Metallurgical Analysis of Shell and Case Shot Artillery from the Civil War Battles of Pea Ridge and Wilson's Creek

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ABSTRACT

Interdisciplinary study in archaeology is important for extracting new information from well-studied artifact sources. The Civil War battles of Wilson's Creek, Missouri in August 1861 and Pea Ridge, Arkansas in February 1862 provide archaeologists with hundreds of testable artillery remains. By utilizing metallurgical analyses in studying artillery fragments, the physical properties involved in their manufacture and use can be determined. The analysis shows that there is measurable variability in the metallurgy of Federal and Confederate ordnance. It also shows that in the western theater Federal ordnance manufacture was more uniform than Confederate manufacture.

Introduction

Battlefields as archaeological sites are a relatively common focus for study. Battlefield archaeology has been somewhat superficial, however, concentrating on actions and events that occurred with an assumption that artifact counts and locations provide a full spectrum of data for interpretation.

While curating ordnance from the early Civil War battles of Wilson's Creek and Pea Ridge, Douglas Scott of the National Park Service noticed that fragments of shell and case shot ordnance were relatively uniform in size and shape (Figures 1 and 2). Scott questioned whether or not it was possible to determine what processes created these artifacts. The following metallurgical tests may be useful in eliciting information to assist in answering this query: finite element analysis, optical and scanning electron microscopy, chemical profiling, and hardness testing.

The results show that metallurgical analysis of military ordnance is a useful and informative tool that provides data unavailable through conventional archaeological methods. It not only aids in understanding their use and the results of their use on the battlefields, but also illuminates the processes of manufacture and procurement in the events leading up to the battles. This is important for understanding foundry practices before and during the Civil War, as arsenal records from this time are poor.

Figure 1. Confederate ordnance fragments from the battles of Pea Ridge, Arkansas and Wilson's Creek, Missouri. (Photo by Alicia Caporaso, 2003.)

Figure 2. Federal ordnance fragments from the battles of Pea Ridge, Arkansas and Wilson's Creek, Missouri. (Photo by Alicia Caporaso, 2003.)

Gray Cast Iron

By the time of the Civil War, metallurgists had appreciable understanding of the properties of cast iron. Artillerists recommended gray cast iron for ordnance use (Gibbon 1860:171). It is likely that the choice factors were its ease of casting and low cost (Lyman 1961:350; Callister 2001:349).

Civil War era metallurgists knew that gray cast iron has high castability, good fluidity and expansion upon cooling in molds, the melting point is low (~1200°C), and the cast form has strength in compression and weakness in tension (Scott 1991). In addition, the metallurgist could produce a consistent product.

All gray irons contain iron, carbon, and silicon as well as appreciable amounts of phosphorus, sulfur, and manganese. The free graphite in the material matrix is formed "as cast" and can take a number of different microstructures (Bolton 1937:80–81). This is archaeologically useful; it can be assumed that artillery produced in different foundries and at different times will have varying microstructures.

The following discussion will often refer to gray iron as eutectic. A eutectic reaction is a reaction in which, upon cooling, a liquid phase transforms isothermally and reversibly into two mixed solid phases. The phases exist as alternating lamellae. In gray iron, the reaction is as follows:

$$Fe_3C \rightarrow 3Fe(\alpha) + C$$

Fe = iron
C = carbon
α = ferrite

For gray cast iron, there are two important periods for cooling. The first occurs between 1135°C and 1150°C, when graphite is formed and the ratio of combined to graphitic carbon is fixed (Lyman 1961:351). The second is at 650°C to 720°C when the matrix is determined (Angus 1976:36). Slow cooling favors graphite production while rapid cooling favors metastable ferrite and some free cementite (iron carbide, Fe_3C) or mottled iron (Davis 1996:8; Lyman 1972:81).

Metallurgical Properties

Cooling rate and temperature determines the chemical composition of ferrite and graphite and the shape of the graphite flakes within the matrix. The typical microstructure is a matrix of pearlite (a layered mixture of ferrite and cementite) with pointed (Callister 2001:410) graphite flakes dispersed throughout. Very slow cooling is likely to produce considerable ferrite throughout the matrix (Lyman 1961:351).

Graphite shape is directly related to strength (Davis 1996:7). Of all the cast irons, gray iron has the lowest impact resistance (Lyman 1961:357, Davis 1996:45). Maximizing this characteristic in ordnance is ideal, as the maximum amount of energy will be transferred to the projectile fragments.

All gray irons fail in a brittle manner. Fracture occurs along the lamellar graphite plates (Davis 1996:4) and at maximum compressive loads (Angus 1976:46). A cannon ball can be considered as a thick-walled spherical pressure vessel and the failure as an impact overload exceeding the compressive strength. The mode of failure can be attributed to thermal stress overload wherein the stress from a thermal change (the charge) demands a specific change of dimension. As gray cast iron cannot expand plastically, the yield strength is exceeded, causing fracture (Davis 1996:347).

Variations in graphite size and distribution cause variations in hardness readings across samples. The hardness of the metallic matrix is constant, however, (Lyman 1961:356). While Angus (1976:48) states that there is no relationship between hardness and tensile strength for cast iron, he does not relate hardness and compressive strength.

Slight variations in the chemical make-up will alter mechanical properties of cast iron. Typical alloying elements in gray cast iron include: silicon and aluminum, which increase graphitization, increase the ferrite-pearlite ratio, and lowers strength; nickel, copper, and tin, which increase graphitization, increase pearlite, and raises strength and hardness; and chromium, molybdenum, tungsten, and vanadium, which decrease graphitization and increase strength (Davis 1996:8). Silicon and nickel decrease hardness due to their tendency to increase graphitization, while phosphorus, manganese, sulphur, chromium, molybdenum, and vanadium increase hardness (Angus 1976:51). In all gray cast iron, the sulfur and manganese content must be balanced according to the following (Davis 1996:34):

$$\%Mn \geq 1.7\%S + 0.3\%$$

Mn = manganese
S = sulfur

The total carbon, phosphorus, and silicon content, as related in the carbon equivalent equation:

$$CE = \%C + (\%Si + \%P)/3$$

CE = carbon equivalent
C = carbon
Si = silicon
P = phosphorus

establishes the solidification temperature and is related to foundry characteristics of the alloy (Davis 1996:6). In impact tests, high phosphorus content decreases energy to rupture (Angus 1976:82). Gray cast iron usually contains from 1.7% to 4.5% carbon and 1.0% to 3.0% silicon (Lyman 1961:349). The carbon equivalent value tells immediately the eutectic state of the iron (Angus 1976:3).

Addition of silicon increases the stability of ferrite while decreasing the stability of carbides (cementite), and promotes graphitization, which adversely affects strength by lowering the percentage of carbon required for the eutectic reaction and raising the eutectic temperature, which can modify graphite distribution. Silicon also increases castability by lowering the casting's total contraction (Davis 1996:5–6; Bolton 1937:135–136).

Ordnance Manufacture

There are two types of artillery projectiles analyzed in this study: spherical shell and case shot. The sphere is a common shape of artillery as it presents the minimum surface for a given volume reducing the effect of wind resistance. If it strikes an object in flight, it is less deflected from its course than any other form (Gibbon 1860:155).

Both ordnance types were manufactured similarly. The mold was made of sand mixed with clay and water. The projectile was allowed to cool while in the mold, allowing for slow cooling of the metal in layers, commencing on the outside of the casting with rising of the ambient temperature of the sand (Gibbon 1860:73, 170–171). Inspected ordnance was polished and coated with lacquer (Gibbon 1860:170–171, 174).

Shells are hollow shot with equal thickness throughout the body of the projectile. There is a conical opening, or eye, used to load the fuse (Gibbon 1860:163). Shells contain a bursting charge of black powder, and are designed to explode in the air or on contact, depending on the fuse type.

Case shot are similar in dimension to shells, but they are usually thin walled to contain the maximum number of bullets, and are filled with small lead or iron balls and a mixture of sulfur pitch or asphalt (Thomas 1985:16). The bullets act as a support to the case and prevent breakage by the force of the discharge from the gun (Gibbon 1860:164–165).

When burst, the pieces of the shell are dispersed in almost every direction. The number of fragments is directly related to the brittleness of the material (Gibbon 1860:163, 250). Theoretical and experimental evidence shows that the least amount of resistance, and crack initiation, propagates through the fuse ring.

Exemplar

On 1 April 1865, the steamboat *Bertrand* sank in the De Soto Bend of the Missouri River in Western Iowa en route from St. Louis to the mining territories of Montana. Among the cargo was 12-pounder mountain howitzer case artillery in crates marked "CANNON SHELLS FOR MOUNTAIN HOWITZER, 1 doz. SHELLS FIXED FEBR. 1865, 18 FRICTION PRIMERS FROM ST. LOUIS ARSENAL" (Petsche 1974:98). These shells are of the same morphology and manufacture as the shell fragments in question, and can be used as exemplars for interior dimensions. Figure 3 shows an example of a howitzer case loaded with lead shot

Figure 3. Cross-section of a howitzer case with an intact Bormann fuse loaded with lead shot and pitch. (Photo by Alicia Caporaso, 2003.)

and pitch, and an intact Bormann fuse. Measurements of the wall thickness show that the inner molds for the cases are irregular.

Procedure and Analysis

Samples

Twenty-one cannonball fragments (Tables 1 and 2) were deaccessioned from the collections of Wilson's Creek National Battlefield and Pea Ridge Military Park by the Midwest Archeological Center, National Park Service, for testing and analysis. They were chosen according to artillery type, location found, and assignation of Federal or Confederate status. All of the samples had fractured into trapezoidal or square shapes. The surfaces have visible large inclusions and have a non-uniform, gray-colored fracture plane.

Approximately half of the samples were cleaned with the following procedure: each piece was placed in a beaker and covered with a buffered solution of hydrochloric acid (6 N hydrochloric solution; 2 grams/liter hexamethylene tetramine). The beaker was then placed into an ultrasonic cleaning bath. Every few minutes, the piece was removed

Table 1. Pea Ridge National Historic Battlefield, Ordnance Indentification.

Artifact no.	Category	Location	Description
4478	US Shell	Big Mountain	12 lb. Shell Fragment
4534	US Shell	Big Mountain	12 lb Shell Fragment
3380	US Shell	Foster's Field	12 lb. Shell Fragment
3418	US Case	Foster's Field	12 lb. Case Fragment
3417	US Case Shot	Foster's Field	Lead Case Shot, Drilled and Faceted
3376	US Fuse Ring	Foster's Field	12 lb. Shell Fragment
2527	CS Shell	Narrow Ridge	12 lb. Shell Fragment
4045	CS Shell	Cox's Field	12 lb. Shell Fragment
4055	CS Shell	Cox's Field	12 lb. Shell Fragment
4144	CS Shell	Wefley's Knoll	12 lb. Shell Fragment
2448	CS Case	Narrow Ridge	12 lb. Case Fragment
2701	CS Case Shot	Narrow Ridge	Iron Case Shot
2419	CS Fuse Ring	Narrow Ridge	12 lb. Shell Fragment

Note: US–United States; CS–Confederate States.

Table 2. Wilson's Creek National Battlefield, Ordnance Identification.

Artifact no.	Category	Location	Description
1028	US Shell	Sharp's Field	12 lb. Shell Fragment (Tentative Identification)
1121	US Shell	Calvary Camp	12 lb. Shell Fragment
3685	US Shell	Counter-Battery Fire	12 lb. Shell Fragment
1175	US Case	Sharp's Field	12 lb. Case Fragment
1089	US Fuse Ring	Sharp's Field	12 lb. Shell Fragment
1018	CS Shell	Sigel's Route	12 lb. Shell Fragment
2645	CS Shell	Bloody Hill	12 lb. Shell Fragment
3221	CS Shell	Bloody Hill	12 lb. Shell Fragment
2536	CS Case	Bloody Hill	12 lb. Case Fragment
2403	CS Case	Bloody Hill	12 lb. Case Fragment

Note: US–United States; CS–Confederate States.

and brushed with a soft toothbrush to remove rust particles. The remaining samples were left soaking under a vapor hood in the acid solution for approximately four to five days, then rinsed. Both methods proved to remove the same amount of oxidation. Once the piece was free of rust, it was removed from the buffered HCL and sprayed with methanol to prevent rusting. It was then rinsed with water, dried with a blow dryer, and soaked in WD-40. The lead case shot was cleaned by soaking the artifact in a 10% glycolic acid solution.

Scanning Electron Microscopy (SEM)

The sample for analysis was selected by visual inspection for significant crack initiation. In addition, the surface had to exhibit minimal corrosion damage. An overloading force was applied to develop the crack into a surface edge revealing a fresh fracture surface for examination. The sample chosen was W2403, a Confederate case.

For W2403 (Figures 4 through 6), initial failure occurred in a brittle manner, expected of cast iron, with transgranular, brittle failures. Figure 4 is a textbook example of a fracture through a dendritic graphite cluster. Transgranular cleavage fracture is shown in Figure 5. In addition, although the example in Figure 6 resembles intergranular fracture, it is actually graphite flakes lifting up off the surface after brittle fracture. The white cuplike structures in Figure 6 are iron oxide corrosion, which grows in all samples when clean surfaces are exposed to air.

Chemical Analysis

A conclusive chemical analysis was needed to determine the exact composition of the samples, all of which were then sent to Chicago Spectro Service Laboratory, Inc. in Chicago, Illinois. The results (Table 3) are consistent with the properties of gray cast iron, indicating no anomalous evidence of ordnance manufacture.

Sectioning and Mounting

Samples of the fragments were cut with a water flux circular saw. Each was mounted in bakelite, then water flux sanded over four grades of sandpaper, and micropolished with water flux aluminum oxide over a felt wheel. This pro-

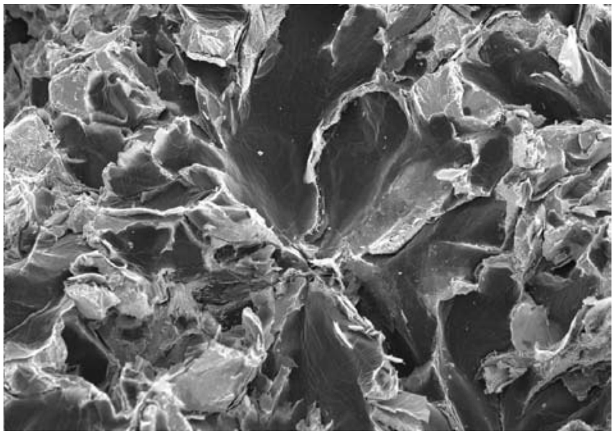

Figure 4. Sample W2403; scanning electron microscopy image of fracture through a dendritic graphite cluster. (Image by Alicia Caporaso, 2003.)

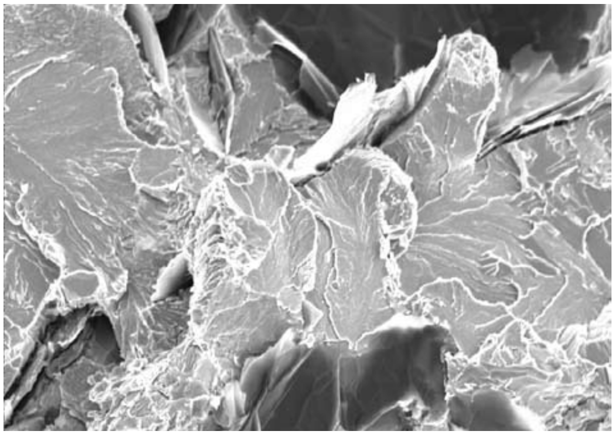

Figure 5. Sample W2403; scanning electron microscopy image of a transgranular cleavage fracture. (Image by Alicia Caporaso, 2003).

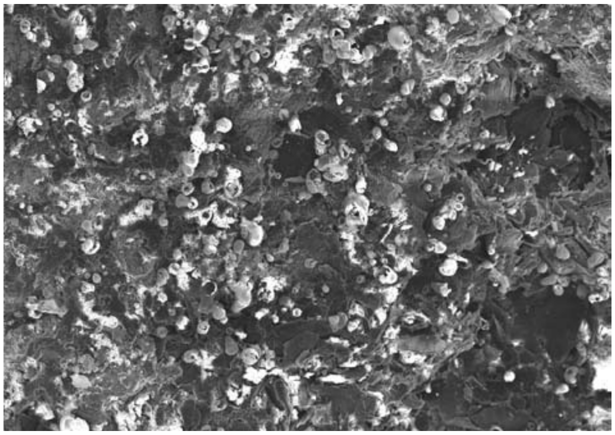

Figure 6. Sample W2403; scanning electron microscopy image of graphite flakes lifting up off the surface after brittle fracture. (Image by Alicia Caporaso, 2003.)

cess removed all cut marks and scratches from the sample surface, allowing for proper material characterization.

Microstructure

The samples exhibit two types of graphite structure: Types B and C (Figures 7 and 8). Type B is formed in near-eutectic compositions that solidify with moderately high undercooling. It appears as a rosette pattern and is common in thin sections and along the surfaces of thick sections. Type C occurs in hypereutectic irons with relatively higher carbon content than Type B. The graphite precipitates during the initial solidification of the iron and appears as superimposed flakes with random orientation (Davis 1996:35).

All samples indicate very slow cooling. It is inferred that the ambient temperature of the foundry determined the cooling rate. In addition, undercooling depends on the melting technique and melt treatment (van de Velde 2004), a characteristic specific to individual foundries.

Hardness

An accurate measurement of hardness for gray cast iron is the Knoop microhardness test. Readings were taken on the interior, center, and exterior of the mounted and polished cross-sections of each sample. Results show that hardness readings are dependent upon the microstructure on which the indenter is resting. An indenter is an apparatus of known surface area that is used to test the resistance of

Table 3. Chemical Analysis of Ordnance.

	Element Percentage								
Artifact no.	**C**	**Mn**	**P**	**S**	**Si**	**Ni**	**Cr**	**Mb**	**Cu**
P2448	3.40	0.86	0.916	0.099	2.70	<0.01	<0.01	<0.01	0.02
P2527	3.62	0.12	0.777	0.075	1.99	0.02	0.03	<0.01	0.02
P3376	3.29	0.38	0.486	0.090	2.54	<0.01	<0.01	<0.01	0.01
P3380	3.50	0.60	1.24	0.058	1.88	<0.01	<0.01	<0.01	<0.01
P3418	3.35	0.57	1.98	0.075	1.72	0.03	0.03	<0.01	0.01
P4045	3.62	0.50	1.09	0.074	3.08	<0.01	<0.01	0.02	<0.01
P4055	3.54	0.48	1.01	0.097	3.23	<0.01	<0.01	<0.01	0.01
P4144	3.37	0.23	1.41	0.097	2.16	<0.01	<0.01	<0.01	<0.01
P4478	3.29	0.62	1.94	0.090	1.96	<0.01	<0.01	<0.01	<0.01
P4534	3.79	0.42	0.395	0.098	1.99	<0.01	<0.01	<0.01	0.01
W1018	3.62	0.53	1.25	0.074	1.65	<0.01	<0.01	0.02	<0.01
W1028	3.54	0.62	0.901	0.096	2.20	<0.01	<0.01	<0.01	<0.01
W1089	3.60	0.38	0.582	0.133	1.34	0.01	<0.01	0.01	0.01
W1121	3.39	0.80	1.96	0.105	1.82	<0.01	<0.01	0.02	<0.01
W1175	3.57	0.40	0.761	0.129	2.12	0.02	0.03	<0.01	0.06
W2403	3.47	0.38	0.988	0.091	2.46	0.03	0.03	<0.01	0.02
W2536	3.69	0.18	0.536	0.060	1.64	<0.01	<0.01	0.02	0.01
W2645	3.44	0.43	1.10	0.093	2.38	<0.01	<0.01	0.02	<0.01
W3221	3.37	0.39	1.03	0.097	2.86	<0.01	<0.01	0.03	<0.01
W3685	3.05	0.43	1.59	0.121	2.43	<0.01	<0.01	0.03	<0.01

Note: Test Method Carbon per ASTM E1019; Manganese, Phosphorus per ASTM E1085; Sulfur per ASTM E350; Others per ASTM E415.

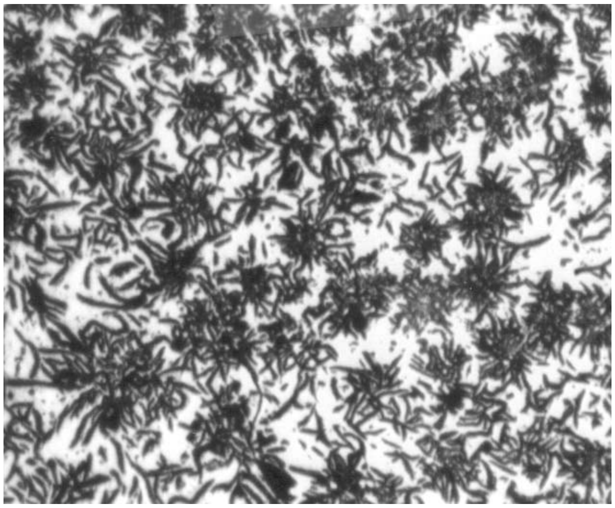

Figure 7. Example of typical graphite structure B in cast iron; study sample P2448 (45x magnification). (Image by Alicia Caporaso, 2003.)

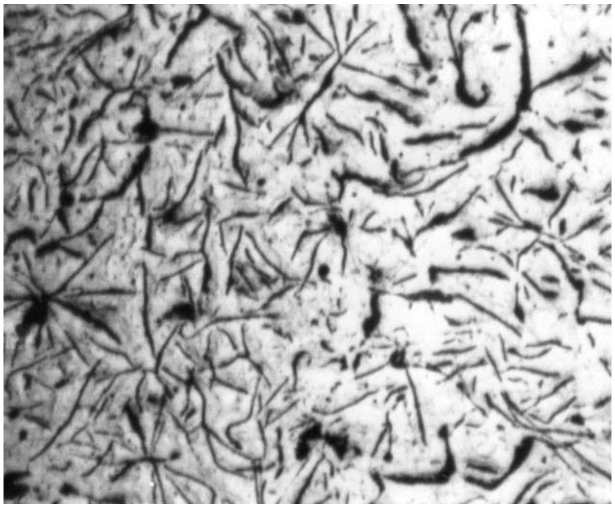

Figure 8. Example of typical graphite structure C in cast iron; study sample W2536 (45x magnification). (Image by Alicia Caporaso, 2003.)

metals and other materials to penetration. This resistance is then translated into a standard hardness number of the material being tested. High readings were obtained when the indenter was placed on ferrite matrix and low readings were obtained when placed on graphite dendrites. The average reading gives a reliable value for the hardness of the sample. Comparison of the samples, however, indicates that hardness is variable amongst all samples (Table 4) and is thus not a reliable tool for delineating differences between the Federal and Confederate ordnance at either battle

Etching

After microhardness testing, each of the mounted samples was etched with nital 2%, a nitric acid solution, which was left on the sample until it turned dull gray in color, then rinsed. It was checked with an optical microscope for the development of microstructures on the sample surface. The process was repeated until the microstructures were clearly delineated.

Results (Table 4)

Wilson's Creek Federal Ordnance

There is less regularity among the three shell, one case, and one fuse ring samples than those from Pea Ridge, though more regularity when compared to Confederate samples. The carbon equivalent is relatively consistent, indicating consistency in melt composition. Unlike Pea Ridge samples, the three body fragments all exhibit graphite structure Type B, though there is some variation. This indicates that either foundry conditions changed in the time between the two battles or that ordnance was requisitioned from a different source. Though different, the overall manufacturing control appears to be the same. It is not unexpected that the fuse ring fragment would have a different graphite structure, Type C, and a lower graphite density than the body fragments. This is likely due to the greater difference in ordnance thickness at the fuse ring required to support and secure the fuse. Solidification of the metal would have therefore taken somewhat longer than for the rest of the body.

Wilson's Creek Confederate Ordnance

Though less regular than the Federal samples, the three shell and two case shot fragments are more similar metallurgically than the Confederate ordnance at Pea Ridge. The carbon equivalent values vary by less than 0.35. All samples except for one shell fragment (W3221) exhibit graphite structure Type C and medium to low graphite density. This possibly indicates that Confederate supplies sourcing, ordnance manufacture, and foundry conditions were standardized at the time of this battle.

Table 4. Results of Analysis.

Artifact no.	Designation	Average Knoop Microhardness	C%	Si%	P%	CE	Graphite Type	Graphite Density
P2448	CS	256 KH	3.40	2.70	0.916	4.61	B; Densely Packed	Medium
P2527	CS	136 KH	3.62	1.99	0.77	4.54	C; Some Grouping	Low
P4045	CS	240 KH	3.62	3.08	1.09	5.01	Equal B and C Sections	Medium
P4055	CS	165 KH	3.54	3.23	1.01	4.95	B; Densely Packed	High
P4144	CS	293 KH	3.37	2.16	1.41	4.56	B; Low Packed	Medium to Low
P3376	US	315 KH	3.29	2.54	0.486	4.30	C	Medium to Low
P3380	US	148 KH	3.50	1.88	1.24	4.54	C	Very Low
P3418	US	79 KH[†]	3.35	1.72	1.98	4.58	C	Very Low
P4478	US	202 KH	3.29	1.96	1.94	4.59	C	Low
P4534	US	214 KH	3.79	1.99	0.395	4.59	C	Medium to Low
W1018	CS	103 KH	3.62	1.65	1.25	4.59	C; Some Grouping	Medium to Low
W2403	CS	99 KH[a]	3.47	2.46	0.988	4.62	C; Some Grouping	Low
W2536	CS	285 KH	3.69	1.64	0.536	4.32	C	Low
W2645	CS	236 KH	3.44	2.38	1.10	4.60	Mostly B; Low Packed, Some C	Medium
W3221	CS	207 KH	3.37	2.86	1.03	4.67	B	Medium to High
W1028	US	212 KH	3.54	2.20	0.901	4.57	C	Low
W1089	US	222 KH	3.60	1.34	0.582	4.24	C; Some Grouping	Low
W1121	US	276 KH	3.39	1.82	1.96	4.65	B	Medium to High
W1175	US	138 KH	3.57	2.12	0.761	4.53	B	Medium to Low
W3685	US	203 KH	3.05	2.43	1.59	4.39	B	Medium to Low

Note: US–United States; CS–Confederate States.

[†] At least one of the measurements was taken over a graphite cluster resulting in a low average KH value.

Pea Ridge Federal Ordnance

All of the Federal ordnance samples from Pea Ridge are highly similar. The regularity of carbon equivalent values indicate that though the two shells and two case shot may have been manufactured at different times and at different foundries, melt composition was consistent between manufacturers. This may also indicate that Federal stores of ordnance were well stocked. Consistent microstructure, Type C, and low graphite density indicates foundry conditions were controlled, rendering a consistent product. This could allow for artillerists' confidence in the expected response of the ordnance.

Pea Ridge Confederate Ordnance

The Confederate ordnance from Pea Ridge exhibited much less regularity than the Federal supplies. The difference between the carbon equivalent values of the samples, though less than 1.0, appears to be nonstandardized, indicating that the Confederate army was requisitioning supplies from several sources at the time of this battle, and that by this time the Confederate ordnance supply chains were disrupted. Additionally, there is no regularity of graphite type or graphite density, indicating highly variable foundry characteristics.

Conclusions

Though the relative amounts of carbon, silicon, and phosphorus vary, at times considerably, the carbon equivalent value across the board is uniform (Table 4). This may indicate that metal mixing, melting, and casting occurred in batches and that none of the samples are from the same piece of ordnance. Notably, the carbon equivalent is uniformly higher for the Confederate ordnance than for the Federal. This could be used as a tool to determine to which army the fragments belong if spatial analysis and other means of visual inspections prove insufficient. Overall, the results show that these are made of undercooled gray cast iron that was manufactured under accurate, but not precise control.

The microstructure of the samples indicates much more uniformity in the Federal projectiles as opposed to those of the Confederates. While uniformity for both armies was greater at Pea Ridge than at Wilson's Creek, the Federal artillery was of nearly complete uniformity at Pea Ridge. This is most likely due to the fact that much of the ordnance fired at Wilson's Creek, the earlier battle and one of the first Western battles in the war, probably was obtained from many sources, possibly even from stocks dating as far back as the war with Mexico in 1848. By the time of the battle at Pea Ridge, enough ordnance would have been fired in the war that the ordnance found at Pea Ridge was likely manufactured just before the battle and would have been procured from fewer suppliers, thus providing more uniformity.

Why Federal ordnance from Wilson's Creek, though highly uniform, was so undercooled (graphite Type B) is a question that remains. This may be due to the assumed season of manufacture. The battle was fought in the spring and the ordnance was likely produced within a few months of the battle. If it is assumed that all foundries followed the instructions provided in *The Artillerist's Manual* with respect to solidification in the sand mold, the ambient temperature of the foundry in the winter may have assisted in the retention of heat in the mold. This is conjecture but it is worth exploring further. Another explanation may be that larger batches were being made at a time or production output of individual foundries was greater at Federal foundries than at Confederate. This could mean that artillery and ordnance were being obtained from fewer Federal suppliers than Confederate.

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REFERENCES

Angus, H.T.
1976 *Cast Iron: Physical and Engineering Properties*. Butterworths, London, UK.

Bolton, John W.
1937 *Grey Cast Iron: General Manufacture, Structural Metallurgy, and Engineering and Physical Properties*. Penton Publishing Co., Cleveland, OH.

Callister, William D., Jr.
2001 *Fundamentals of Materials Science and Engineering*, 5th edition. John Wiley and Sons, Inc., New York, NY.

Cutrer, Thomas W.
1993 *Ben McCulloch and the Frontier Military Tradition*. University of North Carolina Press, Chapel Hill.

Davis, J.R. (editor)
1996 *ASM Specialty Handbook: Cast Irons*. ASM International, Materials Park, OH.

Gibbon, John
1860 *The Artillerist's Manual*. Benchmark Publishing Company, Inc., Glendale, CA.

Hartje, Robert G.
1967 *Van Dorn: The Life and Times of a Confederate General*. Vanderbilt University Press, Nashville, TN.

Lyman, Taylor (editor)
1961 *Metals Handbook: Properties and Selection of Metals*. American Society for Metals, Metals Park, OH.

1972 *Metals Handbook: Atlas of Microstructures of Industrial Alloys*. American Society for Metals, Metals Park, OH.

Monaghan, Jay
1955 *The Civil War on the Western Border: 1854–1865*. University of Nebraska Press, Lincoln.

Petsche, Jerome E.
1974 *The Steamboat Bertrand: History, Excavation, and Architecture*. National Park Service, Washington, DC.

Piston, William G., and Richard W. Hatcher III
2000 *Wilson's Creek: The Second Battle of the American Civil War and the Men Who Fought it*. University of North Carolina Press, Chapel Hill.

Scott, David A.
1991 *Metallography and Microstructure of Ancient and Historic Metals*. Getty Conservation Institute, J. Paul Getty Museum, Los Angeles, CA.

Shea, William and Earl Hess
1992 *Pea Ridge: Civil War Campaign in the West*. University of North Carolina Press, Chapel Hill.

Thomas, Dean S.
1985 *Cannons: An Introduction to Civil War Artillery*. Thomas Publications, Gettysburg, PA.

van de Velde, Cees
2004 A New Approach to the Solidification of Ductile Cast Iron, Bergen op Zoom, The Netherlands. <http://members.lycos.nl/cvdv/primarygray.htm>. Accessed 1 June 2006.

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