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Metallurgical Examination of M61A1 Breech Bolt Assembly Components

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Abstract

The Naval Air Warfare Center (NAWC) requested the Army Research Laboratory (ARL) to perform a metallurgical investigation on 20mm M61A1 Gatling gun system breech bolt assembly components. An unused breech bolt assembly, and an individual locking block (a component of the breech bolt assembly) were both examined. Each part was taken from inventory at NAWCAD, Patuxent River. The Navy had experienced numerous failures of this system in practice gun mount testing and in service. Failures have coincided with the use of a recently developed more potent replacement for the 20mm M50 Series ammunition. This new ammunition is designated as 20mm PGU Series ammunition. The investigation performed by ARL concentrated on determining the conformance of each component to the governing specifications. The examination included high-voltage testing, visual examination, surface finish measurement, dimensional analysis, magnetic particle inspection, metallography, mechanical testing, chemical analysis, and coating measurements. Findings included a nonconforming surface finish upon the individual locking block, a complete layer of decarburization around the periphery of the individual locking block, and an improper hardness level within the individual locking block. In addition, the firing pin had a nonconforming chemistry, the top and bottom bolt shafts did not contain a nitrided case and had nonconforming chemistry, the assembly locking block had nonconforming chemistry, and the spring pins failed to achieve the minimum double shear load, and had nonconforming chemistry. The author presented these findings to Navy, Air Force and AMCCOM representatives on three seperate occasions. Warner-Robins Air Force Base, the Tri-Service procurring activity for the breech bolt assembly, informed the contractor of these deficiencies.

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Background

The Naval Air Warfare Center (NAWC) requested the U.S. Army Research Laboratory-Materials Directorate (ARL-MD) to characterize a 20mm M61A1 Gatling gun system breech bolt assembly, and a separate locking block which is a component of the M61A1 breech bolt assembly. The M61A1 system is utilized by the Air Force on the F-15 and F-16 aircraft, and by the Navy on the F-14 and F-18 aircraft. The Army utilizes a similar gun system (designated M197), on the Cobra and Comanche attack helicopters. The locking block is a critical element of the breech bolt assembly, sustaining the load of firing pressure in the gun system. Similar components have exhibited accelerated wear during F-14 gun mount firing tests conducted at NAWCAD, Patuxent River. Therefore, special attention was given to these components during this analysis. In addition, the two spiral type spring pins of the assembly were also scrutinized, at the request of John Fahnestock of NAWCAD, Patuxent River, because of the recent history of increased failures.

NAWCAD shipped a new (unused) breech bolt assembly and a new (unused) locking block to ARL-MD. These components were designated "After-Market" by the NAWC. Contracts awarded by Robins Air Force Base indicated that over 11,000 of these breech bolt assemblies have been procured. A trace of these assemblies shows the parts may be in service, used for practice, or within the inventory of the aforementioned services. The intent of this investigation was to determine if the components conformed to the governing engineering drawings and associated specifications.

A test plan was formulated by ARL-MD and approved by NAWC. The following summarizes the testing which was performed, and serves as an outline for this report. A test matrix is included which summarizes this testing.

Breech Bolt Assembly Testing

Breech Bolt Assembly per Eng. Dwg. 11691422

*Continuity test per Note 3.
*High voltage test per Note 4.
*Measure Firing Pin protrusion in "locked position" per Note 7.
*Measure Firing Pin protrusion in "unlocked position" per Note 8.

Individual Locking Block Examination

Locking Block per Eng. Dwg. 11691430

*Visual Inspection.
*Measure surface finish (μin RMS) per Note 2.
*Dimensional analysis per Eng. Dwg.
*Magnetic particle inspect per MIL-F-7190.
*Verify grain flow per Note 4.
*Chemical analysis to verify AISI 4140 (MIL-S-5626).
*Metallography (microstructure, inclusion content, defects, decarburization).
*Microhardness testing (verification of decarburization by Knoop 100 gm load).
*Macrohardness testing (HRC per Note 7).

Individual Component Examination

Cam Pin per Eng. Dwg. 11691417

*Dimensional analysis per Eng. Dwg.
*Magnetic particle inspection per MIL-I-6868, Note 7.
*Chemical analysis to verify material per QQ-S-763 (Note 1).
*$HR_{15\text{-}N}$ hardness tests to verify prior heat treatment (Note 4).
*Metallography (microstructure, inclusion content, defects, decarburization).

Firing Pin per Eng. Dwg. 11691418

*Dimensional analysis per Eng. Dwg.
*Magnetic particle inspection per MIL-I-6868, Note 10.
*Measure nickel plating thickness per Note 6.
*Chemical analysis to verify material per Note 1.
*$HR_{15\text{-}N}$ hardness tests to verify prior heat treatment per Note 4.
*Metallography (microstructure, inclusion content, defects, decarburization).

Bolt Shaft, Top per Eng. Dwg. 11691411

*Dimensional analysis per Eng. Dwg.
*Magnetic particle inspection per MIL-I-6868, Note 6.
*Chemical analysis to verify material.
*Microstructure to verify heat treatment, per Note 4.
*Inspect metallographically for inclusions, defects, and/or decarburization.
*Case depth measurements by metallography, Knoop microhardness, and $HR_{15\text{-}N}$.
*HRC hardness tests to verify prior heat treatment.

Bolt Shaft, Roller per Eng. Dwg. 7268635

*Dimensional analysis per Eng. Dwg.
*Magnetic particle inspection per MIL-I-6868, Note 4.
*Chemical analysis to verify material.
*Microstructure to verify heat treatment, per Note 3.
*Inspect metallographically for inclusions, defects, and/or decarburization.
*HRC hardness tests to verify prior heat treatment.

Bolt Shaft, Bottom per Eng. Dwg. 11691416

*Dimensional analysis per Eng. Dwg.
*Magnetic particle inspection per MIL-I-6868, Note 6.
*Chemical analysis to verify material.
*Microstructure to verify heat treatment, per Note 4.
*Metallography (microstructure, inclusion content, defects, decarburization).
*Case depth measurements by metallography, Knoop microhardness, and HR_{15-N}.
*HRC hardness tests to verify prior heat treatment, per Note 5.

Breech Bolt Body per Eng. Dwg. 11691423

*Dimensional analysis per Eng. Dwg.
*Magnetic particle inspect per MIL-STD-1949, Note 27.
*Grain flow per Note 3.
*Chemical analysis to verify material per Note 1.
*Metallography (microstructure, inclusion content, defects, decarburization).
*HRC hardness tests to verify prior heat treatment, per Note 23.

Locking Block per Eng. Dwg. 11691430

*Dimensional analysis per Eng. Dwg.
*Measure surface finish (μin RMS) per Note 2.
*Dimensional analysis per Eng. Dwg.
*Magnetic particle inspect per MIL-F-7190.
*Verify grain flow per Note 4.
*Metallography (microstructure, inclusion content, defects, decarburization).
*Microhardness testing (verification of decarburization by Knoop 100 gm load).
*Chemical analysis to verify AISI 4140 (MIL-S-5626).
*Macrohardness testing (HRC per Note 7).

Extra Heavy-Duty Spiral Type Spring Pin per Eng. Dwg. 11691266

*Dimensional analysis per Eng. Dwg.
*Double shear test per Note 1E.
*Microhardness tests (Knoop) per Note 1F.
*Chemical analysis to verify material (300 Maraging - MIL-S-46850) per Note 1B.
*Metallography (microstructure, inclusion content, defects, decarburization).
*Check finish per Note 2.

Helical Compression Spring per Eng. Dwg. 11691419

*Perform dimensional verification.
*Check load at compressed length of 0.51 inches (2.0 +/- 0.2 lb) per drawing.
*Chemical analysis to verify material (QQ-W-47C) per Eng. Dwg.
*Measure plating thickness.
*Metallography (microstructure, inclusion content, defects, decarburization).

After–Market Breech Bolt Assembly Test Matrix

	CO	HV	FP–L	FP–UL	VI	SF	DA	MP	MT	CA	Micro	Macro	PL	ST	DST	CT
Breech Bolt Assembly	X	X	X	X												
Lock. Block–Ind.					X	X	X	X	X	X	X	X				
Cam Pin							X	X	X	X		X				
Firing Pin							X	X	X	X		X	X			
Bolt Shaft, Top							X	X	X	X	X	X		X		
Bolt Shaft, Roller							X	X	X	X		X				
Bolt Shaft, Bottom							X	X	X	X	X	X		X		
Breech Bolt Body							X	X	X	X		X				
Lock. Block–Ass'y					X	X	X	X	X	X	X	X				
Spiral Spring Pins							X		X	X	X		X		X	
Hel. Comp. Spring							X		X	X			X			X

CO–Continuity Test, HV–High Voltage Test, FP–L–Firing Pin Protrusion (Locked Position), FP–UL–FiringPin Protrusion (Unlocked Position)
VI–Visual Inspection, SF–Surface Finish, DA–Dimensional Analysis, MP–Magnetic Particle Inspection, MT–Metallographic Inspection
CA–Chemical Analysis, MICRO–Microhardness Testing, MACRO–Macrohardness Testing, PL–Plating Inspection, ST–Surface Treatment Inspection
DST–Double Shear Test, CT–Compression Test

Pertinent Drawings and Specifications

*US Army ARDC Drawing No. 7268635, Roller, Bolt Shaft.
*US Army ARDC Drawing No. 11691411, Shaft, Top.
*US Army ARDC Drawing No. 11691416, Body, Shaft, Bottom.
*US Army ARDC Drawing No. 11691417, Pin, Cam.
*US Army ARDC Drawing No. 11691418, Pin, Firing.
*US Army ARDC Drawing No. 11691419, Spring, Compression, Helical.
*US Army ARDC Drawing No. 11691421, Shaft Assembly, Bolt.
*US Army ARDC Drawing No. 11691422, Bolt Assembly, Breech.
*US Army ARDC Drawing No. 11691423, Body, Breech Bolt.
*US Army ARDC Drawing No. 11691480, Locking Block.
*US Army ARDC Drawing No. 11698266, Pin, Spring, Spiral Type, Extra Heavy Duty.
*QQ-P-35, Passivation Treatments for Corrosion Resistant Steel.
*MIL-STD-171, Finishing of Metal and Wood Surfaces.
*QQ-N-290, Nickel Plating (Electrodeposited).
*QQ-P-416, Plating, Cadmium (Electrodeposited).
*QQ-W-470, Wire, Steel, Carbon, Spring, Music.
*ASTM B 633, Standard Specification for Electrodeposited Coatings of Zinc on Iron and Steel.
*QQ-S-763, Steel Bars, Wire, Shapes and Forgings, Corrosion Resisting.
*MIL-STD-1949, Inspection, Magnetic Particle.
*AMS 2301, Aircraft Quality Steel Cleanliness Magnetic Particle Inspection Procedure.
*AMS 2755, Liquid Salt Bath Nitriding.
*MIL-S-5000, Steel, Chrome-Nickel-Molybdenum (AISI E4340) Bars and Reforging Stock.
*AMS 5617, Steel Bars, Wire and Forgings, Corrosion Resistant.
*MIL-S-5626, Steel: Chrome-Molybdenum (AISI 4140) Bars, Rods and Forging Stock.
*MIL-I-6868, Inspection Process, Magnetic Particle.
*MIL-H-6875, Heat Treatment of Steel, Process For.
*MIL-F-7190, Forging, Steel, For Aircraft/Aerospace Equipment and Special Ordnance.
*MIL-P-10971, Pin, Spring, Tubular (Coiled and Slotted).
*MIL-S-13572, Springs, Helical, Compression and Extension.
*MIL-W-13855, Weapon, Small Arms and Aircraft Armament Subsystem.
*MIL-C-13924, Coating, Oxide, Black, For Ferrous Metals.
*MIL-S-46850, Steel: Bar, Plate, Sheet, Strip, Forgings and Extrusions, Maraging, Grade 300, High Quality.
*MIL-W-63150, Weapons and Support Materiel, Standard Quality Assurance Provisions For.
*ASTM E 3 Methods of Preparation of Metallographic Specimens.
*ASTM E 18 Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials.
*ASTM E 384 Test Methods for Microhardness of Materials.
*ASTM E 407 Methods for Microetching Metals and Alloys.
*ASTM B 487 Test Method for Measurement of Metal and Oxide Coating Thicknesses by Microscopal Exam.
*ASTM E 883 Guide for Metallographic Photomicroscopy.

Breech Bolt Assembly Testing

The breech bolt assembly was received in the packing shown in Figure 1. Although the packing was punctured (see figure), visual inspection of the well lubricated component showed no sign of corrosion. Figures 2 through 4 show the top, side and end view of the breech bolt after being removed from its original package.

The breech bolt assembly was subjected to a continuity test and a high potential test per Eng. Dwg. 11691422. These tests were conducted with the locking block in the locked position (down 15° 30'). The cam pin was depressed until the firing pin extended 0.030 inches. The **continuity test** was conducted utilizing a Fluke multimeter. It was determined that there was electrical continuity between the cam pin and the firing pin of the breech bolt assembly, conforming to the requirements of Eng. Dwg. 11691422.

The **high potential test** was conducted using a Fluke Precision Power Amplifier. A test voltage of 800 volts at 60 Hz frequency was applied for one minute between the cam pin and ground. No voltage breakdown was noted during that time frame, conforming to the requirements of Eng. Dwg. 11691422.

The **firing pin protrusion (in the locked position)** was subsequently measured, with the locking block in the locked position (down 15° 30'), and the cam pin fully depressed. A firing pin protrusion of 0.0610 inch was measured from the assembly, conforming to the requirements of Eng. Dwg. 11691422 (0.033 inch minimum).

The **firing pin protrusion (in the unlocked position)** was also measured with the locking block up the maximum distance. With the cam pin depressed to its maximum travel (against the block) the firing pin did not protrude beyond the face of the bolt, conforming to the requirements of Eng. Dwg. 11691422.

Individual Locking Block Examination

Visual inspection of the component revealed areas of corrosion along the top side, most heavily within the two machined recesses which act as potential sources of moisture entrapment. The low magnification macrographs of Figures 5 and 6 show the corrosion within each recess. Note the rust and pitting. The surface of the part was also rough exhibiting an as-forged profile. In addition, when the black oxide coating was scraped away, remnants of corrosion product could be observed beneath. This may have been the result of heat treat scale or corrosion if the part was set aside for a period of time before the sequence of manufacturing operations was complete. Figures 7 and 8 show the extent of the corrosion at higher magnification. This component was received by ARL-MD in an unlubricated condition, but was coated as specified within MIL-STD-171, (Finish No. 3.3.1, *Class I, alkaline oxidizing process for wrought iron, plain carbon and low alloy steels*). As stated within Section 1.1 of MIL-C-13924, this coating provides only very limited corrosion protection, under mildly corrosive conditions. Therefore, if the part is unlubricated, corrosion will most likely occur when the component is exposed to moisture from the environment during prolonged storage.

From a corrosion standpoint, a black oxide coating is not very protective, and is not recommended for parts subjected to long term storage. A coating of this type is designated because dimensional buildup cannot be tolerated for this application. However, if the part is subjected to long term storage, dimensional buildup may be noted due to the oxides formed by corrosion. A supplementary water displacing preservative coating such as MIL-C-16173, Grade 3 or VV-L-800 should be specified for corrosion protection.

Surface Finish

The surface roughness of the locking block was measured with the Mitutoyo Surftest 401 Analyzer. Readings were taken across the top and sides of the part (see schematic in Figure 9). These were the regions of the component which exhibited excessive machining marks (Figures 10 and 11). The required average surface roughness of the top and sides of this component is 125 μin RMS (Eng. Dwg. 11691480). The top surface registered an average of 132 μin RMS, while the sides averaged 161 μin RMS (Table 1, Appendix A). These results indicate the part had a rougher surface than required. Excessive machine marks could be detrimental, in that they may act as stress risers while the part is in service, leading to premature failure.

Dimensional Analysis

The major dimensions of the component were measured with a Bausch and Lomb Optical Comparator, as well as a vernier caliper. All measured dimensions conformed to Engineering Drawing 11691430.

Magnetic Particle Inspection

The component was subjected to magnetic particle inspection per MIL-STD-1949. The wet continuous method was employed. Testing was conducted on a Magnaflux inspection machine. No indications were revealed as a result of this inspection.

Chemical Analysis

Chemical analysis was performed on a section of the component to verify the composition per MIL-S-5626 (AISI 4140). The carbon content was determined by combustion-infrared detection, the sulfur by combustion-automatic titration, and all other elements by direct current plasma emission spectroscopy. The results of this analysis are listed in Appendix A, Table 2. The chemistry conformed to the specified requirements of MIL-S-5626.

Grain Flow

The grain flow of the locking block was examined to verify conformance to Engineering Drawing 11691430. The component was sectioned lengthwise, mounted, and metallographically prepared. Rough polishing was accomplished by utilizing silicon carbide papers, while fine polishing was performed with 9μm and 0.25μm diamond grit. A macroetch of 50% HCl and 50% distilled water at 180°F was used to reveal the flow lines. Figure 12 shows the resultant structure after application of the etchant, and the schematic from the engineering drawing showing required flow direction. The flow lines conformed to the governing drawing. However, the region above the pin hole of the bail did not exhibit a different structure from the remainder of the part (Figure 13). This region was supposed to be induction hardened to 50-55 HRC, while the remainder of the part was supposed to be 38-43 HRC. It was anticipated that this difference in hardness would have produced two distinct structures within the part. This suggested that the part was the same hardness throughout (see *Macrohardness Testing* section for verification).

Microstructure

The sectioned portion of the locking block which was macroetched to verify grain flow, was also utilized to examine the microstructure of the material. A 4% nital etchant was applied to the polished surface, to reveal the fine tempered martensitic structure shown in Figure 14. This microstructure is consistent with the prior heat treatment (austenitize, quench and temper). Section 3.5 of MIL-F-7190 states that, *"the structure of the part shall be essentially uniform and free from defects."* The microstructure displayed no inherent material defects, and the material conformed to this requirement. However, noted around the periphery of the component was a layer of decarburization. Figure 15 shows a representative region of this decarburization. Note the distinct ferritic decarburized layer, the transition zone of ferrite and lower-carbon martensite, and the normal matrix of tempered martensite. Section 3.3.3.1 of MIL-H-6875 states that,

> *"Partial decarburization shall be judged excessive if greater than 0.003 inch deep on any machined surface for parts HRC 46 (220 ksi) and above...Any total decarburization at the surface is not acceptable."*

According to the American Society for Materials (ASM) "Carburizing and Carbonitriding" reference handbook [1], the surface of a part is totally decarburized when a layer of free-ferrite exists. Conversely, partial decarburization does not exhibit this layer of ferrite because the presence of precipitated intergranular carbide particles prevents complete decarburization. Figure 16, taken from the aforementioned reference, shows the difference in appearance between a totally (a) versus partially (b) decarburized surface structure. The material is AISI 4118H steel, etched with 4% nital at 250x magnification. Compare the representative macrograph of the locking block decarburization (Figure 15) to Figure 16. Although not as severe as the decarburized layer shown in Figure 16, the decarburized layer of the locking block appeared to compare favorably to that of a totally decarburized surface layer, which does not conform to 3.3.3.1 of MIL-H-6875.

Microhardness Testing

Knoop microhardness profiles were performed to determine the depth of the decarburized layer on key areas of the individual locking block. A mounted and polished section of the component was utilized for this testing. The areas chosen for this testing was the bail section above the eyelet (Profiles A and B of Table 3, Appendix A), the top of the component (Profile

C), the bottom of the component (Profile D), the front of the component (Profile E) and the back of the component (Profile F). The bail was chosen since this area was required to be induction hardened to 50-55 HRC, and most likely encountered increased impact loading in service. The front and back regions were chosen because these areas are subjected to contact with the rotor after each firing. Figure 17 shows one of the four Knoop hardness profiles taken through the decarburized layer, in the as-polished condition. Figure 18 shows this same profile, with a 4% nital etchant applied to the sample. Note the difference in size between the indents near the surface of the part (in the decarburized region) and the indents within the core of the part. As a result of Knoop microhardness testing, the size of the indent is an indication of the hardness of the material; ie. the larger the indent, the softer the material. Hence, the readings closer to the surface are lower in magnitude than those further away from the decarburized layer. The microhardness values which correspond to these indents are listed in Appendix A, Table 3 (Profile A). Also listed in this table, are the results of Profiles B, C, D, E and F.

The core average was derived by tallying the readings which remained constant and displayed no further upward gradient. For example, the Profile A readings show that measurements 6-10 were similar to one another in magnitude, and therefore represent the values within the core. Section 4.3.3.1 of MIL-H-6875 states, *"The boundary of the decarburization shall be at the depth at which the hardness rises to the equivalent of 20 points Knoop below the core hardness."* For Profile A, the reading of 516 HK is 95 points below the core hardness, and represents a significant change in hardness. The decarburization boundary was determined to be between reading 5 and 6. Measured from the micrograph, this reading is 0.00547 inch in depth. For Profile B, the first five readings were also within the decarburized layer. From the macrograph, this reading is 0.00594 inch in depth. The first six readings of Profile C were also within the decarburized region. This depth was measured to be 0.00625 inch. The first seven readings of Profile D fell within the decarburized layer. The measured depth of this layer was 0.00688 inch. The decarburization measured 0.00635 inch in depth from Profile E, and 0.00531 inch in depth from Profile F. These results are summarized in Table 4 of Appendix A. Each measured depth failed to conform to the requirement set forth in Section 3.3.3.1 of MIL-H-6875 (0.003 inch maximum).

Macrohardness Testing

The sectioned locking block was subjected to macrohardness testing (Hardness Rockwell "C" scale). Readings were taken on the sectioned surface of the locking block to determine conformance to the governing drawing. Drawing 11691430 indicates the part must be 50-55 HRC in the bail section above the pin hole, and 38-43 HRC throughout the remainder of the part. Readings 1 through 5 were taken in the bail section (2 through 4 above the pin hole in the induction hardened zone) while readings 6 through 15 were taken in the body. The hardness results indicated the part was hardened to 50-55 HRC throughout, as shown in Appendix A, Table 5. This did not conform to the governing requirement of 38-43 HRC, and could account for rotor wear which has been noted during F-14 gun mount testing at NAWCAD, Patuxent River. The locking block contacts the chromium-molybdenum-vanadium alloy steel rotor (which is hardened to 50-55 HRC) after each round is fired. If the locking block approaches the same hardness as the rotor, wear of the rotor will most likely occur.

Macrohardness measurements were also taken on the exterior surface of the part to determine the effect of decarburization on surface hardness. Readings were taken on the bail, side, top and bottom surfaces of the component. It was noted that the readings were substantially lower than those taken on the sectioned surface, by as much as 14 HRC points. Had the part exhibited its required hardness range (38-43 HRC) rather than the 50-55 HRC range, this layer of decarburization would have lowered the hardness of the part to a range of approximately 24-29 HRC. At this hardness range, it is most likely that "mushrooming" of the back surface of the locking block (as noted with previous "After-Market" locking blocks after gun mount testing) could occur during repeated contact with the 50-55 HRC rotor. This condition greatly reduces the service life of the locking blocks. Table 6; Appendix A lists the results of this testing.

Disassembled Component Examination

The breech bolt assembly was disassembled in order that the individual components could be examined. Figure 19 shows the individual components which comprised the breech bolt assembly.

Cam Pin per Eng. Dwg. 11691417

Dimensional Analysis

The major dimensions of the component were measured with a Bausch and Lomb Optical Comparator as well as a vernier caliper. All measured dimensions conformed to Engineering Drawing 11691417.

Magnetic Particle Inspection

The component was subjected to magnetic particle inspection per MIL-I-6868. The wet continuous method was employed. Testing was conducted on a Magnaflux inspection machine. No indications were revealed as a result of this inspection.

Chemical Analysis

Chemical analysis was performed on a section of the component to verify the composition per QQ-S-763 (CRES), Class 440A. The carbon content was determined by combustion-infrared detection, the sulfur by combustion-automatic titration, and all other elements by direct current plasma emission spectroscopy. The results of this analysis are listed in Appendix B, Table 7. The chemistry conformed to the specified requirements of QQ-S-763 (CRES), Class 440A.

Hardness Testing

Hardness measurements utilizing the HR_{15-N} scale were taken on a sectioned and mounted portion of the cam pin. The piece was mounted in Bakelite with edge retention, and metallographically prepared. Drawing 11691417 indicated the part must conform to 84.5-88.0 HR_{15-N}. Appendix B, Table 8 shows that the average of ten readings fell within this required range although some readings slightly exceeded the upper limit.

Metallography

The sectioned and mounted portion of the cam pin was subsequently etched with Fry's reagent, in order to reveal the microstructure. The structure consisted of partly spheroidized chromium carbide particles in a martensitic matrix, as shown in Figure 20. This structure was consistent with prior the heat treatment (austenitize, quench and temper) of CRES Class 440A material. Note the presence of prior austenitic grain boundaries.

Firing Pin per Eng. Dwg. 11691418

Dimensional Analysis

The major dimensions of the component were measured with a Bausch and Lomb Optical Comparator as well as a vernier caliper. All measured dimensions conformed to Engineering Drawing 11691418.

Magnetic Particle Inspection

The component was subjected to magnetic particle inspection per MIL-I-6868. The wet continuous method was employed. Testing was conducted on a Magnaflux inspection machine. No indications were revealed as a result of this inspection.

Coating Thickness and Verification

The coating of the firing pin was measured and verified. The coating thickness measurements were performed from micrographs of the mounted and polished part (Figure 21, representative), while the coating verification was performed through energy dispersive spectroscopy (EDS). Drawing 11691218 specifies Watts nickel finish per QQ-N-290, 0.00005 to 0.00015 inch thick prior to electroless nickel coating per 1.4.3.2 of MIL-STD-171, 0.0003 to 0.0005 inch thick (total= 0.00035 - 0.00065 inch). The coating was uniform and measured 0.00034 inch in thickness, which was slightly below the required thickness (see Table 9, Appendix C). EDS of the coating confirmed nickel plating, as shown in Figure 22. The presence of phosphorus on the EDS spectrum is attributable to constituents within the electroless nickel bath.

Chemical Analysis

Chemical analysis was performed on a section of the component to determine if the composition of the material conformed to MIL-S-46850, Maraging Steel, Type III, Grade 300, or corrosion resistant steel (CRE) per AMS 5617. The carbon content was determined by combustion-infrared detection, the sulfur by combustion-automatic titration, and all other elements by direct current plasma emission spectroscopy. The results of this analysis are listed in Appendix C Table 10. This table shows that the chemistry closely resembles that of maraging steel, rather than the corrosion resistant steel alternative. However, the nickel and molybdenum content (both subjected to double checks) were higher and lower, respectively, than specified within MIL-S-46850. In addition, the titanium and silicon contents were higher than specified within this specification. Excess nickel and titanium within a maraging steel most likely do not have a detrimental affect on mechanical properties. The molybdenum and silicon results, however, could affect mechanical properties. Molybdenum aids the age hardening process, and a less than nominal amount of this element may tend to lower the component yield strength. Silicon in maraging steel has been shown to lower notch tensile strength as the content surpasses the maximum limit [2]. Since hardness testing (see *Hardness Testing* section) conformed to the required specifications, it is likely the mechanical properties were not drastically impacted by the nonconforming chemistry. However, this nonconformance does suggest a lack of melt control on behalf of the manufacturer.

Hardness Testing

Hardness measurements utilizing the $HR_{15\text{-}N}$ scale were taken on a sectioned and mounted portion of the firing pin. The piece was mounted in Bakelite with edge retention, and metallographically prepared. Drawing 11691418 indicates the part must conform to 85.5 $HR_{15\text{-}N}$ minimum. Table 11, Appendix C lists the results of this testing. Each reading conformed to the governing drawing.

Microstructure, Grain Size

The sectioned and mounted portion of the firing pin was subsequently etched with 4% nital, in order to reveal the microstructure. The structure consisted of aged low-carbon martensite, as shown in Figure 23. This structure was consistent with the prior heat treatment (solution-anneal, age, air cool). Section 3.6.3 of MIL-S-46850 states that for Grade 300, Type III material, *the grain size shall be predominantly six or finer with grains as large as four permissible in accordance with the applicable ASTM E 112 chart.* The 100x micrograph of Figure 24 shows the grain size to be between seven and eight, in conformance to the governing specification. No internal or surface defects were noted within the microstructure.

Bolt Shaft, Top per Eng. Dwg. 11691411

Dimensional Analysis

The major dimensions of the component were measured with a Bausch and Lomb Optical Comparator, as well as a vernier caliper. All measured dimensions conformed to Engineering Drawing 11691411.

Magnetic Particle Inspection

The component was subjected to magnetic particle inspection per MIL-I-6868. The wet continuous method was employed. Testing was conducted on a Magnaflux inspection machine. No indications were revealed as a result of this inspection.

Chemical Analysis

Chemical analysis was performed on a section of the component to verify the composition per MIL-S-46850, Maraging Steel, Type III, Grade 300. The carbon content was determined by combustion-infrared detection, the sulfur by combustion-automatic titration, and all other elements by direct current plasma emission spectroscopy. The carbon and sulfur content was analyzed by the Leco combustion method. The results of this analysis are listed in Appendix D, Table 12. The silicon content was nearly double the required limit. As mentioned previously, silicon is detrimental to this alloy and should be kept to a minimum.

Microstructure, Grain Size

A sectioned, mounted and metallographically prepared portion of the bolt shaft, top was subsequently etched with 4% nital, in order to reveal the microstructure. The structure consisted of aged low-carbon martensite, as shown in Figure 23 (microstructure of firing pin, however, representative of bolt shaft, top). This structure was consistent with the prior heat treatment (solution-anneal, age, air cool). The mounted sample, etched with 4% nital was utilized for grain size determination. Section 3.6.3 of MIL-S-46850 states that for Grade 300, Type III material, *the grain size shall be predominantly six or finer with grains as large as four permissible in accordance with the applicable ASTM E 112 chart.* The 100x micrograph of Figure 24 (structure of firing pin, but representative of the bolt shaft, top) shows the grain size to be between seven and eight, in conformance to the governing specification.

Nitride Case Verification - Metallography

The bolt shaft, top was required to be nitrided according to AMS 2755 to a case depth of 0.0005 inch. The case hardness was required to be HRC 60, minimum. An alternate method of heat treatment specified the application of a phosphate coating, followed by nitriding per AMS 2756. This method requires a case depth of 0.001 inch, and a case hardness of 60 HRC minimum. Maraging steels are commonly simultaneously nitrided and aged to provide a shallow but hard case to improve wear resistance and/or fatigue properties [3]. AMS 2755 indicates that alloy steels when etched with nital will reveal a dark zone which represents approximately 1/4 of the total nitrogen diffusion. ASM, on the other hand, suggests the use of Fry's reagent instead of nital to reveal a nitrided case in maraging steels [4]. Subsequently, the sectioned and mounted portion of the bolt shaft, top was repolished to remove the 4% nital etchant. A nitrided case, which would have etched dark as a result of immersion within Fry's reagent, was not detected (Figure 25).

Nitride Case Verification - Microhardness

A Knoop microhardness profile was conducted to determine the presence of a nitrided case on the mounted sample, in the as-polished condition. In general, case depth measurements determined by this method are more accurate than those made by metallographic inspection of etched specimens. No significant hardness gradient was noted as shown in Table 13 of Appendix D. From the micrograph of the etched sample shown in Figure 26, the reading closest to the surface should be completely within the case, assuming a 0.0005 inch case depth. For a case depth of 0.001 inch, the first two readings would be fully within the nitrided case. Each of the readings supposedly within the nitrided case converted to an HRC of 50-55, not HRC 60, as specified.

Nitride Case Verification - Macrohardness

The $HR_{15\text{-}N}$ test is commonly used to measure the case hardness of the actual component, as discussed in ASM's Heat Treating Reference Handbook, Volume 4, Ninth Edition [5]. A total of ten readings were taken along the outer surface of the bolt shaft, top. The results, listed in Table 14 of Appendix D, show an HRC equivalent of 60 was not attained. The readings ranged from 87.5 to 88.5 $HR_{15\text{-}N}$, which correlates to approximately 54 to 56 HRC. The depth of hardness indentation was calculated to ensure the 15 kg load did not penetrate the case, and measure the hardness of the core. The depth of penetration of the $HR_{15\text{-}N}$ diamond indenter was calculated from the following formula, taken from the ASM Mechanical Testing Reference Handbook, Volume 8, Ninth Edition [6]:

$$(100 - HR_{15\text{-}N}) \times 0.001\text{mm} = \text{depth of penetration}$$

Applying this formula, a hardness of 87.5 $HR_{15\text{-}N}$ (the lowest reading measured) had a depth of penetration of 0.00049 inch, barely within a 0.0005 inch case, and safely within a case depth of 0.001 inch. The highest reading measured, 88.5 $HR_{15\text{-}N}$, had a depth of indentation of 0.00045 inch, safely within each of the case depths. In short, this technique was a valid method for measuring the surface hardness of the part.

In addition, a sectioned piece of the component was examined through energy dispersive spectroscopy (EDS) in conjunction with a scanning electron microscope (SEM). EDS examination of the surface layer at high magnifications did not reveal the presence of nitrogen. It can be stated with certainty, from each of these four nitride case verification procedures utilized, that a nitrided case did not exist on the bolt shaft, top component.

It was learned at the 20mm PGU Series Ammunition Performance Investigation Meeting II (June 13-15, 1994) that a catastrophic failure of top and bottom bolt shafts ("After-Market") had occurred during recent gun mount firing tests at NAWCAD, Patuxent River. The failure of these components was attributed to fatigue upon investigation by a Naval contractor representative. Once disassembled, another bolt shaft, top was noted to be cracked from the same gun. The presence (or lack thereof) of a nitrided case was not investigated at that time [7]. Recently, ARL examined these components as part of a parallel investigation (refer to ARL letter report entitled "Product Verification of Disassembled and Failed M61A1 Locking Blocks and Bolt Shaft Assemblies", dated 19 September 1994), and determined that each failed component lacked a nitrided case. ARL strongly believes these components had failed due to a coexistence of manufacturing deficiencies and the utilization of the PGU Series ammunition.

Macrohardness Testing

Hardness measurements utilizing the HRC scale were taken on a sectioned and mounted portion of the bolt shaft, top. The piece was mounted in Bakelite with edge retention, and metallographically prepared. Drawing 11691411 indicates the part must conform to 50-55 HRC. Table 15, Appendix D lists the results of this testing. Each reading conformed to the governing drawing.

<u>Bolt Shaft, Roller per Eng. Dwg. 7268635</u>

Dimensional Analysis

The major dimensions of the component were measured with a Bausch and Lomb Optical Comparator, as well as a vernier caliper. All measured dimensions conformed to Engineering Drawing 7268635.

Magnetic Particle Inspection

The component was subjected to magnetic particle inspection per MIL-I-6868. The wet continuous method was employed. Testing was conducted on a Magnaflux inspection machine. No indications were revealed as a result of this inspection.

Chemical Analysis

Chemical analysis was performed on a section of the component to verify the composition per AISI 4140 of ASTM A 322 and ASTM A 331. The carbon content was determined by combustion-infrared detection, the sulfur by combustion-automatic titration, and all other elements by direct current plasma emission spectroscopy. The results of this analysis are listed in Appendix D, Table 16. The chemistry conformed to the specified requirements of AISI 4140 per ASTM A 322.

Metallography

A sectioned and mounted portion of the bolt shaft, roller was prepared metallographically and subsequently etched with 4% nital, in order to reveal the microstructure. The structure of the AISI 4140 steel consisted of fine tempered martensite, as shown in Figure 27. This structure was consistent with the prior heat treatment (austenitize, quench and temper). No internal or surface defects were noted within the microstructure.

Hardness Testing

Hardness measurements utilizing the HRA scale were taken on the sectioned and mounted portion of the bolt shaft, roller. Drawing 7268635 indicates the part must conform to 70.4-73.1 HRA. Table 17, Appendix D lists the results of this testing. Each reading conformed to the hardness limits of the governing drawing.

Bolt Shaft, Bottom per Eng. Dwg. 11691416

Dimensional Analysis

The major dimensions of the component were measured with a Bausch and Lomb Optical Comparator, as well as a vernier caliper. All measured dimensions conformed to Engineering Drawing 11691416.

Magnetic Particle Inspection

The component was subjected to magnetic particle inspection per MIL-I-6868. The wet continuous method was employed. Testing was conducted on a Magnaflux inspection machine. No indications were revealed as a result of this inspection.

Chemical Analysis

Chemical analysis was performed on a section of the component to verify the composition per MIL-S-46850, Maraging Steel, Type III, Grade 300. The carbon content was determined by combustion-infrared detection, the sulfur by combustion-automatic titration, and all other elements by direct current plasma emission spectroscopy. The results of this analysis are listed in Appendix D, Table 18. The nickel content was slightly higher than specified, while the silicon content was almost double the allowable limit. As mentioned previously, the nickel content most likely would not heavily impact the mechanical properties of the alloy, however, silicon should be kept to a minimum.

Microstructure, Grain Size

The sectioned and mounted portion of the bolt shaft, bottom was subsequently etched with 4% nital, in order to reveal the microstructure. The structure consisted of aged low-carbon martensite, as shown in Figure 23 (microstructure of firing pin, however, representative of bolt shaft, bottom). This structure was consistent with the prior heat treatment (solution-anneal, age, air cool). The mounted sample, etched with 4% nital was utilized for grain size determination. Section 3.6.3 of MIL-S-46850 states that for Grade 300, Type III material, *the grain size shall be predominantly six or finer with grains as large as four permissible in accordance with the applicable ASTM E 112 chart.* The 100x micrograph of Figure 24 (structure of firing pin, but representative of bolt shaft bottom) shows the grain size to be between seven and eight, in conformance to the governing specification.

Nitride Case Verification - Metallography

The bolt shaft, bottom (similar to bolt shaft, top) was required to be nitrided according to AMS 2755 to a case depth of 0.0005 inch. The case hardness was required to be HRC 60, minimum. An alternate method of heat treatment specified the application of a phosphate coating, followed by nitriding per AMS 2756. This method requires a case depth of 0.001 inch, and a case hardness of 60 HRC minimum. The sectioned, mounted portion of the bolt shaft, bottom was repolished to remove the 4% nital etchant. Similar to bolt shaft, top, a nitrided case was not detected as a result of this etching with Fry's reagent (Figure 28)

Nitride Case Verification - Microhardness

A Knoop microhardness profile was conducted to determine the presence of a nitride case on the mounted sample, in the as-polished condition. No significant hardness gradient was noted as shown in Table 19 of Appendix D. From the micrograph of the etched sample shown in Figure 29, the reading closest to the surface should be completely within the case, assuming a 0.0005 inch case depth. For a case depth of 0.001 inch, the first two readings would be fully within the nitrided case. Each of the readings supposedly within the nitrided case converted to an HRC of 50-55, not HRC 60, as specified.

Nitride Case Verification - Macrohardness

A total of ten $HR_{15\text{-}N}$ readings were taken along the curved outer surface of the bolt shaft, bottom. The results, listed in Table 20 of Appendix D, show an HRC equivalent of 60 was not attained. The readings ranged from 86.0 to 87.3 $HR_{15\text{-}N}$, which correlates to approximately 51 to 54 HRC. The depth of hardness indentation was calculated to ensure the 15 kg load did not penetrate the case, and measure the hardness of the core.

Applying the formula utilized for bolt shaft, top, all hardness readings would have penetrated a case 0.0005 inch in depth. However, the indents would have fell safely within a case depth of 0.001 inch. All readings fell at or below 87.3 HR_{15-N}, which was the cutoff point, correlating to a depth of indentation of 0.0005 inch. However, if a nitrided case was present on the component, and it was HRC 60 as required, the indenter would not have had penetrated this far into the material.

In addition, a sectioned piece of the component was examined through energy dispersive spectroscopy (EDS) in conjunction with the scanning electron microscope (SEM). EDS examination of the surface layer at high magnifications did not reveal the presence of nitrogen. It can be stated with certainty, from each of these four nitride case verification procedures utilized, that a nitrided case did not exist on the bolt shaft, bottom component.

Macrohardness Testing

Hardness measurements utilizing the HRC scale were taken on a sectioned and mounted portion of the bolt shaft, bottom. The piece was mounted in Bakelite with edge retention, and metallographically prepared. Drawing 11691411 indicates the part must conform to 50-55 HRC. Table 21, Appendix D lists the results of this testing. Each reading conformed to the governing drawing.

<u>Breech Bolt Body per Eng. Dwg. 11691423</u>

Dimensional Analysis

The major dimensions of the component were measured with a Bausch and Lomb Optical Comparator, as well as a vernier caliper. All measured dimensions conformed to Engineering Drawing 11691423.

Magnetic Particle Inspection

The component was subjected to magnetic particle inspection per MIL-STD-1949. The wet continuous method was employed. Testing was conducted on a Magnaflux inspection machine. No indications were revealed as a result of this inspection.

Grain Flow

The grain flow of the forged component was inspected to determine conformance with the figure shown on Drawing 11691423 - 1 of 3 (see Figure 30). The part was sectioned lengthwise and macroetched with a 50% HCl and 50% distilled water solution at 180°F. The resultant flow lines conformed to the governing figure.

Chemical Analysis

Chemical analysis was performed on a section of the component to verify the composition per MIL-S-5000 (AISI E4340). The carbon content was determined by combustion-infrared detection, the sulfur by combustion-automatic titration, and all other elements by direct current plasma emission spectroscopy. The results of this analysis are listed in Appendix E, Table 22. The chemistry conformed to the specified requirements of MIL-S-5000.

Metallography

A portion of the breech bolt body was sectioned and prepared metallographically, in order to examine the microstructure of the component. A 4% nital etchant was applied to the polished surface. As shown in Figure 31, the structure of the AISI E4340 steel consisted of fine tempered martensite, consistent with the prior heat treatment (austenitize, quench and temper). No defects were noted internally, and no decarburization existed on the outer surface.

Hardness Testing

Hardness tests were conducted on the sectioned and mounted section of the breech bolt body. Drawing 11691423 indicates that the part must be hardened to 43-48 HRC. Table 23, Appendix E lists the results of this testing. Each reading fell within the specified hardness limits.

Locking Block from Assembly per Eng. Dwg. 11691430

Visual inspection revealed a marked difference in appearance between the individual locking block, and the locking block from the assembly. The difference in surface finish was perhaps the most striking contrast between the two components. As shown earlier, the individual locking block had excessive machining marks, while the assembly locking block was much smoother. Moreover, the surface of the assembly locking block did not contain the "as-forged" appearance of the individual component. Also, the machined recesses of each part were of different widths (both were within specification). These differences suggest that the process was not repeatable by the primary contractor, or that maybe two different subcontractors were utilized. In addition, no corrosion was noted on the well lubricated assembly locking block.

Surface Finish

The surface roughness of the locking block was measured with the Mitutoyo Surftest 401 Analyzer. Readings were taken across the top and bottom of the part (see schematic in Figure 32). These were the regions of the component which exhibited machining marks, although not as severe as the machining marks noted on the locking block shipped separately (Figures 33 and 34). The required average surface roughness of the top and bottom of this component was 125 μin RMS (Eng. Dwg. 11691480). The top surface registered an average of 58.4 μin

RMS, while the bottom averaged 82.0 μin RMS. These results (shown in Table 24, Appendix F) indicate the surface roughness of the part was well within the specified range.

Dimensional Analysis

The major dimensions of the component were measured with a Bausch and Lomb Optical Comparator as well as a vernier caliper. All measured dimensions conformed to Engineering Drawing 11691430.

Magnetic Particle Inspection

The component was subjected to magnetic particle inspection per MIL-STD-1949. The wet continuous method was employed. Testing was conducted on a Magnaflux inspection machine. No indications were revealed as a result of this inspection.

Grain Flow

The grain flow of the locking block was examined to verify conformance to the figure on Engineering Drawing 11691430. The component was sectioned lengthwise, mounted, and metallographically prepared. Rough polishing was accomplished through silicon carbide papers, while fine polishing was performed with 9μm and 0.25μm diamond grit. A macroetch of 50% HCl and 50% distilled water at 180°F was used to reveal the flow lines. The flow lines conformed to the governing drawing. In addition, two distinct structures were noted between the induction hardened region above the pin hole (50-55 HRC) and the remainder of the component (38-43 HRC), as shown in Figure 35 (contrast to Figure 13-locking block, individual).

Microstructure

The sectioned portion of the locking block which was macroetched to verify grain flow, was also utilized to examine the microstructure. A 4% nital etchant was applied to the polished surface, to reveal a fine tempered martensitic structure. This microstructure was consistent with the prior heat treatment (austenitize, quench and temper). Figure 14, although that of the other locking block, was typical of the microstructure noted within this locking block. The structure of the part was free from deleterious defects, and, in contrast to the other locking block, the outer surface contained no signs of decarburization (Figure 36).

Chemical Analysis

Chemical analysis was performed on a section of the component to verify the composition of the material per MIL-S-5626 (AISI 4140). The carbon content was determined by combustion-infrared detection, the sulfur by combustion-automatic titration, and all other elements by direct current plasma emission spectroscopy. The results of this analysis are listed in Appendix F, Table 25. The carbon content was checked three times, and was found to be higher than specified. This excess carbon had no affect on the component hardness (see *Macrohardness Testing Section).*

Microhardness Testing

Knoop microhardness testing was conducted in a similar manner to that performed on the individual locking block shipped separately. The purpose was to verify that no decarburization existed. Six profiles were measured; two in the bail region, two emanating from the top and bottom surfaces of the component, and two from the front and back surfaces of the component. As shown in Appendix F, Table 26, there was not an appreciable difference in microhardness between readings taken close to the surface, and readings deeper within the core. This, along with metallography, verified that little to no decarburization existed on this component.

Macrohardness Testing

The sectioned locking block was subjected to macrohardness testing (Hardness Rockwell "C"). Readings were taken on the sectioned surface of the locking block to determine conformance to the governing drawing. Drawing 11691430 indicates the part must be 50-55 HRC in the bail section above the pin hole, and 38-43 HRC throughout the remainder of the part. The hardness results suggest the part was hardened to 50-55 HRC in the required region, and within the specified range throughout the remainder of the component, as shown in Appendix F, Table 27. Readings 1 through 5 (2 through 4 above the pin hole) were taken in the bail section, while readings 6 through 15 were taken within the body.

Macrohardness measurements were also taken on the exterior surface of the part to determine the effect of decarburization on surface hardness. Readings were taken on the bail, side, top and bottom surfaces of the component. No substantial loss of hardness due to decarburization was noted. Table 28, Appendix F lists the results of this testing.

<u>Extra Heavy-Duty Spiral Type Spring Pins per Eng. Dwg. 11691266</u>

Dimensional Analysis

The major dimensions of the component were measured with a Bausch and Lomb Optical Comparator, as well as a vernier caliper. All measured dimensions conformed to Engineering Drawing 11691266.

Double Shear Testing

The two pins from the assembly were subjected to double shear testing in an Instron 20K pound electromechanical test machine. The pins were labelled "Top" (the pin which affixed the shaft to the body of the bolt shaft assembly) and "Bottom" (the pin which joined the locking block to the breech bolt body). A standard double shear fixture was utilized. The results listed in Table 29 of Appendix G indicate that each spring pin failed to achieve the minimum required load as specified on Drawing 11691266. The fact that the carbon content was extremely high (see "Chemical Analysis" section), may be the reason the "bottom" pin failed by such a great magnitude.

Microhardness Testing

A broken half of each spring pin was mounted in Bakelite and subsequently prepared for microhardness testing. A minimum Knoop hardness of 542 was specified on Drawing 11691266. Although some of the readings fell below this limit, the average of ten readings for both of the parts conformed to the required hardness, as shown in Table 30 of Appendix G.

Chemical Analysis

Chemical analysis was performed on a section of the components to verify the composition of the material per MIL-S-46850, Maraging Steel, Type III, Grade 300. The carbon content was determined by combustion-infrared detection, the sulfur by combustion-automatic titration, and all other elements by direct current plasma emission spectroscopy. The results of this analysis are listed in Appendix G, Table 31. Each spring pin contained a higher silicon content than specified. Silicon in this alloy should be kept below the maximum allowed because of its tendency to lower yield strength. In addition, the carbon content of the "Bottom" pin was higher than specified by an order of magnitude. Just slight increases of carbon (total=0.05% C) in Grade 300 maraging steel have been shown to lower the notch-tensile strength significantly. [8]

Metallography

The sectioned and mounted portions of the spring pins were examined in the as-polished condition. Figures 37 and 38 are of the "Top" and "Bottom" pins, respectively. Note the increased carbides contained internally within the "Bottom" pin. These carbides act as "perforations" with the onset of a crack front, offering little to no resistance to crack propagation, compared to a structure with no inclusions. This may explain the low double shear load achieved by the "Bottom" pin. The samples were subsequently etched with Fry's reagent, in order to reveal the microstructure. The structure of the "Top" spring was that of aged low-carbon martensite, consistent with the prior heat treatment (solution-anneal, age, air cool). The finer grains (compared to the other maraged components) are most likely the result of a lower annealing temperature (Figure 39). Note the difference in the etched structure of the "Bottom" pin (Figure 40). This microstructure that of aged low-carbon martensite, with increased carbides. No internal or surface defects were noted within the microstructures of each pin.

Coating Thickness and Verification

The pins were designated to be plated with copper flash for identification purposes. The coatings of each of the spring pins were measured and verified. The coating thickness measurement was performed from micrographs of the mounted and polished parts (Figure 41 representative), while the coating verification was performed through energy dispersive spectroscopy (EDS). Drawing 11691266 specifies a flash copper plate not to exceed 0.0001 inch in thickness, most likely because dimensional buildup could not be tolerated. Coating thickness measurements of each component indicated nonconformance to this requirement.

Measurements of the coating on the "Top" sample ranged from 0.00013 to 0.00019 inch, with an average of 0.00015 inch, while the coating thickness of the "Bottom" sample ranged from 0.00016 to 0.00022 inch with an average of 0.00019 inch (see Table 32, Appendix G). A thicker than nominal coating would cause a tighter fit as this component is forced into the pin hole.

EDS of the coating on the "Top" spring, confirmed that copper plating was utilized. The iron peak represents the base metal, while the silicon and cobalt peaks represent elements found within the chemistry of the base material. EDS of the coating of the "Bottom" spring also confirmed the presence of copper plating, as shown in Figure 42.

<u>Helical Compression Spring per Eng. Dwg. 11691419</u>

Dimensional Verification

The coil outer diameter, the spring free length, the spring solid length and the total coils were each measured with a vernier caliper. Each dimension conformed to those listed on Drawing 11691419 (see Table 33 of Appendix H).

Load at Compressed Length of 0.51 Inch

The spring was subjected to compression tests to determine conformance with the governing drawing. The drawing states that a load of 2.0 +/- 0.2 pounds must be attained at a compressed length of 0.51 inch. Testing was conducted on the Instron 20K pound electromechanical tabletop test machine. A 225 pound load cell was utilized with the 4.5 pound range. Two tests were performed; one at 0.02 inch/minute compression rate, and the other at 0.08 inch/minute compression rate. An identical load (1.88 pound) was attained for each rate (see Table 34, Appendix H). This load conformed to the governing drawing.

Chemical Analysis

Chemical analysis was performed on a section of the component to verify the composition per QQ-W-470. The carbon content was determined by combustion-infrared detection, the sulfur by combustion-automatic titration, and all other elements by direct current plasma emission spectroscopy. The results of this analysis are listed in Appendix H, Table 35. The chemistry conformed to the specified requirements of QQ-W-470.

Coating Thickness and Verification

The coating of the compression spring was measured and verified. The coating thickness measurement was performed from micrographs of the mounted and polished parts (Figure 43 representative), while the coating verification was performed through energy dispersive spectroscopy (EDS). Drawing 11691419 specifies the coating shall conform to Grade B of MIL-S-13572. Grade B springs are required to be cadmium plated in accordance with QQ-P-416, Type II, Class 2, or zinc coated in accordance with ASTM B 633, Condition SC 3.

EDS of the coating was performed to determine which coating was utilized, and therefore, which specification applied. EDS of the coating revealed that zinc was utilized (Figure 44), and thus specification ASTM B 633 applied. Measurements of the coating ranged from 0.00044 to 0.00047 inch, with an average of 0.00045 inch (see Table 36 Appendix H). This average thickness fell slightly below the requirement set forth in specification ASTM B 633, which indicated a minimum coating thickness of 12 um, or 0.00047 inch.

Metallography

The sectioned and mounted portion of the helical compression spring was subsequently etched with 4% nital, in order to reveal the microstructure. The structure of the QQ-W-470 wire consisted of elongated ferrite and fine pearlite grains, as shown in Figure 45. This structure was consistent with cold drawn, high carbon steel wire. No internal or surface defects were noted within the microstructure.

Conclusion

ARL has revealed many significant material and/or process deficiencies as a result of this investigation. Each of the noted deficiencies would most likely have an impact on the service life of the affected component. Substantiating this claim, is the fact that bolt shaft assemblies which have failed in service were determined to have lacked a nitrided case, crucial to fatigue and wear resistance. The use of recently developed, more powerful PGU ammunition most likely increases the risk of failure when used in conjunction with these deficient components.

SUMMARY OF SIGNIFICANT FINDINGS

Locking block (Individual)

*Visual examination revealed corrosion and a rough surface finish on the unlubricated part.
*Surface finish measurements confirmed the top and sides had excessive machining marks. The surface roughness did not conform to the Eng. Dwg.
*Metallography revealed a complete layer of decarburization along the periphery of the component, which was prohibited according to the governing specification. The depth of decarburization was greater than specified.
*Macrohardness testing showed that the entire component (not just the region above the bail) was hardened to 50-55 HRC, not 38-43 HRC as specified. Macrohardness tests also showed a substantial loss of surface hardness due to the layer of decarburization.

Bolt Shaft, Top

*Chemical analysis revealed a higher than nominal silicon content.
*Metallography, micro- and macrohardness testing failed to confirm the presence of a nitrided case.

Bolt Shaft, Bottom

*Chemical analysis revealed a higher than specified nickel content, and a high silicon content.
*Metallography, micro- and macrohardness testing failed to confirm the presence of a nitrided case.

Locking Block from Assembly

*Chemical analysis revealed a higher than specified carbon content.

Spiral Spring Pins

*Both the "Top" and "Bottom" spring pins failed to attain the specified 3,900 pound double shear load. The "Top" pin achieved a load of 3,775 pounds, while the "Bottom" pin achieved a load of only 1,990 pounds.
*Chemical analysis of the "Top" pin revealed a higher than nominal silicon content, while analysis of the "Bottom" pin revealed an enormous amount of carbon (10 times the maximum specified) and a high silicon content. The high carbon content most likely attributed to the poor results in the double shear testing of the "Bottom" pin.

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7. Conversation with Mr. John Fahnestock, NAWCAD, Patuxent River, 20 June 1994.
8. Decker, R.F., Eash, J.T., Goldman, A.J., *18% Nickel Maraging Steel*, Source Book on Maraging Steels, American Society for Metals, p. 9, 1979.

APPENDIX A - Individual Locking Block Testing

Table 1 Individual Locking block surface finish measurements
Table 2 Individual Locking block chemical analysis
Table 3 Individual Locking block microhardness results
Table 4 Individual Locking block decarburization depth measurements
Table 5 Individual Locking block macrohardness results (interior)
Table 6 Individual Locking block macrohardness results (exterior)

Table 1
Individual Locking Block Surface Finish Measurements
μin RMS

	Top	Side
	135	125
	129	150
	132	153
	140	200
	118	180
	126	160
	139	171
	133	152
	130	130
	137	185
Average	132	161
Dwg. 11691480	125	125

Table 2
Individual Locking Block Chemical Composition
Weight Percent

Element	Component	MIL-S-5626 (AISI 4140)
Carbon	0.39	0.38-0.43
Manganese	0.95	0.75-1.00
Phosphorus	0.016	0.025 max.
Sulfur	0.018	0.025 max.
Silicon	0.21	0.20-0.35
Chromium	0.86	0.80-1.10
Molybdenum	0.16	0.15-0.25
Copper	0.09	0.35 max.
Nickel	0.15	0.25 max.
Iron	remainder	remainder

Table 3
Individual Locking Block Microhardness Testing
Knoop Microhardness Profiles
100gm Load - 20X Objective

Prof. A (bail)	Prof. B (bail)	Prof. C (Top)	Prof. D (Bott.)	Prof. E (Fnt.)	Prof. F (Back)
245 HK	268 HK	219 HK	223 HK	208 HK	313 HK
476	470	413	371	404	465
523	538	465	473	433	534
523	559	548	521	518	599
516	588	592	576	546	589
611	610	602	619	598	633
637	641	646	623	631	633
623	626	632	654	622	642
627	651	658	645	620	647
647	660	652	641	644	643
Core Avg. 634	Core Avg. 645	Core Avg. 647	Core Avg. 647	Core Avg. 629	Core Avg. 640

Table 4
Individual Locking Block Decarburization Measurements
Micrograph Measurements

	Depth (inch)
Profile A	0.0054
Profile B	0.0059
Profile C	0.0062
Profile D	0.0069
Profile E	0.0064
Profile F	0.0053
MIL-H-6875	0.003 maximum

Table 5
Individual Locking Block Macrohardness Testing (Interior)
HRC-150 kg
Location - Sectioned Surface

Ind. Hard. Avg. = 54.1 HRC
Dwg. 11691430 = 50-55 HRC

Main body Avg. = 54.3 HRC
Dwg. 11691430 = 38-43 HRC

Reading	HRC		
1	54.4		
2	53.9	Ind. Hard.	Bail
3	54.2	Region	
4	54.2		
5	54.7		
6	53.5		
7	53.1		
8	51.3		
9	52.9		
10	52.5	Main body	
11	55.8		
12	55.8		
13	56.0		
14	55.9		
15	55.5		

Table 6
Individual Locking Block Macrohardness Testing (Exterior)
HRC-150 kg
Exterior Surfaces

	Bail	Top	Side	Bottom
	54.7	45.3	47.4	52.8
	45.9	44.4	49.1	49.2
	47.7	41.9	49.6	45.6
	41.9	44.1	49.3	44.8
	46.9	56.7	49.4	45.6
Average	47.4	46.5	49.0	47.6
Dwg. 11691430	50-55	38-43	38-43	38-43

APPENDIX B - Cam Pin Testing

Table 7 Cam pin chemical analysis
Table 8 Cam pin macrohardness results

Table 7
Cam Pin
Chemical Analysis
Weight Percent

Element	Component	QQ-S-763, Class 440A
Carbon	0.63	0.60-0.75
Manganese	0.41	1.00 max.
Phosphorus	0.012	0.04 max.
Sulfur	<0.001	0.03 max.
Silicon	0.40	1.00 max.
Chromium	16.1	16.0-18.0
Molybdenum	0.44	0.75 max.
Iron	remainder	remainder

Table 8
Cam Pin
$HR_{15\text{-}N}$ -15 kg
Sectioned Surface

	88.2
	88.3
	87.8
	88.3
	88.1
	88.2
	87.7
	86.6
	88.1
	88.0
Average	87.9 $HR_{15\text{-}N}$
Dwg. 11691417	84.5-88.0 $HR_{15\text{-}N}$

APPENDIX C - Firing Pin Testing

Table 9 Firing pin nickel plating thickness measurements
Table 10 Firing pin chemical analysis
Table 11 Firing pin macrohardness results

Table 9
Firing Pin Nickel Plating Thickness
Micrograph Measurements (Inch)

	0.00034
	0.00034
	0.00034
	0.00034
	0.00034
Average	0.00034 inch
Dwg. 11691418	0.00035-0.00065 inch

Table 10
Firing Pin Chemical Analysis
Weight Percent

Element	Component	MIL-S-46850, Grade 300	CRE (AMS 5617)
Nickel	19.6*, 19.8*	18.0-19.0	7.0-9.0
Cobalt	9.2	8.5-9.5	N/A
Molybdenum	4.53*, 4.46*	4.6-5.2	0.50 max.
Titanium	0.87*	0.5-0.8	0.90-1.40
Aluminum	0.11	0.05-0.15	N/A
Carbon	0.009	0.03 max.	0.03 max.
Manganese	0.015	0.10 max.	0.50 max
Silicon	0.15*	0.10 max.	0.50 max.
Phosphorus	0.054	0.01 max.	0.015 max.
Sulfur	<0.001	0.01 max.	0.015 max.
Boron	<0.001	0.003 max.	N/A
Zirconium	0.003	0.020 max.	N/A
Calcium	0.002	0.050 max.	N/A
Copper	-----	N/A	1.50-2.50
Nitrogen	-----	N/A	0.015 max.
Columb. + Tant.	-----	N/A	0.50 max.
Iron	remainder	remainder	remainder

* - Does not meet requirement of MIL-S-46850

Table 11
Firing Pin Hardness Testing
HR_{15-N} -15 kg
Sectioned Surface

	87.5
	87.6
	88.2
	88.2
	87.8
	87.9
	87.9
	88.1
	88.6
	88.0
Average	88.0 HR_{15-N}
Dwg. 11691418	85.5 HR_{15-N} minimum

APPENDIX D - Bolt Shaft Assembly Testing

Table 12 Bolt shaft (top) chemical analysis
Table 13 Bolt shaft (top) nitride case verification - microhardness testing
Table 14 Bolt shaft (top) nitride case verification - macrohardness testing
Table 15 Bolt shaft (top) macrohardness testing
Table 16 Bolt shaft (roller) chemical analysis
Table 17 Bolt shaft (roller) hardness testing
Table 18 Bolt shaft (bottom) chemical analysis
Table 19 Bolt shaft (bottom) nitride case verification - microhardness testing
Table 20 Bolt shaft (bottom) nitride case verification - macrohardness testing
Table 21 Bolt shaft (bottom) macrohardness testing

Table 12
Bolt Shaft Assembly (Top) Chemical Analysis
Weight Percent

Element	Component	MIL-S-46850, Grade 300
Nickel	19.1	18.0-19.0
Cobalt	9.3	8.5-9.5
Molybdenum	4.6	4.6-5.2
Titanium	0.7	0.5-0.8
Aluminum	0.098	0.05-0.15
Carbon	0.008	0.03 max.
Manganese	0.031	0.10 max.
Silicon	0.17*	0.10 max.
Phosphorus	<0.004	0.01 max.
Sulfur	<0.001	0.01 max.
Boron	<0.001	0.003 max.
Zirconium	0.002	0.020 max.
Calcium	0.002	0.050 max.
Iron	remainder	remainder

Table 13
Bolt Shaft (Top) Microhardness Testing
Knoop 100g, 40x Objective
Verification of Case Depth

633
638
629
620
615
640
635
638
608
640

No significant gradient

Table 14
Bolt Shaft (Top) Macrohardness Testing
HR_{15-N}, 15kg
Verification of Case Depth
Exterior Surface

	88.1
	87.9
	88.0
	88.5
	87.9
	87.5
	87.9
	87.9
	88.3
	88.2
Average	88.0 HR_{15-N}
HRC Equiv.	55 HRC
Drawing 11691411	60 HRC minimum

Table 15
Bolt Shaft Assembly (Top) Macrohardness Testing
HRC-150 kg
Sectioned Surface

	54.0
	54.5
	54.5
	54.7
	54.8
	54.5
	54.7
	54.5
	54.3
	54.9
Average	54.5 HRC
Drawing 11691411	50-55 HRC

Table 16

Bolt Shaft Assembly (Roller) Chemical Analysis
Weight Percent

Element	Component	ASTM A 322 (AISI 4140)
Carbon	0.42	0.38-0.43
Manganese	0.87	0.75-1.00
Phosphorus	0.011	0.035 max.
Sulfur	0.018	0.04 max.
Silicon	0.30	0.15-0.35
Chromium	0.93	0.80-1.10
Molybdenum	0.15	0.15-0.25
Calcium	0.005	0.01 max.
Iron	remainder	remainder

Table 17

Bolt Shaft Assembly (Roller) Hardness Testing
HRA-60 kg
Sectioned Surface

	71.3
	71.8
	71.8
	71.5
	70.9
	71.8
	71.8
	71.5
Average	71.6 HRA
Drawing 7268635	70.4-73.1 HRA

Table 18

Bolt Shaft Assembly (Bottom) Chemical Analysis
Weight Percent

Element	Component	MIL-S-46850, Grade 300
Nickel	19.6*	18.0-19.0
Cobalt	9.53	8.5-9.5
Molybdenum	4.60	4.6-5.2
Titanium	0.68	0.5-0.8
Aluminum	0.10	0.05-0.15
Carbon	0.015	0.03 max.
Manganese	0.026	0.10 max.
Silicon	0.17*	0.10 max.
Phosphorus	<0.004	0.01 max.
Sulfur	0.001	0.01 max.
Boron	<0.001	0.003 max.
Zirconium	0.001	0.020 max.
Calcium	0.002	0.050 max.
Iron	remainder	remainder

Table 19

Bolt Shaft (Bottom) Microhardness Testing
Knoop 100g, 40x Objective
Verification of Case Depth

603
633
612
629
644
631
644
610
631
621

No significant gradient

Table 20

Bolt Shaft (Bottom) Macrohardness Testing
HR_{15-N}, 15kg
Verification of Case Depth
Exterior Surface

	86.7
	87.3
	87.0
	87.3
	86.2
	86.0
	86.8
	86.4
	87.0
	86.3
Average	86.7 HR_{15-N}
HRC Equiv.	53 HRC
Drawing 11691411	60 HRC minimum

Table 21

Bolt Shaft Assembly (Bottom) Macrohardness Testing
HRC-150 kg
Sectioned Surface

	54.4
	55.2
	54.2
	55.2
	54.8
	55.5
	55.6
	54.9
Average	55.0 HRC
Drawing 11691416	50-55 HRC

APPENDIX E - Breech Bolt Body Testing

Table 22 Breech bolt body chemical analysis
Table 23 Breech bolt body hardness testing

Table 22
Breech Bolt Body Chemical Analysis
Weight Percent

Element	Component	MIL-S-5000 (AISI E4340)
Carbon	0.41	0.38-0.43
Manganese	0.73	0.65-0.85
Phosphorus	0.007	0.025 max.
Sulfur	0.012	0.025 max.
Silicon	0.27	0.15-0.35
Nickel	1.69	1.65-2.00
Chromium	0.84	0.70-0.90
Molybdenum	0.24	0.20-0.30
Copper	0.14	0.35 max.
Iron	remainder	remainder

Table 23
Breech Bolt Body Hardness Testing
HRC-150kg

	45.4
	45.8
	46.4
	46.3
	45.7
	45.8
	46.3
	46.4
	46.5
	46.0
Average	46.1 HRC
Dwg. 11691423	43-48 HRC

APPENDIX F - Locking Block (From Assembly) Testing

Table 24 Locking block (from assembly) surface finish measurements
Table 25 Locking block (from assembly) chemical analysis
Table 26 Locking block (from assembly) microhardness results
Table 27 Locking block (from assembly) macrohardness results (interior)
Table 28 Locking block (from assembly) macrohardness results (exterior)

Table 24
Locking Block (From Assembly) Surface Finish Measurements
μin RMS

	Top	Side
	56	90
	53	89
	81	73
	56	90
	63	86
	51	89
	60	85
	52	81
	55	75
	57	62
Average	58	82
Dwg. 11691480	125	125

Table 25
Locking Block (From Assembly) Chemical Composition
Weight Percent

Element	Component	MIL-S-5626 (AISI 4140)
Carbon	0.46*, 0.48*, 0.46*	0.38-0.43
Manganese	0.94	0.75-1.00
Phosphorus	0.006	0.025 max.
Sulfur	0.024	0.025 max.
Silicon	0.30	0.20-0.35
Chromium	1.10	0.80-1.10
Molybdenum	0.18	0.15-0.25
Copper	0.12	0.35 max.
Nickel	0.087	0.25 max.
Iron	remainder	remainder

Table 26
Locking Block (From Assembly) Microhardness Testing
Knoop Microhardness Profiles
100gm Load - 20X Objective

	Prof. A (Bail)	Prof. B (Bail)	Prof. C (Top)	Prof. D (Bott.)	Prof. E (Fnt.)	Prof. F (Back)
	615 HK	620 HK	495 HK	480 HK	488	501
	623	618	530	519	499	522
	638	633	517	524	503	534
	649	641	516	529	520	510
	626	621	513	532	531	505
	632	625	498	525	525	526
	619	619	519	529	518	517
	634	629	496	524	522	536
	626	632	505	534	530	520
	619	626	494	539	509	515
Ave	628	626	508	524	515	519

Table 27
Locking Block (From Assembly) Macrohardness Testing (Interior)
HRC-150 kg
Sectioned Surface

Ind. Hard. Avg. = 54.8 HRC
Dwg. 11691430 = 50-55 HRC

Main body Avg. = 42.9 HRC
Dwg. 11691430 = 38-43 HRC

Reading	HRC	Region
1	36.6	Bail
2	54.7	Bail – Ind. Hard. Region
3	54.9	Bail – Ind. Hard. Region
4	54.8	Bail – Ind. Hard. Region
5	45.0	Bail
6	43.8	Main body
7	43.8	Main body
8	44.4	Main body
9	43.0	Main body
10	42.7	Main body
11	44.2	Main body
12	42.7	Main body
13	43.3	Main body
14	42.2	Main body
15	42.9	Main body

Table 28
Locking Block (From Assembly) Macrohardness Testing (Exterior)
HRC-150 kg
Exterior Surfaces

	Bail	Top	Side	Bottom
	54.1	42.4	43.2	43.9
	51.0	42.9	42.0	42.5
	54.7	44.2	43.7	45.5
	53.8	43.7	42.5	41.6
	53.5	43.1	40.6	43.7
Average	53.4	43.3	42.4	43.4
Dwg. 11691430	50-55	38-43	38-43	38-43

APPENDIX G- Extra Heavy Duty Spiral Type Spring Pin Testing

Table 29 Extra heavy duty spiral type spring pin double shear testing
Table 30 Extra heavy duty spiral type spring pin microhardness results
Table 31 Extra heavy duty spiral type spring pin chemical analyses
Table 32 Extra heavy duty spiral type spring pin plating thickness measurements

Table 29

Extra Heavy Duty Spiral Type Spring Double Shear Testing
20 KIP Instron Electromechanical Test Machine
20K lb. Load Cell, 5K lb. Range

	Maximum Load (Pounds)
Top	3,775
Bottom	1,990
Dwg. 11691266	3,900 minimum

Table 30

Extra Heavy Duty Spiral Type Spring Microhardness Testing
Knoop - 500gm, 20X Objective

	Top	Bottom
	547	558
	627	660
	516	637
	603	503
	619	543
	617	542
	555	639
	570	668
	663	626
	661	502
Average	598 HK	588 HK
Dwg. 11691266	542 HK minimum	542 HK minimum

Table 31

Extra Heavy Duty Spiral Type Spring "Top" Chemical Composition
Weight Percent

Element	Component	MIL-S-46850, Grade 300
Nickel	18.4	18.0-19.0
Cobalt	8.73	8.5-9.5
Molybdenum	4.71	4.6-5.2
Titanium	0.76	0.5-0.8
Aluminum	0.12	0.05-0.15
Carbon	0.03	0.03 max.
Manganese	0.056	0.10 max.
Silicon	0.13*	0.10 max.
Phosphorus	<0.004	0.01 max.
Sulfur	0.001	0.01 max.
Boron	<0.001	0.003 max.
Zirconium	0.001	0.020 max.
Calcium	0.003	0.050 max.
Iron	remainder	remainder

Extra Heavy Duty Spiral Type Spring "Bottom" Chemical Composition
Weight Percent

Element	Component	MIL-S-46850, Grade 300
Nickel	18.1	18.0-19.0
Cobalt	8.59	8.5-9.5
Molybdenum	4.61	4.6-5.2
Titanium	0.67	0.5-0.8
Aluminum	0.11	0.05-0.15
Carbon	0.32*	0.03 max.
Manganese	0.055	0.10 max.
Silicon	0.12*	0.10 max.
Phosphorus	0.004	0.01 max.
Sulfur	0.002	0.01 max.
Boron	<0.001	0.003 max.
Zirconium	0.007	0.020 max.
Calcium	0.003	0.050 max.
Iron	remainder	remainder

Table 32

Extra Heavy Duty Spiral Type Spring Plating Thickness (Inch)

	Top	Bottom
	0.00022	0.00016
	0.00019	0.00013
	0.00016	0.00019
	0.00016	0.00013
	0.00022	0.00016
Average	0.00019 inch	0.00015 inch
Dwg. 11691266	0.0001 inch maximum	0.0001 inch maximum

APPENDIX H- Helical Compression Spring Testing

Table 33 Helical compression spring dimensional verification
Table 34 Helical compression spring load at 0.51" compression
Table 35 Helical compression spring chemical analysis
Table 36 Helical compression spring plating thickness

Table 33

Helical Compression Spring Dimensional Verification

	Measured	Dwg. 11691419
Coil Outer Diameter	0.247 inch	0.251 +/- 0.006 inch
Free Length	1.078 inch	1.09 +/- 0.02 inch
Solid Length	0.217 inch	0.235 inch maximum
Total Coils	10	10

Table 34

Helical Compression Spring Load at 0.51" Compression

225 lb. Load Cell, 4.5 lb. Range

	@ 0.02 inch/min.	@ 0.08 inch/min.
Measured	1.88 lb.	1.88 lb.
Dwg. 11691419	1.8-2.2 lb.	1.8-2.2 lb.

Table 35

Helical Compression Spring Chemical Composition

Weight Percent

Element	Component	QQ-W-470
Carbon	0.85	0.70-1.00
Manganese	0.45	0.20-0.60
Silicon	0.21	0.12-0.30
Phosphorus	0.014	0.025 max.
Sulfur	<0.005	0.030 max.
Iron	remainder	remainder

Table 36

Helical Compression Spring Plating Thickness

Micrograph Measurements (Inch)

	0.00044
	0.00044
	0.00047
	0.00047
	0.00044
Average	0.00045 inch
Dwg. 11691418	0.00047 inch minimum

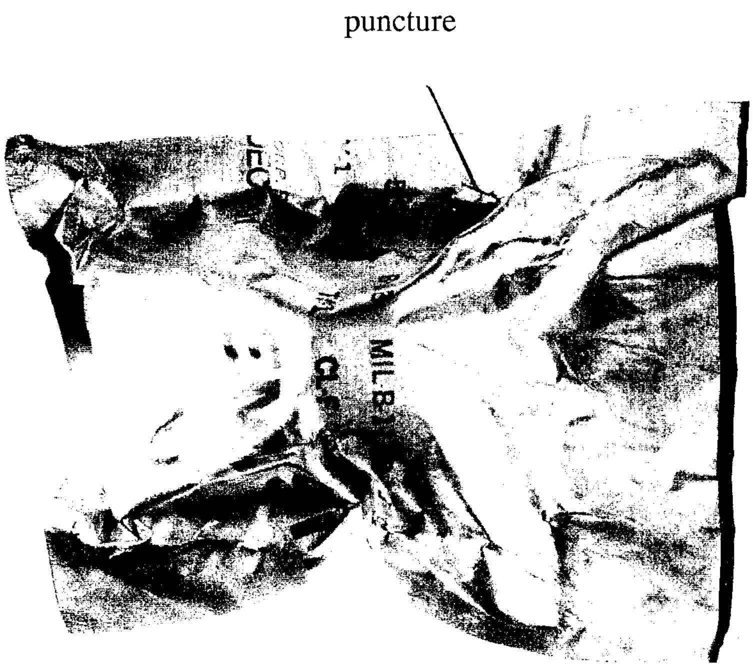

FIGURE 1 Breech bolt assembly in the as-received condition. Note puncture in protective packing, exposing part to environment. Reduced 20%.

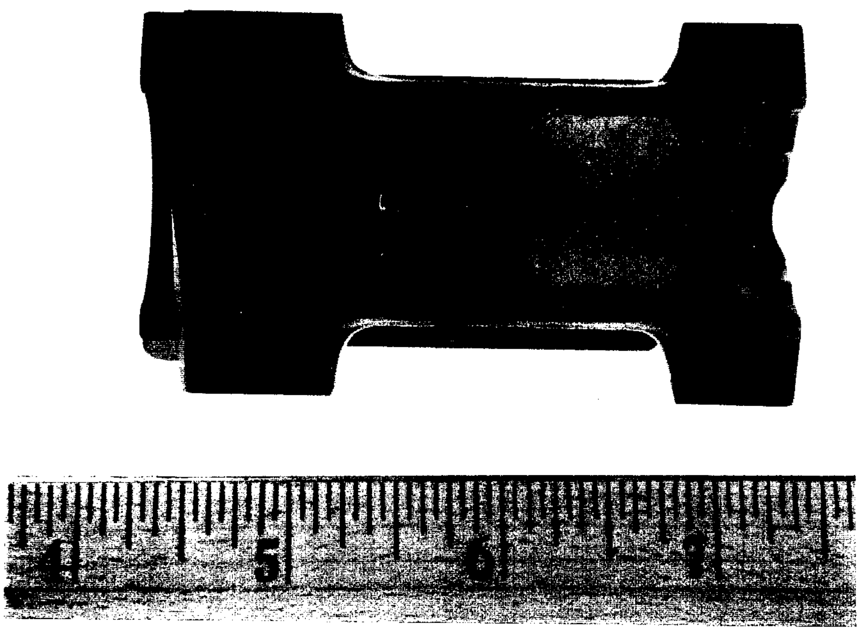

FIGURE 2 Top view of the as-received breech bolt assembly. Mag. 1x.

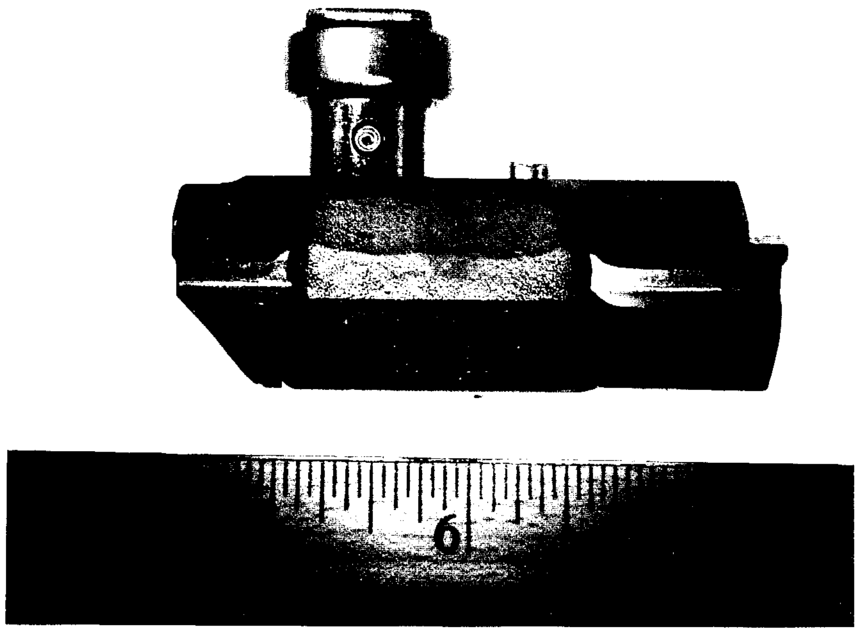

FIGURE 3 Side view of the as-received breech bolt assembly. Mag. 1x.

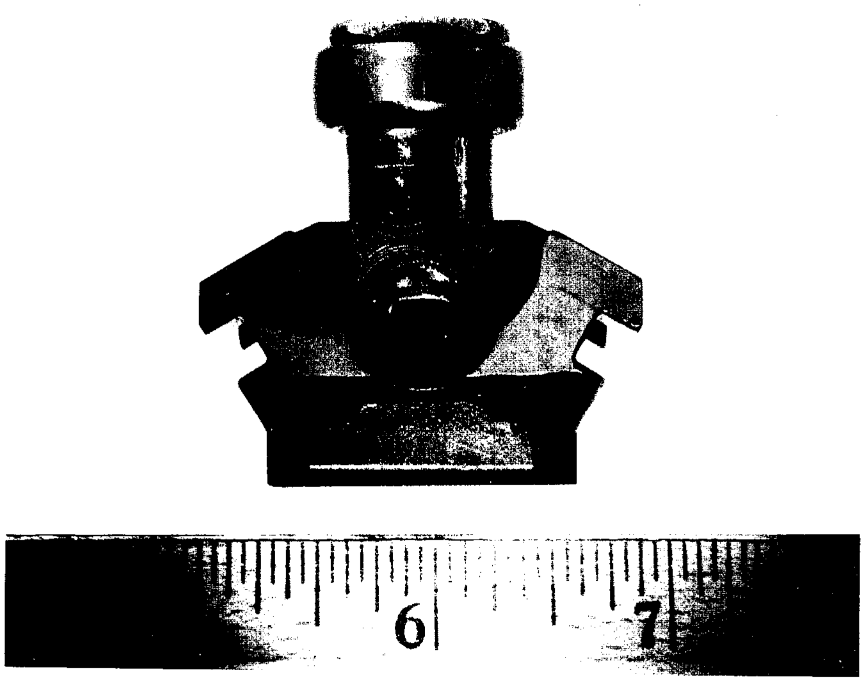

FIGURE 4 End view of the as-received breech bolt assembly. Mag. 1x.

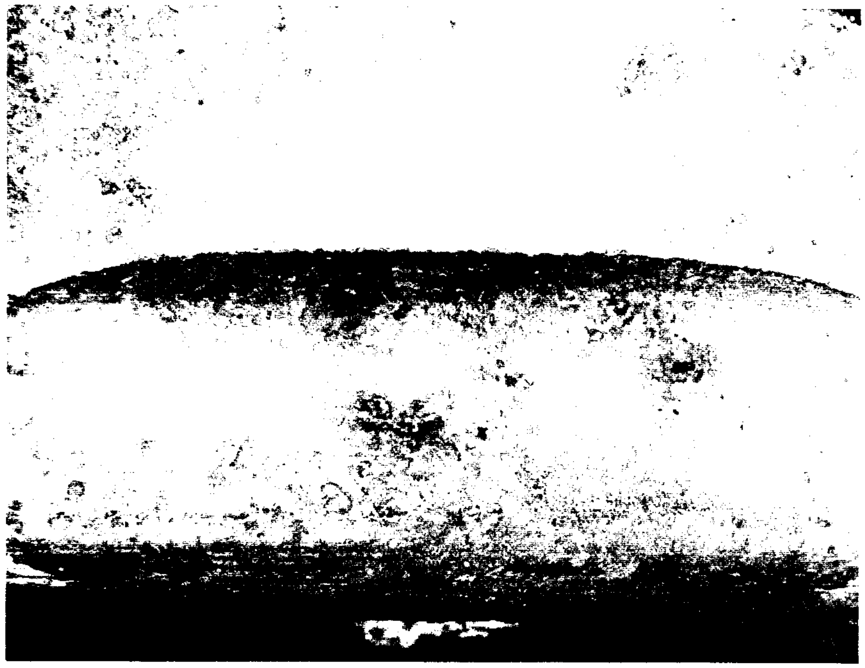

FIGURE 5 Optical macrograph of one of the machined recesses within the individual locking block, in the as-received condition. Note the rough surface profile and corrosion. Mag. 7.5x.

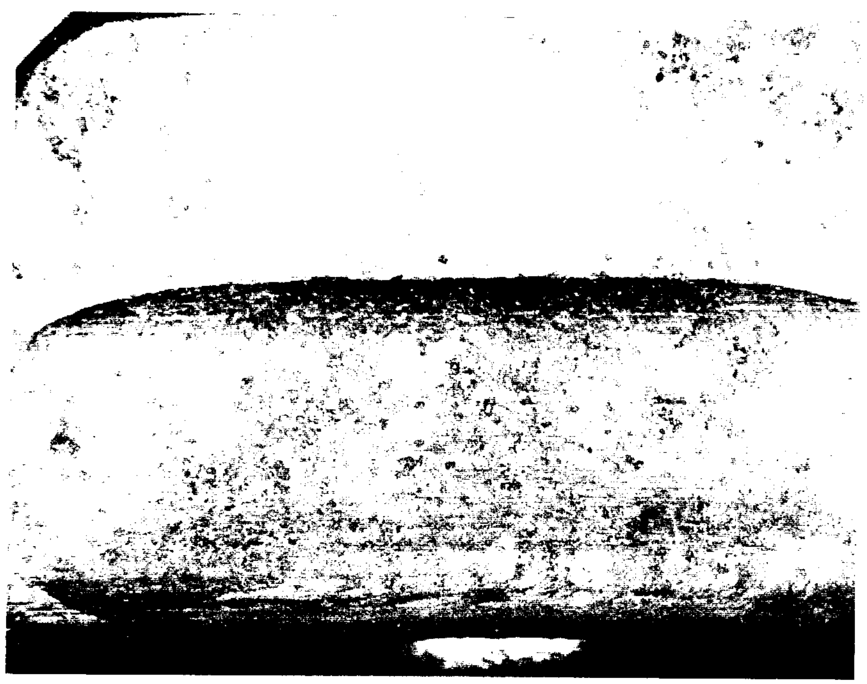

FIGURE 6 Optical macrograph of the other machined recess within the individual locking block, in the as-received condition. Note the rough surface profile and slight corrosion. Mag. 7.5x.

FIGURE 7 A higher magnification optical macrograph of Figure 5 showing extent of roughness and corrosion. Mag. 12x.

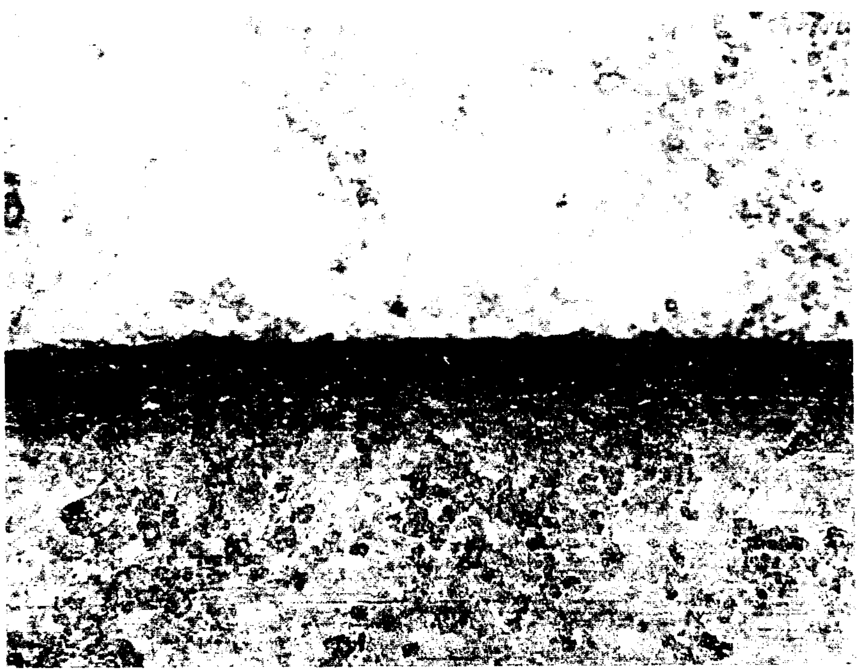

FIGURE 8 A higher magnification optical macrograph of Figure 6 showing extent of roughness and corrosion. Mag. 12x.

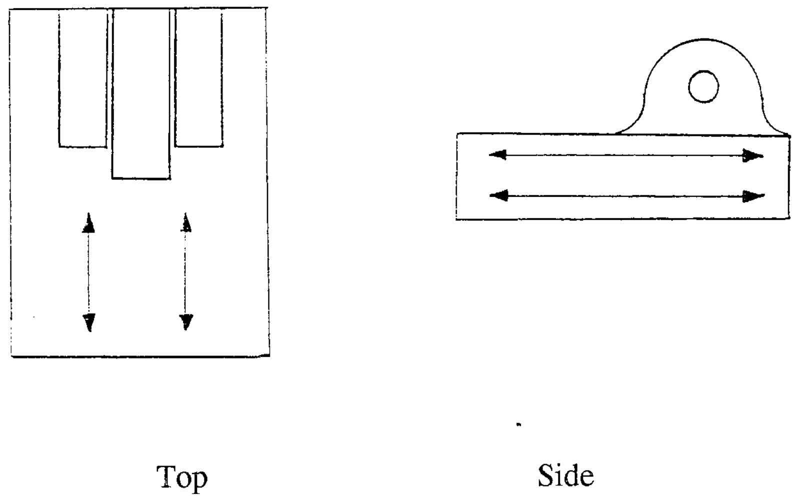

FIGURE 9 A schematic showing directions of surface finish measurement on the individual locking block.

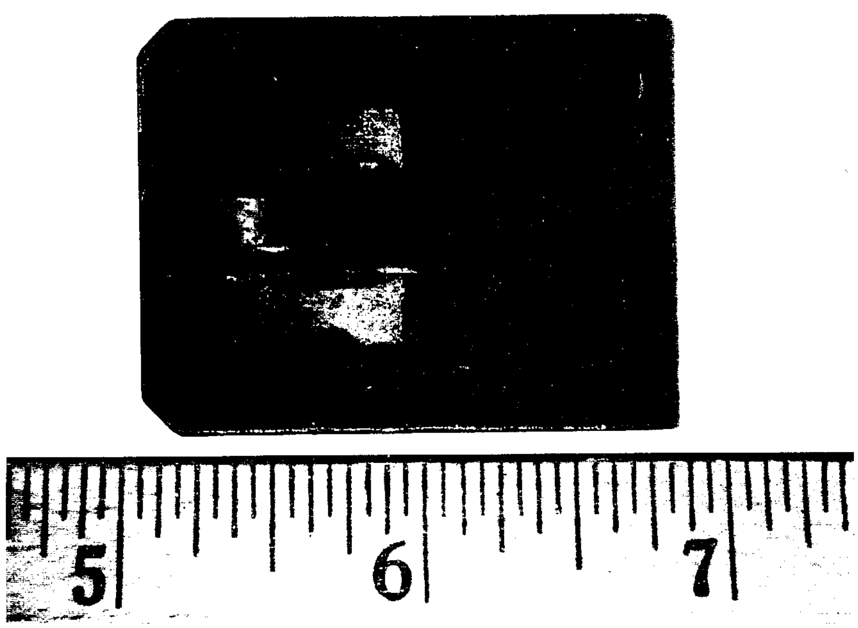

FIGURE 10 Top view of the individual locking block showing excessive machine marks. Surface finish was determined to be out of specification. Mag. 1.5x.

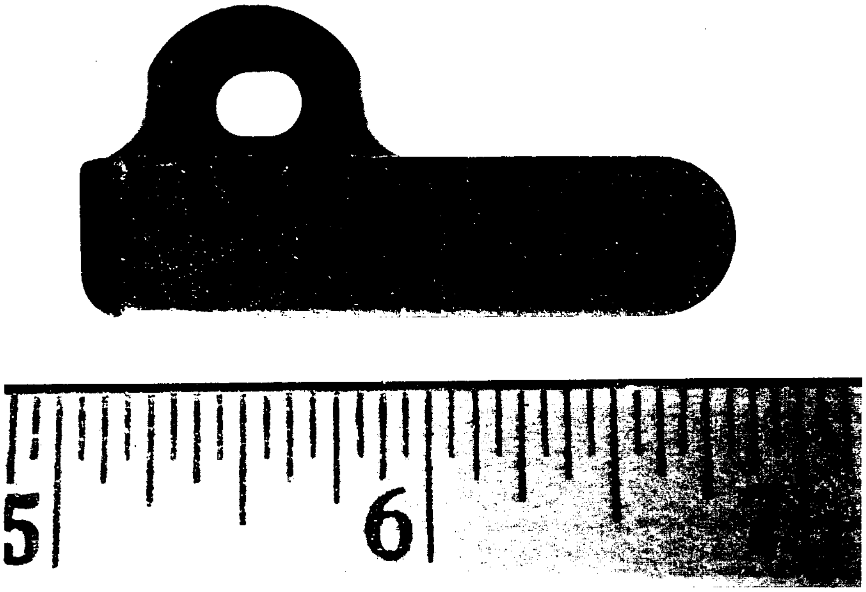

FIGURE 11 Side view of the individual locking block showing excessive machine marks. Surface finish was determined to be out of specification. Mag. 1.5x.

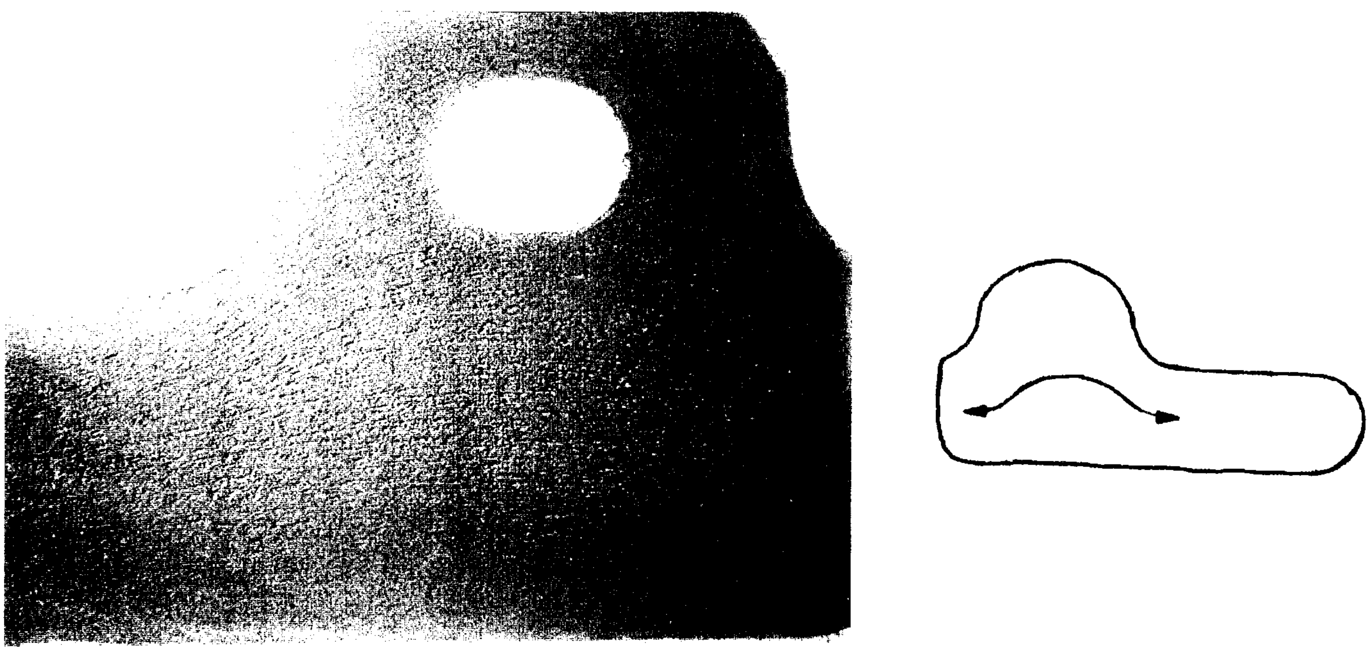

FIGURE 12 Etched (50% HCl and 50% distilled H_2O, @ 180°F) section of the individual locking block showing grain flow in conformance to Eng. Dwg. 11691480. Mag. 4x.

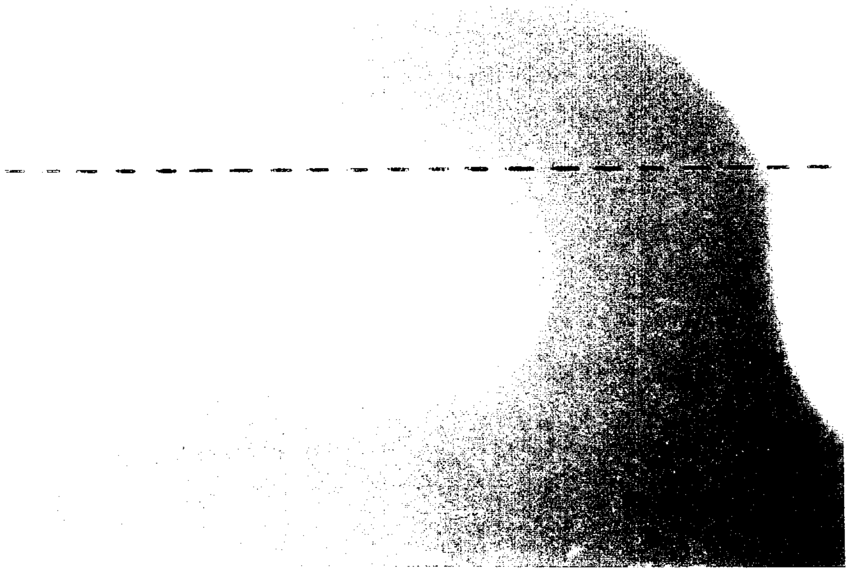

FIGURE 13 Etched macrograph of the bail section of the individual locking block. The required induction hardened region, highlighted by the dashed line, did not etch differently, suggesting same structure throughout. Mag. 4x

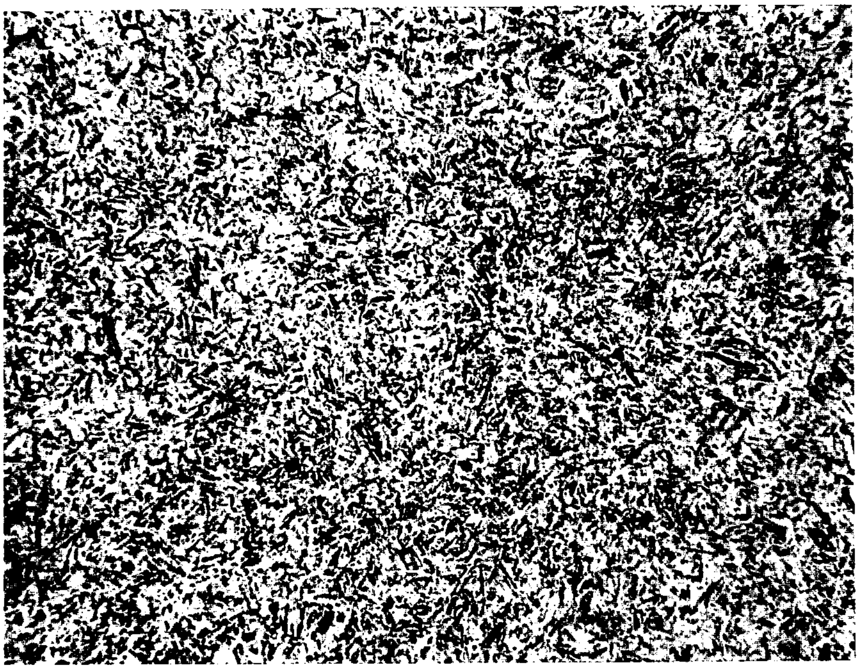

FIGURE 14 Individual locking block microstructure (AISI 4140) consisting of fine tempered martensite, typical of prior heat treatment. 4% nital. Mag. 300x.

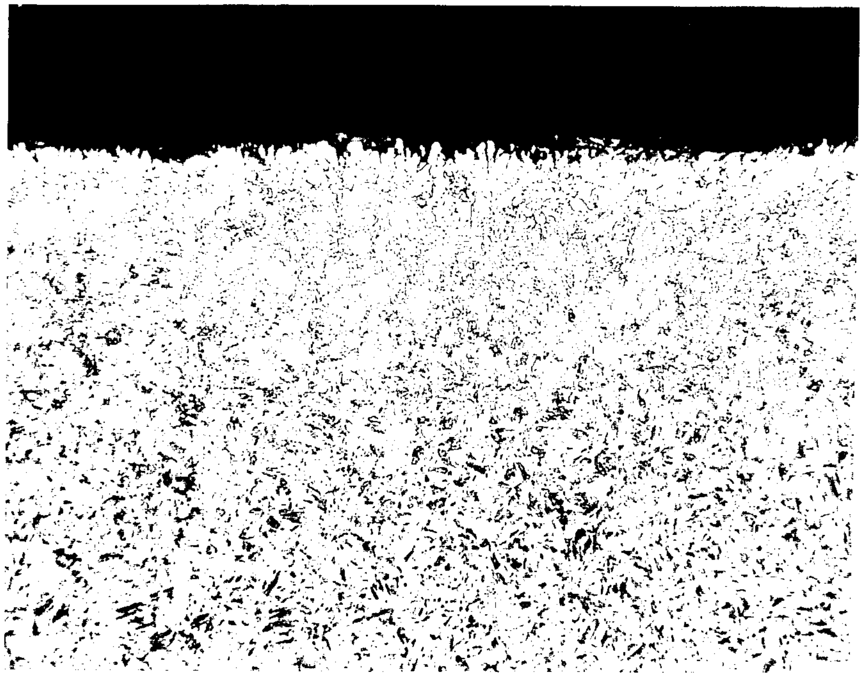

FIGURE 15 A decarburized layer found around the periphery of the individual locking block microstructure. Note the soft, blocky ferrite grains at the surface of the component. 4% nital. Mag. 250x.

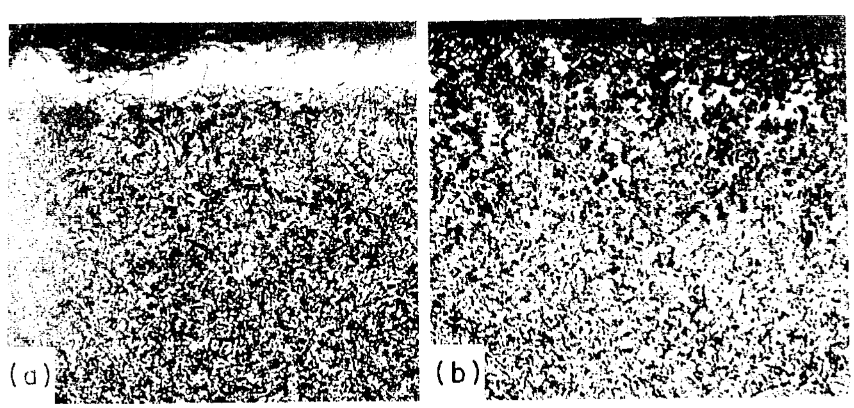

FIGURE 16 A "total" (a) and "partial" (b) decarburized layer of a hardened steel, utilized for reference. The decarburized layer found around the periphery of the individual locking block compared favorably to that of a total, or complete decarburized layer (Compare to Figure 15).

FIGURE 17 One of four Knoop microhardness profiles (Profile A) taken through the decarburized layer found around the periphery of the individual locking block. Note the larger indents (softer material) nearer the exterior of the component. As-polished. Mag. 200x.

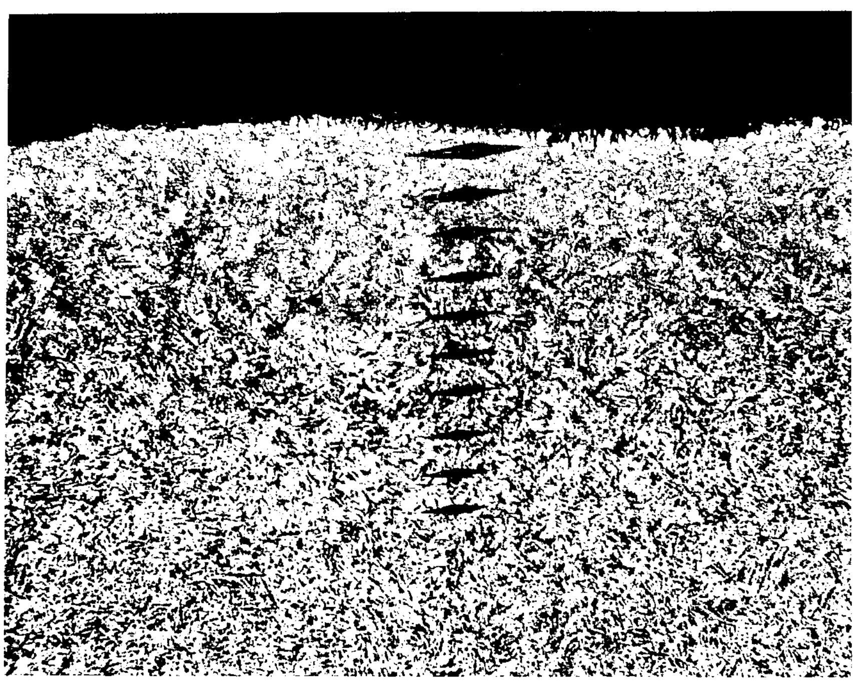

FIGURE 18 The Knoop microhardness profile shown in Figure 17 after application of an etchant. 4% nital. Mag. 200x.

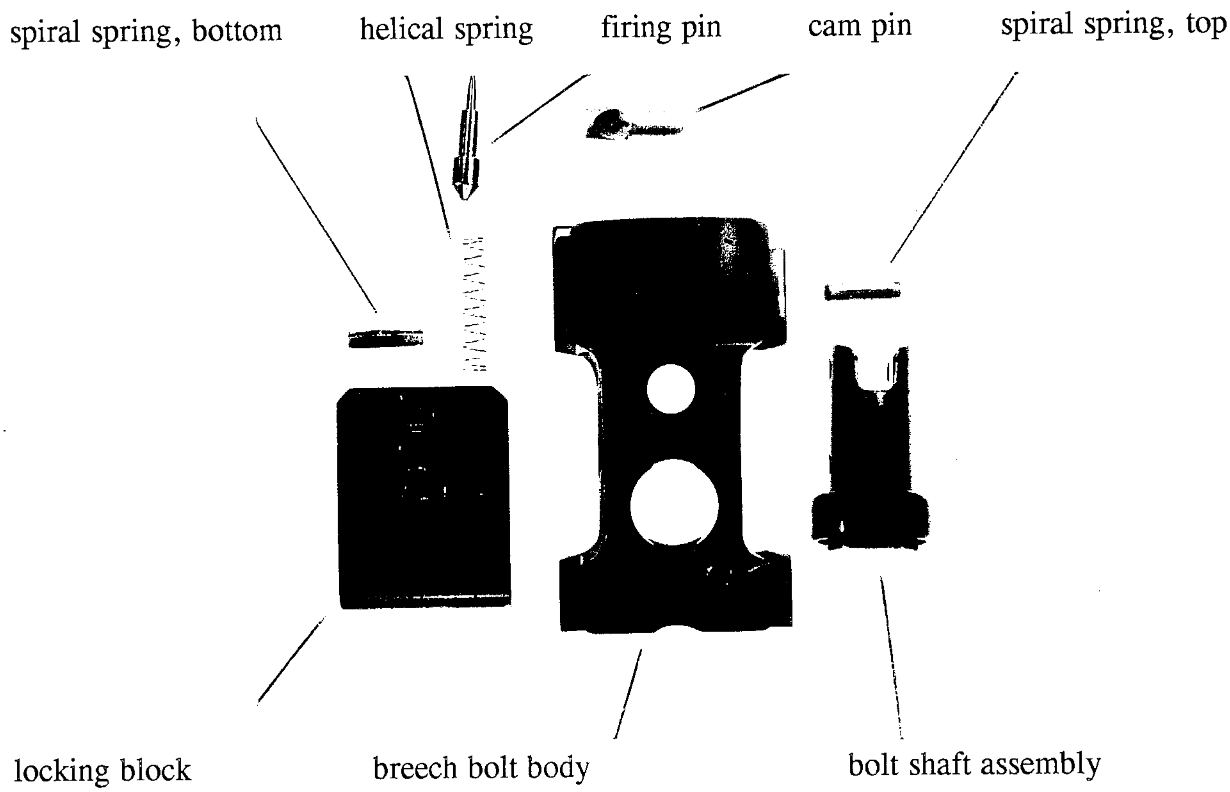

FIGURE 19 Macrograph of the disassembled breech bolt assembly. Reduced 50%.

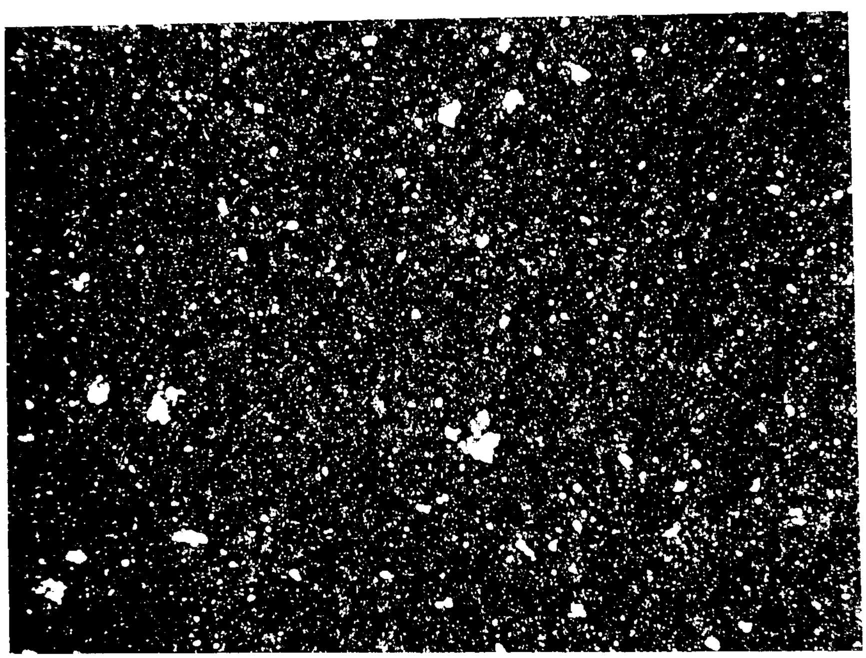

FIGURE 20 Cam pin microstructure (CRES, Class 440A) consisting of partly spheroidized chromium carbide particles in a martensitic matrix, typical of prior heat treatment. Note prior austenitic grain boundaries. Fry's reagent. Mag. 500x.

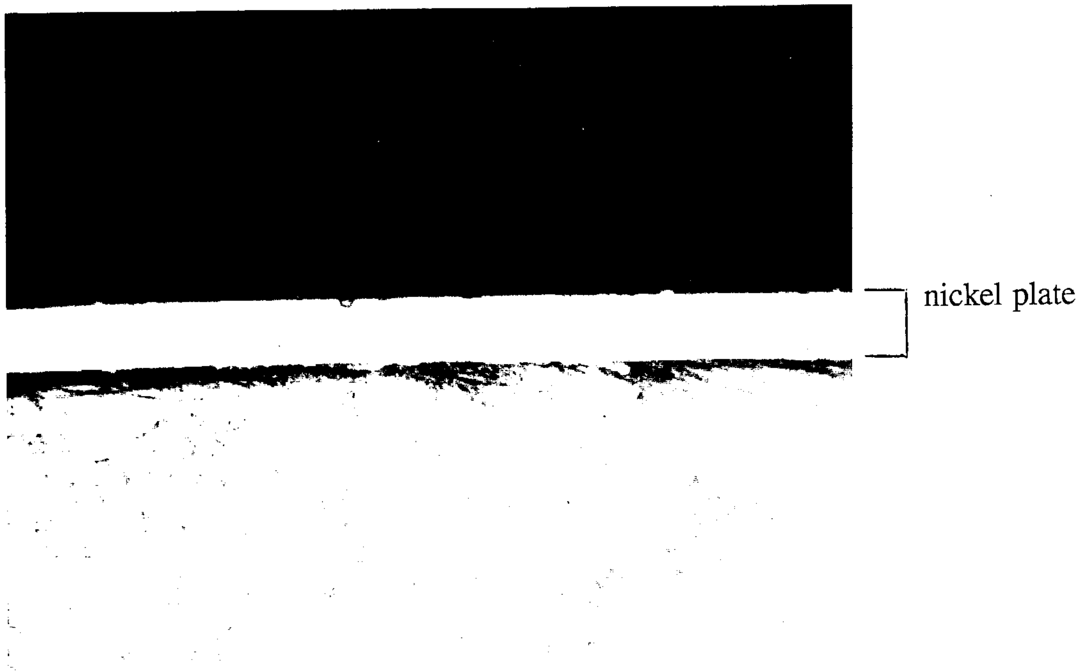

FIGURE 21 Representative region of nickel plating atop the firing pin. Fry's reagent. Mag. 1000x.

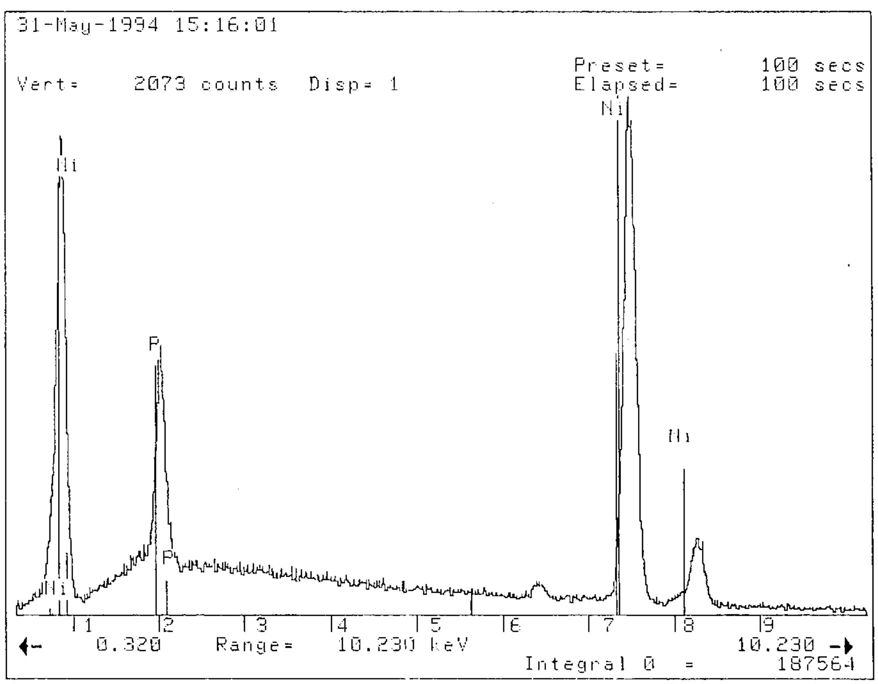

FIGURE 22 EDS spectrum of the plating atop the cam pin. Nickel plating was verified. The presence of phosphorus is the result of the electroless nickel process.

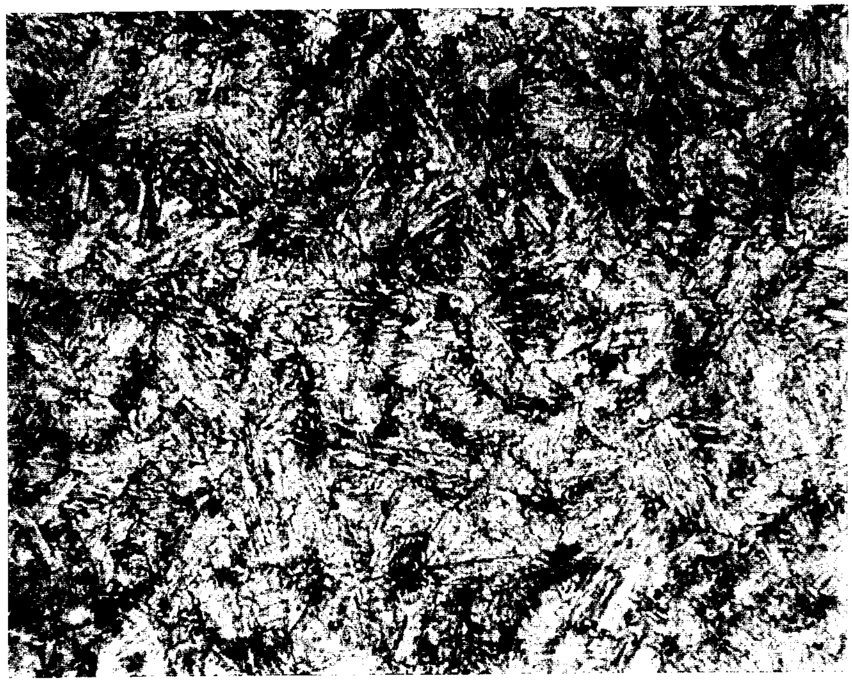

FIGURE 23 Firing pin microstructure (Maraging, Grade 300) consisting of low carbon martensite, consistent with prior heat treatment. Fry's reagent. Mag. 300x.

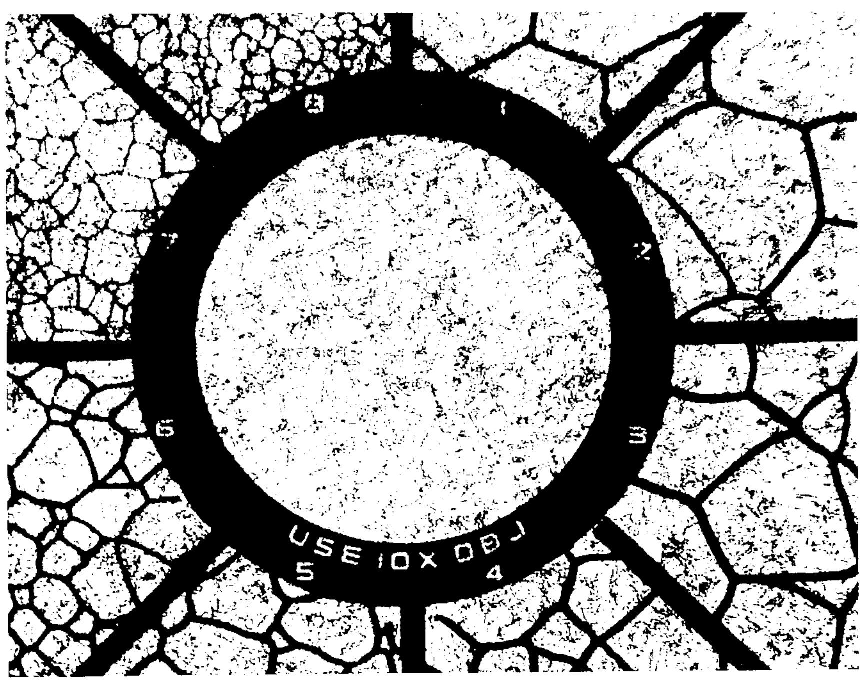

FIGURE 24 Grain size of the firing pin. Spec. MIL-S-46850 requires a grain size of six or finer (four is permissible). From micrograph, grain size is between six and seven. Fry's reagent. Mag. 100x.

FIGURE 25 Microstructure of the region which was supposed to be nitrided on the bolt shaft, top. A darkened case was not noted along the surface of the component. Fry's reagent. Mag. 500x.

FIGURE 26 Microhardness profile conducted to verify nitrided case on the bolt shaft, top. No significant hardness gradient was noted. Fry's reagent. Mag. 300x.

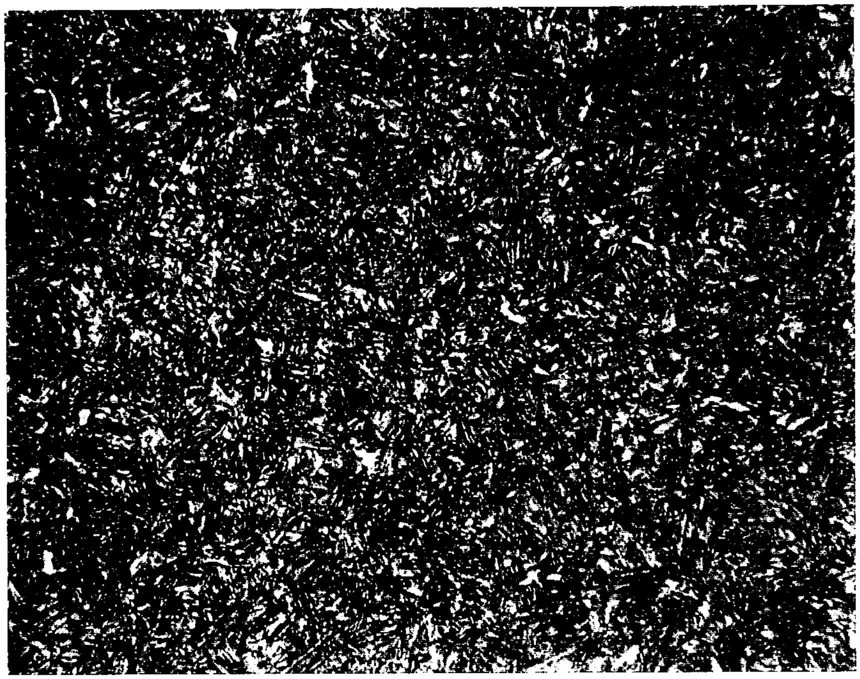

FIGURE 27 Bolt shaft, roller microstructure (AISI 4140) consisting of a fine tempered martensite, typical of prior heat treatment. 4% nital. Mag. 500x.

FIGURE 28 Microstructure of the region which was supposed to be nitrided on the bolt shaft, bottom. A darkened case was not noted on the surface of the component. Fry's reagent. Mag. 300x.

FIGURE 29 Microhardness profile conducted to verify nitrided case on the "After-Market" bolt shaft, bottom. No significant hardness gradient was noted. Fry's reagent. Mag. 300x.

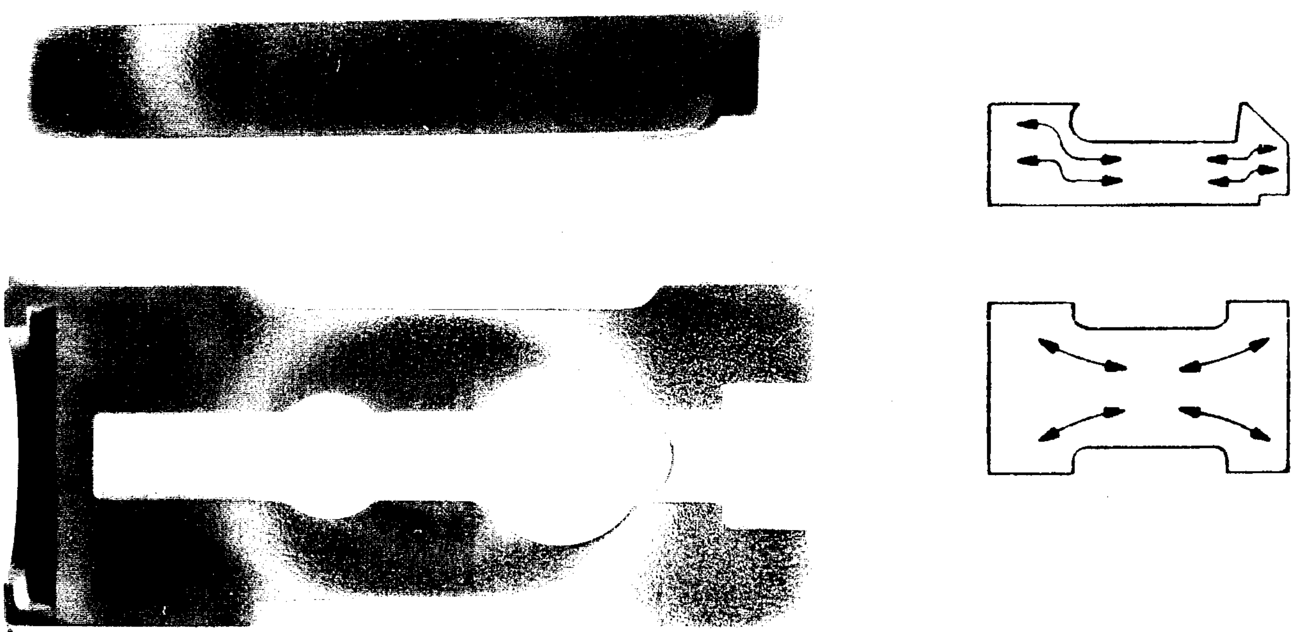

FIGURE 30 Breech body grain flow with schematic of allowable grain flow per drawing 11691423. Photos Mag. 1.5x

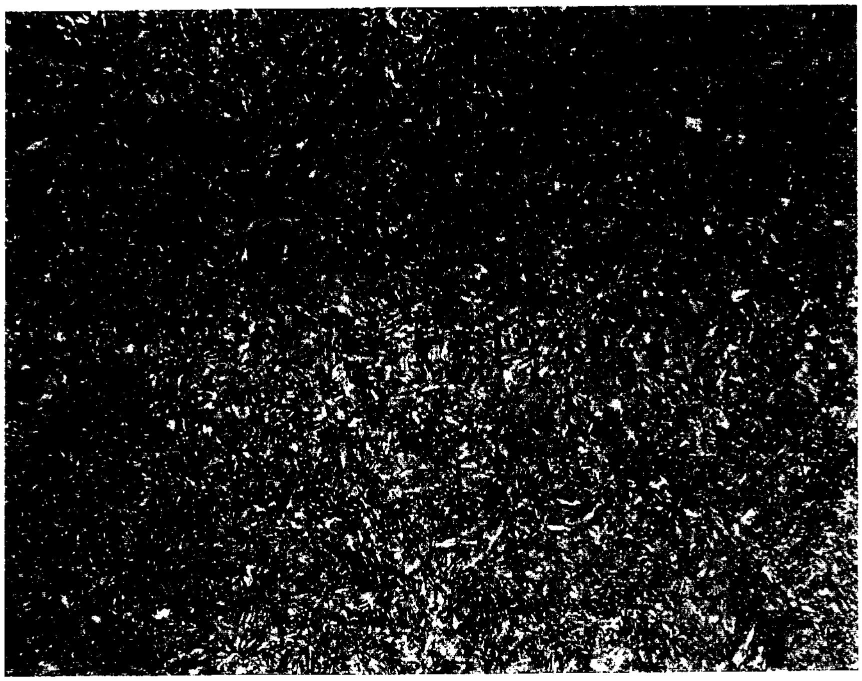

FIGURE 31 Breech bolt body microstructure (AISI E4340) consisting of a fine tempered martensite, consistent with prior heat treatment. 4% nital. Mag. 500x.

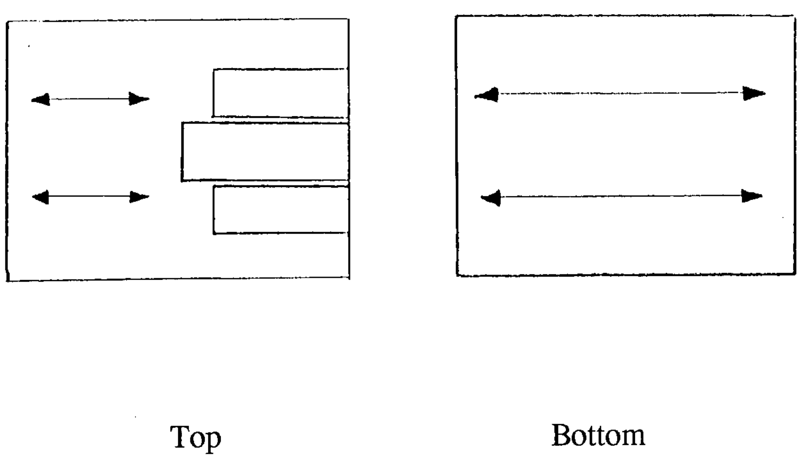

FIGURE 32 A schematic showing directions of surface finish measurement on the locking block.

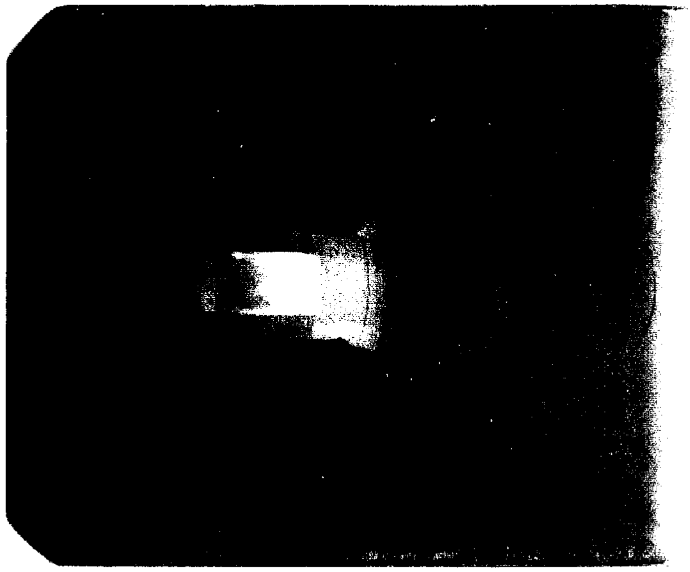

FIGURE 33 Top view of the assembly locking block showing machining marks. Surface finish was determined to be within specification. Mag. 1.5x.

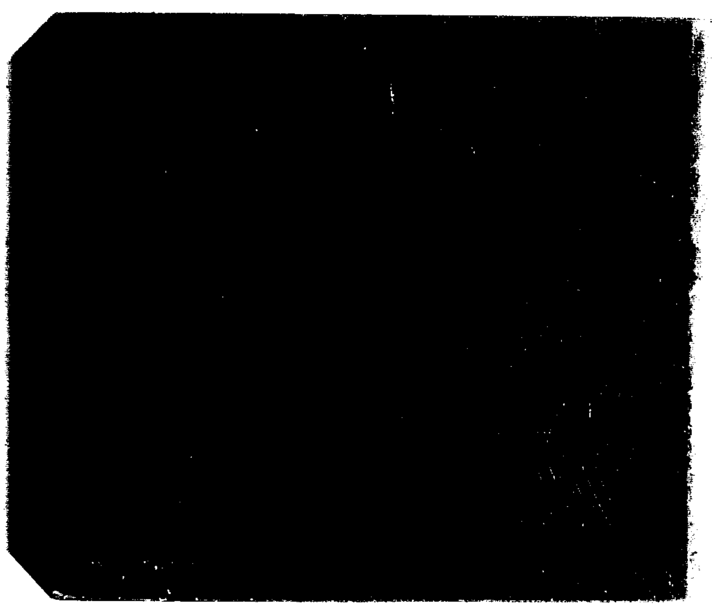

FIGURE 34 Bottom view of the assembly locking block showing machining marks. Surface finish was determined to be within specification. Mag. 1.5x.

FIGURE 35 Etched macrophotograph of the bail region of the assembly locking block. Note the different structures observed within the induction hardened region (above dashed line) and the remainder of the part. Mag. 4x.

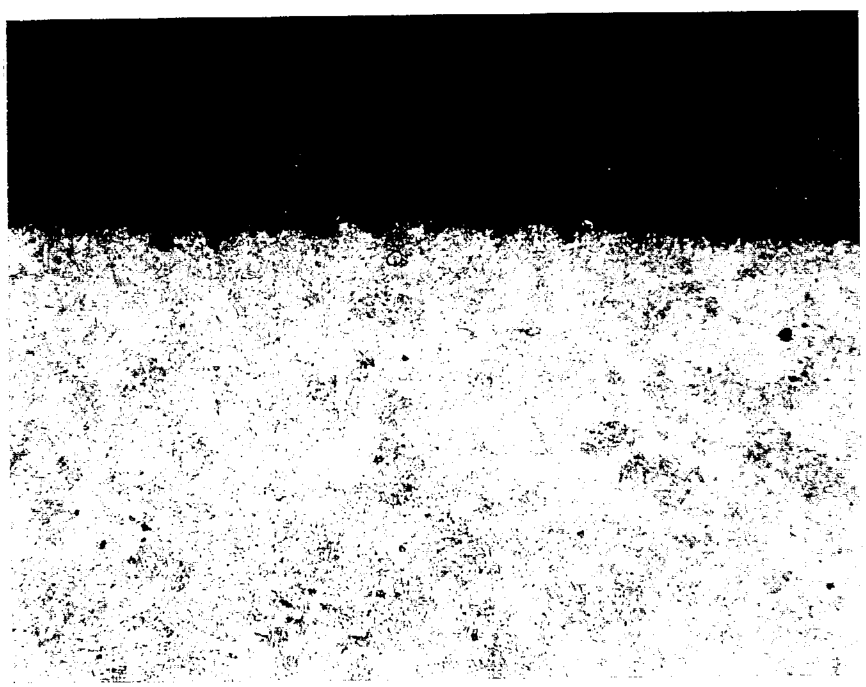

FIGURE 36 Surface microstructure of assembly locking block showing no signs of decarburization. Compare to Figure 15 (decarburized surface of the individual locking block). Mag. 250x.

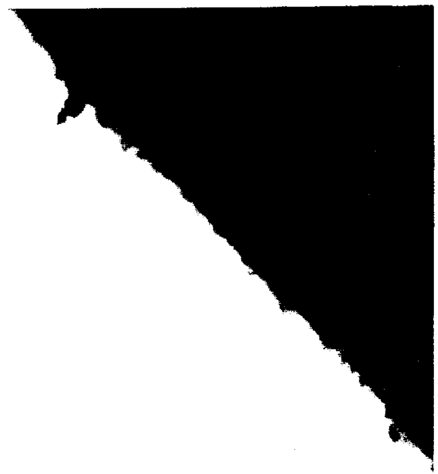

FIGURE 37 As-polished micrograph of the spiral spring pin ("Top"). Mag. 1000x.

FIGURE 38 As-polished micrograph of the spiral spring pin ("Bottom"). Note the increased carbides. Mag. 1000x.

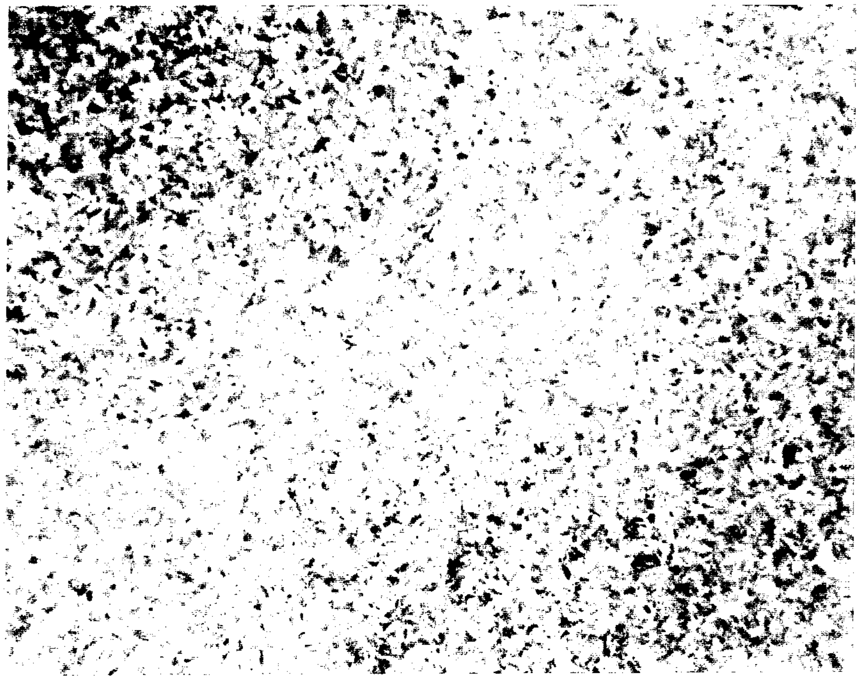

FIGURE 39 Spiral spring ("Top") microstructure consisting of a fine tempered martensite consistent with the required heat treatment. Fry's reagent. Mag. 500x

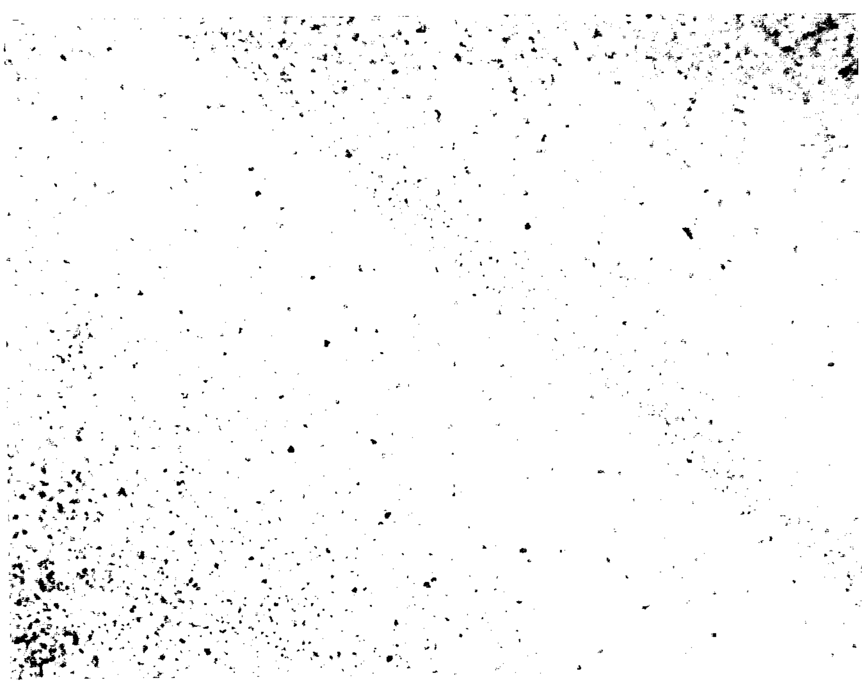

FIGURE 40 Spiral spring ("Bottom") microstructure consisting of a fine tempered martensite with increased carbides. Fry's reagent. Mag. 500x

FIGURE 41 Representative region of the plating on the spring pins. Coating was determined to be slightly above the maximum limit. Fry's reagent. Mag. 1000x.

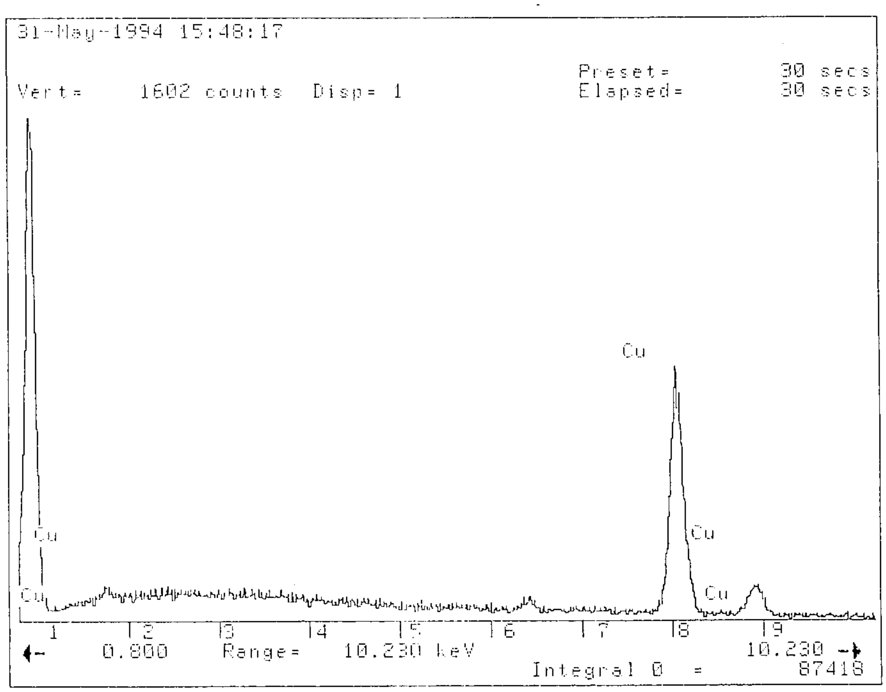

FIGURE 42 Representative EDS spectrum of the plating on the spiral spring pins, verifying that copper was utilized, as represented by the copper peaks.

FIGURE 43 Micrograph of the plating on the helical compression spring. Mag. 1000x.

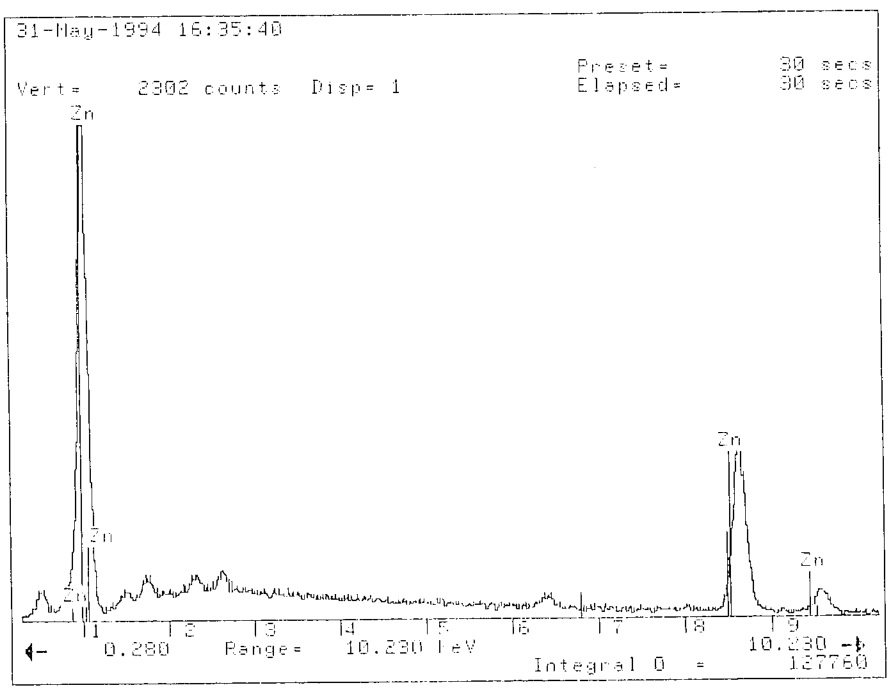

FIGURE 44 EDS spectrum of the plating on the helical compression spring verifying that zinc was utilized instead of cadmium, as represented by the zinc peaks.

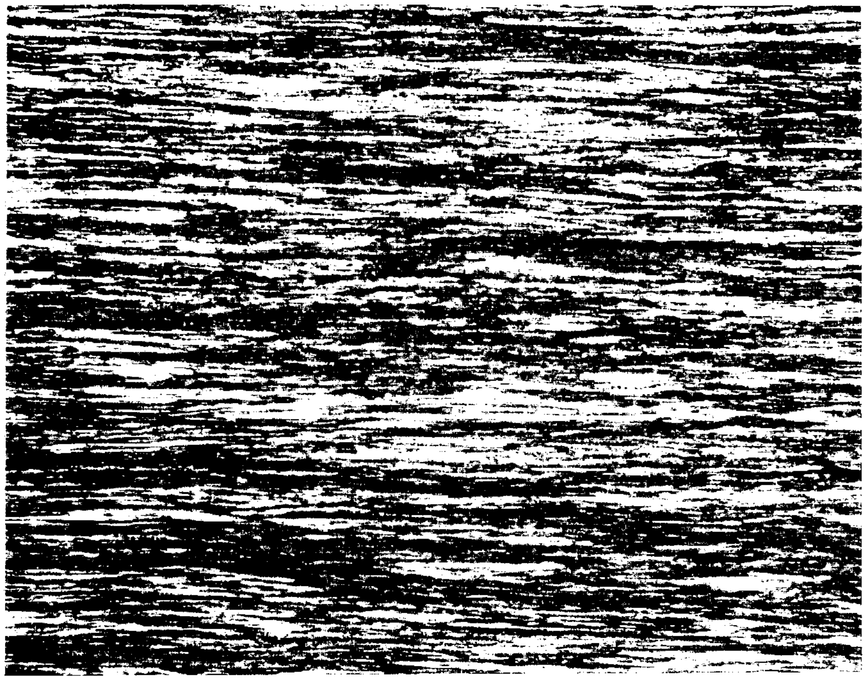

FIGURE 45 Helical compression spring microstructure consisting of elongated ferrite and fine pearlite grains, typical of a cold drawn, high carbon steel wire. 4% nital. Mag. 400x.

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