2003 Keith Millis Symposium on Ductile Cast Iron

Casting Defect Analysis Procedure and a Case History

A. Alagarsamy
Citation Corporation, Birmingham, Alabama

ABSTRACT

Foundries are still using trial and error methods to solve casting problems. There are benefits to using a more disciplined approach to define, identify and determine the root cause of a defect. Use of international standard defect codes for classifying the defects is illustrated. Powerful techniques such as defect mapping, questioning to narrow down the root causes and design of experiments to identify and control the variables are explored. An actual case history in solving shrinkage porosity is described to illustrate these techniques in practical use.

INTRODUCTION

A tremendous amount of productivity is lost through defective castings. By employing a disciplined approach to understand the nature of defects and the mechanism of defect formation and controlling the key process variables we can significantly reduce the scrap both in-house and at the customer. Misidentification of defects leads to costly scrap, lost time and customer dissatisfaction. It is not uncommon to have different names for the same defect, making it difficult to compare the successes and failures of other foundries in solving the same problems. The AFS has published a book standardizing the names of almost all the defects seen in the industry, but the foundries have not yet adopted the standardized codes and names. Even if in-house names unique to the foundry are used they can be cross-referenced with the published codes to help disseminate the knowledge for solving casting defect problems.

Shrinkage porosity revealed during machining plagues the customers as well as foundries. Foundries are now increasingly required to pay for the machining expenses for scrapped castings. Shrinkage porosity occurs sporadically making it difficult to determine the root cause. It is very difficult to verify in the foundries by using NDT techniques due to complex shapes, and the cost or time required to test the castings.

BACKGROUND

Ever since the start of production of ductile iron castings, foundries have been working on understanding the effect of process variables on the shrinkage formation and controlling these variables to minimize defects. The Ductile Iron Society undertook a study to do just that. It was determined that silicon level has a significant effect on the internal porosity in unfed sections of the castings.

CASTING DEFECT CODES

The International Atlas of Casting Defects handbook divides the defects into seven major categories. The entire defect codes and their names are given in the appendix. New names were added shown in italics. In addition to the codes listed in the handbook, AFS committee 4E has added codes at the end of the current codes to further identify the material of the casting such as gray iron, aluminum, etc. and to identify the process by which the castings were made. Use of these codes, in addition to in-house names or codes, will enable foundrymen to use data from one foundry to another without any confusion.

MAJOR DEFECT CODES
A – Metallic projections
B – Cavities
C – Discontinuities
D – Defective surface
E – Incomplete casting
F – Incorrect shape and dimension
G – Inclusions and structure

ALLOY CATEGORIES
GI – Gray iron
DI – Ductile iron
CS – Carbon steel
SS – Stainless steel
OF – Other ferrous
AL – Aluminum
MG – Magnesium
CU – Copper
ZN – Zinc
OA – Other non ferrous

PROCESS
GS – Green sand
BK – Baked sand
NB – No bake
CB – Cold box
HB – Hot box/shell
PM – Permanent mold
DC – Die casting

LF – Lost foam
IV – Investment casting
VP – ‘V’ Process
CN – Centrifugal
IG – Ingot
CC – Continuous cast
OM – Other methods

A fully coded defect will appear as B214-DI-GS, which will be read as shrink at the riser contact in ductile iron castings made in green sand molding process. This information is available at the website given below. http://www.castingsolutions.com

As we have come up with new processes and new materials, we also have created new types of defects with new names not covered in the present atlas. Some of the new defect names that are considered, for the newer materials and processes and to classify them in more detail are listed here.

- Vermicular graphite
- Chunk graphite
- Mesh graphite
- Exploded graphite
- Inverse chill carbides
- Grain boundary carbides
- Gas voids with graphite layer
- Gas void with oxide layer
- Blister
- Doughnut (fisheye)
- Leaker
- Riser break-in
- Shrink at riser contact

IDENTIFICATION OF DEFECTS

Most of the defects seen in the foundries are easy to recognize and identify by the correct defect name and code. There are a few defects that may appear to be similar but may be entirely different types. If we do not correctly diagnose these defects we may get into more problems trying to correct something or change something that may not be necessary. It may be better to keep the defect as neutral prior to classifying into a more specific defect. If distinction could not be made between gas defect and shrinkage defect, then it should be kept as porosity until it is clearly determined to be either shrink or gas defect. Ambiguous defects include inclusions (sand or slag). There are several places information is available to help determine the true defect name and code. Every foundry should have known defect standards that have been identified previously for reference and training new personnel. Defect handbooks, in-house manuals, and the internet are a few of the sources that are readily accessible. Suppliers also have a lot of information collected through the years in helping solve foundry problems. It is important to have good knowledge of the mechanics of casting defect formation, probable locations and the nature of the defects. In some difficult cases, analytical tools such as the SEMs are used to pinpoint the nature and cause of the defects. One should use any and all tools available to make sure the defect is identified correctly.

GATHERING DATA – INFORMATION

In solving casting quality problems, we must start with reliable data for key process variables that affect the quality of the castings. Data gathered in the foundries should be reliable. Gage R and R for the measuring equipment should be in the acceptable range. For evaluating casting defects, instead of having two categories (acceptable castings and rejects), a range of quality standards should be established with a reproducible measuring system, e.g. 1 through 5, 1 denoting no defects and 5 representing worst case defect. Once a valid measurement system is established then any experimentation can be undertaken to study the effect of variables on the casting quality.

Routine documentation of all process data should be easily obtainable for analysis of conditions causing the defects. More frequent data gathering may be necessary to zero in on the causes of defects. Any data that are used for analysis should be dependable.

DEFECT MAPPING

It is very important to analyze the defects by carefully cataloging details of the defects. It will be very informative when the defects are plotted on a pattern layout diagram. The details will indicate how many defects of one kind occur at a particular location of a cavity in the casting, cope or drag and relative location with respect to a gating schematic. Defects documentation should also contain the time the castings were made, especially for persistent types of defect. From this kind of detailed mapping it is easy to see where the defects are mainly located, what type of defects and which cavities are prone to the defects under consideration. For shrink type of defects, information about the risers (how well it is functioning-piping) should also be documented.

From the defect mapping information and process data during high scrap times and low scrap times, useful contrast information can be derived. By asking and answering questions listed below, one can remove processes not contributing to the defect. By eliminating a broad process, quite a few variables need not be considered thus simplifying the work ahead. One should be careful not to eliminate variables that may be influencing the defect formation. It should also be noted that there may be interaction between variables as well as design features.

When the defect is:	**Processes not contributing to the defect**
In only one of several cavities	Melt, molding, pouring core,
Shrink at riser connection	Sand, molding, core
Shrink at hot spot	Sand, molding, core
Tear-up, stickers	Core, melt, pouring
Crush at certain times	Core, tooling, melt, pouring
Misrun at start of a shift	Tooling, sand, molding, core
Sand at the bottom	Melt, pouring

Table 1. Examples of elimination of processes not contributing to the defect

Prior to investigating casting defects, one should gain knowledge about the nature of defects, the appearance and possible location of the defects and the mechanism of defect formation. During the investigative phase, by asking and answering pertinent questions, more insight into the defects can be gained
.

Some of the questions for root cause analysis:

- Where are the defects?
  - Drag, side walls, above or below core
  - Closer to gates or farther away from gates
  - At the surface, interior or sub surface
- Are the defects found at the same location?
- Are the defects occuring all the time?
- Are the defects people related?
- Are the defects time related?
- Are the defects cavity related?
- Do these defects occur in other similar jobs?

Further questions as to related defects can shed light as to the causes of defects.
Are there related defects in the same castings?

  - Misrun, short pour, run-outs, laps
  - Rat tails, buckles, scabs
  - Rough surface, burn-in, penetration
  - Swells, erosion, stickers
  - Shrinkage, gas porosity, leakers

When related defects occur in the same castings, it may indicate a system related problem.

We are going to look at a case history of a porosity defect and the procedure that was followed to reduce the defect occurrence. The schematic view of a sectioned casting is shown in **Figure 1**. Porosity occurs sporadically in a heavier section not fed directly by a riser, at the location shown, **Figure 2.** shows two different locations where a riser is attached for different cavities, due to layout of patterns for maximizing number of cavities in the mold.
What else is known:

- Porosity shows up after machining the casting.
- Porosity is three times more when the riser is at location 'B' than when the riser is at location 'A'.
- Occassionally in some heat codes there is a spike in the defect severity.
- Overall, the incidence of porosity is low.

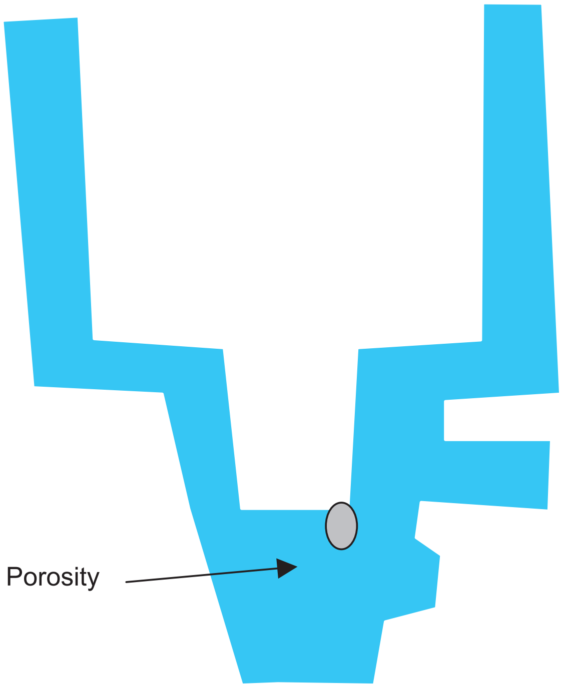

Figure 1. Schematic view of cut view of casting

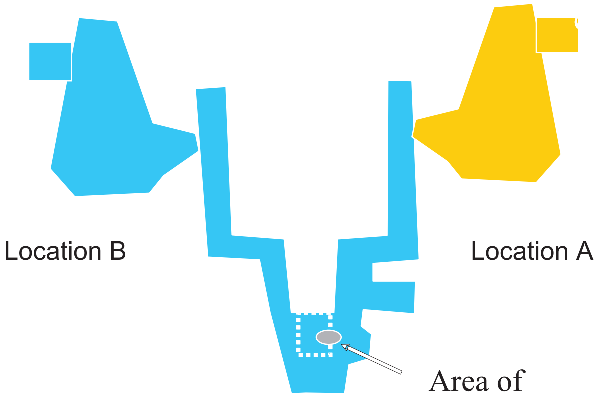

Figure 2. Alternate locations for riser

ANALYSIS OF THE DEFECT

By the appearance (dendritic) and the location (below the core) and in the center of the isolated heavy section, it was concluded this was a shrinkage defect. This defect is remote area (centerline) porosity. The international code for this defect is determined to be **B222 – Centerline or axial shrinkage porosity.** As the section where the defect occurs is isolated from the riser by a thinner section of the casting, the riser is not able to compensate for the shrinkage that occurs at the end of solidification of the isolated section. Solidification models predict there will be shrinkage at this location. Even then, over 98% of the time the castings are sound. Most of the time the expansion due to graphite precipitation compensates for the shrinkage occuring at this late stage of the solidification process.

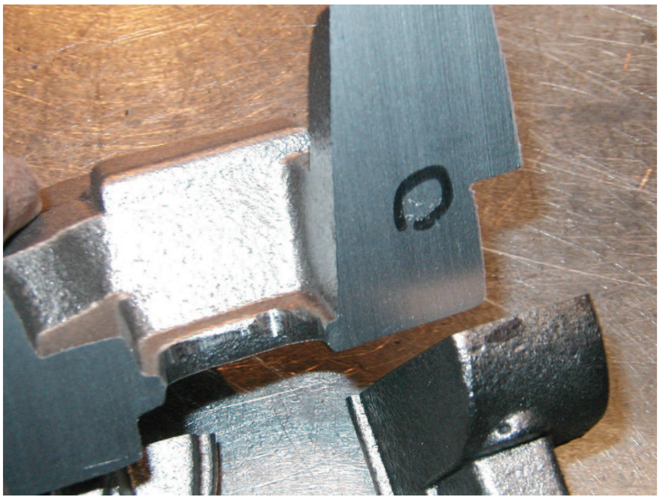

Figure 3. Example of micro shrinkage in the center of unfed area of a casting

When there is microshrinkage, there has been insufficient graphite expansion at the end of solidification to compensate for shrinkage due to austenite formation.

EXPANSION AND SHRINKAGE

Expansion and shrinkage occcurs simultaneously during solidification of a casting. In many instances expansion due to graphite precipitation pushes liquid metal into the voids or into the free surface of a riser. This can readily be seen by observing the piping behavior in the risers as shown in **figures 4 and 5** There is absence of continuous piping in most cases, which indicates at different times expansion is greater than the shrinkage, pushing liquid metal into the riser. Process variations within mold and from mold to mold affect the rate and relative values of shrinkage and expansion. If the casting design and riser design is marginal, then shrinkage defects may exhibit different forms.

Figure 4. Riser piping behavior

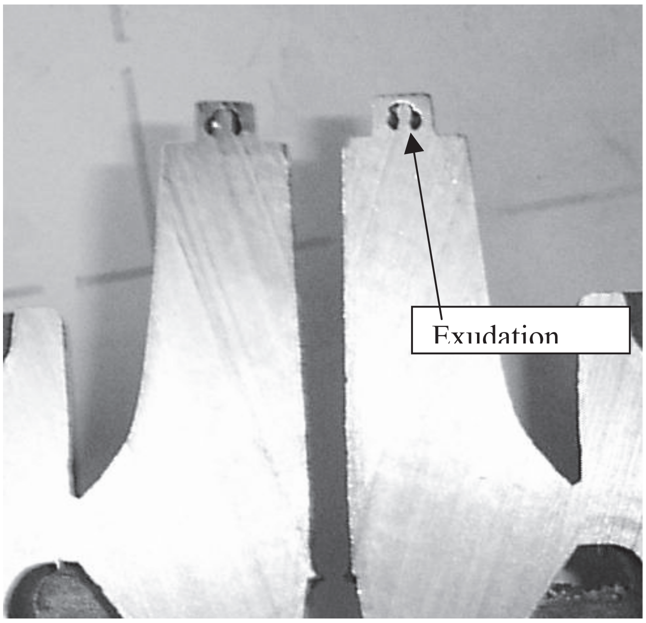

Figure 5. Exudation of metal is clearly seen into the riser piping cavity.

Evidence of exudation is clear in cases where the metal was semisolid and solidified very quickly maintaining its shape. There are some rare instances where the exudation is into a primary liquid shrinkage cavity inside a casting. One such instance is shown in **figure 6**.

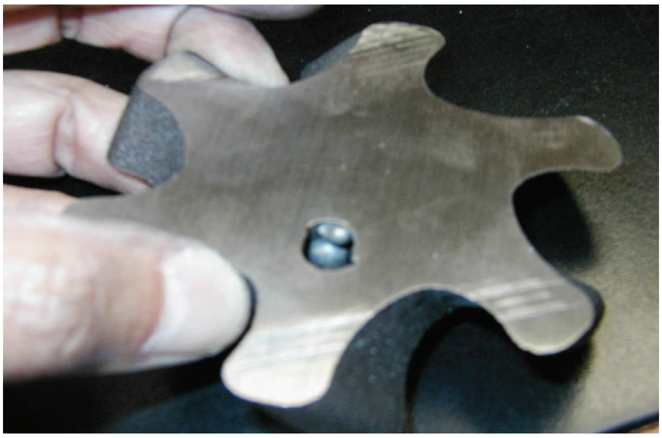

Figure 6. Exudation of semisolid metal into a void in the center of a casting

In the case study under discussion here, the factors inherent in the design of both the casting and gating makes the casting susceptible to shrinkage porosity. Since a very small percentage of castings have defects and they occur in spikes, it suggests that there are some significant variables or combination of variables that influence the shrinkage porosity.

The fact that riser location ‘A’ **figure 2**. results in much less frequency of shrinkage defects than riser location ‘B’ suggests that casting design has a significant effect. By looking at the results of casting solidification simulation, we can detect that the feeding path is open for a slightly longer duration for the ‘A’ location than for the ‘B’ location. This means that when the feeding path is cut off, the remaining volume of liquid in the isolated area is slightly smaller with ‘A‘ riser than with ‘B’ riser. This fact then leads us to conclude that the variables which influence the amount of liquid remaining in the isolated area have a direct effect on the shrinkage defects. The other set of variables that will affect the shrinkage are metallurgical,variables which affect graphite precipitation especially at the end of solidification.

VARIABLES

Prior to running design of experiments, a matrix study was done to determine the key variables that in this case will affect the shrinkage porosity. Listed below are the variables considered to have effect on the shrinkage.

Metallurgical factors that affect the shrinkage:
- ➢ Carbon equivalent
- ➢ Cumulative level of forward segregating elements
- ➢ **Magnesium and cerium residuals**
- ➢ Level of base iron nucleation
- ➢ **Silicon level**
- ➢ **Precipitation rate and timing of graphite nodules**

Factors influencing the volume of liquid metal:
- ➢ **Pouring temperature**
- ➢ Green sand heat conductivity-density
- ➢ Core sand heat conductivity
- ➢ Mold quality – mold wall movement
- ➢ Pouring rate

Design of casting
- ➢ **Core length-affecting mass at hot spot**

The top ranked factors listed in bold letters were thought to influence the shrink most, and warranted further study. The graphite precipitation rate and timing is an important variable but is not directly controlled like the other variables. Graphite nodule precipitation is influenced by several other variables listed and/or by inoculation effectiveness. For instance, over-inoculation or very high carbon equivalent can result in primary graphite precipitation, which results in duplex nodule size distribution. There is some evidence this type of graphite nodule distribution leads to increased shrinkage. A DIS research project at CANMET showed that excess inoculation increases shrinkage.

Also from this study and other experiences, we know that an increased magnesium residual level for the section thickness and final sulfur increases shrinkage. Increased level of silicon contributes to increased shrinkage. Silicon level is also controlled to minimize carbide formation. There may be less freedom in some shops to lower the silicon level, due to common iron being poured for many jobs, some of which require higher silicon to control carbides and/or pearlite levels in the casting. In some cases a minimum silicon may be specified by the customer for operational benefits.

DESIGN OF EXPERIMENTS

Considering all the above factors it was decided to conduct a design of experiment to determine the variable factors that influence shrinkage the most. The first set of variables considered for the study are:

1. Magnesium residual level
2. Core design
3. Pouring temperature

From the feedback from the customer and analyzing the internal process data, a strong correlation was found that pointed to the magnesium residual level contributing to an increase in shrinkage defects on some days.

Core design was chosen as a factor that affects the volume of liquid metal in the hot spot area. By lengthening the core, liquid mass could be reduced. It was expected that the longer core will result in reduced shrinkage.

Pouring temperature was selected as another variable due to its influence on the volume of liquid metal remaining when the feed path is cut off. Generally in larger casting sections lower temperature seemed to help minimize shrinkage.

A full factorial design was used to determine if there were any interactions between the three variables selected. A set of 8 heats were poured as shown in **Table 2**, Numbers 1 through 8 show the sequence when the heats were poured.

Table 2. Three factor full factorial experiments

	Short cores		Long cores	
	Low temp	High temp	Low temp	High temp
Low Mg	1	5	3	7
Hi Mg	2	6	4	8

Castings from these heats were radiographed and rated by two people as to the severity of shrinkage. Shrinkage was rated from 0 to 5, 0 being no shrinkage and 5 being the worst case observed. The points for each condition were totalled and used as a response from the experiments for analysis. See **Table 3.** and **Figure 7**.

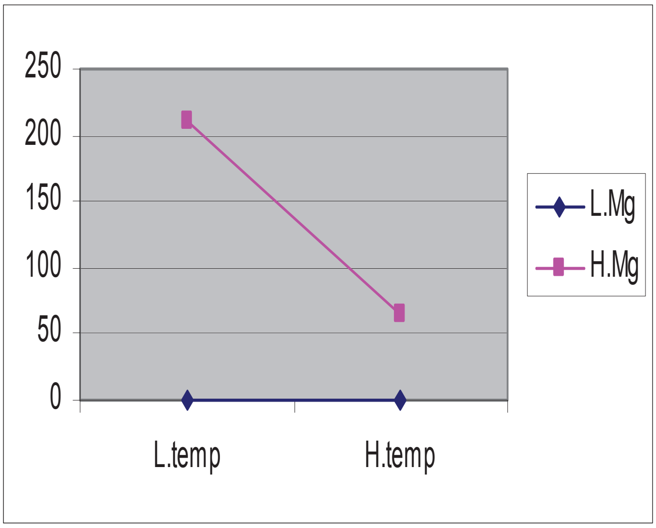

Figure 7 : Total shrinkage porosity at low and high levels of Mg and temperature

Table 3. Shrinkage severity response

	Short cores		Long cores	
	Low temp	High temp	Low temp	High temp
Low Mg	0.7	0	0	0
Hi Mg	110	35	101	31

At lower magnesium levels there was no shrinkage seen. At higher magnesium levels, temperature has an effect, with higher temperature reducing the amount of shrinkage. Core design did not affect the shrink. The major effect is Mg, followed by temperature. Interaction between magnesium and temperature can be seen.

After the study the process variables for magnesium residual and pouring temperature were adjusted to a more favorable range. This change resulted in a significant improvement in the level of defects found after machining. Even with the reduced defect severity, porosity still occurs at the same pattern/location as before. As we know, the silicon level also has an influence on shrinkage, so the silicon level is also adjusted lower, while monitoring for an increase in carbides.

We continue to audit the castings with radiography and are not seeing any defects in the radiographs. We are still investigating other variables such as green sand density and core sand density that affect the volume of liquid when the feed path is cut off. .

SUMMARY

A systematic approach to defect identification and analytical techniques to find root causes is explained in detail. One example of a defect case history is shown to explain the procedure that was followed to identify and resolve the problem.

ACKNOWLEDGMENTS

The author is grateful to Citation Corporation for permission to present this paper. Thanks also to Mike Barstow, Gene Muratore and Rosa Armstrong for help in editing the manuscript.

REFERENCES

1. International Atlas of casting defects. AFS publication
2. Analysis of casting defects. AFS publication
3. Citation Corporation in-house publications
4. Sillen, Rudolf., Shrinkages in Iron Castings, Communication to Ductile Iron Society, 2002
5. Sparkman, David., "Offsetting Macro-Shrinkage in Ductile Iron" DIS News, Issue 3, 2001

Appendix 1.

Defect Codes From International Atlas of Casting Defects Handbook

A - Metallic Projections

A 100 Metallic projections in the form of fins or flash

A 111 Joint flash or Finning
A 112 Veining or Finning
A 113 Heat Checked Mold or Die
A 114 Fillet Vein
A 121 Cope Raise, Raised Mold
A 122 Sag or Strain
A 123 Cracked or Broken Mold

A 200 Massive projections

A 211 Swells
A 212 Erosion, Cut, or Wash
A 213 Crush
A 221 Mold Drop or Sticker
A 222 Raised Core or Mold Element, Cutoff
A 223 Raised Sand
A 224 Mold Drop
A 225 Corner Scab
A 226 Broken or Crushed Core

B - Cavities

B 100 Cavities with generally rounded smooth walls detectable to the naked eye

B 111 Blowholes, Pinholes
B 112 Blowholes near inserts, chills, chaplets
B 113 Slag Blowholes
B 121 Surface or Subsurface Blowholes
B 122 Corner Blowholes, Draws
B 123 Surface Pinholes
B 124 Dispersed Shrinkage

B 200 Cavities with rough walls, shrinkage

B 211 Open or External Shrinkage
B 213 Core Shrinkage
B 214 Shrink at riser contact*
B 221 Internal or Blind Shrinkage
B 222 Centerline or Axial Shrinkage Porosity
B 223 Center line porosity at isolated hot spots*
B 300 Porous structures caused by many small cavities
B 311Macro,Micro,shrinkage porosity-leakers

C - Discontinuities

C 100 Discontinuities caused by Mechanical effects

C 111 Breakage (Cold)
C 121 Hot Cracking
C 211 Cold Tearing
C 221 Hot Tearing

C 300 Discontinuities caused by lack of fusion.

C 311 Cold Shut or Cold Lap
C 321 Interrupted Pour
C 331 Cold Shut (At Chill or Insert) Unfused Chaplet

C 400 Discontinuities caused by metallurgical defects

C 411 Conchoidal or Rock-Candy Fracture
C 412 Intergranular Corrosion

D. Defective Surface

D 100 Casting surface Folds, Gas Runs

D 112 Cope Defect, Elephant Skin, Laps
D 113 Seams or Scars
D 114 Flow Marks
D 121 Rough Casting Surface
D 122 Severe Roughness, High-Pressure Molding
D 131Buckle
D 132 Rat Tail
D 133 Flow Marks, Crow Feet
D 134 Metal-Mold Reaction, Orange Peel
D 135 Soldering, Die Erosion
D 141Sink Marks, Draw, Suck-In
D 142 Slag Inclusions

D 200 Serious surface defects

D 211 Push-Up, Clamp Off
D 221 Burn On
D 222 Burn In
D 223 Metal Penetration
D 224 Dip Coat Spall, Scab
D 231 Scab, Expansion Scab
D 232 Cope Spall, Boil Scab, Erosion Scab
D 233 Blacking Scab
D 241 Oxide Scale
D 242 Adherent Packing Material
D 243 Scaling

E. Incomplete Casting

E 100 Missing portion of casting (no fracture)
E 111 Misrun
E 112 Defective Coating (Tear-Dropping) or Poor Mold Repair
E 121 Misrun (a)
E 122 Poured Short
E 123 Runout
E 124 Excessive Cleaning
E 125 Fusion or Melting during Heat Treatment
E 200 Missing portion of casting (with fracture)
E 211 Fractured Casting
E 221 Broken Casting (At Gate, Riser or Vent)
E 231 Early Shakeout

F. Incorrect Dimensions or Shape

F 100 Incorrect dimensions, correct shape
F 111 Improper Shrinkage Allowance
F 121 Hindered Contraction
F 122 Irregular Contraction
F 123 Excessive Rapping of Pattern
F 124 Mold Expansion during Baking
F 125 Mold wall Movement, Mold Cavity Enlargement
F 126 Distorted Casting
F 200 Casting shape incorrect or in certain locations
F 211 Pattern Error
F 212 Pattern Mounting Error
F 222 Shifted Core
F 223 Ramoff, Ramaway
F 231 Deformed Pattern
F 232 Mold Creep, Deformed Mold, Springback
F 233 Casting Distortion
F 234 Warped Casting

G. Inclusions

G 100 Inclusions or Structural Anomalies
G 111 Metallic Inclusions
G 112 Cold Shot
G 113 Internal Sweating, Phoshphide Sweat
G 121 Inclusions of Slag, dross or Flux: Ceroxide
G 122 Slag-Blowhole Defect
G 131 Sand Inclusions
G 132 Blacking or Refractory Coating inclusions
G 141 Black Spots
G 142 Oxide Inclusions or Sinks, Seams
G 143 Lustrous Carbon Films, Kish Tracks
G 144 Hard Spots
G 200 Structural anomalies-macroscopic
G 211 Primary Chill, Chilled Spots or Edges
G 212 Unmottled Chill, Clear Chill
G 213 Inverse Chill*
G 214 Ferritic Skin*
G 221 Primary Graphite White Iron
G 222 Excessive Pearlite Layer
G 223 Localized Hard Spots, Inclusions
G 224 Flake Graphite*
G 225 Chunk graphite*
G 226 Exploded Graphite*
G 262 Kish Graphite Inclusions
G 263 Carbon Floatation
G 264 Faceted (Dendritic) Fracture

*** additional codes**