Casting Solutions for Readiness
Casting Alloy Data Search (CADS)

American Foundry Society

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1.0 Abstract

Accessing state-of-the-market technical, specification and training materials for castings is challenging. There is a need for better cast part design and specification data for longer service life, scrap reduction and improved performance. The American Foundry Society (AFS) is working to provide current and qualified information in a network friendly form to users of castings. This effort includes both archival and recent technical information in searchable databases. Specifications and standards are summarized, and the user is guided in their application. Tutorials covering the fundamental design concerns are also presented. These tools facilitate more effective and efficient procurement to both Department of Defense (DoD) and industry. Along with data from various AFS research projects, such as projects for the Development of Fatigue Properties Database, AFS has also incorporated the USAMP USAMP/USCAR Light Metals Materials Database properties and strain life fatigue data for CGI Grade 400 and a hi-alloy Class 40 Gray Iron into the AFS Casting Alloy Data Search (CADS) tool onto the AFS design website.

As part of the American Metalcasting Consortia (AMC) Casting Solutions for Readiness (CSR) program, a new project, Casting Alloy Data Search (CADS) tool was developed by AFS in partnership with PDA LLC and has been funded through the Defense Logistics Agency Research & Development Office. CADS, an online material design property database, is an enhancement of previous AFS AMC efforts to provide supply chain tools to facilitate reduction of lead time for castings and streamline the casting supply chain. This work builds on previous AMC, DOE, AFS, Steel Founders' Society of America (SFSA) and North American Die casting Association (NADCA) funded work, as well as on previous AFS sponsored research and DOE USAMP/USCAR work to develop material and physical properties benefiting designers. CADS greatly enhances the ability of the component design engineer to create the lightest weight and most efficient parts more quickly and at lower cost. The work planned under this project will add design properties for 4-5 additional cast metal alloys per year, while continuing to upgrade the CADS online database.

Industry users of this website will find CADS easy to use with step by step instructions on the website. Information has been disseminated through metalcasting industry associations via conferences, committee meetings, research reviews, periodicals, specification standards, webinars, and web sites. Presentations have been given at the AFS Casting Congress, Casting Design Conference, AFS Cast Iron Committee, SAE Fatigue chapter, and Investment Casting Institute conference. The AFS publication Modern Casting has included articles introducing readers to CADS. A webinar is also planned to introduce CADS users to the database and how to use it.

This work is valuable for the DLA supply chain by providing capable suppliers and enhanced supply base to ensure availability of critical cast parts to keep weapons systems operational. It also assists with obtaining optimized cast part performance and light-weighting.

2.0 Background/Motivation

Preliminary engineering design properties that reflect the capability of cast metals are not readily available in a convenient searchable form from a recognized source. The American Foundry Society is the recognized industry source for process technology and the logical source to establish a searchable database for cast metal properties. Qualified data is vital to design engineers to effectively design more sophisticated parts and components. Light-weighting often results in more highly stressed parts due to thinner section thicknesses. Castings are becoming extremely complex with the capabilities of 3D sand printing.

Current handbooks contain material properties which are either inadequate, printed format, generated with outdated test methods and lack the pedigree information such as process, chemistry, etc. Due to a continuous decrease in the number of metalcasters and to critical design properties sometimes being difficult to find or simply not available, there are times when substantial delays occur in the procurement of castings.

Task 1: CADS Upgrade

The CADS database provides casting process and design guidance for quality and performance. The properties within a casting differ as the cooling rate differs, so that it becomes important to realize the differences in properties as a function of cooling rate (section size or microstructure). To address these differences in properties, the CADS upgrade to Version 2.0 includes temperature dependent physical and mechanical property data. Additionally, this new Version 2.0 separates each sub-group of the data category for better viewing and printing individually.

The upgraded CADS Version 2.1 separates each sub-group of the data category for better viewing and printing individually. Temperature dependent physical properties and mechanical properties are incorporated into an existing database. Other improvements in this version are: allowance of the typical or actual chemistry to be added for which the properties are developed; expansion of the chemical elements to allow for some trace and alloying elements; additional extra fields for aluminum such as SDAS, grain size, eutectic modification; addition to expand the strain life fatigue data for various iron and steel grades. Moreover, there is a tutorial incorporating strain life fatigue data.

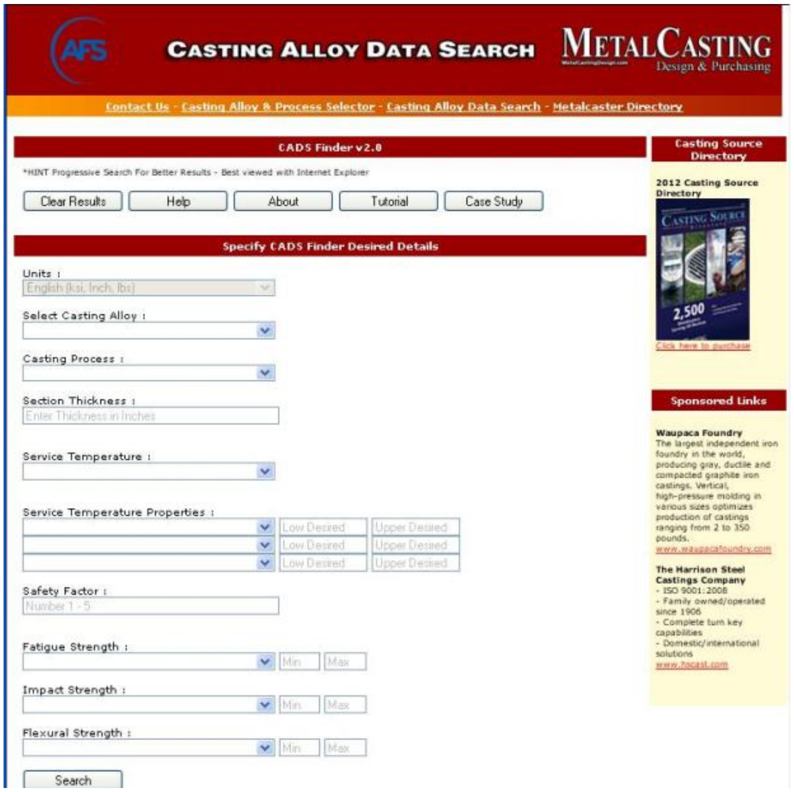
The upgraded CADS Version also has a new module, Mold Material Data Selector, (MMDS). This new module is a tool for engineers to select mold and core materials engineering data for various processes and alloys as applicable to enable a quick method of mold material selection dependent on the casting requirements. It provides a search tool to design engineers with engineering and simulation data digitally. Thermo-physical and mechanical properties for four different samples, including 3D printed sand, have been entered. This additional module was part of the original Statement of Work for the CADS project.

Task 2: Additional new alloys

Over the last 10 years, AFS has been developing a material database, which now includes over 32 grades of cast iron for strain-life fatigue properties per SAE J1099 and a comprehensive mechanical and fatigue database for various other cast alloys, such as Aluminum E357, 535, A356 and A206, for inclusion into the AFS CADS. This is an online database search and retrieval tool maintained by AFS, in partnership with PDA to benefit design engineers for Finite Element Analysis (FEA) based validations for new product development and optimization and by the casting and design community. It is an Open Access Database, which has been shared with other design communities. Additionally, previously developed alloy data by USCAR/USAMP for various cast aluminum and magnesium alloys are also incorporated into CADS.

3.0 Results/Discussion

The CADS (Casting Alloy Data Search) Tool has been developed as an online casting material database to assist DoD, OEMs, and metalcasters with easy accessibility to all critical design properties. This database has been designed so that the material properties can be imported into CAE design and FEA programs. CADS assists the casting design engineer with the latest data sets for engineering properties including strain life fatigue determined using the latest test methods available. The CADS tool is integrated with the other tools, such as Casting Alloy and Process Selector Tool (CAPS) and Metalcaster Directory developed for the casting OEM design engineers and buyers as an assistance with detail design and to match the right metalcaster with their product anywhere in North America. There is a tutorial with detailed instructions of the use of CADS, as well as a help function and a case study. The CADS tool can be accessed directly on the AFS website by going to http://www.metalcastingvirtuallibrary.com



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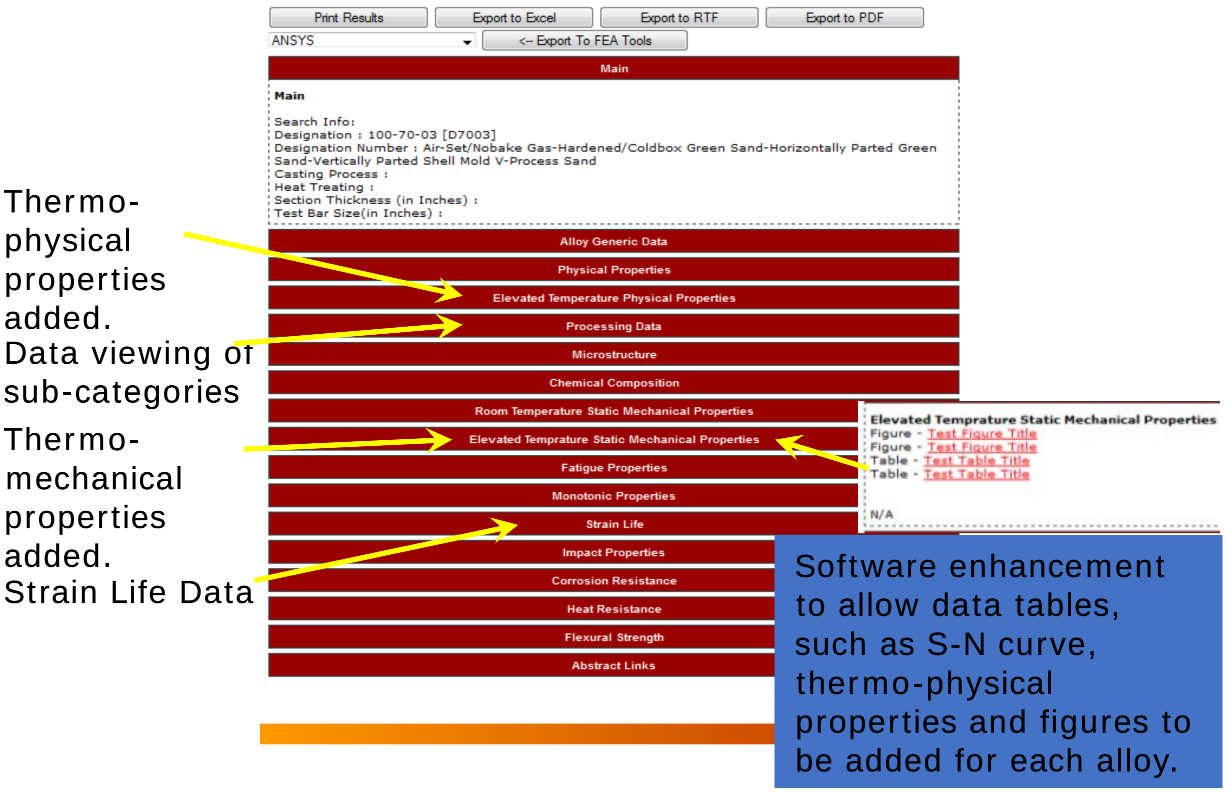
In CADS Version 2.1, the tool was enhanced to included thermo-physical properties and thermo-mechanical properties to assist process modeling. Also, capability to add data tables such as stress vs. number of cycles (S-N) curves and figures for each alloy was added.



Main

Search Info:
Designation : 100-70-03 [D7003]
Designation Number : Air-Set/Nobake Gas-Hardened/Coldbox Green Sand-Horizontally Parted Green Sand-Vertically Parted Shell Mold V-Process Sand
Casting Process :
Heat Treating :
Section Thickness (in Inches) :
Test Bar Size(in Inches) :

Elevated Temprature Static Mechanical Properties
Figure - Test Figure Title
Figure - Test Figure Title
Table - Test Table Title
Table - Test Table Title

N/A

Thermo-physical properties added.
Data viewing of sub-categories
Thermo-mechanical properties added.
Strain Life Data

Software enhancement to allow data tables, such as S-N curve, thermo-physical properties and figures to be added for each alloy.

As a continuation of the mission to populate more cast alloy properties into this database generated using the most modern test methods and approaches for design optimization thus promoting the use of castings over wrought or fabricated products, additional data has been generated and additional alloys have been added to the database. At times, statistical methods were used, considering the sensitivity to section thickness and casting process used to pour test bars or test castings from which test specimens are extracted. The test bars were poured with typical process variations found from foundry to foundry at the same time keeping a narrow spread in the major factors. To keep a narrow spread in the major factors in those instances where heat treatment was outsourced, all sample test bars went to the same heat treater to be treated in the same furnace to eliminate/minimize the variation in this factor.

This database continues to grow with the addition of several alloys each year and now has over 300 data sets for various irons including Austempered Ductile Iron (ADI), High Silicon Molybdenum iron (HiSiMo), various grades of common cast steels, and aluminum and magnesium alloys imported from USCAR/USAMP research projects. Some of the alloys tested and added most recently include WCB steel, 4330 steel, 8630 steel, CF8M (316) stainless steel, 420 (CP40) stainless steel, and Solution Strengthened Ferritic Ductile Iron (SSFDI). 17-4 and 15-5ph steel data and A206 aluminum data from the CHAMPS project have also been added. Leveraging AMC membership, five steel alloys have been added from SFSA data. Neenah Foundry supplied data for GJS500 (lower hardness version of 80-55-06); Waupaca Foundry supplied data for Class 25

Gray iron; Chrysler Corporation supplied data for HiSiMo ductile iron; Eck Industries supplied data for the new proprietary Al-Ce alloy developed by ORNL and licensed to Eck Industries.

Details on how to use the strain life fatigue data are given in Appendix A. Testing methods are given in Appendix B, which is the Element test report for the SSF ductile iron alloy that has been tested. Similar test methods were used for other alloys that were tested. The applicable standards were applied for the various materials. For example, CF8M austenitic steel was cast in accordance with ASTM standard specification A351/A351M-16 for “Castings, Austenitic, for Pressure-containing parts” and CA40 was cast in accordance with ASTM standard specification A743/A743M-13AE1 for “Castings, iron-chromium, iron-chromium-nickel, corrosion resistant for general application”. Appropriate ASTM standards were used for each material in each step of the processing and testing. The tables below list the various materials that were tested: cast irons; cast steels; and cast aluminum.

Austempered Ductile Iron: ASTM A 897-06

ASTM Grade	*Material Condition*	*Section Size*
110 / 70 / 11	Austempered	48 mm by 43 mm by 185 mm section of rectangular casting
125 – 80 – 10 (130 / 90 / 09)		25 mm Y-block
150 – 100 – 7 (150 / 110 / 07)		
175 – 125 – 4		
200 – 155 – 1		

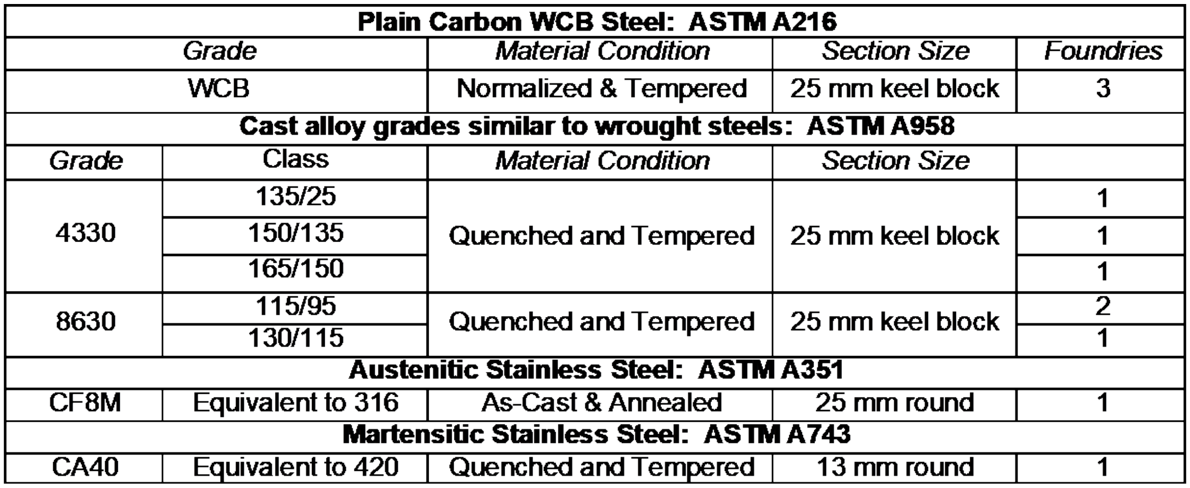
Ductile Iron: ASTM A 536-84 (Re 1999)

ASTM Grade	*Material Condition*	*Section Size*
60 – 40 – 18	As-cast	25 mm Keel block
	Subcritical Anneal	25 mm Keel block
	Full Anneal	25 mm Y-block
	Heavy Section; As-Cast	76 mm Y-block

65 – 45 - 12	As-cast	25 mm Keel block
100 – 70 – 03	As-cast	25 mm Keel block
	Normalized	25 mm Keel block
		76 mm Y-block
120 – 90 – 02	Quenched and Tempered	25 mm Keel block
Ductile Iron: DIN EN 1563:2012-03		
DIN Grade	*Material Condition*	*Section Size*
EN-GJS-500-7	As-cast	25 mm Y-block
EN-GJS-500-7	As-cast	76 mm Y-block
EN-GJS-500-14	As-cast, SSF	25 mm Y-block
Si-Mo Ductile Iron: SAE J2582 Jun 2004		
SAE Grade 2	As-cast	Bars
Compacted Graphite Iron: ASTM A 842-85(Re 1997)		
ASTM Grade	*Material Condition*	*Section Size*
300	As-Cast	25 mm Y-block
350		
400	As-Cast	25 mm Y-block
	As-Cast	76 mm Y-block
Gray Iron: ASTM A 48-00		
ASTM Grade	*Material Condition*	*Section Size*
20B	As-Cast	25 mm Y-block
30B	As-Cast	13 mm Round
	As-Cast	25 mm Y-block
	As-Cast	76 mm Y-block

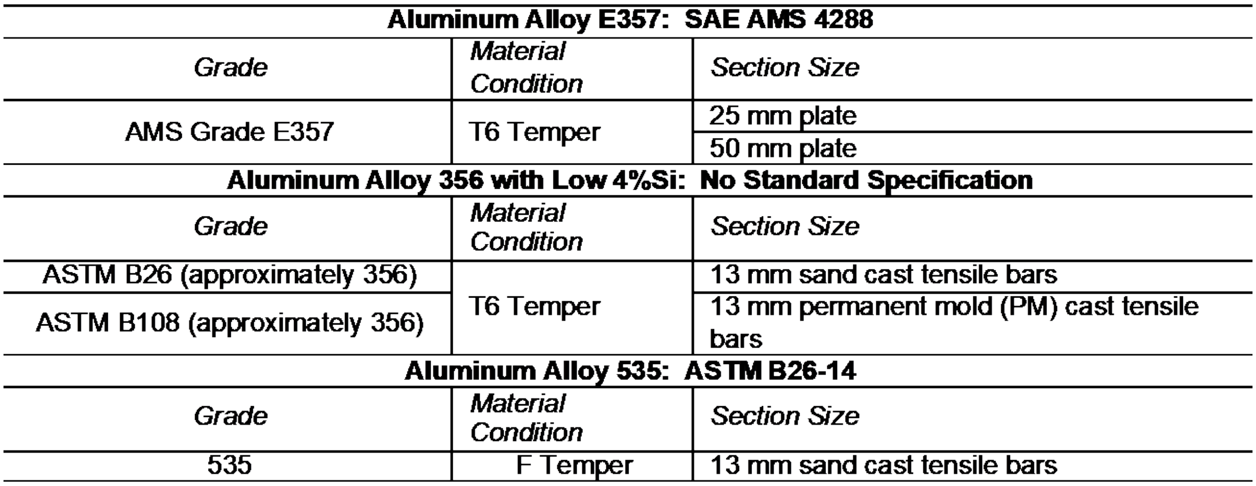
35B	As-Cast	25 mm Y-block
40B	As-Cast with C.E.= 3.7	25 mm Y-block
	As-Cast with Normal C.E. = 4.0	25 mm Y-block
Austempered Gray Iron: No Standard Specification		
Base Iron	*Material Condition*	*Section Size*
Class 30B	Austempered	25 mm Y-block
Abrasion-Resistant Cast Iron: ASTM A 532		
ASTM Grade	*Material Condition*	*Section Size*
Class III Type A Level 2 (25%Cr)	Quenched & tempered	16 mm rectangular bars

Table 1: Cast Irons



Plain Carbon WCB Steel: ASTM A216				
Grade		*Material Condition*	*Section Size*	*Foundries*
WCB		Normalized & Tempered	25 mm keel block	3
Cast alloy grades similar to wrought steels: ASTM A958				
Grade	Class	*Material Condition*	*Section Size*	
4330	135/25	Quenched and Tempered	25 mm keel block	1
	150/135			1
	165/150			1
8630	115/95	Quenched and Tempered	25 mm keel block	2
	130/115			1
Austenitic Stainless Steel: ASTM A351				
CF8M	Equivalent to 316	As-Cast & Annealed	25 mm round	1
Martensitic Stainless Steel: ASTM A743				
CA40	Equivalent to 420	Quenched and Tempered	13 mm round	1

Table 2: Cast Steels



Aluminum Alloy E357: SAE AMS 4288		
Grade	*Material Condition*	*Section Size*
AMS Grade E357	T6 Temper	25 mm plate
		50 mm plate
Aluminum Alloy 356 with Low 4%Si: No Standard Specification		
Grade	*Material Condition*	*Section Size*
ASTM B26 (approximately 356)	T6 Temper	13 mm sand cast tensile bars
ASTM B108 (approximately 356)		13 mm permanent mold (PM) cast tensile bars
Aluminum Alloy 535: ASTM B26-14		
Grade	*Material Condition*	*Section Size*
535	F Temper	13 mm sand cast tensile bars

Table 3: Cast Aluminums

A representative table of the type of data generated for the alloys in Tables 1, 2, and 3 is show in Table 4.

Aluminum Type		Aluminum Alloy Castings				Aluminum Alloy Castings		
Grade:		**Low Si 356.0-T6**				**7.0Si-0.58Mg-0.15Ti (E357.0-T6)**		
Material Condition		*ASTM B26/B26M-12 Standard (except for %Si)*	Sand Cast Tensile Bar	*ASTM B108/B108M-12 Standard (except for %Si)*	PM Cast Tensile Bar	*SAE AMS 4288 Standard*	As-cast	As-cast
Cast Section Size			13 mm (0.5 inch) Diameter by 180 mm (7 inch) Long Dogbone		13 mm (0.5 inch) Diameter by 203 mm (8 inch) Long Dogbone		25 mm (1 inch) Plate "Verification"	50 mm (2 inches) Plate "Test"
Material Code (Folder Title)			LowSi-356Sand		LowSi-356PM		E357 25 mm Verification	E357 50 mm Test
Chemical Analysis								
Element (wt%)	Si	*4.0 nominal*	3.9	*4.0 nominal*	4.1	*6.5-7.5*	7.08	7.14
	Fe	*0.6 max.*	0.11	*0.6 max.*	0.11	*0.10 max.*	0.06	0.05
	Mn	*0.35 max.*	<0.005	*0.35 max.*	<0.005	*0.10 max.*	<0.01	<0.01
	Mg	*0.20-0.45*	0.33	*0.20-0.45*	0.34	*0.55-0.6*	0.60	0.61
	Ti	*0.25 max.*	0.01	*0.25 max.*	0.01	*0.10-0.20*	0.124	0.123
	Be	-	<0.0003	-	<0.0003	*0.002 max.*	<0.002	<0.002
	Ca	-	<0.005	-	<0.005	-	<0.005	<0.005
	Cr	-	<0.005	-	<0.005	-	<0.01	<0.01
	Cu	*0.25 max.*	<0.005	*0.25 max.*	<0.005	-	<0.01	<0.01
	Ni	-	0.005	-	0.005	-	<0.01	<0.01
	P	-	<0.005	-	<0.005	-	<0.005	<0.005
	Pb	-	<0.005	-	<0.005	-	<0.01	<0.01
	Sn	-	<0.005	-	<0.005	-	<0.01	<0.01
	Sr	-	0.03	-	0.03	-	0.0165	0.0165
	Zn	*0.35 max.*	0.01	*0.35 max.*	0.01	-	<0.01	<0.01
	Other, Each	*0.05 max.*	<0.05	*0.05 max.*	<0.05	*0.05 max.*		
	Other, Total	*0.15 max.*	<0.15	*0.15 max.*	<0.15	*0.15 max.*		
	Al	Remainder	Remainder	Remainder	Remainder	Remainder	Remainder	Remainder
Microstructure								
Maximum Interconnected Pore Size (mm)		-	0.22	-	0.15	-	7	7
Porosity Content (%)		-	0.18	-	0.12	-	0.1	0.3
Matrix Microhardness (HV200gf)		-	101	-	95	-	128	127
Dendrite Arm Spacing (DAS) (um)		-	37	-	30	-	24	30
Macroscopic Grain Size (AFS chart)		-	Medium	-	Medium	-	Fine	Medium
Degree of Silicon Modification (AFS chart)		-	5	-	5	-	5	5
Monotonic Properties (Hardness and Tension)								
Brinell Hardness (HBW500)		*[70]*	86.6	*[85]*	83	*[>90]*	110	109
Ultimate Tensile Strength (S_U), ksi (MPa)		*>30 (205)*	40.7 (281)	*>33 (230)*	40.8 (281)	*>45 (310)*	53.4 (368)	50.5 (348)
Tensile 0.2% Offset Yield Strength (S_{ys}), ksi (MPa)		*>20 (140)*	32.2 (222)	*>22 (150)*	31.2 (215)	*>36 (248)*	45.5 (314)	44.6 (308)
Percent Elongation (%)		*>3*	5.4	*>3*	9.1	*>2*	7.2	3.6
Percent Reduction in Area (%)		-	4.6	-	10.3	-	11.3	5.9
Strain Hardening Exponent (n)		-	0.116	-	0.137	-	0.074	0.063
Strength Coefficient (K), ksi (MPa)		-	60.5 (417)	-	62.3 (430)	-	69.5 (479)	65.0 (448)
Elastic Modulus (E), ksi (MPa)		-	10500 (72400)	-	10500 (72400)	-	10700 (73800)	10700 (73800)
Poisson's Ratio (μ)		-	0.331	-	0.330	-	0.330	0.319
Cyclic Stress-Strain Properties: Strain-life Method (ASTM E606; SAE J1099)								
Elastic Modulus (E), ksi (MPa)		-	10500 (72400)	-	10500 (72400)	-	10700 (73800)	10700 (73800)
Cyclic Strain Hardening Exponent (n')		-	0.243	-	0.201	-	0.241	0.199
Cyclic Strength Coefficient (K'), ksi (MPa)		-	264 (1820)	-	166.7	-	322.3 (2222)	211.5
Strain-life Properties: Strain-life Method (ASTM E606; SAE J1099)								
Fatigue Ductility Coefficient (ε'_f)		-	0.0509	-	0.0677	-	0.0237	0.0798
Fatigue Ductility Exponent (c)		-	-0.6453	-	-0.6613	-	-0.6045	-0.6873
Fatigue Strength Coefficient (σ'_f), ksi (MPa)		-	128.7 (882)	-	97.1 (669)	-	130.7 (901)	127.9 (882)
Fatigue Strength Exponent (b)		-	-0.157	-	-0.1328	-	-0.1458	-0.1366

Table 4: Example of Typical Data Generated

Photomicrographs were taken of each material at 50x, 100x and 500x, etched and un-etched. An example of the SSF ductile iron microstructure at 100x is shown in Figure 1.

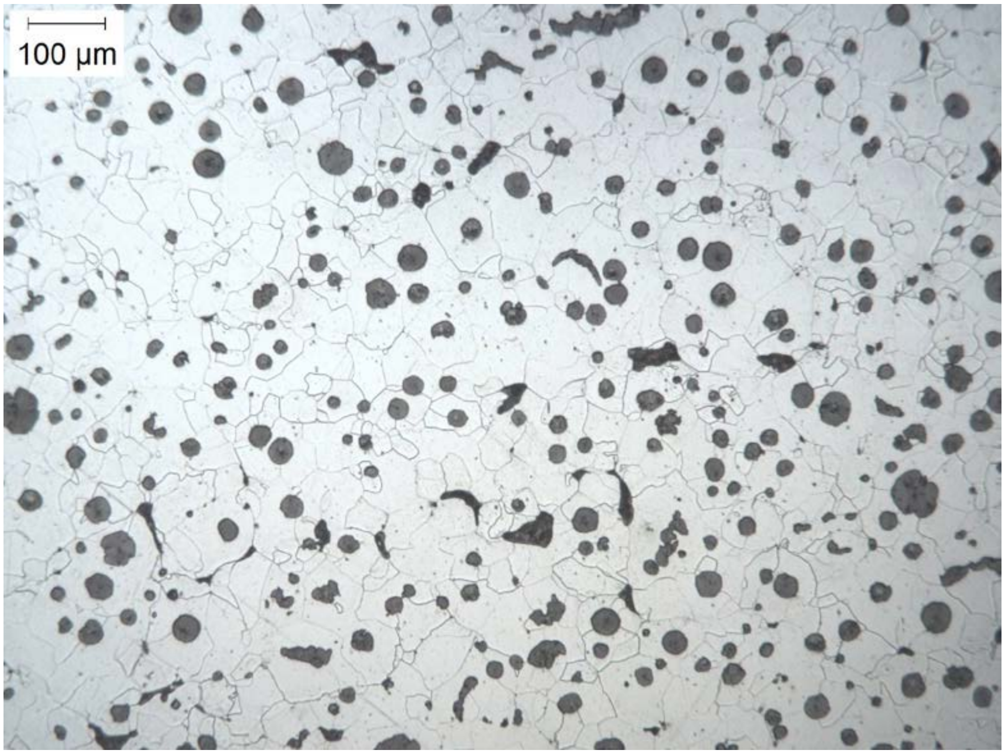
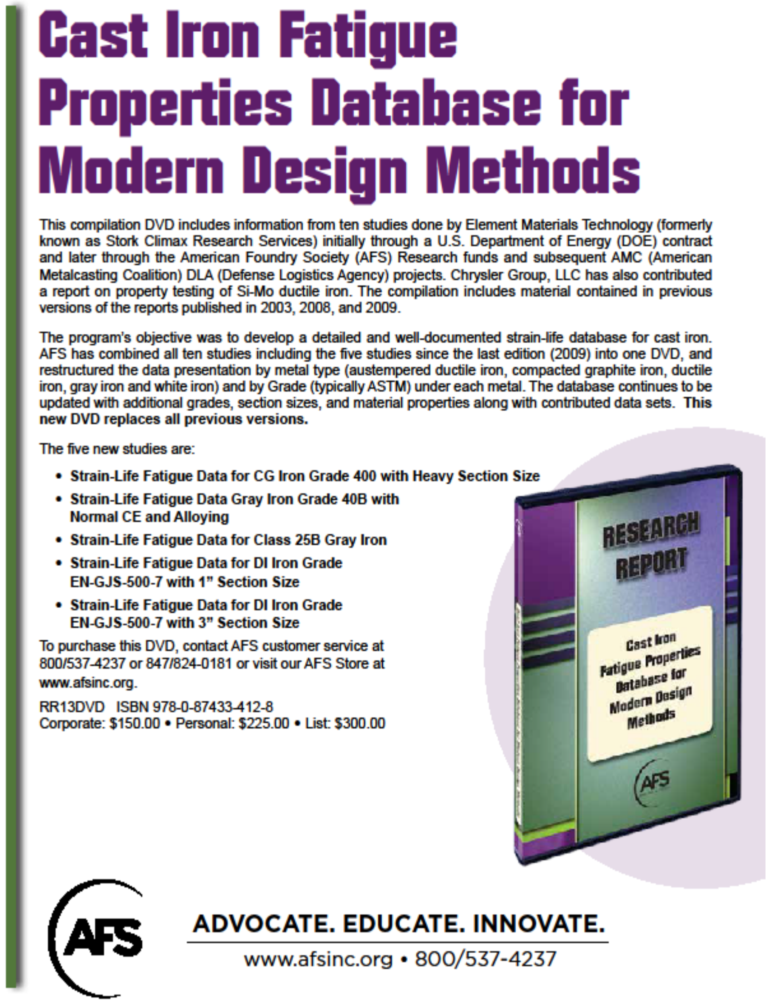


Figure 1: Photomicrograph of SSF Ductile Iron

4.0 Technology Transfer

One of the primary objectives of the American Foundry Society (AFS) is Technology Transfer. There are several ways in which this is accomplished by the American Foundry Society. There are more than 800 corporate members and 7000 individual members. This big footprint makes reaching a multitude of industry partners possible. Many industry foundries supplied data and/or in-kind for this project and have a vested interest in this database. This information has also been distributed to multiple industry OEMs. The properties have been entered into the American Society of Materials database. Presentations have been made at eight major industry conferences, such as SAE, TMS, MS&T, Aeromat and SME Rapid 2016. A webinar is being scheduled for November 2017 to introduce how this database is used. The CADS tool has been promoted on the AFS website and in thee AFS publications. An example of one of these promotional articles is shown in the figure at the right. AFS CADS has been incorporated into the AFS Institute Metalcasting Design Course.



Cast Iron Fatigue Properties Database for Modern Design Methods

This compilation DVD includes information from ten studies done by Element Materials Technology (formerly known as Stork Climax Research Services) initially through a U.S. Department of Energy (DOE) contract and later through the American Foundry Society (AFS) Research funds and subsequent AMC (American Metalcasting Coalition) DLA (Defense Logistics Agency) projects. Chrysler Group, LLC has also contributed a report on property testing of Si-Mo ductile iron. The compilation includes material contained in previous versions of the reports published in 2003, 2008, and 2009.

The program's objective was to develop a detailed and well-documented strain-life database for cast iron. AFS has combined all ten studies including the five studies since the last edition (2009) into one DVD, and restructured the data presentation by metal type (austempered ductile iron, compacted graphite iron, ductile iron, gray iron and white iron) and by Grade (typically ASTM) under each metal. The database continues to be updated with additional grades, section sizes, and material properties along with contributed data sets. **This new DVD replaces all previous versions.**

The five new studies are:

- **Strain-Life Fatigue Data for CG Iron Grade 400 with Heavy Section Size**
- **Strain-Life Fatigue Data Gray Iron Grade 40B with Normal CE and Alloying**
- **Strain-Life Fatigue Data for Class 25B Gray Iron**
- **Strain-Life Fatigue Data for DI Iron Grade EN-GJS-500-7 with 1" Section Size**
- **Strain-Life Fatigue Data for DI Iron Grade EN-GJS-500-7 with 3" Section Size**

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5.0 Summary of Work/Conclusions

The CADS tool is continuously upgraded with more data and more data fields. PDA maintains the database and has added thermal-physical properties, thermal-mechanical properties, and strain life fatigue data. Additionally, data generated for more steel, aluminum and iron alloys has been added to the database. These additions are needed for process simulation modeling. These upgrades will allow the designers, specifiers, producers and users of DoD and civilian components to more readily select the best casting alloy for the application and model that design for the lightest weight and lowest scrap thereby reducing lead time and producing the lowest cost and highest quality parts. With the consolidation of this information in the hands of designers and OEM suppliers, the DLA supply chain will be improved by reduction in lead time and cost at the same time improving quality. Furthermore, it will allow for the training of design engineers and scientists.

6.0 Acknowledgements

AMC’s Casting Solutions for Readiness program is funded through the U.S. Department of Defense (DoD), the Defense Supply Center Philadelphia, Philadelphia, PA and the Defense Logistics Agency (DLA), Ft. Belvoir, VA. Notably, AFS acknowledges Jiten Shah, PDA LLC for his contributions to this program. AFS recognizes Steve Robison, AFS Senior Technical Director, and Tom Prucha, former AFS Vice President Technical Services (retired), for their expertise and project management skills to this project.

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MCM Precision Castings
Metal Tek-Wisconsin Investment Cast
Signicast Corp
Tech Cast
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AFS consultant

Doug Kurkul, CEO

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Appendix A

A CASE STUDY OF FINITE ELEMENT ANALYSIS AND DESIGNING WITH DATA FROM THE AFS STRAIN-LIFE FATIGUE DATABASE

Jiten Shah
Product Development & Analysis (PDA) LLC, Naperville, IL, USA

Dr. John M. Tartaglia
Element Materials Technology, Wixom, MI, USA

Abstract

This paper estimates total fatigue and transition life using strain-controlled fatigue data generated for various cast materials, using a practical example of a structural hub casting that has been in service for many years. The material data generated from recent testing, service loads and boundary conditions from the potential failure modes are entered into a finite element analysis (FEA) to predict the stress amplitudes using the same geometry that is employed for predicting the fatigue life.

For the same loading, the investigators observed that the elastic modulus and specific strength have an impact on the predicted stresses. Strain-life material parameters impact the predicted strain fatigue life. At low loads (in the elastic regime), the overall exercise yields a different choice of material than at higher loads (in the elastic-plastic regime), which is driven by the strain-controlled material data properties.

As an example, a sensitivity analysis was done on one alloy by varying all of its properties as well as by individually varying relevant material property data and constants. The loading and geometry were kept constant in this sensitivity analysis, to illustrate the significance of the potential error a design engineer might encounter in estimating service life.

In the real world at the early design stage, various candidate cast alloys can be evaluated using this approach to achieve the desired fatigue life for the identical service loads. This methodology will yield an optimized geometry through FEA-based validations using the latest strain controlled fatigue material database for various cast alloys generated by the American Foundry Society (AFS) through sponsored research.

***Keywords:** strain-life fatigue, low cycle fatigue, cast iron, ductile cast iron, cast aluminum, cast steel, life prediction, Finite Element Analysis (FEA), Casting Alloy Database Selector (CADS), Casting Alloy and Process Selector (CAPS)*

Introduction

The purpose of this paper is to show how a design engineer can utilize strain-life fatigue data to perform product development and design assessments. The paper utilizes a hub casting as a case study to explain the effect of different cast materials on estimated fatigue life, while keeping the geometry and the cyclic service loads the same. The significance of the potential variability in each strain-life related material properties and constants on the estimated fatigue life is also demonstrated using an example in this paper.

Description of the Database and Fatigue Life Prediction Approach

A strain-life fatigue database for cast metals was developed utilizing AFS and the United States Department of Energy (DOE) and Department of Defense (DOD) funding.[1-3] The database contains monotonic and cyclic property data, as well as the associated chemical analysis and microstructural data for a variety of cast irons, including gray, ductile, compacted graphite, and white cast irons, as well as a few aluminum alloys. The fatigue data in the database were obtained with fully reversed strain-life testing at room temperature on smooth samples with 8mm (0.31 in.) diameter and 16mm (0.63 in.) long gauge sections, in accordance with ASTM standard E606 over a life range of 100 cycles to 5 million cycles. Tensile data in the database were obtained with 12.7mm (0.5 in.) gauge diameter and 50.8mm (2.0 in.) gauge length tensile samples in accordance with ASTM standard E8. The basis of fatigue and the development and structure of the database were described in a recent IJMC paper.[4] Only a brief description will be given in this paper. This database has been incorporated into an online tool developed by AFS as a part of the virtual digital library, called CADS (Casting Alloy Database Selector).

The stress-life or S-N method was the first approach used historically in an attempt to quantify and design by fatigue. Although the S-N approach can be used in design applications where the applied stress is primarily within the elastic range of material response, the strain-life approach is required for low cycle fatigue life predictions between 10 and 10,000 cycles.

For most cast structural components, the response of the material is strain or deformation in critical locations such as sharp corners, notches or discontinuities (surface or sub-surface internal flaws). At high service loads, in the low cycle fatigue (LCF) regime, the cyclic stress-strain response and material behavior are best modeled under strain-controlled conditions as opposed to stress-controlled conditions. In the strain-life approach, plastic deformation is measured and quantified beyond the elastic range, which produces optimized designs and lighter components for the same loads. Linear elastic fracture mechanics (LEFM) and stress-life approaches do not account for plastic strain. The low cycle or strain-life approach also offers the advantage that both fatigue stress and strain are tested, analyzed, and modeled, and both stress and strain can be calculated from each other. Furthermore, the fatigue strength in the range of 10 thousand to 10 million cycles, the fatigue limit or the limiting value of fatigue strength for survival after 10 million cycles is usually reported for high cycle fatigue analysis. Low cycle fatigue on the other hand considers the regime where fatigue lives are evaluated in the low cycle range of 10 to 10,000 cycles.

Modern fatigue databases do not contain fatigue limits. Rather, finite element modeling programs must be able to use strain-life data to predict lives and locations of fatigue fractures in the vicinity of holes, thickness changes, and other stress concentrators. The cast metals strain-life fatigue database offers designers the opportunity to select optimal materials and design geometries to foster:

(a) lighter products;
(b) energy efficient operations;
(c) longer and more predictable product service life; and
(d) more energy efficient product manufacture.

For more information about fatigue and the cast metals strain-life fatigue database, the reader is directed to Reference 4.

Strain-Life Fatigue Data Analysis

This section of the paper summarizes the strain-life fatigue data analysis that was conducted in the database development effort.[3,4] The reader is directed to other references for further details.[5-7]

A fundamental step in the strain-life analysis of cyclic property data is the decomposition of the total cyclic strain amplitude ($\Delta\varepsilon_t/2$) or ($\Delta\varepsilon/2$) into its component strains, i.e., plastic strain amplitude ($\Delta\varepsilon_p/2$) and elastic strain amplitude ($\Delta\varepsilon_e/2$) according to the equation:

$$(\Delta\varepsilon/2) = (\Delta\varepsilon_e/2) + (\Delta\varepsilon_p/2) \qquad \text{Eqn.1}$$

In practice, the elastic component of strain is determined by dividing the stress amplitude ($\Delta\sigma/2$) at specimen half-life ($0.5N_f$) by the elastic modulus (E). The plastic strain amplitude is then given as the difference between the total strain amplitude and the elastic strain amplitude. The plastic strain data determined by this method are used in the calculation of both the strain/stress-life and cyclic stress-strain constants.

Using data obtained from each fatigue specimen at half-life, the cyclic stress-strain constants n' (cyclic strain hardening exponent) and K' (cyclic strength coefficient) were determined by regressing the stress amplitude ($\Delta\sigma/2$) versus plastic strain amplitude ($\Delta\varepsilon_p/2$) in logarithmic coordinates.**

**_Although K' and n' in this paper were determined by direct regression, the cyclic stress-strain constants K' and n' can also be calculated directly from the strain-life and stress-life constants as follows:_

$$K' = \sigma'_f/(\varepsilon'_f)^{n'}$$
$$n' = b/c$$

Thus, the databases contain K' and n' constants that were calculated by two methods, i.e., direct log-linear regression of the stress and plastic strain amplitudes and simple manipulation with the above two equations. Note that the two calculation methods often do not produce similar values for the constants,[6] but the calculated stress-strain curves themselves are usually similar.

The cyclic stress-strain constants are related as follows:

$$\Delta\sigma/2 = K'(\Delta\varepsilon_p/2)^{n'}$$

The cyclic stress-life and strain-life constants σ'_f, b, ε'_f and c were calculated as follows:

$$\Delta\sigma/2 = \sigma'_f\,(2N_f)^b$$

Where:
$\Delta\sigma/2$ = stress amplitude
$2N_f$ = reversals to failure (1 reversal = ½ cycle)
σ'_f = fatigue strength coefficient
b = fatigue strength exponent

and

$$\Delta\varepsilon_p/2 = \varepsilon'_f\,(2N_f)^c$$

Where:
$\Delta\varepsilon_p/2$ = plastic strain amplitude
$2N_f$ = reversals to failure
ε'_f = fatigue ductility coefficient
c = fatigue ductility exponent

As discussed previously, the total strain is the sum of the elastic and plastic strains. In terms of strain amplitude:

$$\Delta\varepsilon/2 = \Delta\varepsilon_e/2 + \Delta\varepsilon_p/2$$

The elastic term can be written as:

$$\Delta\varepsilon_e/2 = \Delta\sigma/2E$$

We can now state this in terms of reversals to failure:

$$\Delta\varepsilon_e/2 = (\sigma'_f / E) \text{ x } (2N_f)^b$$

The plastic term is:

$$\Delta\varepsilon_p/2 = \varepsilon'_f(2N_f)^c$$

The total strain can now be rewritten:

$$\Delta\varepsilon/2 = (\sigma'_f / E) \text{ x } (2N_f)^b + \varepsilon'_f(2N_f)^c \qquad \text{Eqn. 2}$$

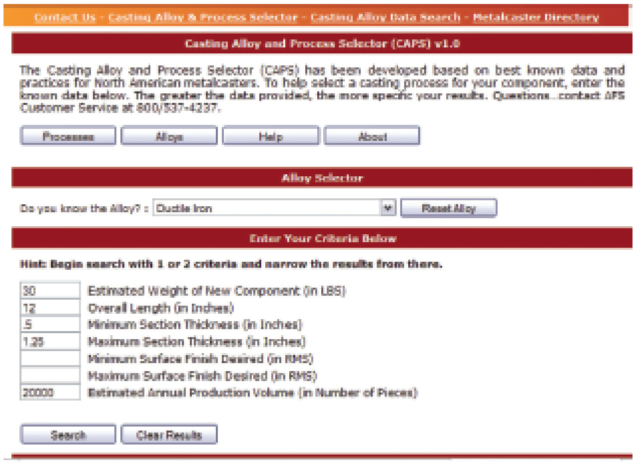
This last equation is the basis of the strain-life method and is termed the "strain-life relation."

One way of determining the cycles where low cycle fatigue transitions to high cycle fatigue is to equate the elastic and plastic terms stated above and calculate the transition life, which is:

$$N_t = 0.5 * (\varepsilon'_f E / \sigma'_f)^{1/(b-c)}$$

Description of CADS and CAPS

To assist casting design engineers, AFS, through sponsored research, as a part of the initiative on the Virtual Digital Library, has launched various online tools linked to the AFS website (www.afsinc.org). The CAPS (Casting Alloy and Process Selector) tool assists a design engineer at a conceptual design stage to provide a list of candidate casting processes and alloys, based on the overall size, section thickness, weight, desired tolerances and as-cast surface finish and production volumes anticipated. Some metalcasting facilities and finite element analysis (FEA) firms have the resources to pour test castings to actually evaluate potential design choices. Although this paper is meant to be a tutorial, the regimen contained herein, and the CADS and CAPS tools offer other firms the opportunity to start and even end with designs based on database contents. Figure 1 shows a typical screen shot of CAPS inputs and Figure 2 shows a typical output; in this case, the design engineer selected and entered ductile iron as a choice of material.



Casting Alloy and Process Selector (CAPS) v1.0

The Casting Alloy and Process Selector (CAPS) has been developed based on best known data and practices for North American metalcasters. To help select a casting process for your component, enter the known data below. The greater the data provided, the more specific your results. Questions...contact AFS Customer Service at 800/537-4237.

Alloy Selector

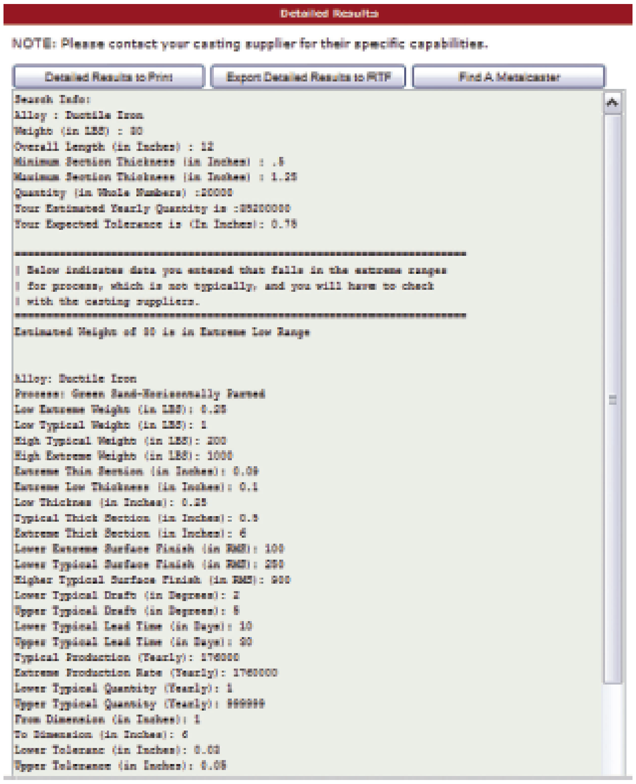
Do you know the Alloy? : Ductile Iron

Enter Your Criteria Below

Hint: Begin search with 1 or 2 criteria and narrow the results from there.

30 Estimated Weight of New Component (in LBS)
12 Overall Length (in Inches)
.5 Minimum Section Thickness (in Inches)
1.25 Maximum Section Thickness (in Inches)
Minimum Surface Finish Desired (in RMS)
Maximum Surface Finish Desired (in RMS)
20000 Estimated Annual Production Volume (in Number of Pieces)

Figure 1. Typical CAPS inputs.



Detailed Results

NOTE: Please contact your casting supplier for their specific capabilities.

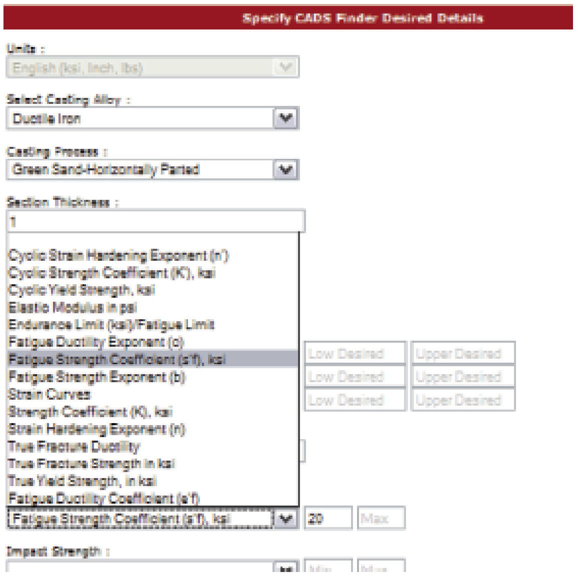
```
Search Info:
Alloy : Ductile Iron
Weight (in LBS) : 30
Overall Length (in Inches) : 12
Minimum Section Thickness (in Inches) : .5
Maximum Section Thickness (in Inches) : 1.25
Quantity (in Whole Numbers) :20000
Your Estimated Yearly Quantity is :35200000
Your Expected Tolerance is (In Inches): 0.78

================================================================================
| Below indicates data you entered that falls in the extreme ranges
| for process, which is not typically, and you will have to check
| with the casting suppliers.
================================================================================
Estimated Weight of 30 is in Extreme Low Range


Alloy: Ductile Iron
Process: Green Sand-Horizontally Parted
Low Extreme Weight (in LBS): 0.25
Low Typical Weight (in LBS): 1
High Typical Weight (in LBS): 200
High Extreme Weight (in LBS): 1000
Extreme Thin Section (in Inches): 0.09
Extreme Low Thickness (in Inches): 0.1
Low Thickness (in Inches): 0.25
Typical Thick Section (in Inches): 0.5
Extreme Thick Section (in Inches): 6
Lower Extreme Surface Finish (in RMS): 100
Lower Typical Surface Finish (in RMS): 250
Higher Typical Surface Finish (in RMS): 900
Lower Typical Draft (in Degrees): 2
Upper Typical Draft (in Degrees): 5
Lower Typical Lead Time (in Days): 10
Upper Typical Lead Time (in Days): 90
Typical Production (Yearly): 176000
Extreme Production Rate (Yearly): 1760000
Lower Typical Quantity (Yearly): 1
Upper Typical Quantity (Yearly): 999999
From Dimension (in Inches): 1
To Dimension (in Inches): 6
Lower Toleranc (in Inches): 0.03
Upper Tolerance (in Inches): 0.05
```

Figure 2. Typical CAPS output.

Once the casting process and generic alloy combination is selected, based on other aspects, such as life cycle cost and manufacturability, a short list of two to three cast alloys with grades are chosen based on the same preliminary strength requirements. The CADS tool will provide all the required material data for design evaluations using FEA, including modulus, static, monotonic as well as cyclic strain-life fatigue properties.

Figure 3 shows a list of material data and properties contained in CADS, with options for exporting data, (e.g., FEA). Figure 4 shows an example of CADS input, where a design engineer knows the strength requirements and alloy generic type. In turn, CADS finds the potential grades that can meet a design engineer's requirements. After the desired fatigue strength coefficient of 20 ksi (128 MPa) is entered in Figure 4, Figure 5 shows the results for ductile iron grade 80-55-06

Figure 3. List of available material data and properties in CADS.



Units : English (ksi, Inch, lbs)

Select Casting Alloy : Ductile Iron

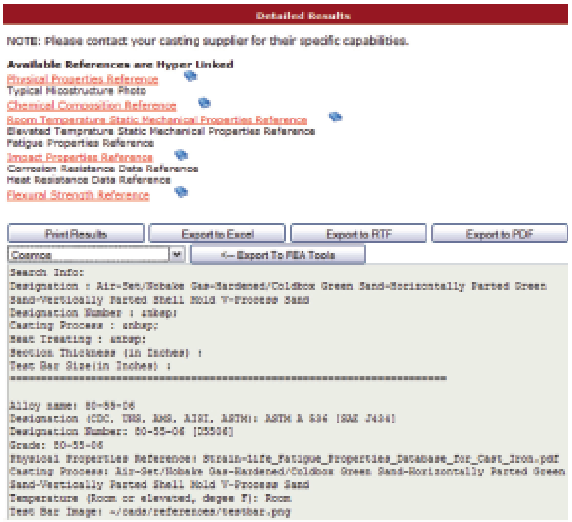
Casting Process : Green Sand-Horizontally Parted

Section Thickness : 1

Fatigue Strength Coefficient (s'f), ksi 20

Impact Strength :

Figure 4. Typical CADS input for searching for an alloy grade.



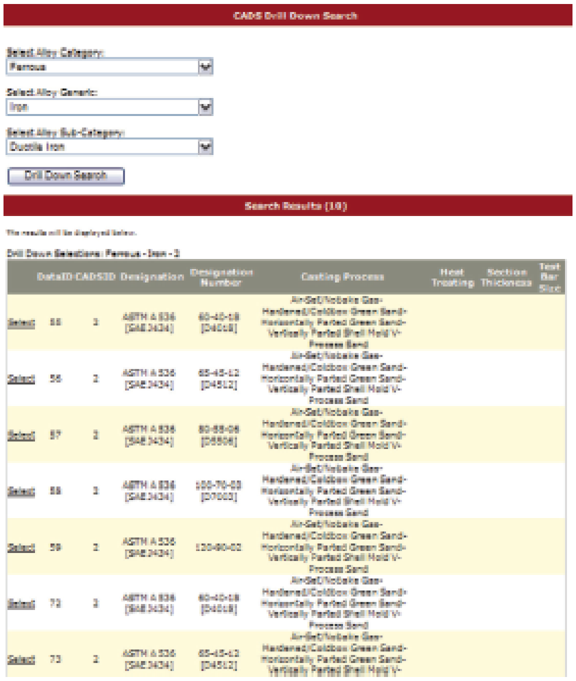
NOTE: Please contact your casting supplier for their specific capabilities.

Available References are Hyper Linked

Physical Properties Reference
Typical Micostructure Photo
Chemical Composition Reference
Room Temperature Static Mechanical Properties Reference
Elevated Temprature Static Mechanical Properties Reference
Fatigue Properties Reference
Impact Properties Reference
Corrosion Resistance Data Reference
Heat Resistance Data Reference
Flexural Strength Reference

```
Search Info:
Designation : Air-Set/Nobake Gas-Hardened/Coldbox Green Sand-Horizontally Parted Green
Sand-Vertically Parted Shell Mold V-Process Sand
Designation Number : &nbsp;
Casting Process : &nbsp;
Heat Treating : &nbsp;
Section Thickness (in Inches) :
Test Bar Size(in Inches) :
=====================================================================


Alloy name: 80-55-06
Designation (CDC, UNS, AMS, AISI, ASTM): ASTM A 536 [SAE J434]
Designation Number: 80-55-06 [D5506]
Grade: 80-55-06
Physical Properties Reference: Strain-life_Fatigue_Properties_Database_for_Cast_Iron.pdf
Casting Process: Air-Set/Nobake Gas-Hardened/Coldbox Green Sand-Horizontally Parted Green
Sand-Vertically Parted Shell Mold V-Process Sand
Temperature (Room or elevated, degee F): Room
Test Bar Image: ~/cads/references/testbar.png
```

Figure 5. Typical CADS output.



Select Alloy Category: Ferrous

Select Alloy Generic: Iron

Select Alloy Sub-Category: Ductile Iron

The results will be displayed below.

Drill Down Selections: Ferrous - Iron - 3

	DataID	CADSID	Designation	Designation Number	Casting Process	Heat Treating	Section Thickness	Test Bar Size
Select	55	2	ASTM A 536 [SAE J434]	60-40-18 [D4018]	Air-Set/Nobake Gas-Hardened/Coldbox Green Sand-Horizontally Parted Green Sand-Vertically Parted Shell Mold V-Process Sand			
Select	56	2	ASTM A 536 [SAE J434]	65-45-12 [D4512]	Air-Set/Nobake Gas-Hardened/Coldbox Green Sand-Horizontally Parted Green Sand-Vertically Parted Shell Mold V-Process Sand			
Select	57	2	ASTM A 536 [SAE J434]	80-55-06 [D5506]	Air-Set/Nobake Gas-Hardened/Coldbox Green Sand-Horizontally Parted Green Sand-Vertically Parted Shell Mold V-Process Sand			
Select	58	2	ASTM A 536 [SAE J434]	100-70-03 [D7003]	Air-Set/Nobake Gas-Hardened/Coldbox Green Sand-Horizontally Parted Green Sand-Vertically Parted Shell Mold V-Process Sand			
Select	59	2	ASTM A 536 [SAE J434]	120-90-02	Air-Set/Nobake Gas-Hardened/Coldbox Green Sand-Horizontally Parted Green Sand-Vertically Parted Shell Mold V-Process Sand			
Select	72	2	ASTM A 536 [SAE J434]	60-40-18 [D4018]	Air-Set/Nobake Gas-Hardened/Coldbox Green Sand-Horizontally Parted Green Sand-Vertically Parted Shell Mold V-Process Sand			
Select	73	2	ASTM A 536 [SAE J434]	65-45-12 [D4512]	Air-Set/Nobake Gas-Hardened/Coldbox Green Sand-Horizontally Parted Green Sand-Vertically Parted Shell Mold V-			

Figure 6. Typical drill down search in CADS.

obtained from the CADS search. Also, Figure 6 shows how CADS allows a coarse drill-down search for ductile iron.

Description of the Hub Case Study

A hub for a brake disk rotor, which bolts onto an axle (see Figures 7 and 8) for a light rail is used to demonstrate the methodology using strain-life fatigue data. This hub was originally designed and manufactured from cast steel in the 1980s. The hub was in operation for about 10 years, and Jiten Shah reverse engineered and contract manufactured the hub in early 2000. He analyzed the hub to assess its fatigue life. After conducting extensive FEA-based analysis and magnetic particle inspection of the hub in critical areas, indications of early stages of crack initiations were noticed; therefore, the hub was destined for replacement.

Figure 7. Hub mounted into cast iron brake disc rotor.

Figure 8. Cast steel hub after finish machining.

Figure 9 shows the FEA model with hub, disk and retaining radial pins. Figure 10 shows the critical areas with predicted stresses for the normal braking load. Based on the stress magnitude, the critical areas and casting quality level were established. The principle stresses are the extreme values of normal stresses in the material; P1 or S1 are the tensile and P3 or S3 are the compressive stresses. Von Mises is an equivalent or effective stress at which yielding is predicted to occur in ductile materials.

Casting process and rigging were designed to achieve the required internal, surface and sub-surface quality and were validated using casting process modeling (filling and solidification); Figure 11 shows predicted primary shrinkage during solidification. A new set of tooling was fabricated and castings were manufactured using the chemically bonded sand process. Then the reversed engineered cast iron brake disk rotor was finished machined, assembled and put back into operation after form, fit and functionality evaluation.

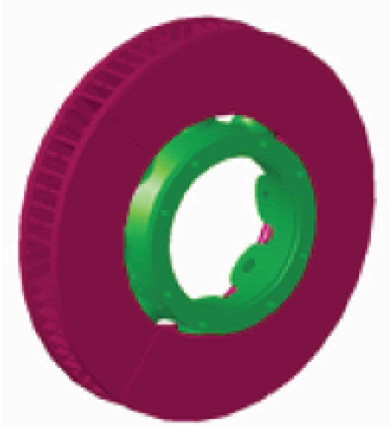


Figure 9. FEA model of the rotor disk with hub assembly.

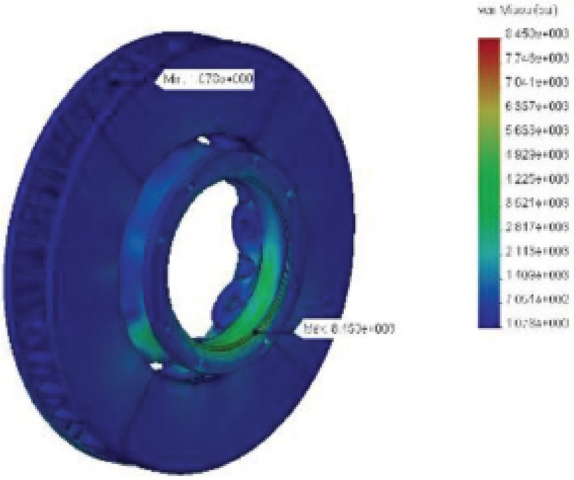


Figure 10. FEA Plot showing von Mises stress for normal service load.

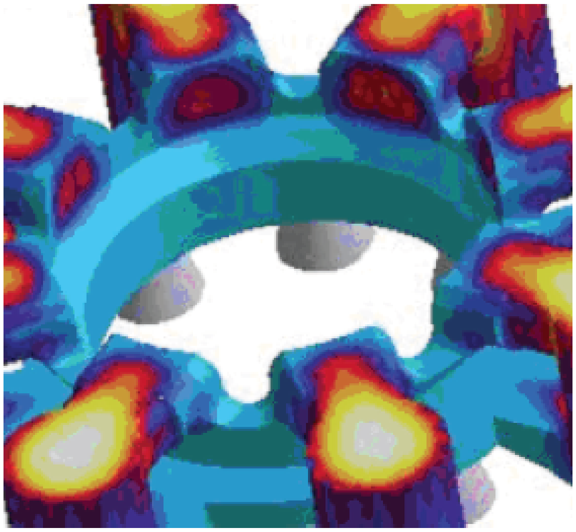


Figure 11. Fraction solid showing hot spots and potential shrinkage locations.

Analysis for the Case Study

Data Selected for Modeling in This Paper

To model the hub in this paper, the authors selected data from two sources, the AFS cast metal database[1,3] and an SAE database.[6] The constants from the two databases for the chosen materials are shown in Table 1. These constants were determined by regression analysis. The AFS database contains the raw data whereas the SAE database only contains the constants.

Currently the hub is manufactured from a steel close to grade 0050A with a Brinell hardness of 174 HBW3000 from the SAE database. Other grades chosen for comparison were grade 80-55-06 ductile iron, a lower strength grade 65-45-12 of ductile iron, and grade 40B gray iron from the AFS database. Although data from cast aluminum grade A356-T6 were also selected from the SAE database for this paper, the SAE results were virtually identical to those obtained by Tartaglia for two 356 cast grades about to be incorporated into the AFS database. These materials are all potential substitutions for the original material, and they provided a wide range in monotonic and cyclic response for illustration purposes.

Predicted Fatigue Response for the Dataset

Using the equations shown in the Introduction of this paper, Figures 12, 13, and 14 respectively show the predicted total strain, plastic strain, and stress versus cycles for the six selected materials for the case study. Note that the fatigue lives of the materials are essentially ranked by increasing ultimate tensile strength in the high cycle region. In the low cycle fatigue region, the fatigue lives of the materials are ranked in the reverse, with increasing life corresponding to increasing tensile ductility. Although fatigue lives were ranked differently, in the two separate regions, the materials essentially behaved elastically such that all the transition lives were in the low cycle region, as shown in the last row of Table 1. Figure 15 shows the transition life for all the candidate materials.

Finite Element Analysis Procedures and Results

Finite element analysis modeling of the hub with rotor disk was used, and braking loads were applied at the brake pad locations, as shown in Figure 16. Finite element analysis was run for service loads due to normal braking as well as emergency braking. Using the properties from Table 1,

Table 1. Constants from Databases Used in Hub Case

Base Alloy			**Aluminum**	**Cast Steel**	**Gray Iron**	**Ductile Iron**	**Ductile Iron (Lower Strength)**	**Austempered Ductile Iron**
Alloy Designation or Grade			**A356-T6**	**0050A-174HB**	**40B**	**80-55-06**	**65-45-12**	**125-80-10**
Condition			**T6 Temper**	**As-Cast**	**As-Cast**	**As-Cast**	**As-Cast**	**Austempered**
Data Source			SAE, Ref. 7	SAE, Ref. 7	AFS, Ref. 1	AFS, Ref. 1	AFS, Ref. 1	AFS, Ref. 1
Parameter	Symbol	Units						
Hardness		HB	93	174	216	227	186	304
Offset Yield Strength	0.2% YS	MPa	229	402	234	383	340	752
Ultimate Tensile Strength	UTS	MPa	283	583	287	690	579	1060
Elongation	El	%			0.7	10.7	13.0	13.3
Reduction of Area	RA	%	5.7	26.0		8.1	11.0	12.0
Monotonic Strength Coefficient	K	MPa	388.0			1660	1060	1600
Monotonic Strain Hardening Exponent	n		0.083			0.242	0.216	0.160
Elastic (Young's) Modulus	E	GPa	70	209	130	165	173	164
Poisson's Ratio	μ or ν		0.33[a]	0.3[b]	0.279	0.29[c]	0.288	0.275
Fatigue Strength Coefficient	σ'_f	MPa	594	869	464	815	757	1440
Fatigue Strength Exponent	b		-0.124	-0.101	-0.093	-0.071	-0.064	-0.086
Fatigue Ductility Coefficient	ε'_f	mm/mm	0.027	0.150	0.007	0.134	0.448	0.526
Fatigue Ductility Exponent	c		-0.530	-0.514	-0.291	-0.558	-0.648	-0.739
Cyclic Strength Coefficient	K'	MPa	379	896	2130	834	793	1620
Cyclic Strain Hardening Exponent	n'		0.043	0.141	0.312	0.145	0.094	0.125
Transition Fatigue Life	N_t		9	2929	20	441	1385	264

[a] From Ref. 1 for similar grade
[b] Assume based on validity for most steels
[c] Assume based on similar materials in Ref. 1

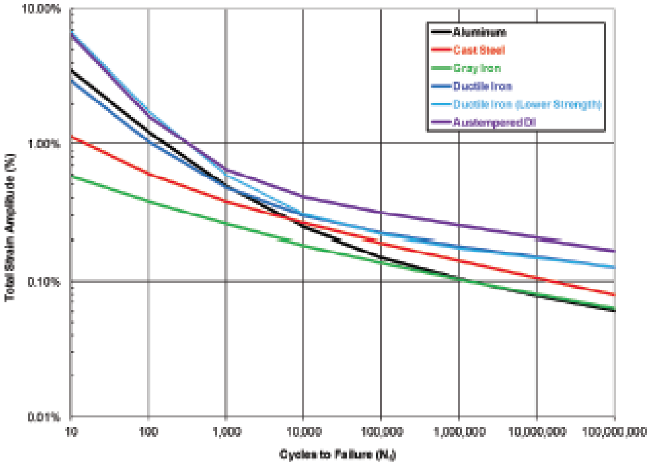


Figure 12. Total strain versus life curve.

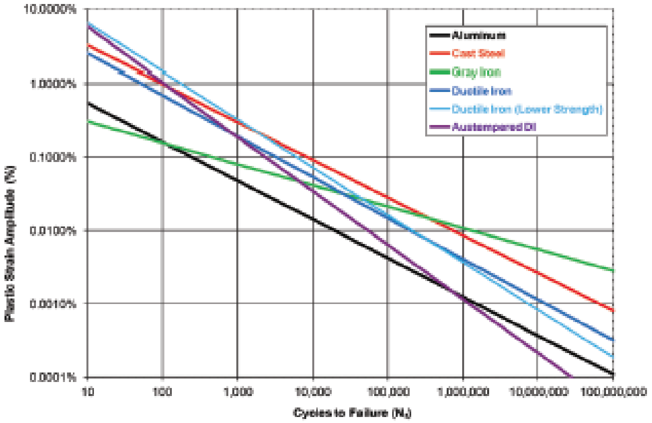


Figure 13. Plastic strain versus life.

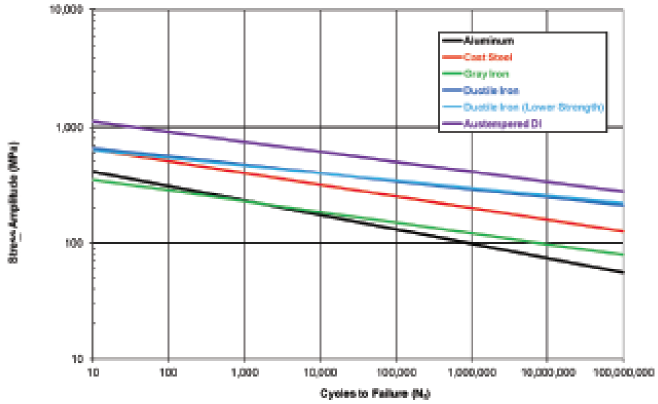


Figure 14. Stress versus cycles to failure.

the same 3D geometry, boundary conditions and loadings were applied for various alloys under consideration. A total of twelve FEA runs were conducted for the six alloys, each with two loading conditions.

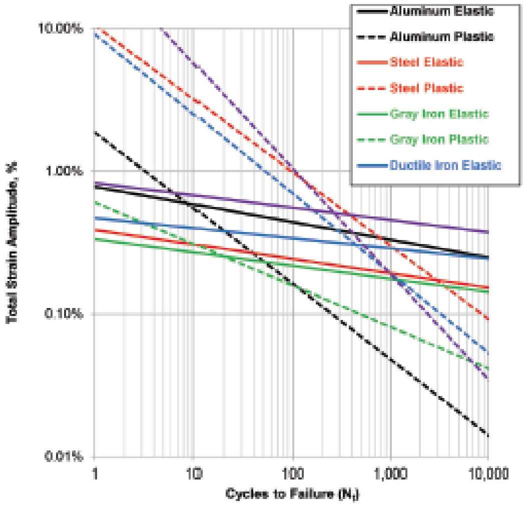


Figure 15. Transition life for candidate cast alloys.

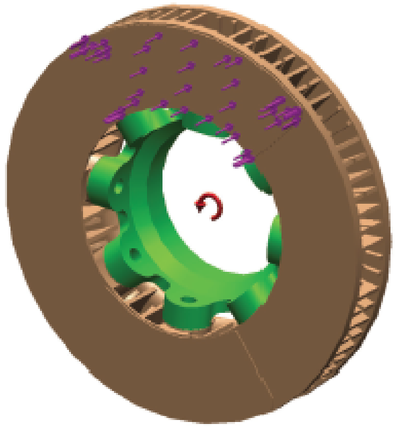


Figure 16. Loading on hub for finite element analysis (FEA).

Table 2 lists the results for all the analyses; the von Mises, Principle stresses (P1/S1 for tensile and P3/S3 for compressive), equivalent strain and resultant displacement are all separately enumerated. Additional fatigue analysis was conducted assuming near fully reversed loading in bending mode (R= -1), with an expected life of 1.75 million cycles.

Table 2 shows the predicted % damage and factor of safety. The % damage is defined as the % material volume that has reached yielding (permanent deformation) or a degradation in stiffness. A ratio of minimum to maximum stress (R ratio) of approximately -0.8 was calculated from FEA. However, for predicting the fatigue life, an R ratio of -1 was used because all the database contents were obtained with a strain ratio of R = -1.0 and this is certainly close enough because the stress ratio varied somewhat. While running FEA, it was assumed that the material is homogeneous, isotropic and free from any flaws. The desired life for operating service load of normal braking is 10 years, which translates to 1.75 million cycles as shown in Table 2. In contrast, for the emergency braking for 10 years lifespan, the desired life is 1,000 cycles.

Figures 17 through 26 show FEA output plots for both normal and emergency braking with various alloys. As presented in Table 2, the predicted principle tensile stress varies from 12.71 ksi (87.63 MPa) in A356-T6 to 14.55 ksi (100.3 MPa) in cast steel for normal braking load, whereas for the emergency braking scenario, it ranges from 25.28 ksi (174.3 MPa) to 29.10 ksi (200.6 MPa) for the same alloys. The cast aluminum has the lowest minimum (compression) principal stress.

By equating total strain (Eqn. 1) with cyclic strain (Eqn. 2), using Mathcad software, the combined equation was solved for N, which is the total number of cycles (or half the reversals). The Mathcad inputs were the actual material strain-life fatigue data and constants, and the FEA predicted $\Delta\sigma$ values, the stress ranges (which are twice the P1 or principle tensile maximum stress amplitude values).

Figure 26 shows the typical Mathcad worksheet for emergency loading generated stress and estimated life for ductile iron grade 80-55-06. The results of estimated total fatigue life for each alloy type and type of loading are shown in Table 3. For the normal braking load, the calculations predict that ductile grade 65-45-12 has the highest life and aluminum the lowest, whereas for the emergency braking load, it is austempered ductile iron (ADI) that has the highest predicted fatigue life and all of the candidate alloys meet the desired life of 1,000 cycles. Table 4 also shows the hub unit weight and specific strength; aluminum is the lightest and ADI has the maximum specific strength.

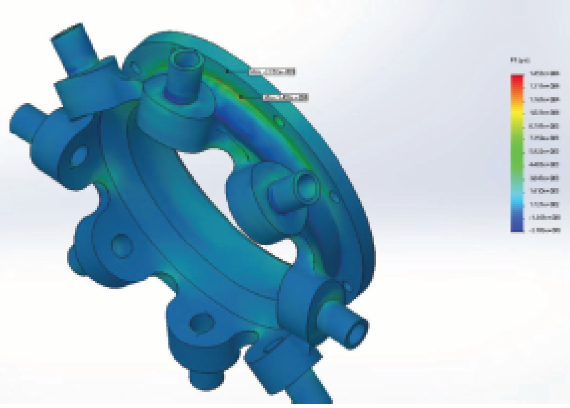


Figure 17. Predicted principle stresses (P1/S1) for normal braking load on a cast steel hub.

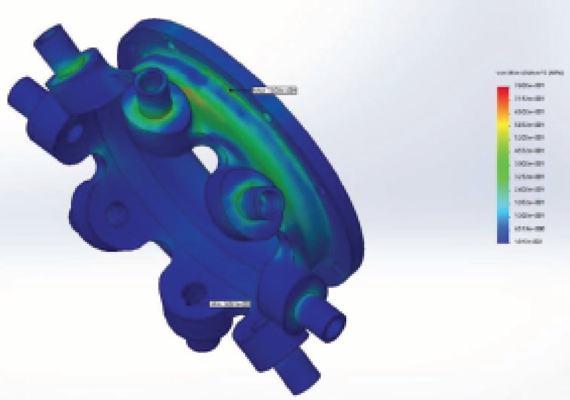


Figure 18. Predicted von Mises stresses for normal braking load on a ductile cast iron grade 65-45-12 (as-cast) hub.

Table 2. Hub FEA Summary for Normal and Emergency Braking Loading for all Candidate Alloys

Operating Details:	4 stations every 10 minutes; 480 cycles per day with 20 hours of operation; 1 million cycles over 10 years or 175,200 cycles per year											
	For normal braking, assume 1.75 million cycles over 10 years											
	For double load (emergency braking), assume 1000 cycles											
FEA Procedures:	**Linear static FEA results using actual material properties and same loading and boundry conditions**											
	Regular Braking Forces						**Emergency Breaking Forces**					
Base Alloy	**Aluminum**	Cast Steel	Gray Iron	Ductile Iron	Ductile Iron (Lower Strength)	Austempered Ductile Iron	**Aluminum**	Cast Steel	Gray Iron	Ductile Iron	Ductile Iron (Lower Strength)	Austempered Ductile Iron
Grade	**A356-T6**	0050A-174HB	40B	80-55-06	65-45-12	125-80-10	**A356-T6**	0050A-174HB	40B	80-55-06	65-45-12	125-80-10
Condition	**T6 Temper**	As-Cast	As-Cast	As-Cast	As-Cast	Austempered	**T6 Temper**	As-Cast	As-Cast	As-Cast	As-Cast	Austempered
Density, lb/cubic inch	0.10	0.28	0.26	0.26	0.26	0.26	0.10	0.28	0.26	0.26	0.26	0.26
weight, lb	14.38	0.00	38.62	38.09	38.09	38.02	14.38	41.84	38.62	38.09	38.09	38.02
von Mises, ksi	10.04	11.46	10.98	11.25	11.32	11.31	19.85	22.81	21.96	22.35	22.47	22.46
Principle, P1/S1, ksi (Tensile)	12.71	14.55	13.49	13.96	14.05	13.21	25.28	29.1	26.85	27.81	28	27.74
Principle, P3/S3, ksi (compression)	-10.08	-11.52	-10.6	-10.98	-11.05	-10.92	-20.26	-23.06	-21.29	-22.03	-22.18	-21.9
R Ratio, minimum/maximum	-0.79	-0.79	-0.79	-0.79	-0.79	-0.83	-0.80	-0.79	-0.79	-0.79	-0.79	-0.79
Equivalent Strain	0.00062	0.00023	0.00035	0.00029	0.00028	0.00029	0.00123	0.00047	0.00071	0.00058	0.00055	0.00058
Resultant Displacement, in	0.00455	0.00351	0.00312	0.00273	0.00266	0.00275	0.00896	0.00472	0.00616	0.00537	0.00524	0.00541
Factor of Safety, FOS	3.31	5.09	3.09	4.94	4.38	9.65	5.49	2.58	1.56	2.49	3.49	4.49
Fatigue Damage, %	35.77	17.52	17.52	17.52	17.51	17.52	10	0.093	10	0.01	0.01	0.01
Design Life	1.75 million						1000 cycles					

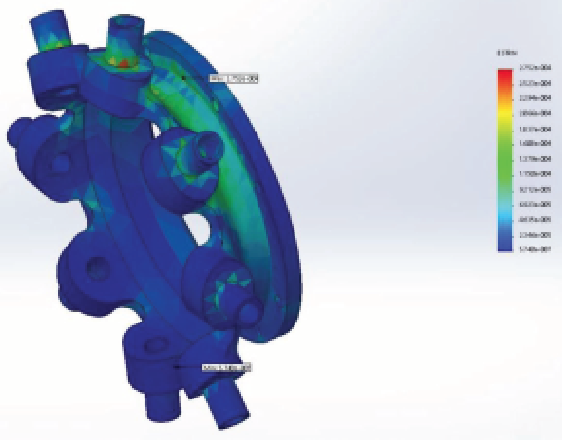


Figure 19. Predicted equivalent strain for normal braking load on ductile cast iron grade 65-45-12 (as-cast) hub.

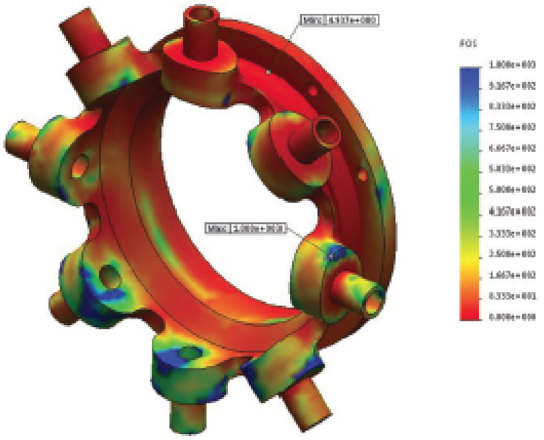


Figure 20. Predicted factor of safety for normal braking load on a ductile cast iron Grade 65-45-12 (as-cast) hub.

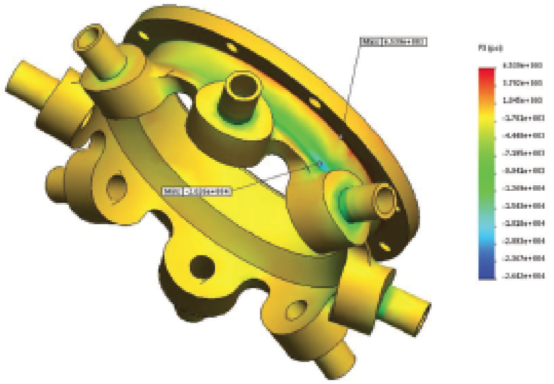


Figure 21. Predicted principle compressive stresses (P3/S3) for emergency braking load on a cast A356-T6 hub.

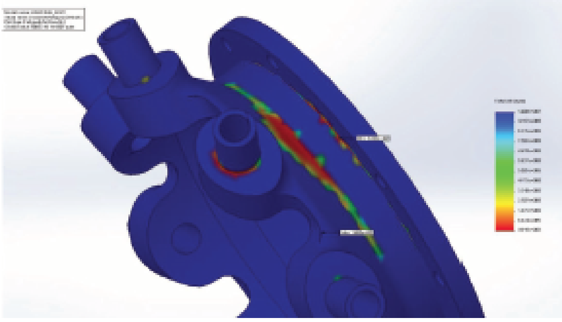


Figure 22. Predicted fatigue life in various areas based off stresses predicted for an emergency braking load on a cast A356-T6 hub.

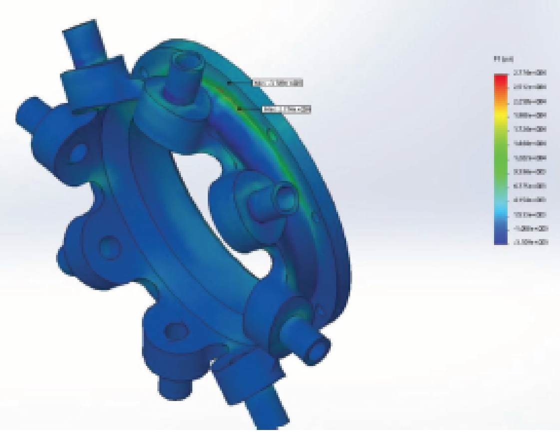


Figure 23. Predicted tensile principle stresses (P1/S1) for emergency braking load on a cast ADI (heat treated) hub.

Sensitivity Study to Constants Variation

To show the sensitivity of various material properties and strain-life fatigue data and constants on estimated fatigue life, the following two types of analysis were conducted for Class 40 gray cast iron:

1. Varying all parameter and property data up and down by 10%.
2. Varying each parameter individually up and down by 10%.

Table 5 shows the results of this sensitivity study. The predicted transition life is higher by less than 10% when all the parameters are increased by 10%; however, the transition life drops by slightly more than 10%, when all the parameters are lowered by 10%. Table 5 also shows that total predicted life is very sensitive to (in the order from highest to the lowest) maximum principle tensile stress, cyclic strain hardening exponent, fatigue strength exponent, fatigue strength coefficient. Since the emergency braking scenario is low cycle, plastic, and strain-controlled fatigue, it is evident that elastic modulus variations do not impact the total predicted life.

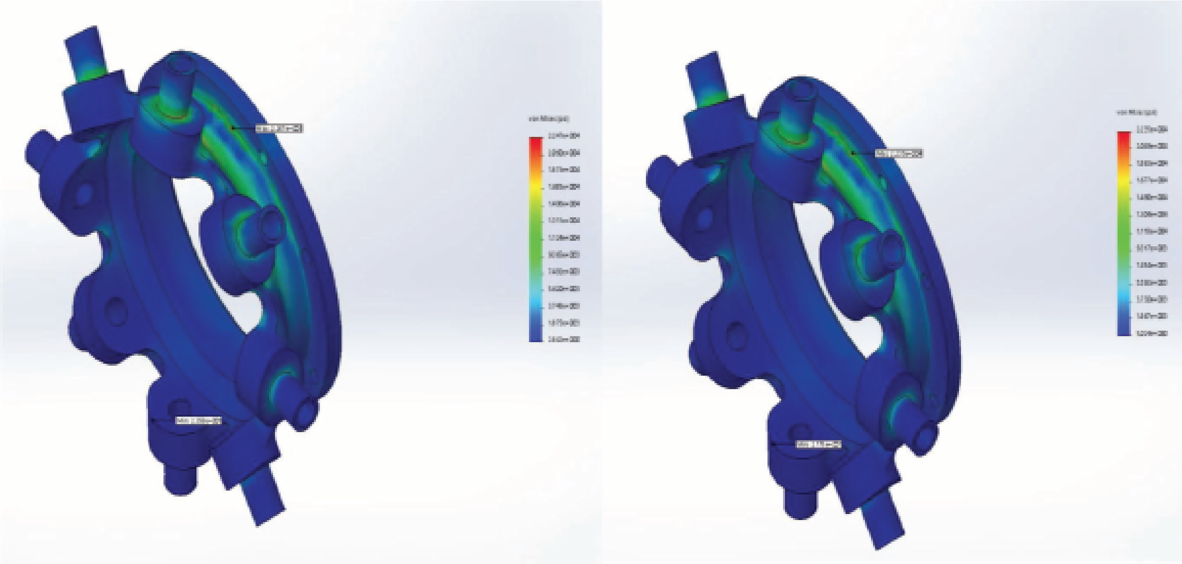


Figure 24. Predicted von Mises stresses for emergency braking load on cast ductile iron grade 65-45-12 (as-cast) versus grade 80-55-10 (as-cast) hubs.

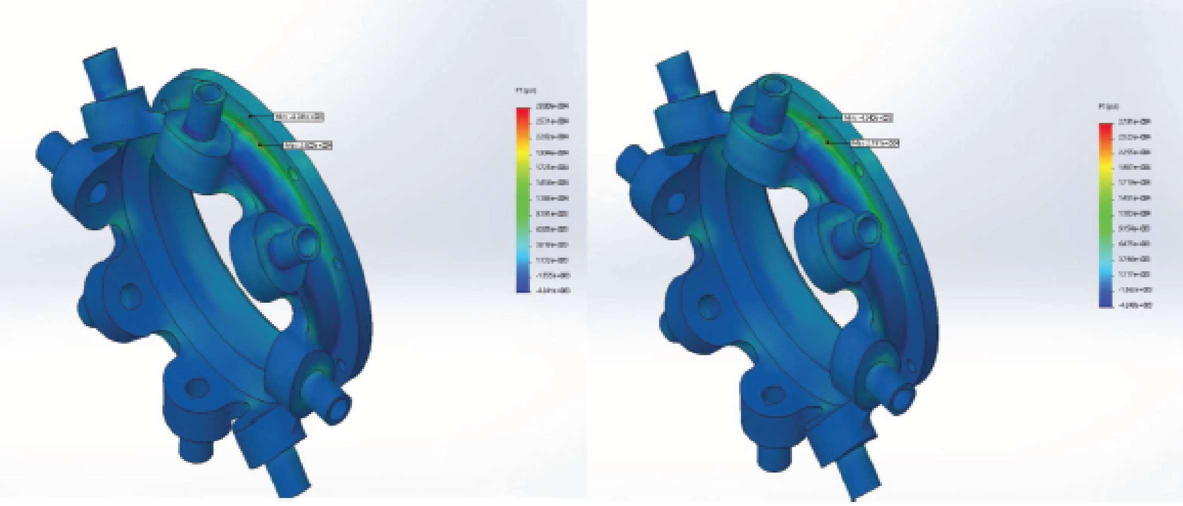
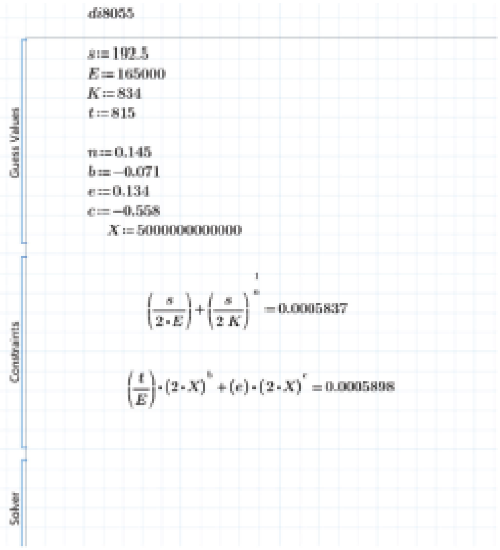


Figure 25. Predicted tensile principle stresses for emergency braking load on cast ductile iron grade 65-45-12 (as-cast) versus grade 80-55-10 (as-cast) hubs.

Table 3. Estimated Life Based on FEA Predicted Stress Amplitudes and Strain-Life Fatigue Data for Candidate Alloys

Operating Details:	4 stations every 10 minutes; 480 cycles per day with 20 hours of operation; 1 million cycles over 10 years or 175,200 cycles per year											
	For normal braking, assume 1.75 million cycles over 10 years											
	For double load (emergency braking), assume 1000 cycles											
Calculation Procedures:	**Strain-Life Fatigue Calculations using MathCAD**											
	Regular Braking Forces						**Emergency Breaking Forces**					
Base Alloy	**Aluminum**	**Cast Steel**	**Gray Iron**	**Ductile Iron**	**Ductile Iron (Lower Strength)**	**Austempered Ductile Iron**	**Aluminum**	**Cast Steel**	**Gray Iron**	**Ductile Iron**	**Ductile Iron (Lower Strength)**	**Austempered Ductile Iron**
Grade	**A356-T6**	**0050A-174HB**	**40B**	**80-55-06**	**65-45-12**	**125-80-10**	**A356-T6**	**0050A-174HB**	**40B**	**80-55-06**	**65-45-12**	**125-80-10**
Condition	**T6 Temper**	**As-Cast**	**As-Cast**	**As-Cast**	**As-Cast**	**Austempered**	**T6 Temper**	**As-Cast**	**As-Cast**	**As-Cast**	**As-Cast**	**Austempered**
Principle, P1, (Stress Amplitude), MPa	87.6	100.3	93.0	96.3	96.9	91.1	174.3	200.6	185.8	192.4	193.1	191.3
Stress Range, $\Delta\sigma$, MPa	175.3	200.6	186.0	192.5	193.7	182.2	348.6	401.3	371.6	384.9	386.1	382.5
Cycles to Failure, N_f	2.00E+06	1.00E+09	1.70E+07	5.00E+12	1.00E+14	4.00E+13	1.40E+04	2.00E+06	9.15E+03	2.00E+08	1.00E+09	1.00E+10
(Reversals to failure will be double)												



$s := 192.5$
$E := 165000$
$K := 834$
$t := 815$

$n := 0.145$
$b := -0.071$
$e := 0.134$
$c := -0.558$
$X := 5000000000000$

$$\left(\frac{s}{2\cdot E}\right)+\left(\frac{s}{2\,K}\right)^{\frac{1}{n}} = 0.0005837$$

$$\left(\frac{t}{E}\right)\cdot(2\cdot X)^{b}+(e)\cdot(2\cdot X)^{c} = 0.0005898$$

Figure 26. Typical Mathcad worksheet for estimating total life in cycles for ductile iron grade 80-55-06 with emergency braking load and stress magnitude of 27.92 ksi (192.5 MPa).

Summary and Conclusions

A materials elastic modulus and specific strength have an impact on the stresses predicted for the same loading. Strain-life material parameters impact the predicted strain fatigue life; hence the accuracy of the data is very important. Other failure criterion drive the design and material selection, such as, section size, heat treatment, weldability, corrosion, castability, machinability, and ultimately, the life cycle cost.

For the hub case study, under the same loading and boundary conditions for normal braking loading, aluminum A356-T6 has the lowest predicted minimum principle stresses and the maximum damage percentage in fatigue. In contrast, for the emergency braking load case, both ductile irons and ADI have the least amount of predicted fatigue damage (less than 0.01%). Using the FEA predicted stresses and the strain-life fatigue constants from databases, for normal loading, ductile grade 65-45-12 has the maximum predicted fatigue life; however all the alloys meet the desired life of 1.75 million cycles or 10 years. For emergency braking loading, ADI has the maximum predicted fatigue life.

Table 4. Hub Unit Weight and Specific Strength for all Candidate Alloys

	Base Alloy	**Aluminum**	**Cast Steel**	**Gray Iron**	**Ductile Iron**	**Ductile Iron (Lower Strength)**	**Austempered Ductile Iron**
	Grade	**A356-T6**	**0050A-174HB**	**40B**	**80-55-06**	**65-45-12**	**125-80-10**
	Condition	**T6 Temper**	**As-Cast**	**As-Cast**	**As-Cast**	**As-Cast**	**Austempered**
Strength (UTS)	MPa	283	583	287	690	579	1060
	ksi	41.0	84.6	41.6	100.1	84.0	153.7
Strength-to-weight ratio	MPa/kg	43.5	30.8	16.4	40.0	33.6	61.6
	ksi/lb	2.86	2.02	1.08	2.63	2.20	4.04

Table 5. Results for Varying Strain-Life Fatigue Parameters for 40 Class Gray Cast Iron for Emergency Braking Load Case

Parameter or Property	Units	Baseline values	Symbol	Emergency Braking Load Case for Gray Cast Iron					
				Change in parameter or property		Esimated Life in cycles, after varying each parameter individually			
						9150	Change vs. 9150 Baseline	9150	Change vs. 9150 Baseline
Maximum Principle Tensile Stress (from FEA)	MPa	186		10% up	10% down	Life up	Life up	Life down	Life down
Cyclic Sress Range (from FEA)	MPa	372	Δσ	409	335	3200	-65%	29000	217%
Offset Yield Strength	MPa	234	0.2% YS	257	211				
Ultimate Tensile Strength	MPa	287	UTS	316	258				
Elongation	%	0.7	El	0.77	0.63				
Elastic (Young's) Modulus	GPa	130	E	143	117	9150	0%	9150	0%
Poisson's Ratio		0.279	μ or v	0.307	0.251				
Fatigue Strength Coefficient	MPa	464	σ'f	510	418	16000	75%	5000	-45%
Fatigue Strength Exponent		-0.093	b	-0.1022	-0.0836	5800	-37%	16500	80%
Fatigue Ductility Coefficient		0.007	ε'f	0.0081	0.0067	11500	26%	8600	-6%
Fatigue Ductility Exponent		-0.291	c	-0.320	-0.262	6000	-34%	15000	64%
Cyclic Strength Coefficient	MPa	2130	K'	2343	1917	14500	58%	5000	-45%
Cyclic Strain Hardening Exponent		0.312	n'	0.343	0.281	2000	-78%	25000	173%
Transition Fatigue Life	Cycles	20	N_t	21.82	17.85				

Overall, the predicted principle stress magnitude has the most significant impact on strain life fatigue life. However, elastic modulus shows no impact.

A sound casting design practice for a structural component with low cycle fatigue and reasonably high stress levels should consist of the following steps:

1. Conduct a coarse selection of the candidate alloys and processes using the best practice data as captured in the CAPS tool.

2. Establish the probable failure modes and establish the desired service life in years or cycles.

3. Conduct a preliminary FEA based validation for the final geometry using various candidate alloys, keeping the same configuration, using CADS tool data. This will also show the high stress areas with their corresponding stress magnitudes. These values will be useful in predicting fatigue life.

4. Design and develop the casting process and rigging to achieve the desired quality level for the internal soundness, surface and subsurface discontinuities, and validate the casting process by simulation.

5. For the final selected grade of material, based on the stress levels and their magnitudes, further optimize the design to reduce the weight and/or improve the life. This could be an iterative process.

6. Always, conduct an actual functional testing of the final design, made with production intent process and alloy before releasing because FEA and all analysis tools are based on certain assumptions. For example, in this exercise it is assumed the hub casting is free of any flaws, homogeneous and isotropic; the reality could be quite different.

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Appendix B

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Author:	John M. Tartaglia, Ph.D.
Report Number:	EWI005176P
Client Reference:	AMC CSR CADS Project

Strain-Life Fatigue Data for Strain-Life Fatigue Data for SSF Ductile Iron Grade EN-GJS-500-14

Prepared by:

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INTRODUCTION

The present study was undertaken to supplement the AFS Research Report by James D. DeLa'O, Richard B. Gundlach, and John M. Tartaglia, entitled "Strain-Life Fatigue Properties Database for Cast Iron". That prior study was conducted under Department of Energy (DOE) Contract Number DE-FC07-00ID13852, and the report was published and distributed by AFS in 2003.

The present study was undertaken to include the data for solid solution strengthened ferrite (SSF) ductile iron EN-GJS-500-14 as specified in DIN EN 1563:2012-03 standard entitled "Spheroidal graphite cast irons".

All the materials that have been tested for the database are shown in Table 1.

MATERIAL TESTED

The present study involved testing of 25 mm Y block of the SSF 500-14 iron. Ten block ends were received for Heat 1 and sixteen block ends were received for Heat 2.

SCOPE OF WORK

The scope of work for the present study was the same as the previous AFS/DOE study for the other grades in the database, i.e., tensile, strain-life fatigue, chemical analysis, metallography and hardness. The sample distribution between the two heats is shown in Table 2.

PROCEDURES

Although much of the procedural information is abstracted from the original report in the subsequent report subsections below, the reader should consult the previous report for the detailed procedures. The same procedures were employed to test these steels as the other grades in the original AFS/DOE study. The original AFS/DOE report (called ORIGINAL DOE REPORT.PDF) is also supplied on this CD.

The fatigue testing and analytical procedures were somewhat complex. Therefore, in the subsequent subsections of this report, these complex procedures are also abstracted from the relevant portions of the original AFS/DOE report.

Qualification Testing

The foundry supplier conducted metallographic analysis, hardness and tensile testing of the contributed material.

X-ray Radiography

X-ray radiography was conducted for each bar for all of the materials. The applicable instruction standard was ASTM E446-15 "Standard Reference Radiographs for Steel Castings up to 2inches in Thickness". No acceptance standard was transmitted to Acuren, but bars were rejected if they did not pass Level 2 and the anomaly was in the gauge section. No bars were rejected.

Chemical Analysis

In the analysis, the concentrations of twenty elements were determined. All elemental concentrations were determined using optical emission spectrometry (OES) in accordance with Bulk chemical analysis by Glow Discharge - Optical Emission Spectrometry (GD-OES) in accordance with Element Wixom SOP CH-IO-002 Leco GDS-850A Glow Discharge Spectrometer, except carbon, sulfur, oxygen and nitrogen, which were determined using combustometric methods (LECO) in accordance with ASTM standard E1019-11. By instruction from AFS, only ranges were published in the database.

Metallography

Three metallographic specimens were prepared and analyzed for the Y-blocks. The samples were mounted from a section where a gauge section would be produced for a mechanical test specimen. The mounts were polished using standard metallographic techniques in accordance with ASTM standard E3-11. The samples were final polished using colloidal silica media with a 0.05 um particle size. The samples were photographed in the as-polished condition at two magnifications, and at two magnifications after etching in 2% nital reagent. The etched specimens were also photographed at low magnification to measure grain size.

Image analysis was conducted on fifty fields for a total analyzed area of 35 mm^2 of each of the specimens for porosity content at a magnification of 100X. The pearlite content was estimated by manual observation.

The macrograin size of each sample was determined by comparison with the AFS wall chart "Microstructure Control in Hypoeutectic Aluminum-Silicon Alloys". The ASTM macrograin size number was determined using ASTM standard E112-13.

Brinell Hardness

Brinell hardness measurements were conducted on the cut face of the same samples used for metallography or tensile testing. All Brinell hardness tests were performed in accordance with ASTM standard E10-15a using a 3000-kg load and 10 mm ball.

Monotonic Tension Testing

Tension test blanks were obtained from the Y-blocks. The 0.2% offset yield strength (YS), ultimate tensile strength (UTS), total elongation (%El), and reduction in area (%RA) were determined. Additionally, the monotonic tensile stress-strain response was characterized for the specimens in terms of elastic modulus and Poisson's ratio.

Tensile tests were conducted at room temperature in accordance with ASTM standard E8-16a. Tests were conducted on standard round tension specimens with 0.5-inch gauge diameter and 2.0-inch gauge length for the as-received blanks.

For determining the room temperature stress-strain response with its concomitant coefficients, Element employed strain gauges (for precision modulus and Poisson's ratio determination) and an extensometer [for determination of the monotonic strength coefficient (K) and monotonic strain hardening exponent (n)]. For determining the room temperature stress-strain response with its concomitant coefficients, Element employed strain gauges (for precision modulus and Poisson's ratio determination). These tests were conducted in accordance with ASTM standard E111-04(2010) for elastic modulus, ASTM standard E132-04(2010) for Poisson's ratio, ASTM standard E646-16 for K and n values. The raw stress-strain data are also presented in unfiltered form in the database.

Charpy V-notch Impact Testing

Six standard Charpy V-notch samples were machined and tested in accordance with ASTM standard E23-12c. Five samples were tested at room temperature.

Strain-Life Fatigue Testing

Room temperature, strain-controlled fatigue tests were conducted on samples from 24 sand cast samples. The samples were tested following the guidelines of ASTM standard E606-12 to determine the strain-life curve for the aluminum material over the range from about 100 cycles to 1,000,000 cycles. Generally, three specimens were tested at each of six to seven strain levels with the specific strain levels chosen to provide fatigue lives that are evenly distributed on a logarithmic scale.

All test specimens were machined and longitudinally polished in general accordance with the recommendations contained in Appendix X3 of ASTM standard E606-12. The geometry of the samples met the requirements of ASTM Standard E466-07. The dimensions were also largely consistent with the requirements of ASTM standard E606-12, with the exception that a more generous blending radius (blending radius = 8 X gage diameter) was used.

Test specimens were machined with a 0.314-inch (8-mm) gage diameter, 0.628-inch (16-mm) gage length, 2.51-inch (64-mm) blending radius, and 0.590 (15-mm) diameter grip ends.

The tests were performed using a triangular waveform at a constant strain rate of 2% per second. Specimens with fatigue lives in excess of 100,000 cycles were switched to stress-controlled testing after 100,000 cycles and thereafter were tested at a constant frequency of 15 Hz. Tests were continued until fracture, or until 5,000,000 cycles were reached without failure. Strain and load data were recorded during the tests and the test data were analyzed following the guidelines of ASTM standard E606-12, ASTM standard E739-10, and SAE standard J1099 AUG2002 to determine the strain-life coefficients for all materials.

Stress-Life Fatigue Analysis and Testing

For each of the three steels, twelve stress-life tests were conducted at room temperature on the same geometry test specimen as was employed with the strain-life specimens. However, the tests were conducted in accordance with ASTM standard E466-15. The tests were conducted using tension-tension cycling at 40 Hz and at a stress ratio of R = + 0.1 wherein the minimum tensile stress is 10% of the maximum tensile stress. The data were analyzed in accordance with ASTM standard E739-10. The fully-reversed strain-life results obtained at a strain ratio of R = -1 were converted to stress-life and also compared to the stress-life test results obtained at a stress ratio of R = +0.1.

DETERMINATION OF CYCLIC PROPERTY PARAMETERS

The following sections describe details of the cyclic property data analyses.

Strain-life Method

The basic principles and analytical procedures associated with the conventional strain-life method are well documented in ASTM standard E606 and SAE standard J1099. However, some discussion regarding noteworthy aspects of the analysis is provided below.

Determination and use of elastic modulus values

A fundamental step in the strain-life analysis of cyclic property data is the decomposition of the total cyclic strain amplitude ($\Delta\varepsilon_t/2$ or $\Delta\varepsilon/2$) into its component strains, i.e., plastic strain amplitude ($\Delta\varepsilon p/2$) and elastic strain amplitude ($\Delta\varepsilon_e/2$) according to the equation:

$$(\Delta\varepsilon_t/2) = (\Delta\varepsilon_e/2) + (\Delta\varepsilon_p/2)$$

In practice, the elastic component of strain is determined by dividing the stress amplitude ($\Delta\sigma/2$) at specimen half-life (0.5Nf) by the elastic modulus (E). The plastic strain amplitude is then given as the difference between the total strain amplitude and the elastic strain amplitude. The plastic strain data determined by this method are used in the calculation of both the strain-life and cyclic stress-strain constants

Elastic modulus values determined by linear regression of the stress-strain data in an approximately linear portion of the stress-strain curve, in accordance with ASTM Standard E111-04(2010), were used in all the cyclic property analyses. Stress-strain data for the modulus determinations were acquired from strain gages affixed to the surfaces of tension and compression specimens as described in earlier sections of this report. The resulting elastic modulus values are presented in the material characterization section for the aluminum material in the database.

Determination of the cyclic stress-strain parameters

Using data obtained from each fatigue specimen at half-life, the cyclic stress-strain constants n' (cyclic strain hardening exponent) and K' (cyclic strength coefficient) were determined by regressing the stress amplitude ($\Delta\sigma/2$) versus plastic strain amplitude ($\Delta\varepsilon p/2$) in logarithmic coordinates. These are related as follows:

$$\Delta\sigma/2 = K'(\Delta\varepsilon_p/2)^{n'}$$

The cyclic stress-strain constants were also calculated directly from the strain-life constants as follows:

σ'_f, b, ε'_f, and c in the following equations:

$$\Delta\sigma/2 = \sigma'_f\,(2N_f)^b$$

where $\Delta\sigma/2$ = true stress amplitude

$2N_f$ = reversals to failure (1 rev = ½ cycle)

σ'_f = fatigue strength coefficient

b = fatigue strength exponent (Basquin's exponent)

and

$$\Delta\varepsilon_p/2 = \varepsilon'_f\,(2N_f)^c$$

where $\Delta\varepsilon_p/2$ = plastic strain amplitude

$2N_f$ = reversals to failure

ε'_f = fatigue ductility coefficient

c = fatigue ductility exponent

As discussed previously, the total strain is the sum of the elastic and plastic strains. In terms of strain amplitude,

$$\Delta\varepsilon/2 = \Delta\varepsilon_e/2 + \Delta\varepsilon_p/2$$

The elastic term can be written as

$$\Delta\varepsilon_e/2 = \Delta\sigma/2E$$

We can now state this in terms of life to failure:

$$\Delta\varepsilon_e/2 = (\sigma'_f / E) \bullet (2N_f)^b$$

The plastic term is

$$\Delta\varepsilon_p/2 = \varepsilon'_f\,(2N_f)^c$$

The total strain can now be rewritten

$$\Delta\varepsilon/2 = (\sigma'_f / E) \bullet (2N_f)^b + \varepsilon'_f (2N_f)^c$$

This last equation is the basis of the strain-life method and is termed the strain-life relation.

Now K' and n' can also be calculated as follows:

$$K' = \sigma'_f / (\varepsilon^{\prime f})^{n'}$$

$$n' = b/c$$

Thus, the K' and n' constants were calculated by simple manipulation with the above two equations.

RESULTS AND DATABASE LAYOUT

Database Layout

The database was originally presented on two "read-only" compact discs (CDROM), and these have been updated with DVDs over time. The CDROM database was published by the American Foundry Society (AFS) as an AFS Research Publication entitled "Cast Iron Fatigue Properties Database for Modern Design Methods" (ISBN 0-87433-267-2).

Files contained at the main level (i.e., the root directory) provide summary information for the steel alloys of this study. The steel information is identical to the original AFS/DOE report (called "ORIGINAL DOE REPORT"). The data for all materials, including basic material description, chemical composition, microstructure, monotonic properties and cyclic properties are summarized in a Microsoft ® Excel file entitled "DATA SUMMARY for Cast Iron".

The directory structure leading to the results folder for a given test material is organized according to the following hierarchy:

- Ductile Cast Iron
- Grade Designation (SSF 500-14 in this case)
- Material Code (a unique character sequence with material condition (not necessary for this material)

The specific results files, analysis files and raw data files associated with each material's data are grouped within the results folder. Briefly, the files at the results level are as follows:

- Cyclic Properties Results (Strain-Life Method): contains tabulated data for each test specimen pertaining to the fatigue-life and cyclic stress-strain analyses according to the conventional strain-life method. The data are plotted and relevant regressions are illustrated.
- Material Characterization: contains the tabulated results from hardness testing, tension testing, compression testing, microstructural analysis and chemical analysis for each test specimen. The file also contains links to micrographs for each metallographic specimen.
- Raw Data: directory containing hysteresis stress-strain data as well as raw monotonic tension stress-strain data. The hysteresis files also contain plots of the hysteresis loops. All of the raw data files from tension specimens contain extensometer data as well as strain gage data. The extensometer data were used in the determination of yield strengths, strain hardening exponents (n) and strength coefficients (K). The reader is cautioned against the use of extensometer data for modulus determination. The more precise data from strain gages are more appropriate for this application.
- Micrographs: directory containing micrographs and macrographs in JPEG format.

RESULTS

Alloy Composition

Ranges for a few elements are provided in the DATA SUMMARY file presented at the main level.

Microstructure

Tabulated microstructural data

The results of microstructural analyses are tabulated for each metallographic specimen in the Material Characterization file, which appears in the folder for the steel materials. Averages of the microstructural results for all metallographic specimens for the materials are tabulated in the DATA SUMMARY file, which in turn is presented at the main level.

Micrographs

Digital micrographs for each specimen are provided in JPEG format in a subdirectory entitled "Micrographs" in the results subdirectory for each of the three steel grades. The images can be accessed directly from the "Micrographs" subdirectory, or via links provided in the Material Characterization file.

Ideally, the micrographs should be viewed on systems with a display resolution set to at least 1024 by 768 (XGA) resolution, or the program used for display should be configured to resize the image to the screen size. Otherwise, it will be necessary to scroll the image to view the micrograph in its entirety.

The magnification documented in the micrograph title simply refers to the magnification associated with the optics of the metallograph, as it was configured when the image was captured. The final display magnification depends on the resolution and physical dimensions of the display area.

The issue of display magnification is unambiguously addressed by referencing the micrometer scale included in the upper left corner of each micrograph (provided that the 4:3 aspect ratio of the image is not changed for display). The magnification documented in the image title is then used simply as an indication of the relative magnifications of the various micrographs.

If desired, the magnification of the displayed image on any system can be calculated from the following expression if the image resolution is not changed (i.e., the image is not "resized") during display:

Display Mag. = (Optical Mag.) × (Scale Factor) / (Display Scale)

where,

- Display Mag. is the actual linear magnification of the image as displayed;
- Optical Mag. is the optical magnification from the metallograph (recorded in the image title);
- Scale Factor is the number of pixels (picture elements) at 1x optical magnification representing one millimeter on the specimen surface (Scale Factor = 6.7 pixels/mm for images in this database);
- Display Scale is the number of pixels per millimeter for the display system.

However, as previously mentioned, the inclusion of a micrometer scale in each image file has rendered such calculations unnecessary.

Hardness and Monotonic Properties

The results of hardness testing and tensile testing are tabulated for each specimen in the Material Characterization file for the given material. The average values for a given parameter are tabulated in the DATA SUMMARY file.

Finally, raw stress and strain-data from modulus, Poisson's ratio, and n and K value determinations in tension are provided as text (ASCII) files in the subdirectory "Tensile". This subdirectory is located in the "Raw Data" folder in the given material directory.

Cyclic Properties

Strain-Life Method

The four strain-life constants [namely, the fatigue strength coefficient and exponent (σ'_f & b) and the fatigue ductility coefficient and exponent (ε'_f & c)] as well as the two cyclic stress-strain curve parameters [namely, the cyclic strength coefficient (K') and the cyclic strain-hardening exponent (n')] were determined. These constants are presented in the DATA SUMMARY file at the main level.

Relevant data and analyses are presented for each specimen in an Excel file entitled "Strain-Life Fatigue Test Summary SSF 700-14 which is located in the "Raw Data\Fatigue" folder. In a worksheet entitled "Fatigue Test Summary SSF 500-14", located within the aforementioned folder, relevant strain-life data such as fatigue life (N_f), total strain amplitude ($\Delta\varepsilon/2$), stress range at half-life ($\Delta\sigma$) and plastic strain range ($\Delta\varepsilon_p$) for each test specimen are tabulated, plotted and analyzed.

Raw cyclic stress-strain peak-valley and hysteresis loops

Hysteresis loops with stress-strain data were saved at selected intervals throughout the life of each test specimen. The sampling intervals were near the beginning, middle and end of tests. The hysteresis loop for each specimen is presented in a pictorial format in a PDF file in the "Fatigue\Raw Data\Summary and Hysteresis" folder. Peak-Valley stress, total strain, modulus, and plastic strain values for each specimen at various sampling intervals are contained in an Excel file in the "Fatigue\Raw Data\Peak-Valley" folder.

Table 1 Materials Tested at Element (as of January 2017)

***Table 1a**: Cast Irons*

Austempered Ductile Iron: ASTM A 897-06		
ASTM Grade	*Material Condition*	*Section Size*
110 / 70 / 11	Austempered	48 mm by 43 mm by 185 mm section of rectangular casting
125 – 80 – 10 (130 / 90 / 09)		25 mm Y-block
150 – 100 – 7 (150 / 110 / 07)		
175 – 125 – 4		
200 – 155 – 1		
Ductile Iron: ASTM A 536-84 (Re 1999)		
ASTM Grade	*Material Condition*	*Section Size*
60 – 40 – 18	As-cast	25 mm Keel block
	Subcritical Anneal	25 mm Keel block
	Full Anneal	25 mm Y-block
	Heavy Section; As-Cast	76 mm Y-block
65 – 45 - 12	As-cast	25 mm Keel block
100 – 70 – 03	As-cast	25 mm Keel block
	Normalized	25 mm Keel block
		76 mm Y-block
120 – 90 – 02	Quenched and Tempered	25 mm Keel block
Ductile Iron: DIN EN 1563:2012-03		
DIN Grade	*Material Condition*	*Section Size*
EN-GJS-500-7	As-cast	25 mm Y-block
EN-GJS-500-7	As-cast	76 mm Y-block
EN-GJS-500-14	As-cast, SSF	25 mm Y-block
Si-Mo Ductile Iron: SAE J2582 Jun 2004		
SAE Grade 2	As-cast	bars
Compacted Graphite Iron: ASTM A 842-85(Re 1997)		
ASTM Grade	*Material Condition*	*Section Size*
300	As-Cast	25 mm Y-block
350		
400	As-Cast	25 mm Y-block
	As-Cast	76 mm Y-block
Gray Iron: ASTM A 48-00		
ASTM Grade	*Material Condition*	*Section Size*
20B	As-Cast	25 mm Y-block
30B	As-Cast	13 mm Round
	As-Cast	25 mm Y-block
	As-Cast	76 mm Y-block
35B	As-Cast	25 mm Y-block
40B	As-Cast with C.E.= 3.7	25 mm Y-block
	As-Cast with Normal C.E. = 4.0	25 mm Y-block
Austempered Gray Iron: No Standard Specification		
Base Iron	*Material Condition*	*Section Size*
Class 30B	Austempered	25 mm Y-block
Abrasion-Resistant Cast Iron: ASTM A 532		
ASTM Grade	*Material Condition*	*Section Size*
Class III Type A Level 2 (25%Cr)	Quenched & tempered	16 mm rectangular bars