickness. Characterization work included macroscopic examination, coating thickness measurements, microstructural analysis, microhardness testing, adhesion testing, scanning electron microscopy, energy dispersive spectroscopy, and X-ray diffraction with stress measurement. Characterization results indicated substantial differences in the quality of the Cr coatings as applied to each barrel. Overall, the M4 Cr coating possesses superior quality in terms of ductility, micro-cracking, flaw density, and coating thickness uniformity. In actual firing of these test assets it is predicted that the erosion life of the M4 barrel would be much improved over that of M16 barrel undergoing identical firing scenarios.

BACKGROUND

Two 5.56 mm bore diameter gun tubes were received for characterization. The first tube is an M4 barrel manufactured by Colt Manufacturing and the 2nd is an M16 barrel manufactured by Fabrique Nationale (FN) Manufacturing. The tubes were received brand new from the manufacturers and delivered to Benét Laboratories as illustrated in Figure 1. What prompted the need for characterization of the barrels and Cr plating was the fact that initial firing tests with a modified round yielded very different results in terms of erosion life of the M4 vs. M16 barrels. The reasons for the disparity in erosion life were unknown. Benét was tasked to determine if any differences are present in the barrel steel or Cr plating that may be responsible for these disparities in performance.

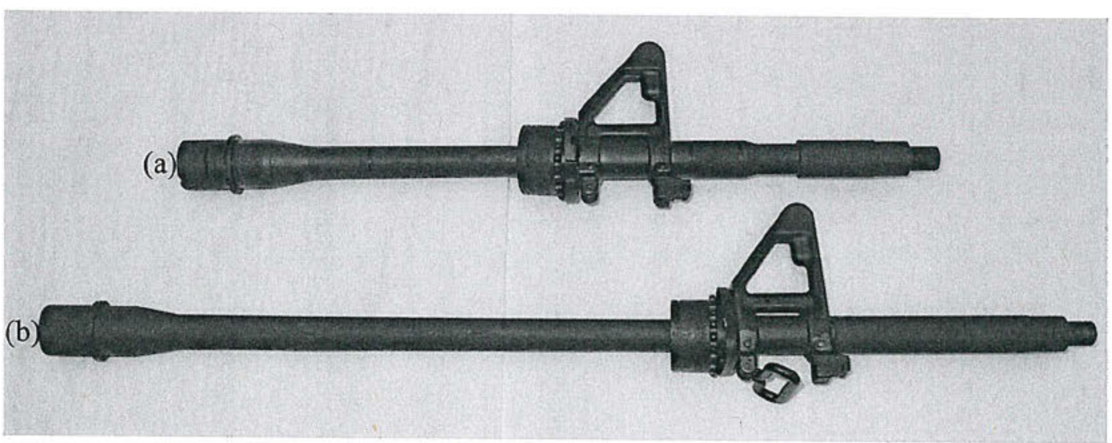

Figure 1: As-received barrels – (a) M4, (b) M16.

CHARACTERIZATION PROCEDURE

The specimens provided were subjected to a characterization protocol based upon Benét Laboratory's established protocol for protective coatings. The specific characterization tests performed on these specimens include:

- Macroscopic examination and sectioning
- Coating thickness measurement
- Microstructural analysis
- Microhardness testing
- Scanning Electron Microscopy (SEM) & Energy Dispersive Spectroscopy (EDS)
- Adhesion testing
- X-Ray Diffraction (XRD) with stress measurement

The results of these tests are described below.

MACROSCOPIC EXAMINATION AND SECTIONING

Both barrels as-received appeared to be in pristine condition. The Cr plating observable at both the muzzle and chamber of both the M4 and M16 appeared bright and reflective.

For the characterization tests to be performed, the barrels were sectioned into rings in the orientation given below in Figure 2. Three characterization regions were designated for each gun tube: Location A - Chamber, Location B - ~1 inch downbore from the origin of rifling, and Location C - ~5 inches from the muzzle.

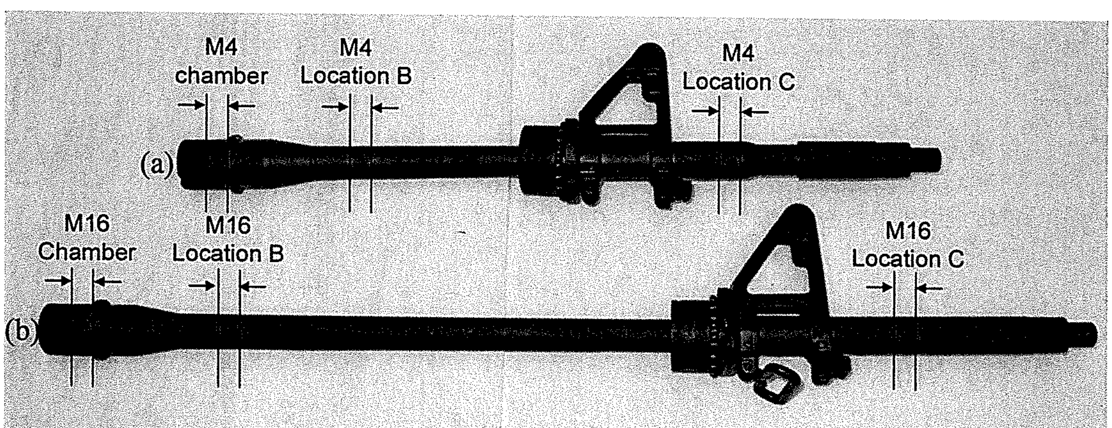

Figure 2: Orientation of regions chosen for characterization – (a) M4, (b) M16.

Following sectioning of the rings, ~0.5" pieces from the chamber, location B, and location C, were sectioned along the axis to clamshell the barrel for inspection of the Cr plated bore surface. Following sectioning it was noted that both barrels exhibited small spots of rust indicating incomplete Cr plate coverage. This was most prevalent on the rifling of the M16 and to a lesser degree on the rifling of the M4.

COATING THICKNESS MEASUREMENT

Electroplated Cr coating thickness measurements were completed on the M4 and M16 barrels as a function of clock position in the three designated axial locations; chamber, location B, and location C. The coating thickness was measured via metallographic mounting and polishing of rings taken from each location. Figure 3 illustrates a typical metallographic image taken with a Nikon laser scanning confocal microscope (LSCM) for thickness measurement where the steel has been etched with nital (2% nitric acid in alcohol) to reveal the tempered martensite structure.

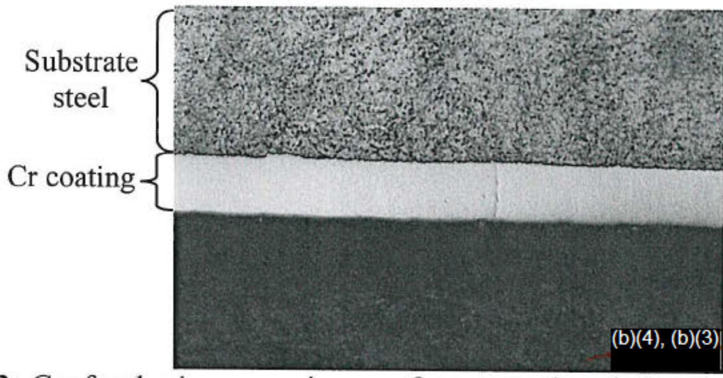

Figure 3: Confocal microscope image of cross-sectioned electroplated Cr coating on a gun steel substrate.

Coating thickness data for both the M4 and M16 are given in Table I. The M4 chamber Cr thickness is thinner than the M16 chamber Cr. Outside of the chamber, the coating thickness uniformity in both the axial direction and around the circumference is inferior in the M16 barrel. In Loc B, the M16 coating thickness drops to an average of [redacted] microns vs. [redacted] in the chamber and [redacted] in Loc C. Additionally, the circumferential uniformity in Loc C is very poor with the coating thickness dropping to as low as [redacted] microns offering very limited bore protection.

TABLE I: Coating Thickness Data

	Coating thickness (microns) as a function of clock position and axial location	
M4	[redacted]	
Chamber		
LocB		
LocC		
M16		
Chamber		
LocB		
LocC		

MICROSTRUCTURAL ANALYSIS

The Cr coatings in the chamber, Loc B, and Loc C, were analyzed metallographically to determine the microstructure of the coatings along the length. Figure 4 illustrates the structure in cross-section within the chamber for both the M4 and M16. The M16 Cr within the chamber is thicker than that for the M4. No significant defects exist within the chamber for either specimen. The M16 Cr does exhibit micro-cracking in this region while this is not observed in the M4 Cr.

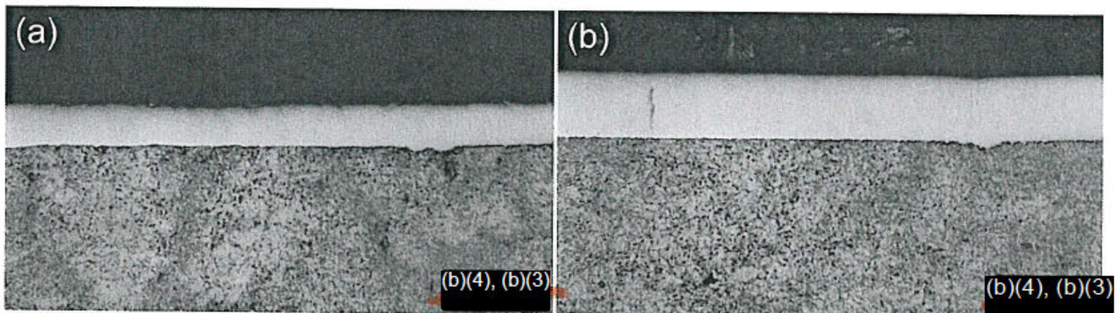

Figure 4: Cross-sectional images of the Cr in the (a) M4, and (b) M16.

Outside of the chamber in the M16 a high density of defects around the circumference of the bore were observed. Figure 5 presents an array of micrographs from Loc B where the approximate circumferential position is indicated by the schematic. The angle of the Cr coating within Figure 5 gives a more exact measure of the o'clock position. As illustrated by the images in Figure 5, numerous cracks that run through the coating and into the substrate are observed. At the base of these cracks there is a substantial degree of corrosion of the underlying steel substrate. In many locations the corrosion is so severe that islands of Cr coating have actually been removed or are in the process of being dislodged.

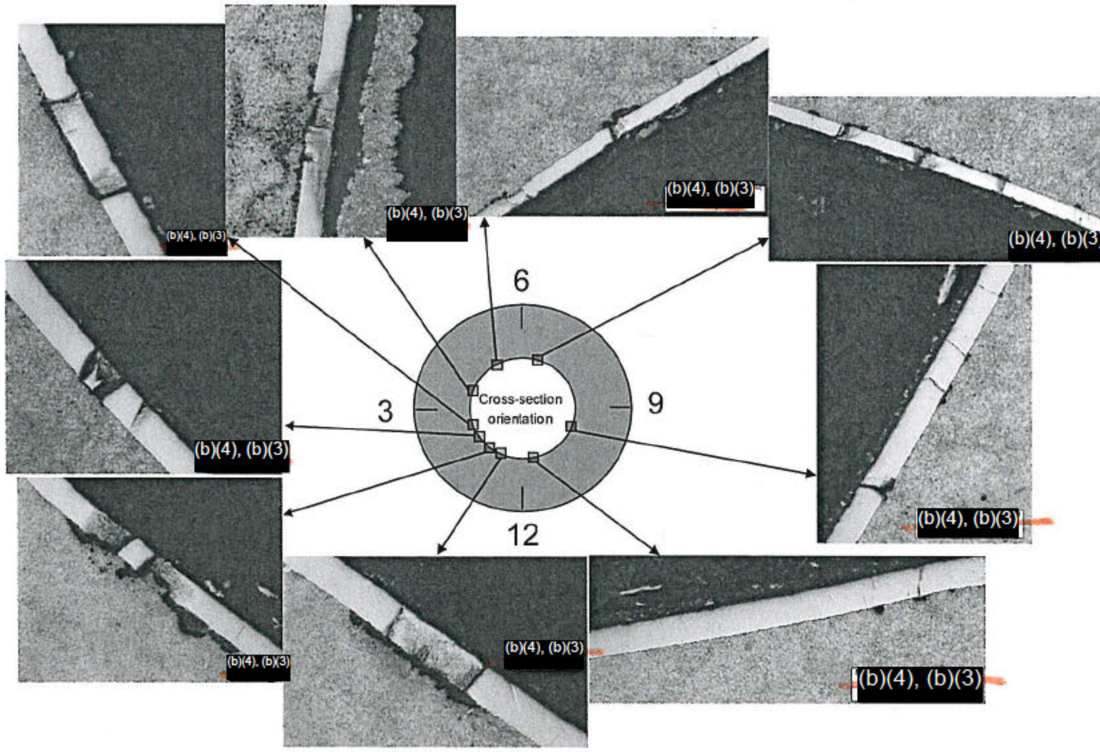

Figure 5: Cross-sectional images of the Cr around the circumference in the M16 at Loc B exhibiting cracking along with substantial corrosion in the steel substrate.

Similar results were observed in Loc C for the M16 as illustrated in Figure 6. Besides the substantial cracking and corrosion of the underlying steel, Figure 6 also illustrates the very poor coating thickness uniformity and the very deep corrosion pits observed in the thinnest coated regions.

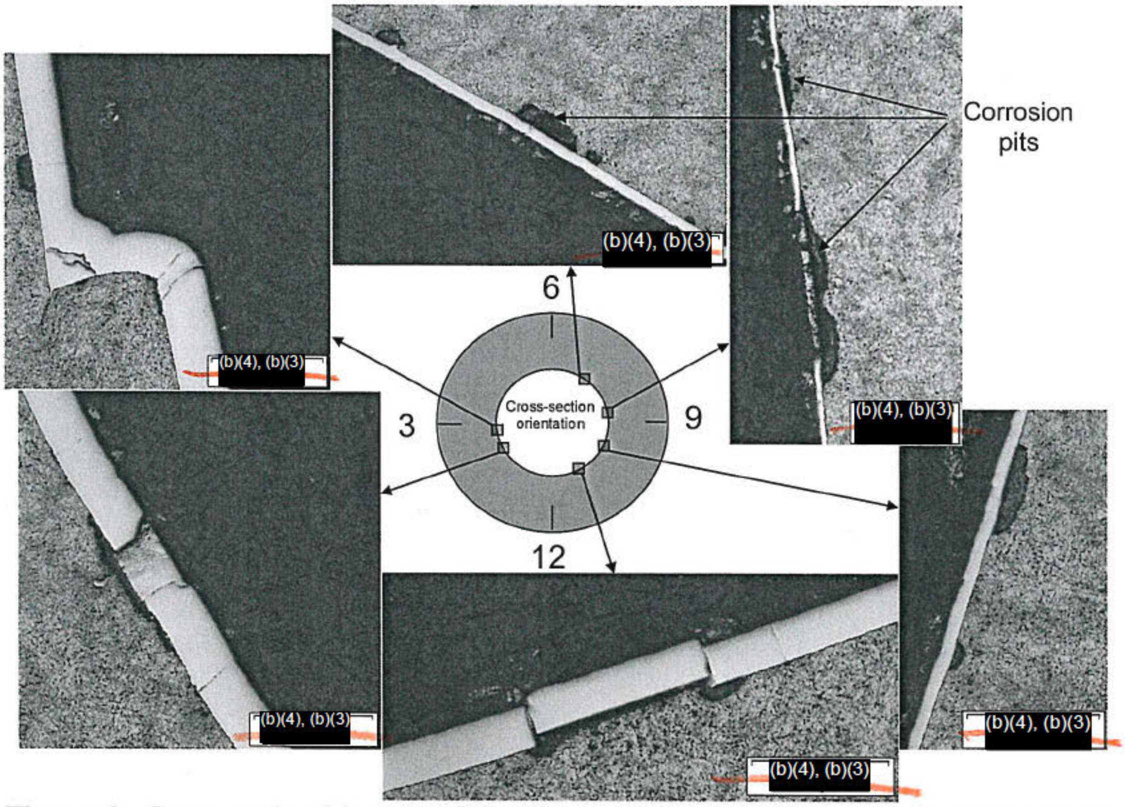

Figure 6: Cross-sectional images of the Cr around the circumference in the M16 at Loc C exhibiting cracking along with substantial corrosion and porosity in the steel substrate.

The state of the coating on the rifling was also closely examined in both Loc B and C for the M16. Figures 7 and 8 present arrays of micrographs in similar format to that of previous figures. Again, the high degree of cracking and substrate corrosion is observed but also, the Cr is dislodged in many regions or in the process of peeling. The poor quality of the Cr is exacerbated by the very poor surface finish on the sides of the rifling lands. It is assumed that a broaching operation was utilized to produce the rifling and the broaching tool does not appear to have very good consistency from land to land in terms of the quality of the finish on the sides of the lands. These rough surfaces lead to very rough morphologies for the Cr. One additional feature that is consistent from land to land is cracking in the steel at the base of each land roughly (b)(4), (b)(3) long.

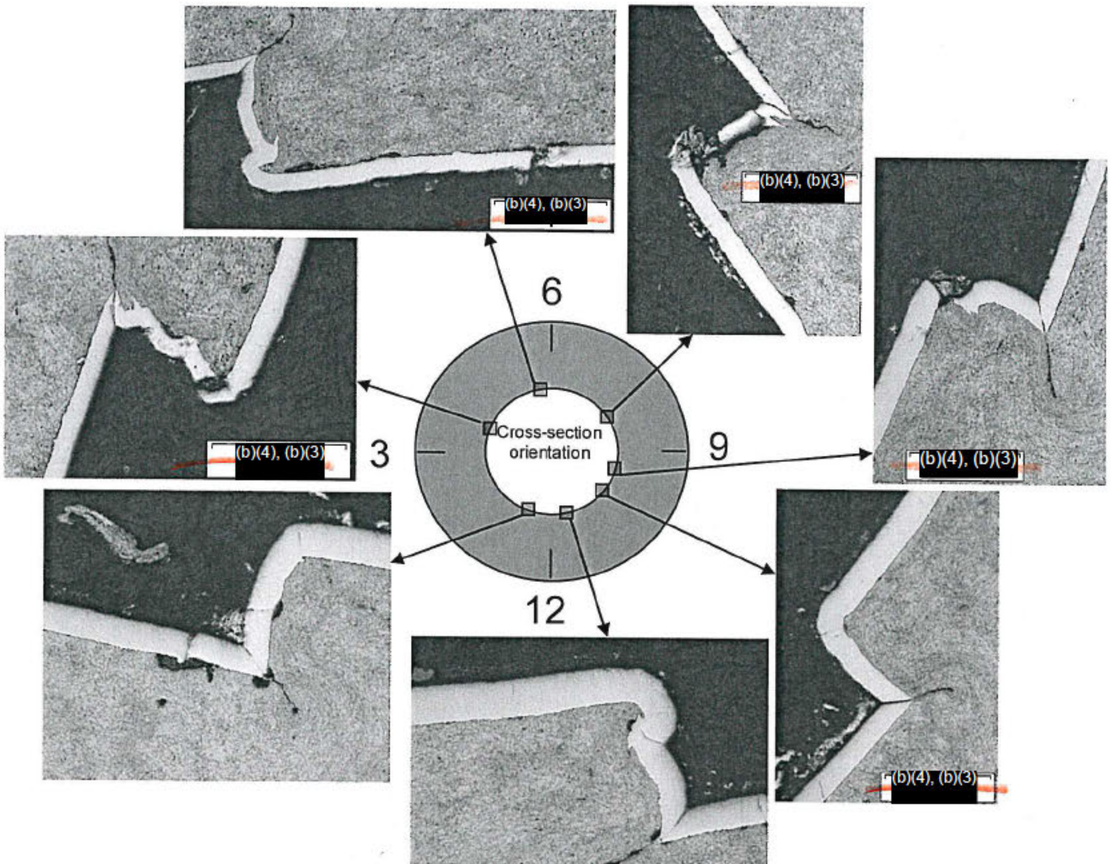

Figure 7: Cross-sectional images of the Cr on the rifling profile around the circumference in the M16 at Loc B exhibiting similar features to Cr in the lands and grooves with the addition of very rough coating morphologies along sides of lands.

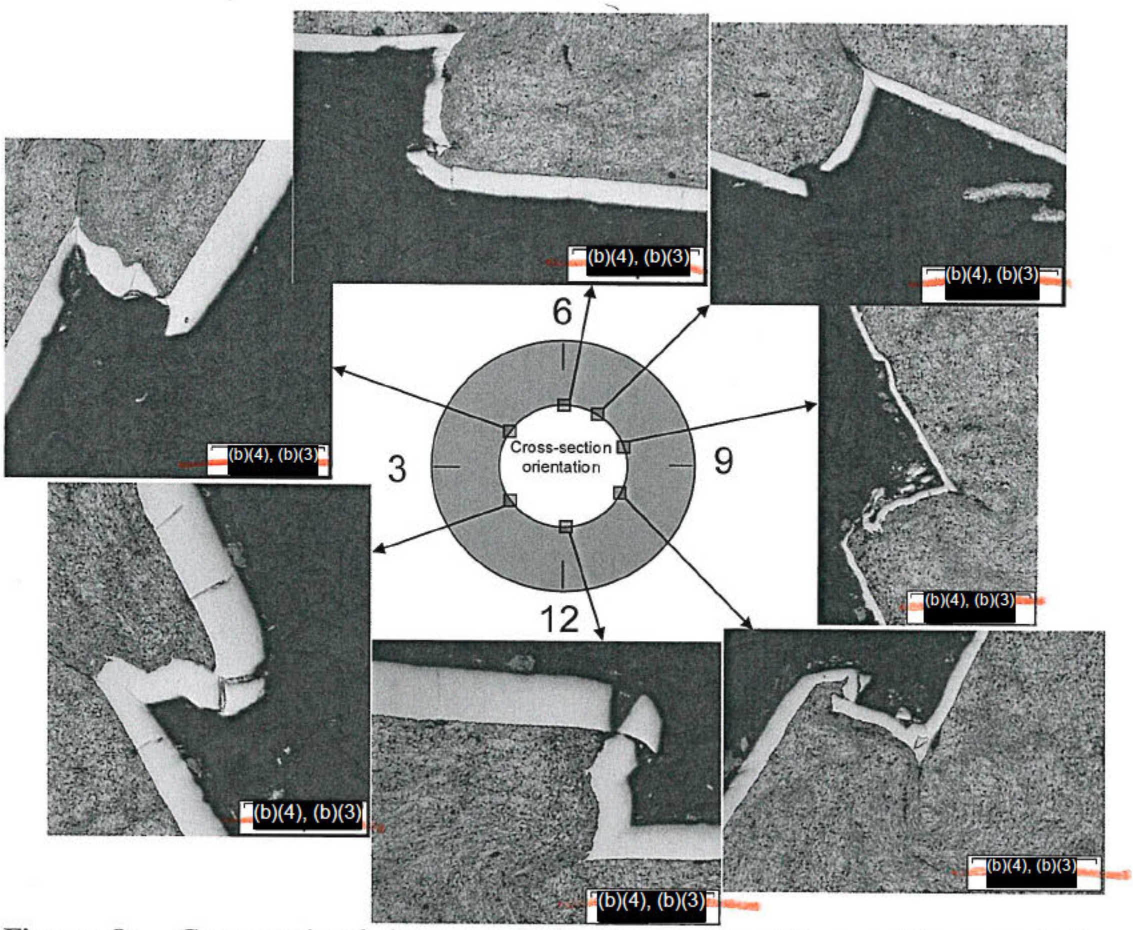

Figure 8: Cross-sectional images of the Cr on the rifling profile around the circumference in the M16 at Loc C exhibiting similar features to Cr in the lands and grooves with the addition of very rough coating morphologies along sides of lands.

Similar metallography was completed on the M4 as was completed for the M16. In contrast to the M16 Cr, the Cr within the M4 is very uniform and of high quality along the length and around the circumference of the bore. This is illustrated by Figures 9 and 10 where the Cr is observed to be fully dense including along the rifling profile at both Loc B and C. The coating is also nearly clear of any cracking or micro-cracking. The broaching operation of the rifling is much more uniform than the M16 and gives a higher quality surface finish on the sides of the lands, which in turn leads to a higher quality coating on the sides of the lands.

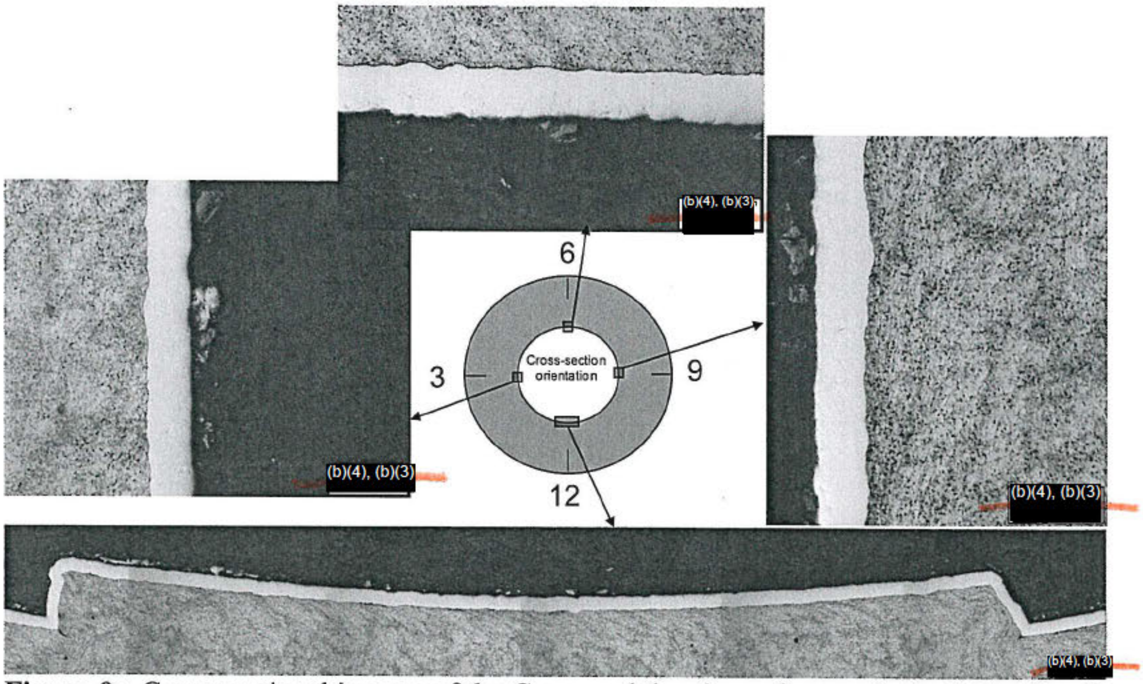

Figure 9: Cross-sectional images of the Cr around the circumference in the M4 at Loc B exhibiting a fully dense structure along the full rifling profile.

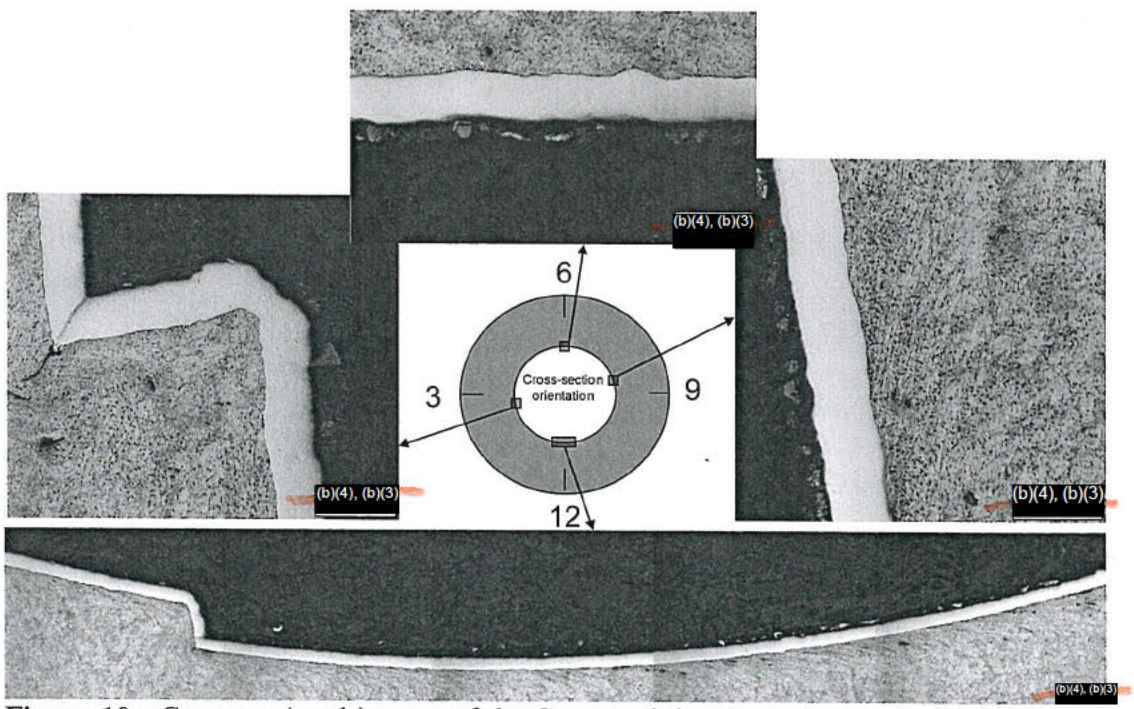

Figure 10: Cross-sectional images of the Cr around the circumference in the M4 at Loc C exhibiting a fully dense structure along the full rifling profile.

MICROHARDNESS TESTING

Microhardness testing was completed on the Cr in Loc B and C from both the M4 and the M16 to obtain an understanding of the mechanical properties of the coatings. A Wilson-Tukon microhardness tester was used for the microhardness testing and the Knoop hardness indenter was used as it is more easily applied to coatings in cross-section due to the indenter geometry. A Knoop load of 50 g was used for the testing. Typical hardness indents for the M4 and M16 Cr are given in Figure 11.

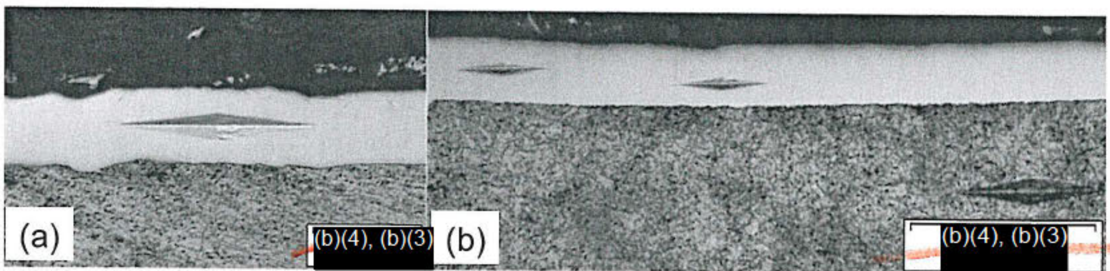

Figure 11: Cross-sectional images of the (a) M4, and (b) M16 Cr subjected to Knoop microhardness testing.

The microhardness results are given in Table II. The average microhardness numbers of the M4 is hardness knoop (HK) 402 and 486 for Loc B and C respectively while the average microhardness numbers for the M16 are HK 888 and HK 1056 for Loc B and C. As noted in Table II, the microhardness of the M16 Cr is much higher than that of the M4 Cr indicating a harder and more brittle structure.

TABLE II: Microhardness Data

	M4 Hardness Knoop 50g load		*M16 Hardness Knoop 50g load*	
	LocB	**LocC**	**LocB**	**LocC**
	475	486	927	1094
	412	499	924	944
	319	474	812	1129
Average	402	486	888	1056
[redacted]				

SEM & EDS

SEM and EDS was performed on the surfaces of samples taken from the M4 and M16 at Loc B to better observe the structure and morphology of the coatings. EDS was performed to determine the material composition of the surfaces.

Figure 12 illustrates the typical surfaces of the M4 and M16 Cr. Both surfaces appear to have been altered following electroplating as noted by the machining marks on both samples. The machining marks on the M4 appear to align with the rifling in both the groove and on the land and run in the axial direction. The machining marks on the M16 run in the axial direction in the land and groove but there are also regular arrays of scratches in the circumferential direction, which are much more pronounced within the groove. Additionally for the M16, as was observed in cross-section, the sides of the lands are rougher and there appears to be some voided regions where steel is exposed.

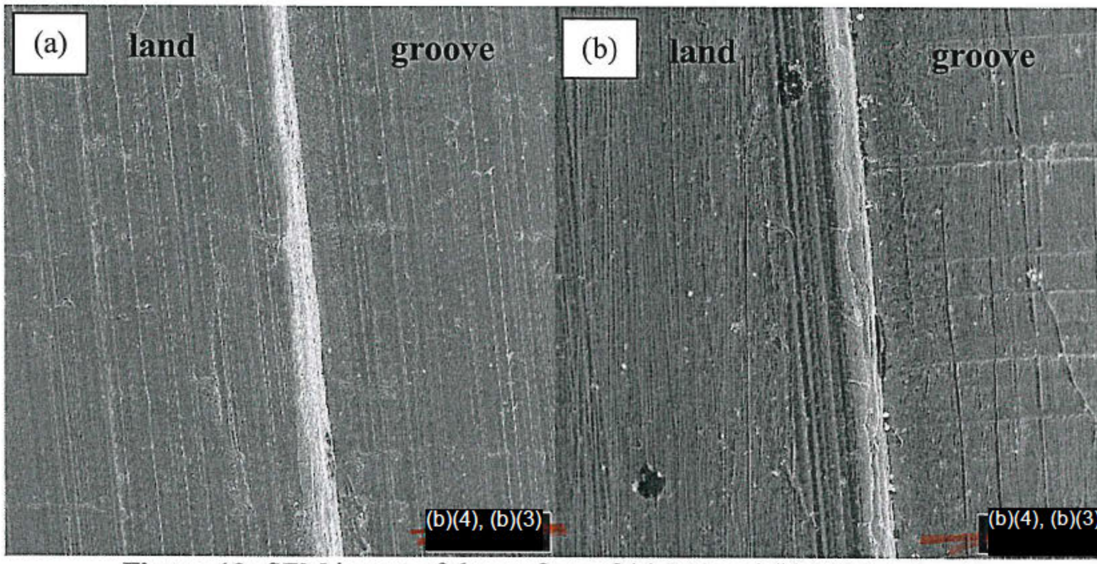

Figure 12: SEM image of the surface of (a) M4 and (b) M16 at Loc B.

Although the surface of the Cr on both the M4 and M16 appear to have received a surface finishing step following electroplating which has masked the surface morphology in most locations, there are areas of Cr where the surface has not been perturbed. This is most likely due to thickness variations in the Cr effectively masking the valleys in the Cr from the machining step. Figure 13 illustrates the unblemished Cr of the M4 in the groove and on the land, while Figure 14 illustrates the same for the M16. For the M4, the surface of the Cr in the as-deposited condition appears nodular which is not unexpected for electroplated Cr. For the M16, the Cr appears nodular in the groove as well and possibly a bit rougher than the Cr in the M4. There weren't any readily viewable regions of unblemished Cr along the lands in the M16 but it is suspected that the Cr in the as-deposited condition would have a similar appearance to that observed in the groove.

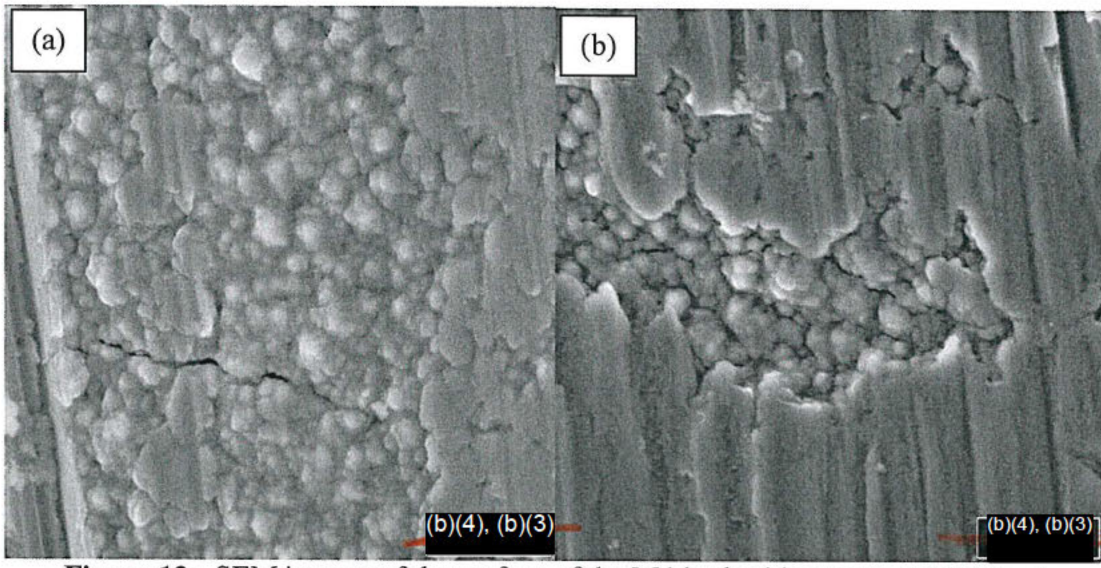

Figure 13: SEM images of the surface of the M4 in the (a) groove and (b) land.

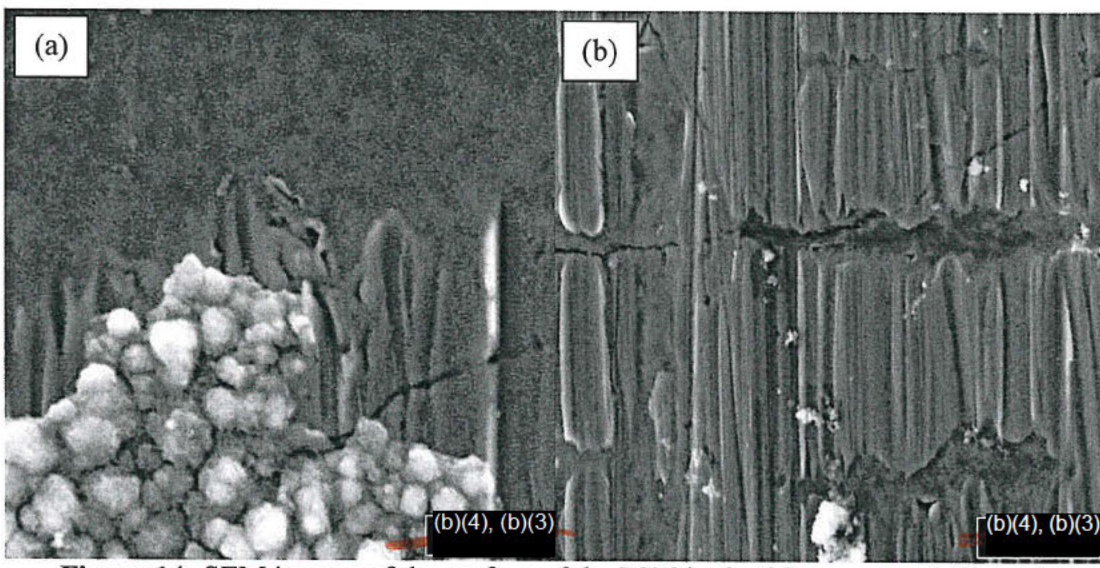

Figure 14: SEM images of the surface of the M16 in the (a) groove and (b) land.

Figure 15 shows a surface view of some of the more severe damage observed along the side of the land in the M16. This level of damage and Cr failure was not observed in the M4 Cr. There are regions within this zone where the substrate steel would be exposed to the gun firing environment.

Figure 15: SEM image of severe damage to Cr along rifling edge in the M16.

One feature of the M16 Cr that is somewhat of a mystery is the presence of foreign material on the sides of the lands. This is illustrated in Figure 16 where a large piece of material is smeared along the side of the land. To determine the nature and composition of the material, EDS was completed. EDS confirmed that the material on the sides of the lands is copper. Further investigation was completed by EDS dot mapping and it was found that copper is present along the entire side of the land as illustrated in the EDS dot map given in Figure 17. It is unclear as to where the presence of Cu stems from. It may be possible that Cu was involved in the final machining operation or that the barrel was proof-fired with a round containing a Cu rotating band. It is not known whether or not the barrel was proof-fired. No such Cu material was found on the surface of the M4.

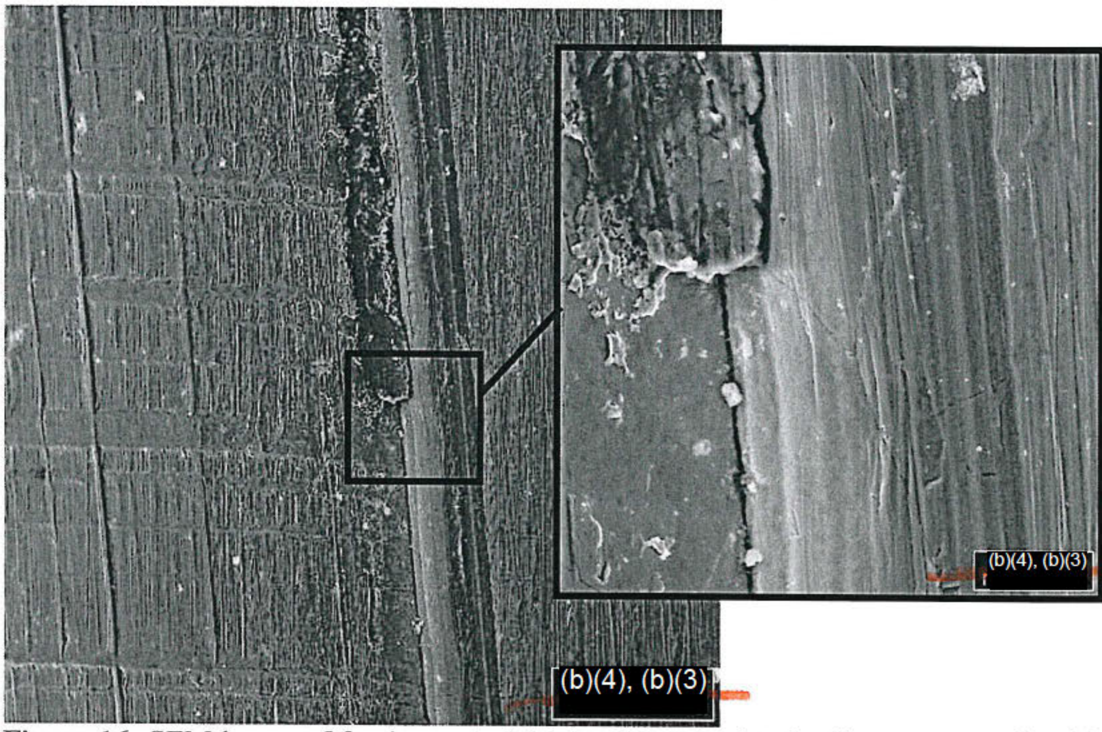

Figure 16: SEM image of foreign material later determined to be Cu present on the side of the land in the M16.

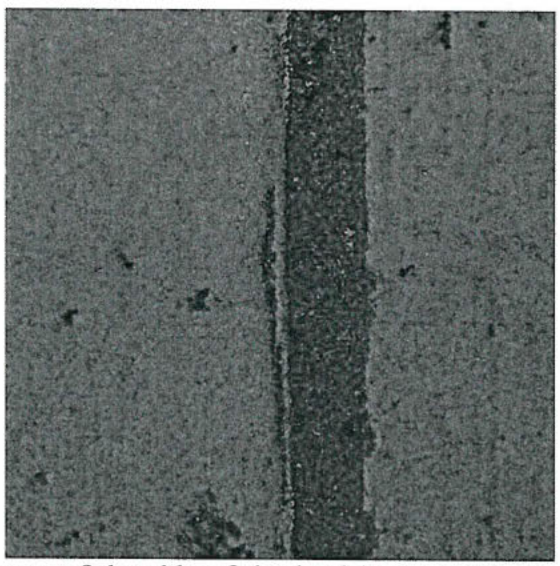

Figure 17: EDS dot map of the side of the land in the M16. Green represents Cr, red represents Fe, and blue represents Cu.

ADHESION TESTING

Samples cut from the chamber of the M4 and M16 were taken and subjected to groove adhesion testing outlined in ASTM standard B 571-97 "Standard Test Methods for Adhesion of Metallic Coatings". Due to the very small ID of the bore and the presence of rifling, groove testing was not completed within the bore ahead of the chamber. The test involves scribing a tungsten carbide toolbit through the Cr coating penetrating to the substrate where the shear stresses generated at the interface by the toolbit attempt to delaminate the coating.

Overall, the adhesion of the coating in the chamber for both the M4 and the M16 are sufficient. This is illustrated in Figure 18, where the groove from the groove test is running left to right and no areas of exposed substrate are visible which would indicate adhesive failure. The only difference between the M4 and the M16 Cr is the brittle cracking that occurred within the M16 Cr as illustrated in Figure 18.

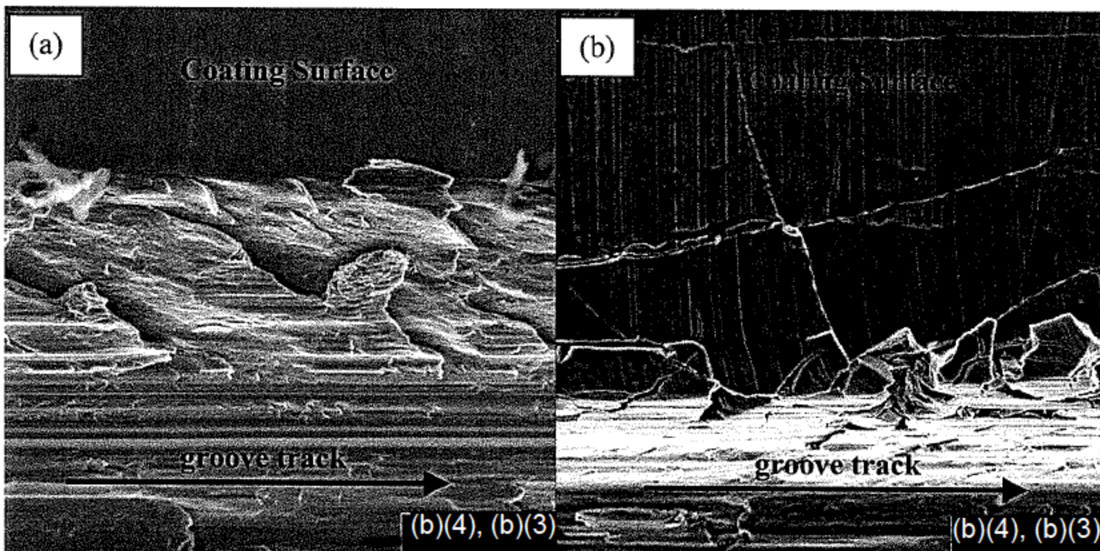

Figure 18: SEM images of the surface of the (a) M4 and (b) M16 subjected to groove adhesion testing.

X-RAY DIFFRACTION

Sections of a ring from Loc C were cut from the M4 and M16 barrels for X-ray diffraction structural analysis and stress measurement. The edges of the samples were further cut at 45 degrees to further facilitate X-ray analysis.

M4 specimen

XRD of the M4 Cr was taken using Cu X-ray tube at 45kv, 40ma. To increase intensity to obtain better statistics, a 0.5 mm detector slit and collimator were used. Data was obtained at 5 degree to 145 degree, at 0.1 degree step, 2-4 sec/pt, using a theta-two theta scan, on a Scintag 4-circle diffractometer.

As shown in Figure 19(a), the XRD pattern obtained was compared to the ICDD data base for random oriented bcc Cr (06-694) as shown in vertical bars. The indices are listed by the reflections. It is observed that the M4 sample has a Cr (110) and Cr (200) preferred orientation. This is very interesting, because past experience has been that thick Cr coatings on large caliber gun barrels (e.g. 120 mm) generally give 98% Cr (222) preferred orientation [1]. The growth of coatings may have started with preferred Cr (110) and Cr (200) preferred in thinner coatings, evolving into Cr (222) when the coatings grow thicker. In Figure 19(b), approximate peak locations and intensities for each reflection are given.

In Table III, peak intensity, peak area, and fwhm (full width half maximum) for the various reflections compared to the ICDD database are shown. Peak fit was not giving correct results for fwhm, especially for weak peaks. Peak widths were thus obtained manually. As the analysis shows, the sample has a mild Cr (110) texture when comparing measured peak intensity to ICDD intensity.

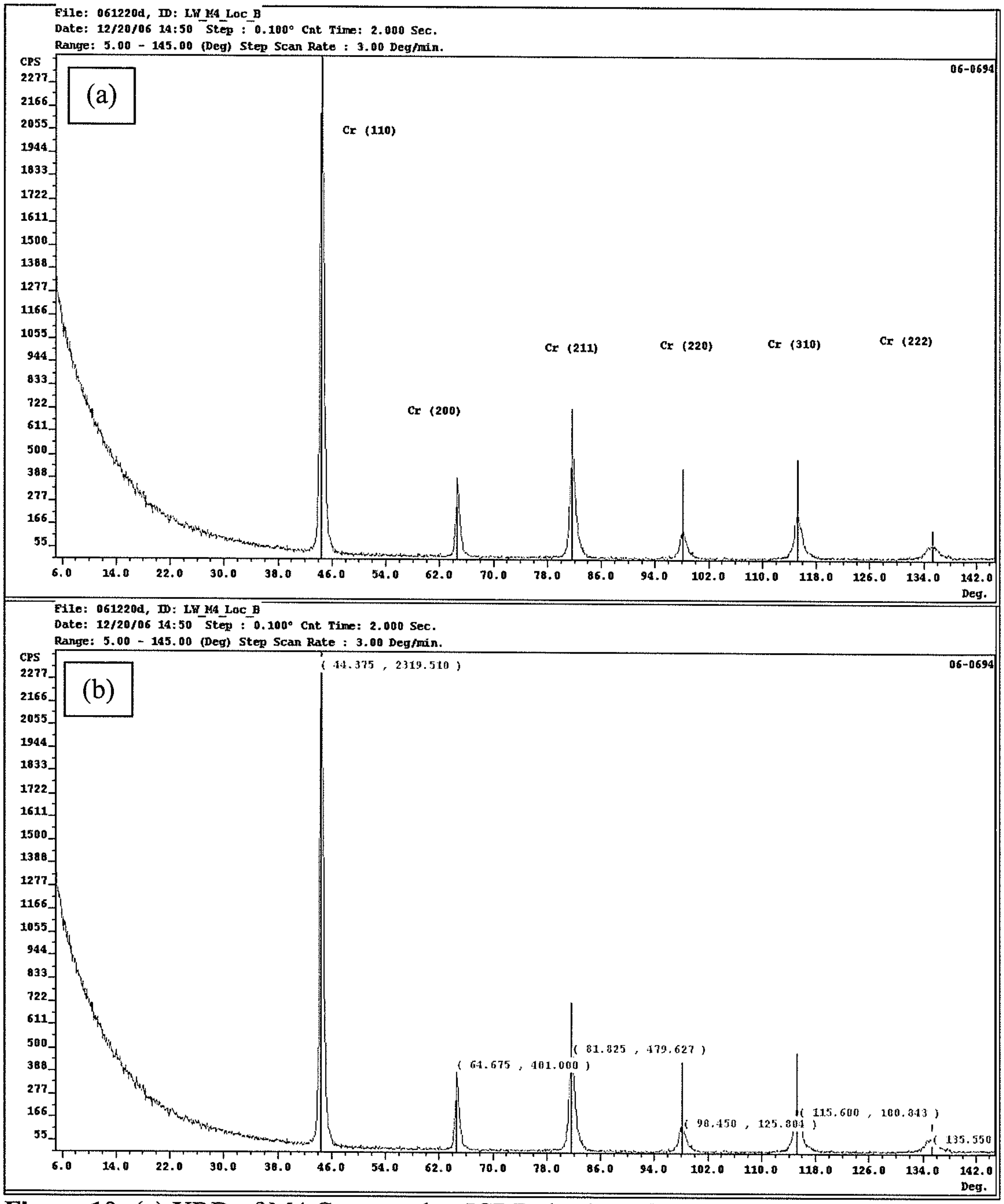

Figure 19: (a) XRD of M4 Compared to ICDD database for random oriented Cr standard and (b) XRD of M4 Compared to ICDD database for random oriented Cr standard with two-theta angles marked.

TABLE III: Small Cal M4 Peak Intensity, FWHM, Peak Area, and Texture Analysis

M4 peak loc	peak int	fwhm	area	reflection	norm int	ICDD peak loc	ICDD peak int	M4/ICDD texture
44.56	2411	0.55	11180	110	100.0	44.39	100	1.0
64.71	399	0.63	1561	200	16.5	64.58	16	1.0
81.81	509	0.89	2584	211	21.1	81.72	30	0.7
98.48	129	1.2	579	220	5.4	98.15	18	0.3
115.58	221	1.3	897	310	9.2	115.26	20	0.5
135.58	80	1.65	382	222	3.3	135.42	6	0.6

M16 Specimen

XRD of the M16 specimen was completed using a Cu X-ray tube with the same parameters of the M4 specimen. As shown in Figure 20(a), the XRD pattern obtained was compared to ICDD data base for bcc Cr (06-694) as shown in vertical bars. Since the substrate steel consisting predominantly of bcc Fe has very similar crystalline structure as bcc Cr, if the coating is thin, steel lines can appear as well as Cr lines. Furthermore, the Cr lattice parameter is 2.8839Å, while steel is 2.8664Å. If Cr lines are plotted against Fe lines, they would be very similar to each other. Fe lines would gradually be displaced towards slightly higher two-theta due to the smaller lattice parameter.

The M16 pattern is also compared to ICDD data base for bcc Fe (06-696) in Figure 20(b). The indices are listed by the reflections. It is obvious that the pattern belongs to Cr (06-0694) and not Fe (06-696). However, the M16 shows a steel component, illustrated by the slight shift of the peaks towards slightly larger two-theta in Figure 20(a). This is most obvious in the Cr (222) peak at 135° two-theta angle. This result shows nondestructively that the Cr coating in the M16 is probably thinner than the M4 in this location, allowing X-ray penetration to observe effects from the substrate steel. In Figure 21, approximate peak locations and intensities for each reflection are given.

The analysis of the peak intensity, peak area, and fwhm (full width half maximum) for the various reflections are shown in Table IV. As the analysis shows, the sample has a mixed Cr (110) and Cr (222) texture.

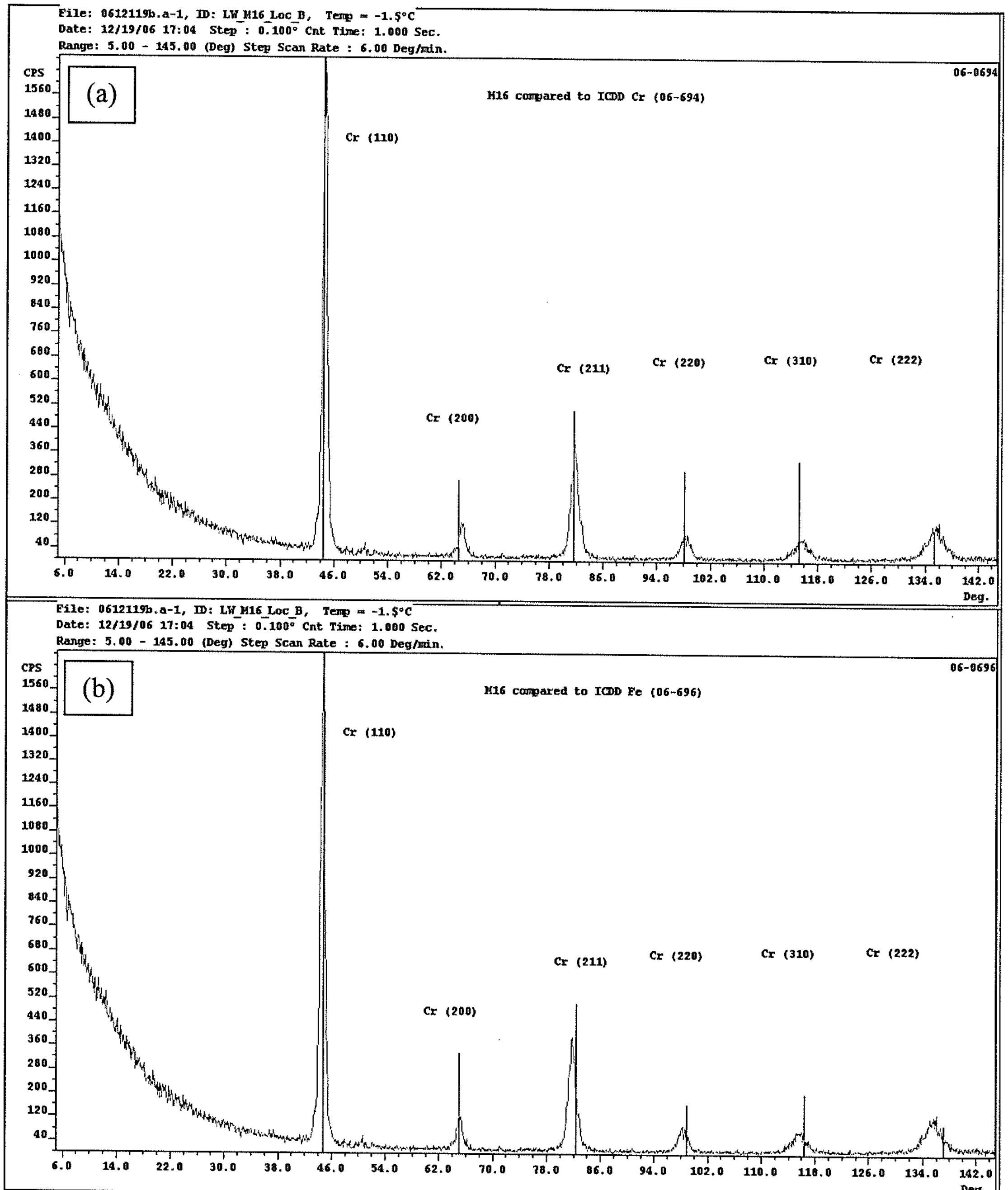

Figure 20: (a) XRD of M16 Compared to ICDD database for random oriented Cr standard and (b) XRD of M16 Compared to ICDD database for random oriented Fe standard.

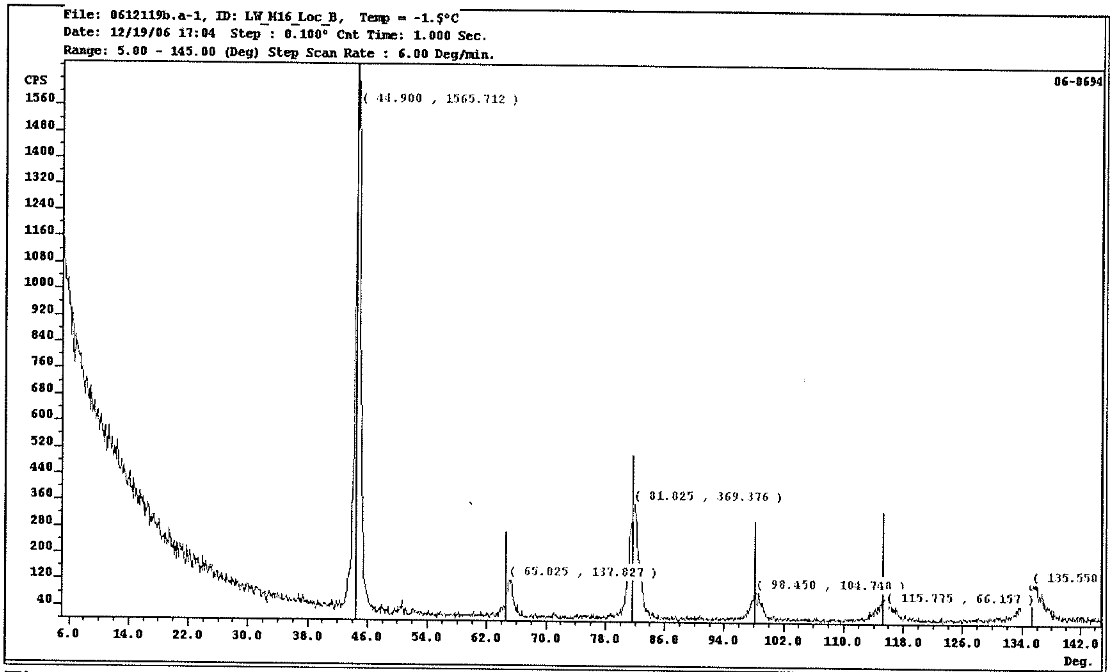

Figure 21: XRD of M16 Compared to ICDD database for random oriented Cr standard with two-theta angles marked.

TABLE IV: Small Cal M4 Peak Intensity, FWHM, Peak Area, and Texture Analysis

M16 peak loc	peak int	fwhm	area	reflection	norm int	ICDD peak loc	ICDD peak int	M4/ICDD texture
44.55	1681	0.71	8239	110	100.0	44.39	100	1.0
65.37	134	1.03	538	200	8.0	44.39	16	0.5
82	386	1.16	2097	211	23.0	44.39	30	0.8
98.63	97	1.77	372	220	5.8	44.39	18	0.3
115.78	81	2.20	529	310	4.8	44.39	20	0.2
136.25	128	2.66	796	222	7.6	44.39	6	1.3

M4 and M16 comparison

Tables III and IV also indicate some differences in peak width. M16 FWHMs are slightly greater than M4 FWHMs. Diffraction peak broadening can be affected by either grain size or microstrains. Microstrains in the M16 Cr are likely higher than in M4.

XRD of M4 and M16 are further compared in Figure 22(a). The two patterns have been normalized to Cr (110) intensity with red indicating M16 and black indicating M4. Obvious intensity deviation are present of the Cr (200) line at 64.58° two-theta, the Cr (310) line at 115° two-theta, and the Cr (222) line at 135° two-theta. In Figure 22(b), the M4 and M16 Cr are compared in expanded scale with black indicating M16 Cr and blue indicating M4 Cr. A close examination shows that the Cr (222) in the M16 is shifted by

0.5° two-theta. A small component of Fe (222) at 137.13° may be present, while the Cr (222) is at 135.42° two-theta.

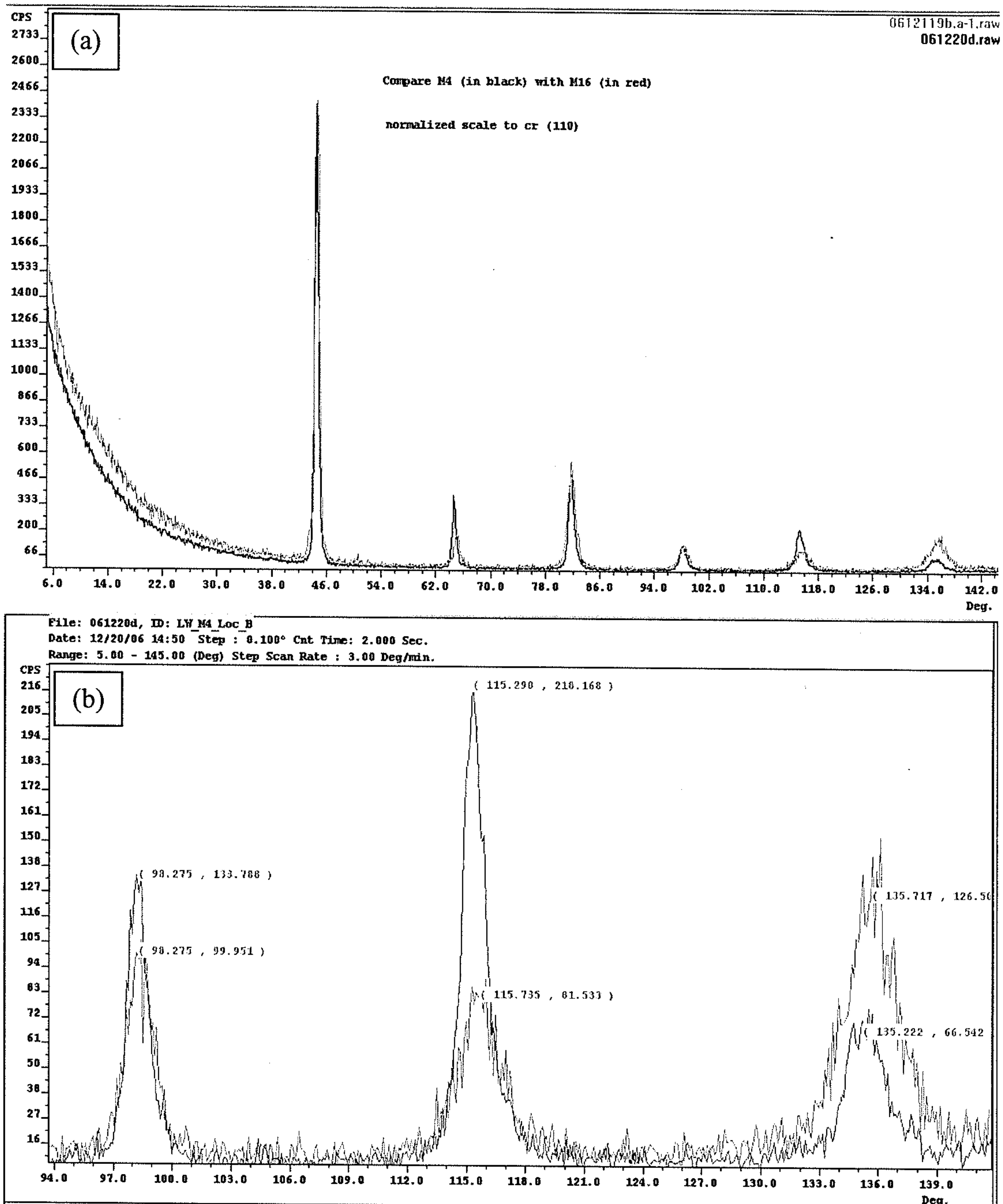

Figure 22: (a) Comparison of XRD of M4 and M16, normalized to Cr (110) intensity and (b) Comparison of XRD of M4 and M16, normalized to Cr (110) intensity with M16 in black and M4 in blue.

M4 and M16 residual stress comparison

Residual stresses were measured using a TEC stress analyzer using a Cr tube. The Cr (211) reflection is located at 153° two-theta. As shown in Figure 23(a), the Cr gave a clear peak near 153 degrees. The steel peak is also observed near 156 degree two-theta. This is expected when the Cr coating is thin, and the substrate peak is observed. In Figure 23(b), the Cr peak profile is displayed at a psi tilt 0-40 degrees. Again, both the Cr and the Fe peaks are observed in the M4. For this specimen, the axial residual stress measured within the coating is -21.2 ksi ± 3.3 ksi.

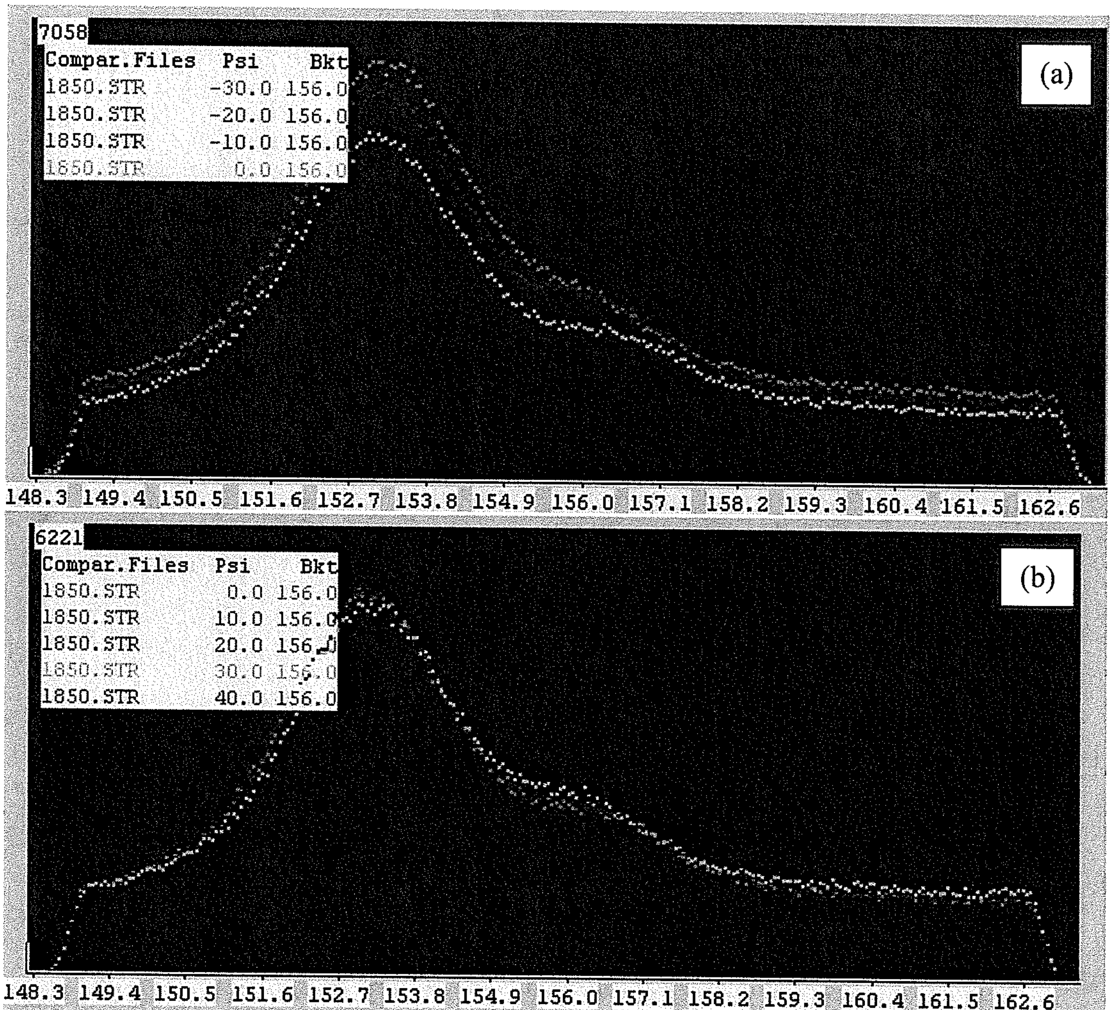

Figure 23: (a) Cr peak profile at psi tilt – (0-30 degrees) in M4 and (b) Cr peak profile at various psi tilt (0-40 degrees) in M4.

Similar analysis was completed on the M16 Cr. As shown in Figure 24, the Cr peak was interfered with by the steel peak near 156 degree two-theta. This shows that in the region tested for the M16, the Cr is very thin. Due to the steel peak interference, the system is not able to give a valid residual stress measurement. Although the residual stress cannot be quantified, based on the greater peak broadening with the M16 Cr, it is expected that the compressive residual stresses are higher.

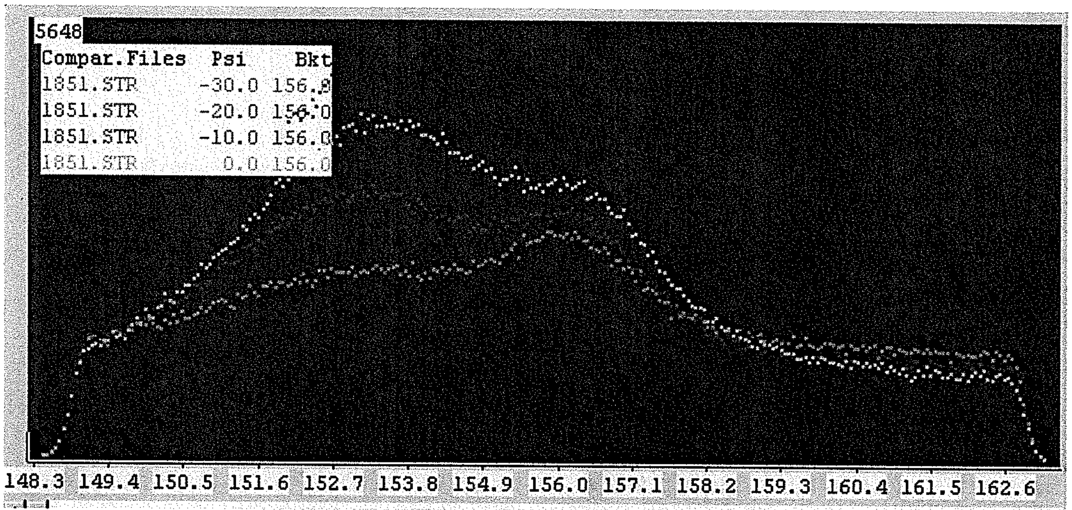

Figure 24: Cr peak profile at psi tilt – (0-30 degrees) in M16.

DISCUSSION & CONCLUSIONS

Overall, there are several characteristics of the M16 Cr that are far inferior to that of the M4 Cr. The two most striking differences between the M16 and M4 Cr are the cracking/pitting characteristics and the coating thickness uniformity. The hardness of the M4 vs. M16 is also a factor in terms of performance and relates to the cracking phenomena observed in the M16.

The poor coating thickness uniformity in the M16, particularly around the circumference in Loc C, would in all likelihood lead to deficient performance during gun firing and may significantly affect the erosion life in a negative way. In particular, the areas where the coating is as thin as 3 microns would offer much reduced protection, especially during the most aggressive firing scenarios. The lack of coating thickness uniformity is most likely due to poor centering of the anode during electroplating and/or non-uniform activation of the Cr target surface leading to uneven deposition. These problems should be fairly easy to address. The straightness of the anodes should also be assessed.

More important than the thickness uniformity however, is the overall poor quality of the electroplated Cr and underlying substrate surface in the M16 vs. the M4. The highly defective Cr in the M16 in terms of the high density of cracks and pits as well as the severe corrosion pits at the base of these cracks within the steel would lead to premature failure of islands of Cr. As previously shown, many islands of Cr have already been dislodged. The further loss of islands of Cr during firing would then leave the steel barrel substrate unprotected from the firing environment and would lead to rapid erosion and coating failure. The Cr surrounding the pitted regions even if well adhered would be removed due to consumption and undermining of the steel adjacent to the pits as is observed in large caliber gun firing[2]. The very poor Cr quality on the sides of the lands would be especially prone to this type of damage when the affects of the engraving stresses and friction are added.

The heavy cracking observed in the M16 sample is related to the high microhardness of the coating. The M16 hardness in the range of HK_{50} 800-1000 is similar to that recorded for high contractile (HC) electroplated Cr applied to large caliber gun tubes after thermal soak [3]. HC-Cr has its name for the reason that the coating itself contracts substantially after electroplating and thermal soak. This is due to the high level of impurities such as hydrogen and water that are co-deposited during electroplating. During this contraction, the electroplated HC-Cr coating undergoes significant micro-cracking as illustrated in Figure 25(a). Following gun firing or equivalent vented erosion simulator testing [4] as in Figure 25(b), the brittle nature of the hard Cr and the presence of micro-cracks leads to cracking that penetrates to the steel after just four rounds much like was observed in the M16 Cr. Based on this comparison, it is expected that the M16 Cr did not undergo a thermal soak, which, along with the much reduced thickness when compared to large caliber HC-Cr, explains the lack of regular arrays of micro-cracks as observed in 120 mm Cr, but it is likely that it was proof fired based on the heavy through cracking observed. The evidence of subsurface corrosion as well as the presence of Cu on the rifling also suggests that the M16 Cr was subjected to firing.

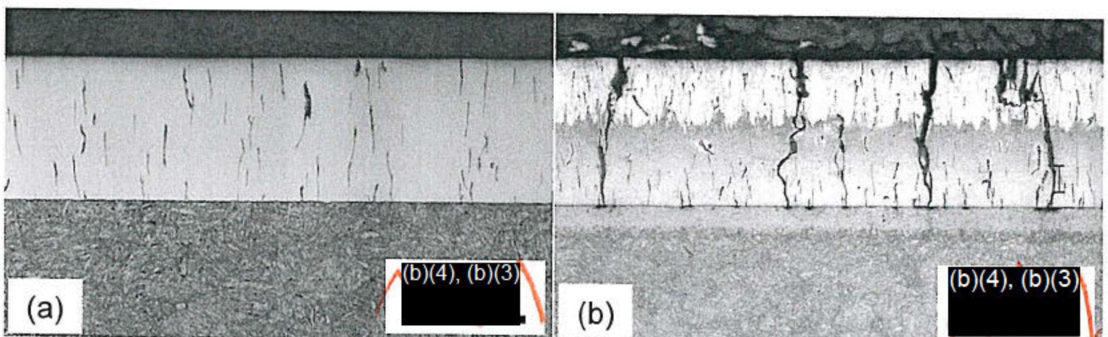

Figure 25: (a) Micrograph of 120 mm barrel HC-Cr in the as-deposited condition and (b) 120 mm barrel HC-Cr following 4 rounds of VES firing, which is near equivalent to 4 rounds of actual gun firing.

Conversely, the M4 Cr is quite soft at ~ HK_{50} 400-500. This is more typical of low contractile (LC) Cr, which contain a much lower percentage of impurities and thus the coatings do not contract as much as the HC variety of electroplated Cr. The reduction in contraction leads to much better fracture resistance. This improved ductility in the M4 Cr is evident in the lack of any significant cracking of the coating.

In summary, the M4 Cr has superior properties in terms of coating thickness uniformity, ductility (inferred from microhardness), substrate coverage, flaw density, and land-groove surface finish. Taking all of these factors into account, it would not be surprising to see deficient performance in the M16 Cr when compared to the M4 Cr.

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Technical Report ARAEW-TR-080010

Characterization of HC Chromium Plated M16 Barrels from Two Manufacturers

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Christopher Rickard

June 2008

ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
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4. TITLE AND SUBTITLE Characterization of HC Chromium Plated M16 Barrels from Two Manufacturers			**5a. CONTRACT NUMBER**
			5b. GRANT NUMBER
			5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Smith, Stephen B. ; Rickard, Christopher			**5d. PROJECT NUMBER**
			5e. TASK NUMBER
			5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army ARDEC, AETC Benét Laboratories, AMSRD-AAR-AEW, B. 40 1 Buffington Street Watervliet Arsenal, NY 12189-4000			**8. PERFORMING ORGANIZATION REPORT NUMBER** ARAEW-TR-08010
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army ARDEC, AETC Benét Laboratories, AMSRD-AAR-AEW, B. 40 1 Buffington Street Watervliet Arsenal, NY 12189-4000			**10. SPONSOR/MONITOR'S ACRONYM(S)**
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13. SUPPLEMENTARY NOTES			
14. ABSTRACT Two M16 barrels were investigated to identify the quality of the chromium bore plating. One barrel was manufactured by Colt, the second by Fabrique Nationale (FN). The barrels were sectioned and analyzed at three locations: the chamber, 5" forward of the breech face, and 5" rearward of the muzzle face. Each location was metallographically prepared and subsequently analyzed, with particular attention paid to the condition of the high contractile (HC) chromium bore coating. Deficiencies in the quality of both barrels were identified, including coating thickness variations in the Colt barrel and excessive hardness and micro-cracking in the FN barrel. Irregular chromium coating and a large crack in the steel of the Colt barrel chamber was also noted.			
15. SUBJECT TERMS M16 Gun Barrels, Metallography, Metallurgical Analysis, Chrome Plating			

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
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Abstract:

Two M16 barrels were investigated to identify the quality of the chromium bore plating. One barrel was manufactured by Colt, the second by Fabrique Nationale (FN). The barrels were sectioned and analyzed according to the protocol established by C. P. Mulligan in "Comparison of electroplated chromium coatings applied to M4 and M16 barrels." (January 2007). US Army-ARDEC.

The barrels were investigated at three locations: the chamber, 5" forward of the breech face, and 5" rearward of the muzzle face. Each location was metallographically prepared and subsequently analyzed, with particular attention paid to the condition of the high contractile (HC) chromium bore coating.

Deficiencies in the quality of both barrels were identified, including coating thickness variations in the Colt barrel and excessive hardness and micro-cracking in the FN barrel. Irregular chromium coating and a large crack in the steel of the Colt barrel chamber was also noted.

Background:

Two M16 barrels were received from AMSRD-AAR-AEW-M(D) in January 2008. One barrel was manufactured by Colt, while the second was manufacture by FN, see Figure 1. The barrels were delivered new, in accordance with prescribed product sampling of production barrels (A. Fultz, personal communication, 3 March 2007).

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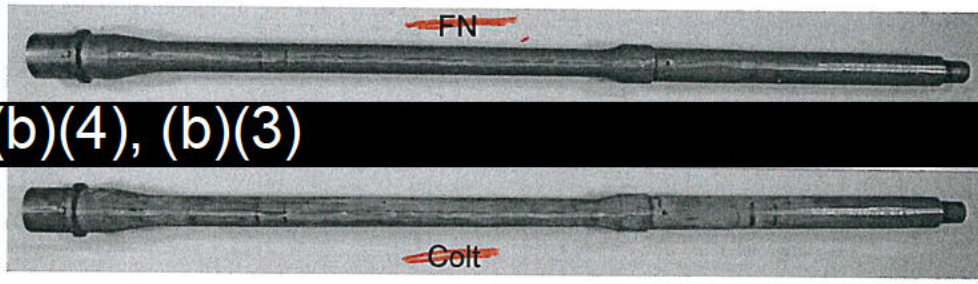


Remove Demensions

Figure 1: M16 Barrels As-Received.

Procedure:

The specimens provided were subjected to a characterization procedure based upon Benét Laboratory's established protocol for protective coatings. The specific characterization tests performed on these specimens include:

- Macroscopic examination and sectioning. The sample will be cut into small segments in order to access areas for further investigation. The sample will be photographed as-received and during the sectioning procedure.
- Coating thickness measurement. Metallographic specimens will be prepared of the sample in cross-section. The coating thickness will be measured with a measuring optical microscope.
- Microstructural analysis. Metallographic specimens will be prepared of the sample and etched for microstructure.
- Microhardness testing. Metallographic specimens will be prepared of the sample in cross-section. Microhardness measurements will be taken through the thickness of the coating and substrate.

- Surface analysis. The surface of sample sections will be investigated with optical and electron microscopes.
- Adhesion testing. Groove testing and subsequent microscopic examination will be performed on a chamber section.

The results of these tests are described below.

Observations:

Macroscopic Examination and Sectioning

Both barrels appeared new upon receipt with the observable chromium plating looking bright and shiny.

The barrels were sectioned to facilitate analysis by the following process. Three sections were identified mirroring the locations used by Mulligan (2007). These locations for analysis are Location A – Chamber, Location B – 5" forward of the breech face, and Location C – 5" rear of the muzzle face, see Figure 2. A ¼" ring was removed from each location for metallographic analysis. A ½" section was also removed and sectioned along the axis (clam shelled) from Location A and Location B for further analysis.

After sectioning, a small ring of dark discreet spots was noted in the clam-shelled chamber of the Colt barrel, see Figure 3. This discolored area was further investigated with the scanning electron microscope (SEM) and energy dispersive x-ray spectrometry (EDS). These areas were very porous and nodular upon magnification. Imaging of a surface scratch through the area of interest shows the discoloration extends through the chromium coating. The EDS identified the composition of the discolored areas as oxygen, phosphorus, manganese, and iron.

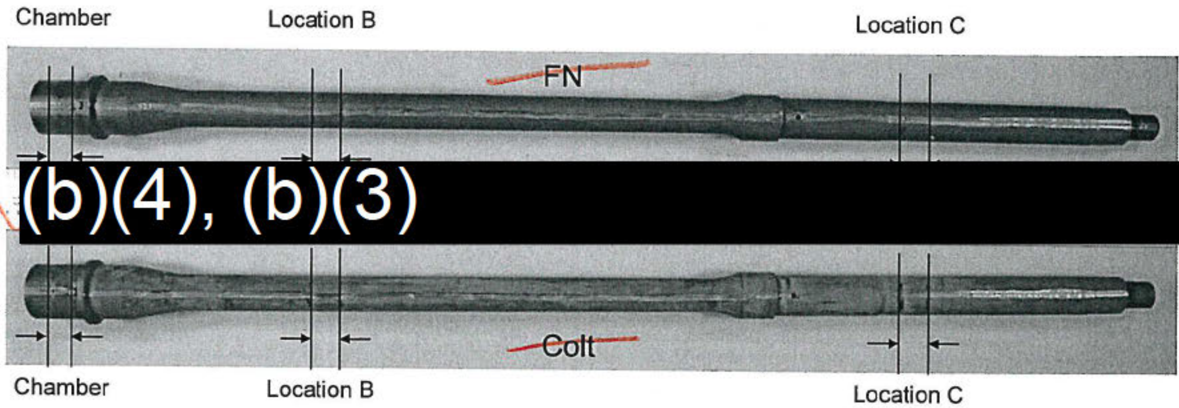


Figure 2: Cut-Plan

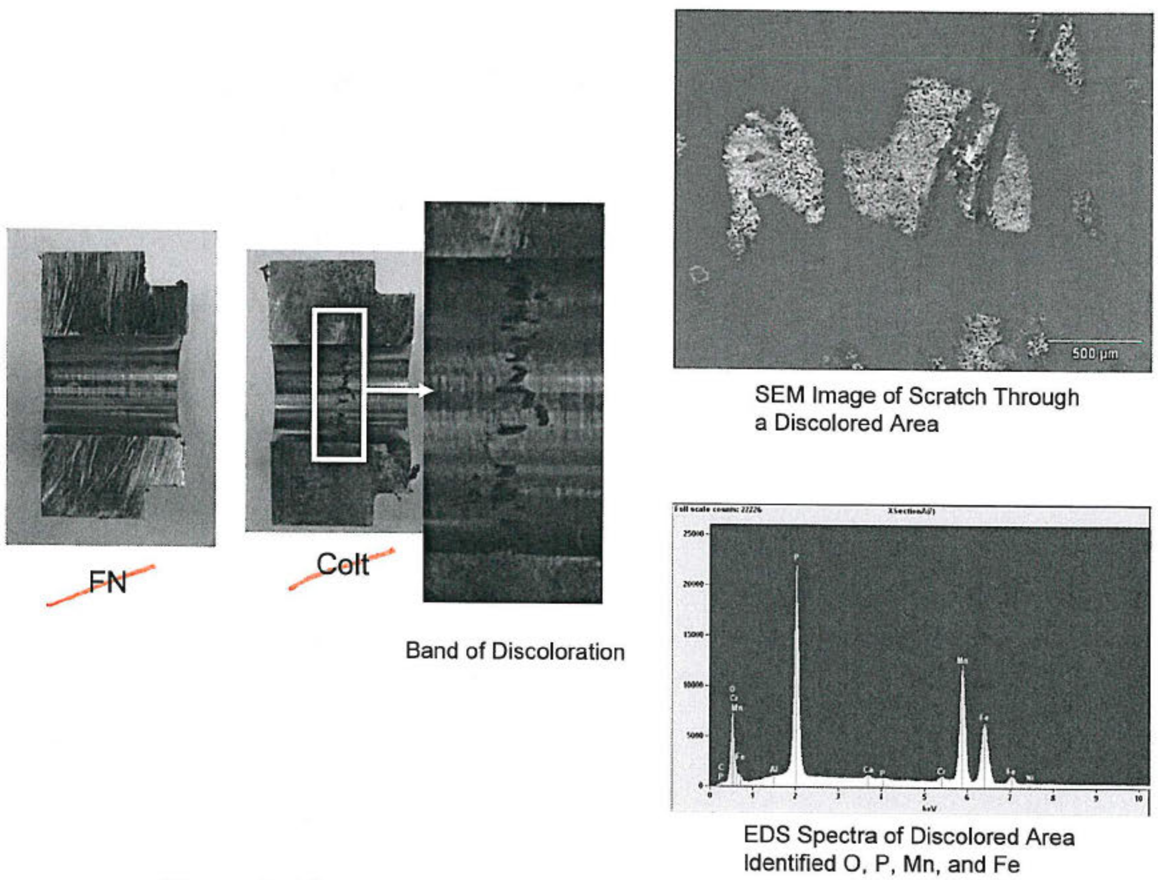


Figure 3: Macro Images of Chamber Clam-Shelled Sections.

Coating Thickness

The samples were metallographically mounted in cross-section, polished to a mirror finish, and etched lightly with Nital. The chromium coating thickness of the two barrels was measured as a function of clock position at Locations A, B, and C using an inverted metallograph with a measuring eye-piece. The thickness of the coating was measured on both the land and groove of the rifling profile at Location B and C, see Table 1. The Colt Location A ring sample had no chromium coating; additional chamber thickness measurements were taken from the clam-shelled specimens, see Table 2.

		Coating thickness (microns) as a function of clock position and axial location.
Colt		[redacted]
LocA	Chamber	
LocB	Land	
	Groove	
LocC	Land	
	Groove	
FN		
LocA	Chamber	
LocB	Land	
	Groove	
LocC	Land	
	Groove	

Table 1: Coating thickness measurement. The average and standard deviation is across all clock positions.

Maximum coating thickness (microns) measured on the clam-shelled LocA chamber specimens.				
Colt	LocA	Chamber		[redacted]
FN	LocA	Chamber		

Table 2: Maximum coating thickness measurement taken from clam-shelled chamber specimens.

US Army-ARDEC drawing #9349054 *Barrel and Barrel Extension Assembly* for the M16 barrel specifies in Note #21 that the thickness of electroplated chromium in the chamber should be between [redacted]. Regions of both the Colt and FN tubes fail to meet this standard, although regions devoid of chromium in the Colt chamber are of more serious concern than the non-concentricity of the FN chamber coating.

Note #21 also states that the chromium thickness in the rifled section of the barrel should be greater than [redacted]. Except for the Location B groove 12 o'clock measurement, the FN barrel meets this standard and appears relatively concentric. The Colt coating at Location B and C is noticeably non-concentric and fails to meet the thickness criteria at: Location B groove at positions 3 and 6; Location B land at position 6 and 9; Location C groove at positions 3, 6, and 9; and Location C land at position 3, 6, and 9.

Microstructure

The metallographic specimens used to measure the coating thickness were also analyzed to discern microstructure information about the barrel steel and the chromium coating, see Figures 4 through 10. Observations of note include:

1 - The chamber of the Colt barrel exhibited an elongated void or tear in the steel near the bore surface, see Figure 5. This cavity was immediately sub-surface to a large area devoid of chromium. This was noted in the 12 and 6 o'clock locations in the clam shelled and

metallographically prepared specimen. These voids line up exactly with the ring of discoloration noted during sectioning.

2 - A limited amount of cracking was noted in the Colt chromium coating at the B and C Locations. This cracking was mostly limited to the root of rifling, see Figures 6 and 7.

3 - A much higher density of micro-cracks was noted in the FN barrel compared to the Colt barrel. These cracks are numerous and universal, see Figures 8, 9, and 10.

4 - Small areas of copper were noted at the root of rifling profile in the FN barrel, see Figure 10.

5 – The thickness of the chromium is not consistent on the sides of the lands at Colt Location C at 6 and 9 o'clock. The sample appears to be lacking chromium on the corner of the land.

6 - The previous investigation into small caliber bore coatings (Mulligan, 2007) identified corrosion of the steel substrate as a major problem. No instances of large scale substrate corrosion were noted in the current investigation, although the issues with the Colt chamber may be related.

Colt – Location A

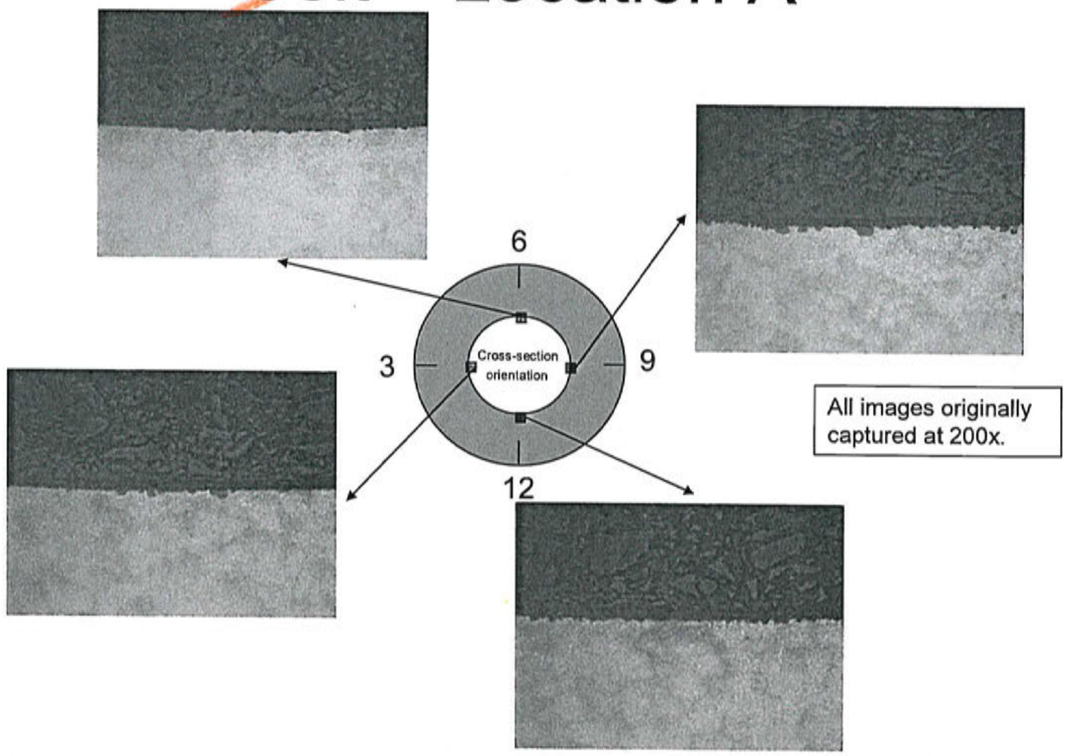


Figure 4: Images of the chamber surface. No chromium coating is observed.

Colt – Location A

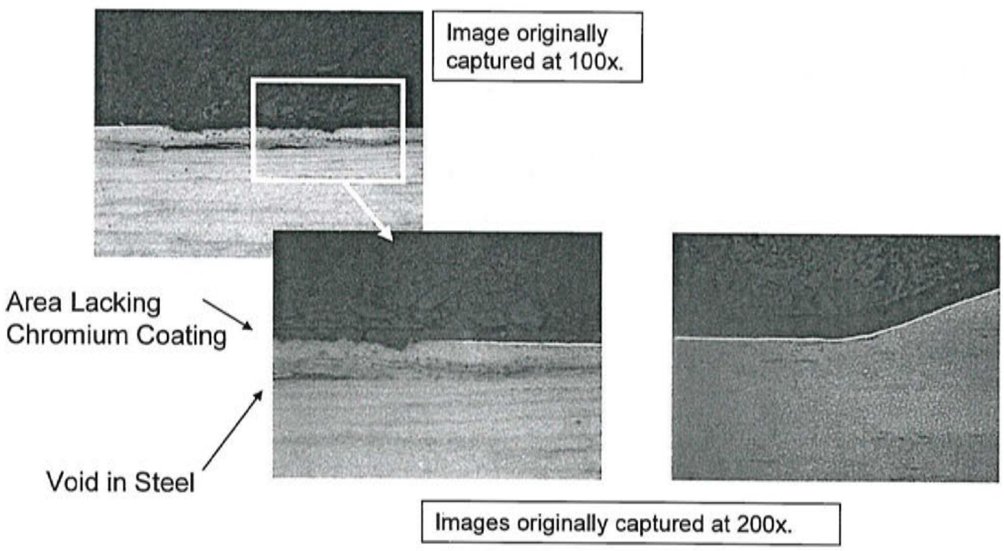


Figure 5: Images of the chamber surface. These images from the clam-shelled segment show a large void in the steel and a region lacking chromium above.

~~Colt~~ – Location B

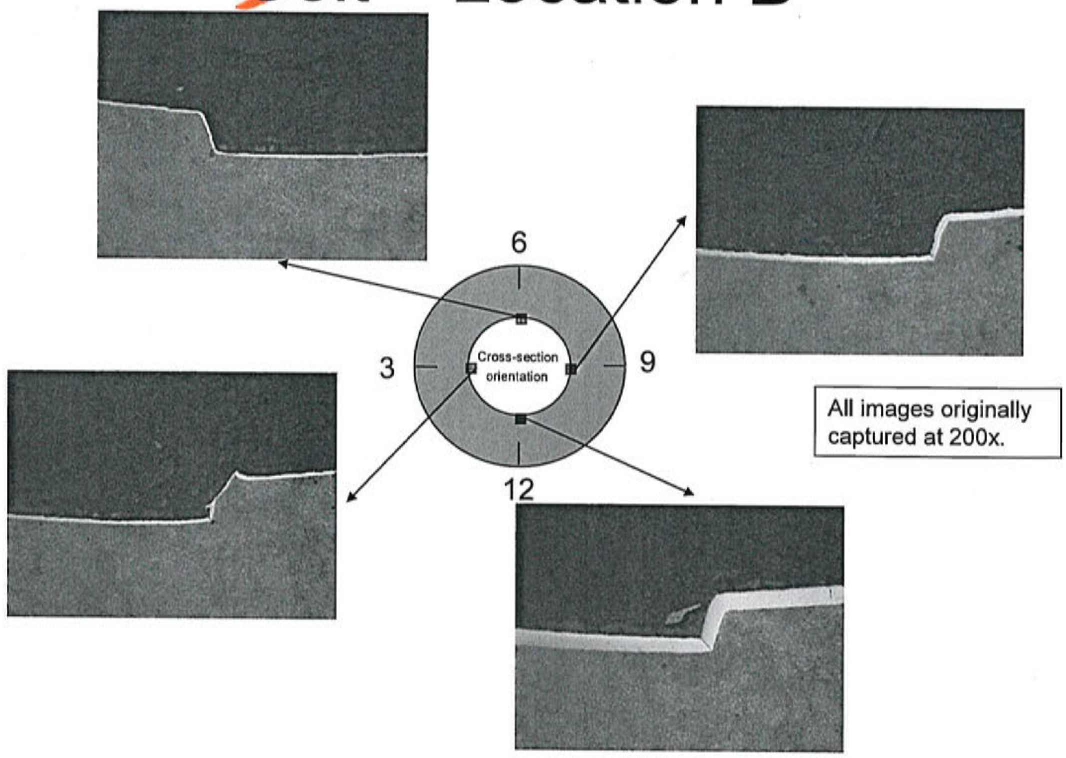


Figure 6: Images of the bore surface. Non-concentricity in the chromium thickness is clearly illustrated.

Colt – Location C

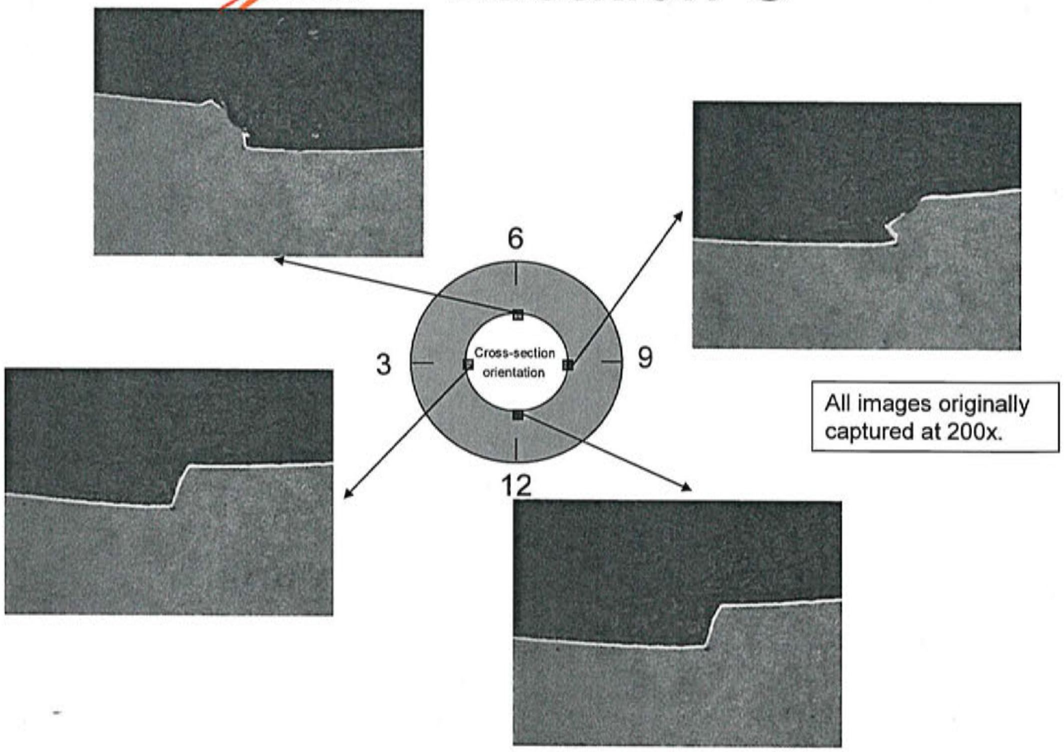


Figure 7: Images of the bore surface.

FN – Location A

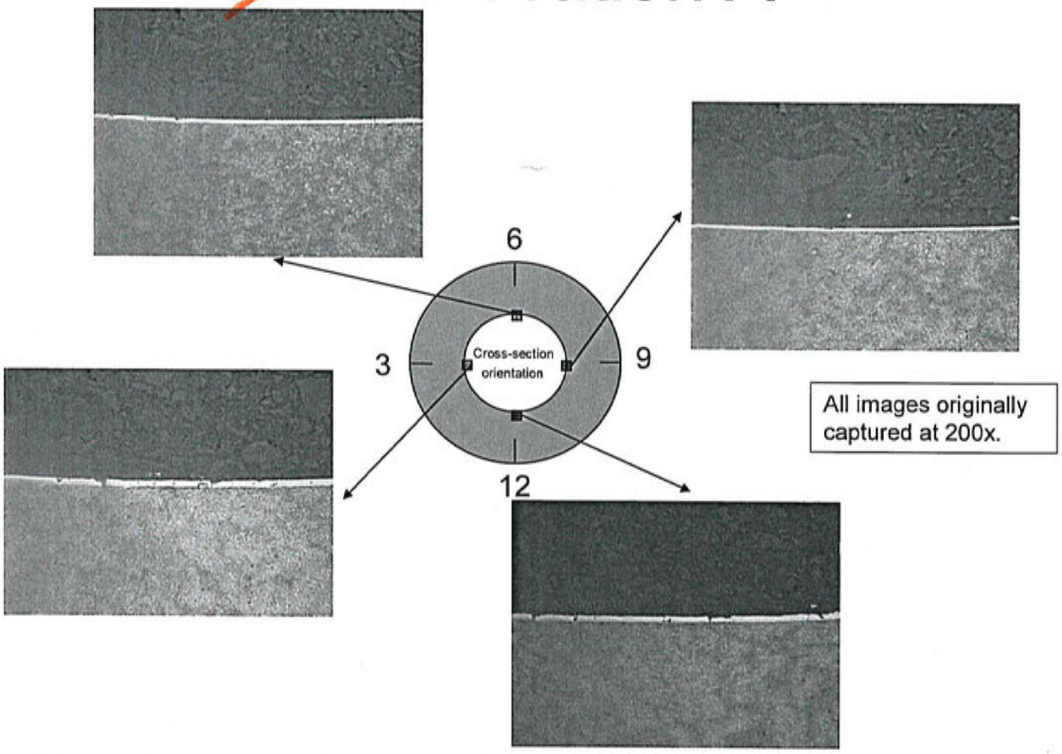


Figure 8: Images of the bore surface. Note presence of micro-cracks.

~~FN~~ – Location B

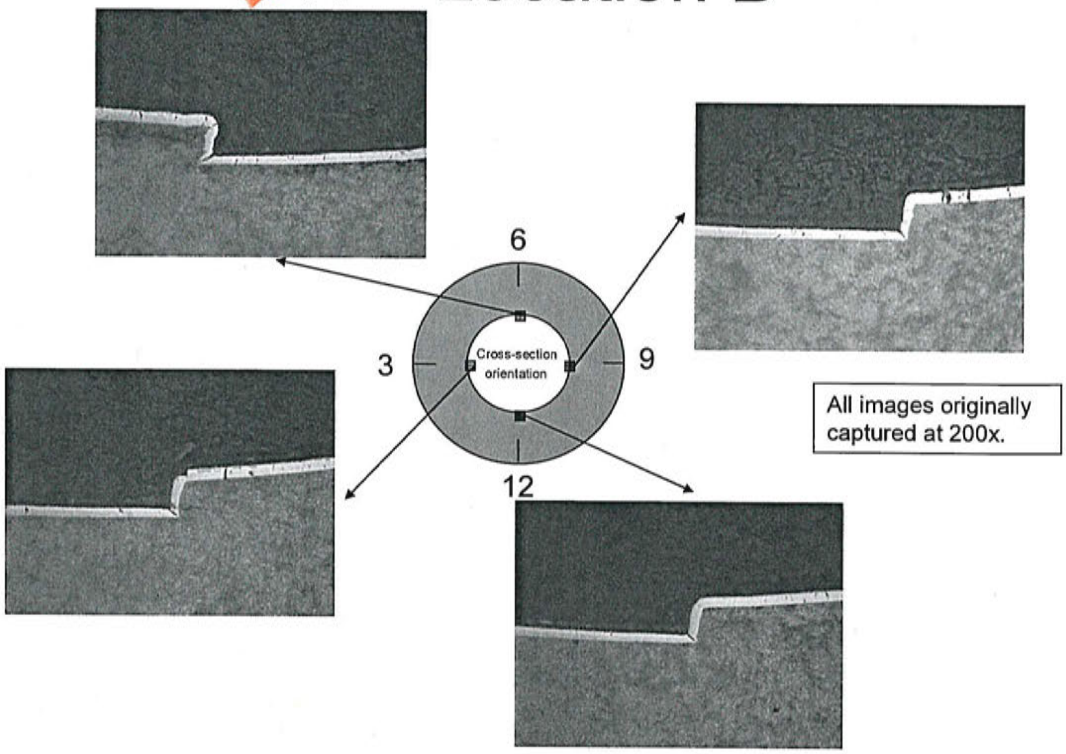


Figure 9: Images of the bore surface. Note presence of micro-cracks.

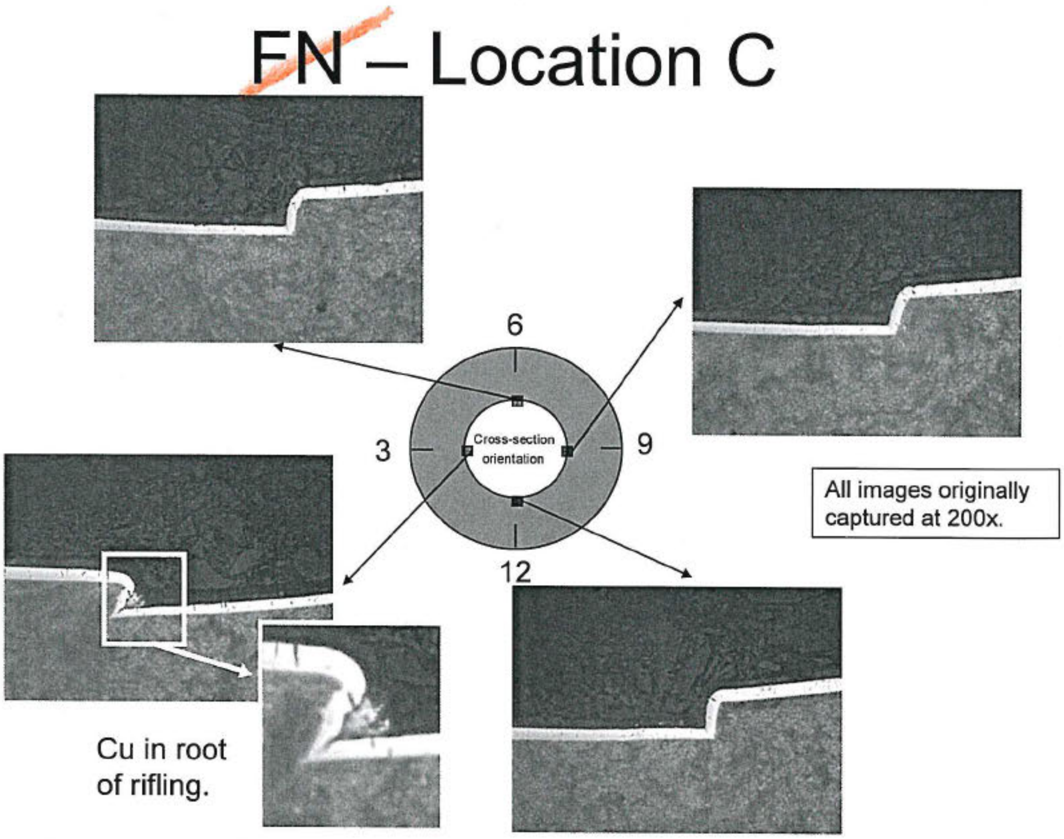


Figure 10: Images of the bore surface. Note presence of micro-cracks and copper in the root of rifling.

The previously referenced Note #21 from the barrel drawing states, "The current density must be maintained so the deposit is essentially of a dense, crack-free character." While neither barrel is totally crack free, the FN chromium exhibits a much higher crack density.

Mircohardness

Microhardness of the FN barrel chromium was much higher than the Colt barrel chromium and the substrate steel. [Table 3] The FN chromium averaged [redacted], while the Colt chromium averaged [redacted]. The steel substrate for both manufactures averaged [redacted].

	Microhardness, Knoop indenter, 0.050kg load.							
	Colt				FN			
	LocB		LocC		LocB		LocC	
	Land	Groove	Land	Groove	Land	Groove	Land	Groove
	546	566	495	533	972	987	1143	1090
	499	586	458	558	888	1029	1086	1025
	515	584	494	487	969	987	1057	987
	509	612	518	515	914		921	
Average	517	587	491	523	936	1001	1052	1034
Stan. Dev.	20	19	25	30	42	24	94	52

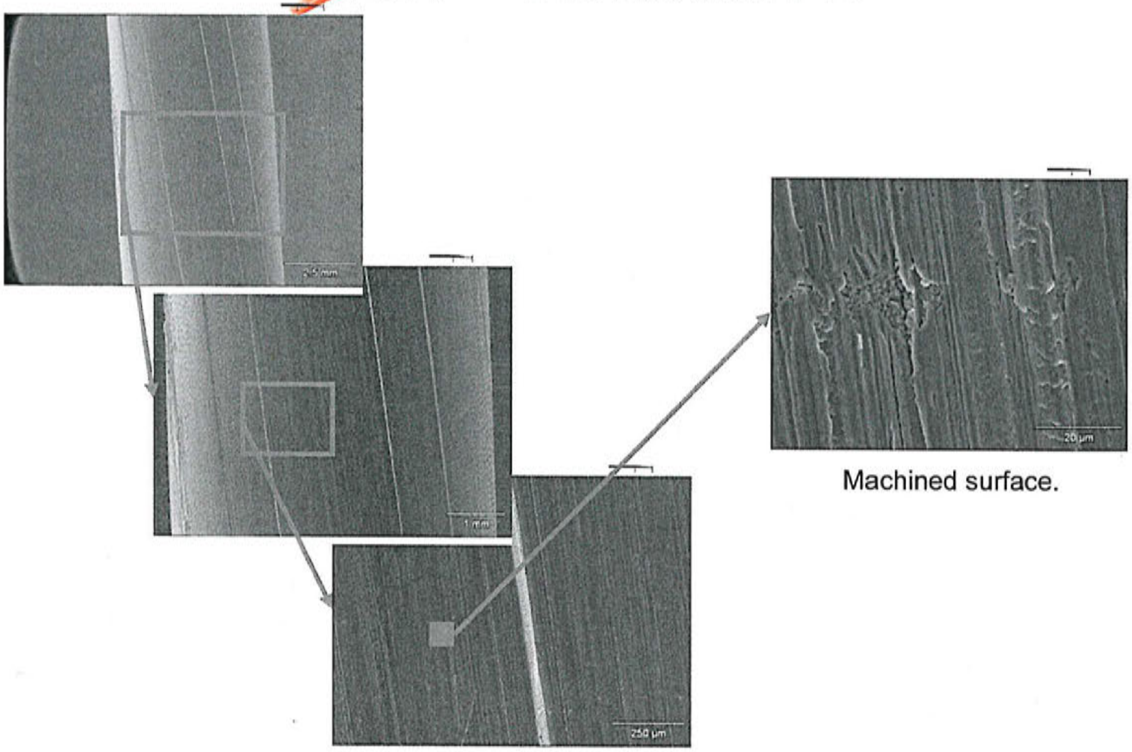
Table 3: Microhardness data.

Surface Condition

The bore surface of both samples exhibited a machined surface, with shallow axial grooves. The FN barrel surface also showed periodic, shallow, radial engraving bands. [Figures 11 and 12]

The FN barrel also had what appeared to be an excessive amount of chromium on one edge of the land. This overhang cracked and spalled in certain locations. [Figure 12]

Colt – Location B



Machined surface.

Figure 11: Surface images of the bore.

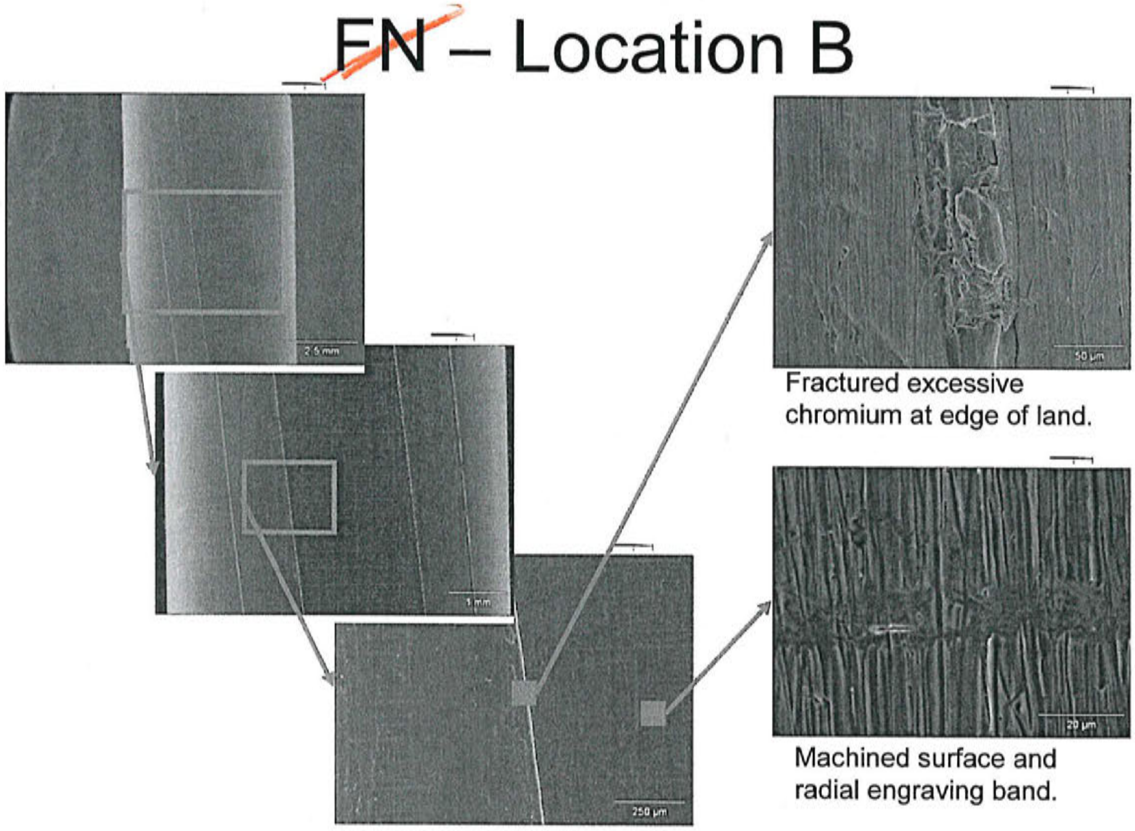


Figure 12: Surface images of the bore.

Adhesion/Cohesion

Groove testing was performed on Location A (chamber sections) of both barrels. The coating survived testing in both tubes. Shallow cracking of the FN barrel chromium occurred adjacent to the groove; this was not observed in the Colt barrel. [Figure 13]

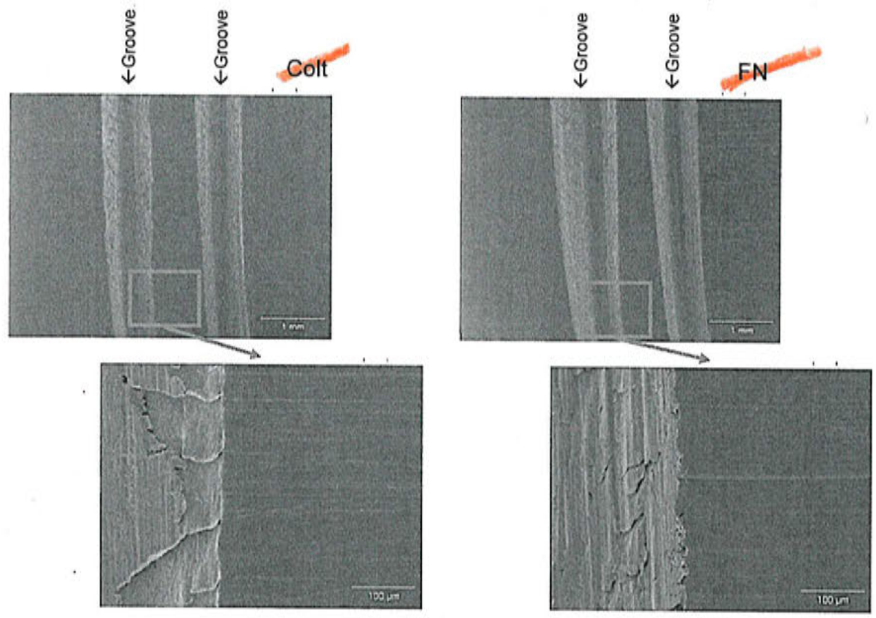


Figure 13: Images of groove tested chamber surfaces.

The cohesive strength of the FN chromium is of notable concern. The high microhardness and high density of micro-cracks in the FN chromium created a tendency for the coating to fracture and spall during metallographic polishing. This was not observed in the Colt coating.

Discussion and Conclusion:

The chromium thickness uniformity of the FN barrel is superior to the Colt barrel. Neither barrel completely met the specifications of Note #21, however the complete lack of chromium in regions of the Colt chamber and the severe thickness non-uniformity in the rifled regions are particularly worrisome. Non-uniform chromium thickness will lead to uneven heating of the barrel and preferential erosion in the thin chromium/high heat-input areas.

The chromium plating of the Colt barrel is of superior quality to the FN barrel. The high hardness, high density of micro-cracks, and propensity to cohesively fail would decrease the performance of the FN barrel compared to a uniformly-plated barrel with Colt-like chromium. Likely fracture and spallation of the coating during firing will cause a loss of obduration. Muzzle velocity and accuracy of the bullet will decrease and localized barrel heating at the point of spallation will greatly increase. This will ultimately shorten the wear life of the barrel.

The chamber of the Colt barrel is of a concern. The non-uniform chromium coating with the inclusion of non-metallics and the voids in the steel will affect the performance. Particularly with substrate voids, inhomogeneity in structural steel would compromise the strength and performance of any component. The Mn-P non-metallics identified in the chamber coating suggest there was an issue with the non-reactive surface treatment for the outer-diameter of the barrel. Great care must be taken to preserve the integrity of the chamber to ensure round chambering and extraction during firing.