

# Analyzing gray cast iron essay



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To: Professor Lyman From: Taylor McManus Date: April 29th, 2011 Subject: Analysis of a 1912 Ford Model-T rear drum brake failure and composition

Executive Summary The analysis of the 1912 Ford Model-T rear drum brake, Figures 1-2, has resulted in the conclusion that the brake material is best described as gray cast iron. The material has been proven to contain the phases of ferrite ( $\alpha$ -Fe), cementite ( $\text{Fe}_3\text{C}$ ), graphite (C), iron phosphide ( $\text{Fe}_3\text{P}$ ), manganese sulfide ( $\gamma$ -MnS), and titanium oxide ( $\text{TiO}$ ), which are all phases commonly found in gray cast iron [9].

The probable casting method is gravity permanent mold casting, commonly used to cast gray iron. The brake failure is due to a brittle fracture occurring in the weak interdendritic regions along the edges containing type D graphite. Crack propagation most likely took place along the edge and then spread through the material along the graphite flakes, which have a much lower tensile strength than the iron matrix. Background The process that was most likely used to cast the 1912 Ford Model-T rear drum brake would be gravity permanent mold casting.

This process was commonly used to cast gray iron. Molten metal is poured into what is commonly a graphite mold. For gray iron, the liquid metal is usually poured at approximately  $1370^\circ\text{C}$  [3]. This method of casting will lead to a higher cooling rate on the sections of the casting that are touching the mold and a lower cooling rate for the center of the cast. Five types of graphite are found in the sample using light optical microscopy. Different types of graphite form due to differences in solidification rate, section thickness, and pouring temperature [4].

Figure 3 is a microphotograph of Type A and C graphite found in the radial cut sample. Type A and C graphite form when undercooling is slight [4]. This type of graphite is the most commonly desired structure if the mechanical properties are to be optimized in terms of wear applicants. Type B graphite, shown in Figure 5, also known as the rosette pattern, forms in iron with near-eutectic composition that undergo a greater amount of undercooling than Types A and C graphite [4]. Type B graphite is commonly found in thin sections (about 10mm thick) and along the surfaces of thicker sections.

Type D graphite, imaged in Figure 4, is found in interdendritic regions and is promoted by rapid solidification of thin sections and high superheating temperatures [4]. This type of graphite is formed near rapidly cooled surfaces or in thin sections and is frequently surrounded by ferrite, resulting in soft spots in the casting. Type D graphite is characterized by a fine graphite pattern sharply delineating the primary dendrites. Type E graphite, seen in Figure 6, forms when the amount of undercooling is high and is also found in interdendritic regions [4].

Unlike Type D graphite, however, type E graphite can be associated with a pearlitic matrix and enables the casting to have wear properties as good as those in type A [4]. Dendrites tend to form on the outside edges of the cut since dendrites form due to rapid cooling. Since the edges cool faster than the middle during cooling, dendrites are more prominent along the edges [4]. Results The density of the sample was measured and found to be 6.99 g/cm<sup>3</sup>. The sample was then examined under a light optical microscope, and a hypothesis was formed that the material is gray cast iron.

The known density of gray cast iron ranges from 7.0-7.3 g/cm<sup>3</sup> [1]. In order to determine the unknown material, all phases must first be identified within the sample. Ferrite ( $\alpha$ -Fe) An X-ray map, shown in Figure 7, taken with a Scanning Electron Microscope (SEM) was taken of the sample at the location of the image in Figure 8. From the map it is clear that iron is heavily present in the material. Figure 9 shows an X-ray spectrum taken with the SEM of the sample. The spectrum shows that iron is the most prominent element in the sample.

A Powder X-ray Diffraction Pattern was then taken of the sample. Inter-planar spacing values (d-values) were calculated from the peaks found in the XRD pattern shown in Figure 9. The calculated d-values matched up closely with the accepted d-values, found by cross referencing the values in the Materials Database with the ICDD-PDF cards, show that there are present peaks with d-values of 2.022Å, 1.430Å, and 1.168Å representing the (110), (200), and (211) planes of iron, respectively. See Table 1 for d-value comparisons.

An Energy Dispersive X-ray spectrum of the matrix of the sample, shown in Figure 10 and then expanded and shown in Figure 11, was produced using a Transmission Electron Microscope (TEM). Table 2 shows the energy values taken from the spectrum and compared against known values. The EDX spectrum shows that  $\alpha$ -iron, at 6.404 keV, has the most intense peak. Iron in BCC crystal structure has a space group of  $Im\bar{3}m$  [5]. PDF Card 04-003-3330 [11] for iron is attached in Figure 26. Graphite The first large peak in the Powder XRD pattern, seen in Figure 9, represents graphite with a d-value of 3.355Å at the (002) plane.

The Powder XRD pattern was then expanded, seen in Figure 12, to show the minor peaks of the material. Graphite is found to be represented by d-values of 1.678 Å and 1.231 Å at the (004) and (110) planes of graphite, respectively. Comparisons of the d-values and relative intensities are shown in Table 1. A graphite flake was thinned using a gallium ion beam, shown in Figure 13, and examined under a TEM to produce an X-ray emission spectrum, seen in Figure 14. In the spectrum, carbon has the most intense peak at an energy level of 0.277 keV. See Table 3 for a full analysis of the spectrum.

An SAED pattern of the graphite flake, indexed in Figure 15, allowed for measured d-values of 3.357 Å and 1.697 Å, which correspond to the (110) and (004) planes of graphite, respectively. See Table 4 for d-value comparisons. The volume fraction of graphite, shown in Table 5, is found to be 12.9 ± 1.91% for the circumferential cut and 12.2 ± 1.24% for the radial cut sample [10]. Graphite has a space group of C6/mmc [5]. PDF Card 00-056-0159 [11] for graphite is attached in Figure 27. Cementite (Fe<sub>3</sub>C)

Analyzing the Powder XRD pattern, cementite was identified with d-values of 2.68 Å, 1.854 Å, and 2.264 Å, representing the (200), (221), and (002) planes of Fe<sub>3</sub>C, respectively. The peak with d-value 2.068 Å, as well as other intense Fe<sub>3</sub>C peaks, are shadowed by the most intense  $\gamma$ -Fe peak at 44.8°, which correlates with the fact that Fe<sub>3</sub>C is mostly composed of iron. Analysis of the d-values can be seen in Table 1. Using a TEM a bright field image of a lath of probable Fe<sub>3</sub>C was taken, seen in Figure 16, and an Energy Dispersive X-ray spectrum was taken on a probable lath of Fe<sub>3</sub>C, shown in Figure 17, and a spectrum was taken just off the lath, shown in Figure 18.

After analyzing the energy values, it is found that carbon, energy of . 277 keV, is present on the lath but is absent just off the lath. Iron has the most intense peaks in both spectrums. See Tables 6-7 for the analysis of the energies. By examining the SEM image seen in Figure 8 it is possible to discern a lamellar structure of cementite and ferrite showing that pearlite is a microstructure of the sample. The volume fraction of cementite in the sample was found to be 20. 3% +/- 4. 71% [9]. Cementite has a space group of Pnma. PDF Card 00-034-0001 [11] for cementite is attached in Figure 30.

Iron Phosphide (Fe<sub>3</sub>P) The X-ray spectrum taken with the SEM, Figure 19, and the X-ray map, Figure 7, show that phosphorous is present in the sample. See Table 8 for indexed energy values of the SEM X-ray spectrum. The powder XRD spectrum, Figure 12, shows that peaks of Fe<sub>3</sub>P are present with d-values of 2. 200 Å and 2. 030 Å, and 1. 127 at the (321), (420), and (651) planes of iron phosphide, respectively. One of the most intense peaks of Fe<sub>3</sub>P, with d-value 2. 230 Å, is in the same location as the most intense iron peak at 44. 5?. Since Fe<sub>3</sub>P is mostly composed of iron, the peaks are in similar locations.

Comparisons for the d-values are shown in Table 1. A long precipitate was found and imaged using the TEM. A bright field image of the precipitate is seen in Figure 20 and a dark field image is seen in Figure 21. An X-ray Emission Spectrum taken on the precipitate, seen in Figure 22, shows that iron is the most prevalent element in the precipitate at an energy of 6. 404 keV. See Table 9 for analysis of the energies. An SAED pattern of the precipitate, seen in Figure 23, was analyzed and d-values of 2. 030Å, 1.

100A, and 1. 210A were found, representing the (201), (321), and (302) planes of Fe<sub>3</sub>P, respectively.

See Table 10 for a comparison of the d-values. Iron phosphide has a space group of I4 (4-bar) [2]. PDF Card 00-019-0617 [11] for iron phosphide is attached in Figure 29. Manganese Sulfide ( $\gamma$ -MnS) After analyzing the SEM X-ray map, Figure 7, it was seen that there are small regions throughout the matrix that contain both manganese and sulfur in the exact same areas, suggesting that both elements are present together. After analyzing the powder XRD pattern, Figure 12, peaks with d-values of 2. 600 A and 1. 838 A were found, representing the (200) and (220) planes of  $\gamma$  manganese sulfide, respectively. Comparisons of the d-values can be seen in Table 1.

Manganese sulfide has a space group of Fm3m [5]. PDF Card 04-007-0192 [11] for manganese sulfide is attached in Figure 28. Titanium Oxide (TiO) The SEM X-ray map seen in Figure 7 shows that titanium is present in the sample. After analyzing the powder XRD pattern, peaks of titanium oxide (TiO) were found with d-values of 2. 450A, 1. 500A, and 1. 280A, representing the (111), (220), and (311) planes of titanium oxide, respectively. See Table 1 for a full d-value comparison.

Titanium inclusions in the metal bonded with oxygen from the air to form small spots of TiO in the sample; see the SEM image in Figure 8 for an image of the TiO phase. Titanium oxide has a space group of Fm3m. PDF Card 00-002-1196 [11] for titanium oxide is attached in Figure 31. Discussion Gray Cast Iron Gray irons are alloys of iron, carbon, and silicon which typically contain 2. 5 to 4% carbon, 1 to 3% silicon, up to 1% manganese, and small amounts of sulfur and phosphorous [9]. The sample material is proven to be

gray cast iron. The sample has density in the range of cast iron density, 7. -7.3 g/cm<sup>3</sup> [4] and also contains the same major phases: ferrite, graphite, and cementite as well as minor phases of manganese sulfide, iron phosphide, and titanium oxide. Failure Mechanism When the brake pad pushes outwards against the drum, it produces force against the circumferential wall, which led to a brittle fracture. This failure was most likely caused by the graphite. Graphite flakes in cast iron act as cracks that are stress concentrators for fatigue crack initiation. During casting, the iron undergoes cooling that is faster on the edges of the casting than in the center.

This rapid cooling rate along the edges produces large dendritic areas populated by Type D and E graphite [4]. The site of the crack propagation was most likely in the regions of type D graphite, which is the weakest type. Seen in the graphite location maps in Figures 24-25, type D graphite is present along the inside edge of the circumferential cut and along the bottom edge of the radial cut sample. Once a crack propagates along the outer edges of the sample in the interdendritic regions, the line of fracture will follow the graphite flakes through the material.

Type A and C graphite have a higher tensile strength than those of types B, D, and E, which means that Type A and C graphite are more brittle in comparison. Once the crack propagated in the weak interdendritic regions of type D graphite, the line of fracture followed the graphite flakes, which have a much lower tensile strength than the iron matrix, into the center of the material where it caused a brittle fracture in the regions with A and C graphite. Figures and Data: Figure 1- Photograph of the 1912 Ford Model-T



rear drum brake failure location Figure 2- Photograph of the 1912 Ford Model-T rear drum brake, whole Type A, C

Figure 3- Light optical photomicrograph of Type A and C Graphite from the radial cut Type D Figure 4- Light optical photomicrograph of Type D Graphite from the Circumferential cut Type B Figure 5- Light optical photomicrograph of Type B Graphite from the circumferential cut Type E Figure 6- SEM image of Type E graphite from the radial cut Figure 7- An SEM X-ray map of the cast iron sample showing the amounts of different elements 6 5 4 3 2 1 Figure 8- An SEM image of the cast iron sample for the X-ray map: (1) Pearlite. (2) Ferrite. (3) Manganese sulfide. (4) Iron Phosphide. (5) Graphite. 6) Titanium oxide Table 1: Comparison of d-values from the powder X-ray diffraction pattern

| Phase                              | Measured d-values (Å) | Accepted d-values (Å) | Relative Intensities (%) | hkl         | PDF Card: |
|------------------------------------|-----------------------|-----------------------|--------------------------|-------------|-----------|
| Iron (α-Fe)                        | 45.00                 | 2.012                 | 2.022                    | 100         | 110       |
|                                    | 65.00                 | 1.424                 | 1.430                    | 11          | 200       |
|                                    |                       |                       |                          | 04-003-3330 |           |
|                                    | 82.50                 | 1.168                 | 1.168                    | 17          | 211       |
|                                    |                       |                       |                          |             |           |
|                                    |                       |                       |                          |             |           |
|                                    |                       |                       |                          |             |           |
| Graphite                           | 26.50                 | 3.355                 | 3.353                    | 100         | 002       |
|                                    | 54.60                 | 1.680                 | 1.678                    | 7           | 004       |
| Cementite (Fe <sub>3</sub> C)      | 77.50                 | 1.230                 | 1.231                    | 12          | 110       |
|                                    | 49.1                  | 1.847                 | 1.854                    | 45          | 221       |
| Manganese Sulfide (γ-MnS)          | 39.8                  | 2.252                 | 2.64                     | 40          | 002       |
|                                    | 34.5                  | 2.560                 | 2.600                    | 100         | 200       |
| Iron Phosphide (Fe <sub>3</sub> P) | 49.5                  | 1.858                 | 1.838                    | 55          | 220       |
|                                    | 40.9                  | 2.204                 | 2.200                    | 100         | 321       |
| Titanium Oxide (TiO)               | 44.6                  | 2.034                 | 2.030                    | 80          | 420       |
|                                    | 86.2                  | 1.124                 | 1.127                    | 65          | 651       |
| C Fe Fe Fe                         | 61.8                  | 1.499                 | 1.500                    | 80          | 220       |
|                                    | 74                    | 1.279                 | 1.280                    | 60          | 311       |

Figure 9- A powder X-ray

diffraction spectrum of the sample showing four main peaks Fe L? 1 Si K? 1 Fe K? 1 Cu K? 1 Cu K edge

Fe K? Figure 10: Wide area matrix x-ray emission spectrum (EDS). Fe L? 1 C K? 1 Si K? 1 Ga K? 1 Fe K? 1 Fe K? Cu K? 1 Mn K? 1 Cu K edge Figure 11:

Wide area matrix x-ray emission spectrum expanded vertically. Table 2:

Energy values taken from the X-ray Emission Spectrum of the matrix in

Figure 11 Approximate Energy (keV)| Energy from Table (keV)| Element|

Radiation| 0. 25| 0. 277| Cu| K? 1| 0. 70| 0. 705| Fe| L? 1| 1. 75| 1. 74| Si| K?

1| 5. 90| 5. 899| Mn| K? 1| 6. 40| 6. 404| Fe| K? 1| 7. 10| 7. 111| Fe| K edge| 8.

05| 8. 048| Cu| K? 1| 8. 90| 8. 98| Cu| K edge| 9. 22| 9. 252| Ga| K? 1| Key: -

Fe Graphite -Fe<sub>3</sub>P -Fe<sub>3</sub>C -MnS Figure 12- The powder X-ray diffraction

spectrum shown in Figure 1, zoomed in to show the small peaks above

the background Graphite Figure 13: Graphite flake. Magnification-30Kx. C K?

1 Cu K edge Cu K? 1 Figure 14: X-ray emission spectrum from graphite flake.

Table 3: Energy values taken from the X-ray emission spectrum of a graphite

flake in Figure 14 Approximate Energy (keV)| Energy from Table (keV)|

Element| Radiation| 0. 25| 0. 277| C| K? 1| 8. 05| 8. 048| Cu| K? 1| 8. 90| 8.

98| Cu| K edge| [110] [101] [121] [011] Figure 15: SAED pattern from

graphite flake.

Table 4: Comparison of d-values from the SAED pattern of a graphite flake |

Measured d-value| Accepted d-value| hkl| Graphite| 3. 357| 3. 355| 110| | 1.

697| 1. 678| 004| Table 5- Volume fraction of all secondary phases from the

rear drum break samples (magnification of 10x). Trial| Circumferential Cut|

Radial Cut| 1| 11| 12| 2| 15| 11| 3| 14| 13| 4| 10| 14| 5| 15| 10| 6| 16| 11| 7| 9|

12| 8| 13| 11| 9| 12| 15| 10| 14| 13| SumAverageStandard Deviation from

<https://assignbuster.com/analyzing-gray-cast-iron-essay/>

Mean | 12912. 91. 91| 12212. 21. 24| Fe<sub>3</sub>C Figure 16- Bright field image of lath of Fe<sub>3</sub>C in Pearlite formation taken with a TEM Fe L? 1

Si K? 1 Cu K edge Fe K? 1 Cu K? 1 Fe K? C K? 1 Figure 17: X-ray emission spectrum from a location on the lath of Fe<sub>3</sub>C. Table 6: Energy values taken from the X-ray emission spectrum on the lath of probable Fe<sub>3</sub>C

| Approximate Energy (keV) | Energy from Table (keV) | Element | Radiation |
|--------------------------|-------------------------|---------|-----------|
| 0. 25                    | 0. 277                  | C       | K? 1      |
| 0. 70                    | 0. 705                  | Fe      | L? 1      |
| 1. 75                    | 1. 74                   | Si      | K? 1      |
| 6. 40                    | 6. 404                  | Fe      | K? 1      |
| 7. 10                    | 7. 111                  | Fe      | K edge    |
| 8. 05                    | 8. 048                  | Cu      | K? 1      |
| 8. 90                    | 8. 98                   | Cu      | K edge    |

1 Fe K? 1 Si K? 1 Cu K edge Cu K? 1 Fe K? Figure 18: X-ray emission spectrum from a location in the matrix just off the lath of Fe<sub>3</sub>C.

Table 7: Energies taken from the X-ray emission spectrum of a location in the matrix just off the lath of probable Fe<sub>3</sub>C

| Approximate Energy (keV) | Energy from Table (keV) | Element | Radiation |
|--------------------------|-------------------------|---------|-----------|
| 0. 70                    | 0. 705                  | Fe      | L? 1      |
| 1. 75                    | 1. 74                   | Si      | K? 1      |
| 6. 40                    | 6. 404                  | Fe      | K? 1      |
| 7. 10                    | 7. 111                  | Fe      | K edge    |
| 8. 05                    | 8. 048                  | Cu      | K? 1      |
| 8. 90                    | 8. 98                   | Cu      | K edge    |

Figure 19- The SEM X-ray spectrum taken at 200X and 15kV showing the present elements in the cast iron sample. Table 8: Energies indexed of the SEM X-ray spectrum of the sample.

| Approximate Energy (keV) | Energy from Table (keV) | Element | Radiation |
|--------------------------|-------------------------|---------|-----------|
| 1. 5                     | 1. 74                   | Si      | K? 1      |
| 2. 00                    | 2. 014                  | P       | K? 1      |
| 5. 90                    | 5. 899                  | Mn      | K? 1      |
| 6. 40                    | 6. 404                  | Fe      | K? 1      |

Long precipitate Figure 20: Bright-field image of long precipitate. Figure 21: Dark-field image of long precipitate. Fe L? 1 Si K? 1 Cu K edge Cu K? 1 Fe K? Fe K? 1 Mn K? 1 Figure 22: TEM X-ray emission spectrum from long precipitate.

Table 9: Energy values from the X-ray emission spectrum of the long precipitate

| Approximate Energy (keV) | Energy from Table (keV) | Element | Radiation |
|--------------------------|-------------------------|---------|-----------|
| 0. 70                    | 0. 705                  | Fe      | L? 1      |
| 1. 75                    | 1. 74                   | Si      | K? 1      |
| 5. 90                    | 5. 899                  | Mn      | K?        |

1| 6. 40| 6. 404| Fe| K? 1| 7. 10| 7. 11| Fe| K edge| 8. 05| 8. 048| Cu| K? 1| 8. 90| 8. 98| Cu| K edge| [201] [321] [302] Figure 23: SAED pattern from long precipitate (includes some matrix spots). Table 10: Comparisons of d-values found in the SAED pattern of the long precipitate (Fe<sub>3</sub>P) | Measured d-value| Accepted d-value| hkl| Fe<sub>3</sub>P| 2. 031| 2. 03| 201| | 1. 11| 1. 1| 321| | 1. 214| 1. 21| 302| Figure 24: Graphite location map of the circumferential cut sample Figure 25: Graphite location map of the radial cut sample Figure 26- (attached) Iron PDF Card 04-003-3330 Figure 27- (attached) Graphite PDF Card 00-056-0159

Figure 28- (attached) Manganese Sulfide PDF Card 04-007-0192 Figure 29- (attached) Iron Phosphide PDF Card 00-019-0617 Figure 30-(attached) Cementite PDF Card 00-034-0001 Figure 31-(attached) Titanium Oxide PDF Card 00-002-1196 Appendix: Procedures: Grinding, Polishing, and Etching: The specimen was ground using 240, 320, 400, and 600 grit paper. No water was used after the grinding stage in order to ensure that graphite doesn't leave the sample. It was then polished with 6- $\mu$ m diamond, then 1- $\mu$ m aluminum oxide, and lastly 0. 04  $\mu$ m colloidal silica. The specimen is flushed with ethanol and cleaned with cotton after each step.

The specimen is then etched in 4% picral to reveal carbides and 2% nital to reveal grain boundaries. Calculating the Camera Constant: On an SAED pattern of a known material, measure the distance from the brightest dot to any other dot. Use the Edington patterns [7] to find the hkl value for the plane of the diffracted dot. Now use the interplanar spacing equation,  $d_{hkl} = a/\sqrt{h^2+k^2+l^2}$ , where ' a ' is the known lattice parameter of the material, in order to calculate the d-value for that plane. Now use the equation ?  $L = rd$

where ' r ' is the distance between the dots and ' d ' is the calculated d-value.  
Solve for ? L.

B [110] [020] [200] A SAED zone axis pattern of matrix (Fe) along [001].

A/B= 1. 414 Sample Calculations: Camera Constant: R<sub>measured</sub>= 16. 1mm

hkl= 200 a= 2. 86A dhkl= d<sub>200</sub>= a/ sqrt(h<sup>2</sup>+k<sup>2</sup>+l<sup>2</sup>) = 2. 86A/sqrt(4) = 1.

43A camera constant = ? L= r\*d = (16. 1mm)\*(1. 43A) = 23. 1 mm-A Powder

X-ray Diffraction Pattern d-values ? = 2d sin(? ) ? = 1. 5406 A Figure 9, most  
intense peak (Iron (110) plane) 2? = 45? d=? /2sin? = (1.

5406A)/(2\*sin(45/2)) = 2. 013A References: [1] Cox, Mike. " Cast Iron Liquid  
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