4. "Process for High Integrity Castings," AFML TR-74-152, General Electric Company, July 1974
5. "Investment Cast Ti-6Al-4V," Technical Bulletin TB1660, Howmet Turbine Components Corporation
6. R. Smickley, L.E. Dardi, and W.R. Freeman, "Development of High Performance Custom 450 Investment Castings--A Progress Report," Paper presented at the 27th Annual Meeting, Chicago, IL, Investment Casting Institute, Oct 1979
7. "Hot Isostatic Pressing of Castings," Draft B86BC, Proposed Aerospace Material Specification
8. T.M. Regan and J.N. Fleck, Case Studies of Castings Replacing Forgings and Fabrications in a Helicopter Engine, in *Advanced Casting Technology,* J. Easwaran, Ed., Proceedings of an Advanced Casting Technology Conference, Kalamazoo, MI, Nov 1986, ASM INTERNATIONAL, 1987, p 103-110
9. D.C. Stewart and G.T. Bennett, "HIP Rejuvenation of Damaged Blades," AFWAL-TR-80-4043, Air Force Wright Aeronautical Laboratories, May 1980
10. D.J. Kenton, N.M. Madhava, and H. Koven, "Hot Isostatic Pressing Rejuvenation of Life Limited Turbine Hardware," PRAM Project 13278-01, Wright-Patterson Air Force Base, Jan 1981

Testing and Inspection of Casting Defects

By the ASM Committee on Nondestructive Inspection of Castings*

Introduction

GENERAL INSPECTION PROCEDURES for castings are established at the foundry to ensure conformance with customer drawings and documents, which are frequently based on various government, technical society, or commercial specifications. For a foundry to ensure casting quality, inspection procedures must be efficiently directed toward the prevention of imperfections, the detection of unsatisfactory trends, and the conservation of material--all of which ultimately lead to reduction in costs. Inspectors should be able to assess on sight the probable strong and weak points of a casting and know where weaknesses and faults would most likely be found.

Inspection of castings normally involves checking for shape and dimensions, coupled with aided and unaided visual inspection for external discontinuities and surface quality. Chemical analyses and tests for mechanical properties are supplemented by various forms of nondestructive inspection, including leak testing and proof loading, all of which are used to evaluate the soundness of the casting. These inspections add to the cost of the product; therefore, the initial consideration must be to determine the amount of inspection needed to maintain adequate control over quality. In some cases, this may require full inspection of each individual casting, but in other cases sampling procedures may be sufficient.

Methods for Determining Surface Quality. Cracks and other imperfections at the surface of a casting can be detected by a number of inspection techniques, including visual inspection, chemical etching, liquid penetrant inspection, eddy current inspection, and magnetic particle inspection (which can also reveal discontinuities situated immediately below the surface). All inspection methods require clean and relatively smooth surfaces for effective results.

Methods for Detecting Internal Discontinuities. The principal nondestructive methods used for detecting internal discontinuities in castings are radiographic, ultrasonic, and eddy current inspection. Of these methods, radiography is the most highly developed technique for detailed inspection; it can provide a pictorial representation of the form and extent of many types of internal discontinuities. Ultrasonic inspection, which is less universally applicable, can give qualitative indications of many discontinuities. It is especially useful in the inspection of castings of fairly simple design, where the signal pattern can be most reliably interpreted. Ultrasonic inspection can also be used to determine the shape of graphite particles in cast iron. Eddy current and other closely related electromagnetic methods are used to sort castings for variations in composition, surface hardness, and structure.

Methods for Dimensional Inspection. There are a number of techniques used to determine the dimensional accuracy of castings. These include manual checks with micrometers, manual and automatic gages, coordinate-measuring machines, and three-dimensional automatic inspection stations (machine vision systems). This section will discuss the use of coordinate-measuring machines. Additional information on methods for dimensional inspection will be provided in *Nondestructive Evaluation and Quality Control*, Volume 17 of *ASM Handbook*, formerly 9th Edition *Metals Handbook.*

Note

* Frederick A. Morrow, TFI Corporation; Mark J. Alcini and Franklin L. Kiiskila, Williams International; Colin Lewis, William Gavin, and Francis Brozo, Hitchcock Industries, Inc.; Michael Wrysch, Detroit Diesel Allison Division of General Motors Corporation; Alvin F. Maloit, Consulting Metallurgist; Kenneth Whaler, Stahl Specialties Company; Lawrence E. Smiley, Reliable Castings Corporation

Casting Defects

Although foundrymen favor referring to the deviations in less-than-perfect castings as discontinuities, these imperfections are more commonly referred to as casting defects. Some casting defects may have no effect on the function or the service life of cast components, but will give an unsatisfactory appearance or will make further processing, such as machining, more costly. Many such defects can be easily corrected by shot blast cleaning or grinding. Other defects that may be more difficult to remove can be acceptable in some locations. It is most critical that the casting designer understand the differences and that he write specifications that meet the true design needs.

Classification of Casting Defects. Foundrymen have traditionally used rather unique names, such as rattail, scab, buckle, snotter, and shut, to describe various casting imperfections (such terms are defined in the "Glossary of Terms" in this Volume). Unfortunately, foundrymen may use different nomenclature to describe the same defect. The International Committee of Foundry Technical Associations has standardized the nomenclature, starting with the identification of seven basic categories of casting defects:

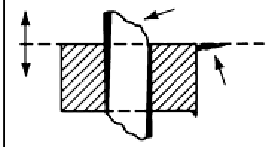
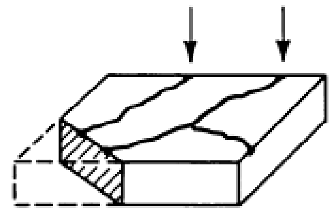
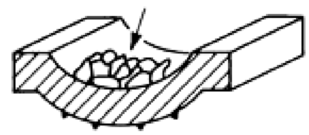
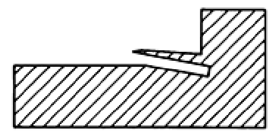
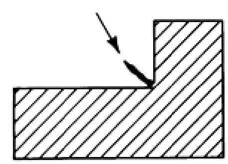
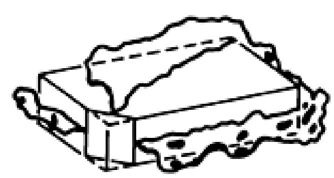
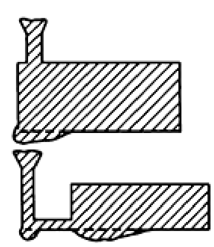
- Metallic projections
- Cavities
- Discontinuities
- Defects
- Incomplete casting
- Incorrect dimension
- Inclusions or structural anomalies

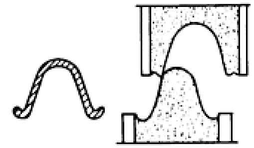
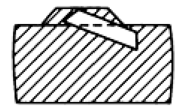
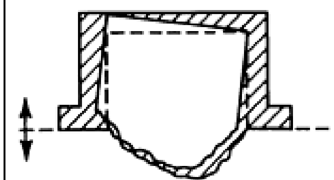
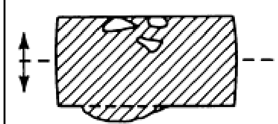
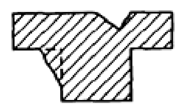
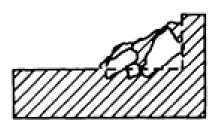
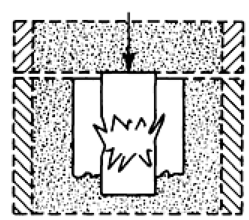
In this scheme, the term discontinuity has the specific meaning of a planar separation of the metal, that is, a crack.

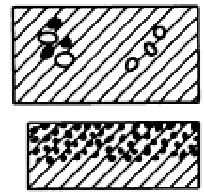
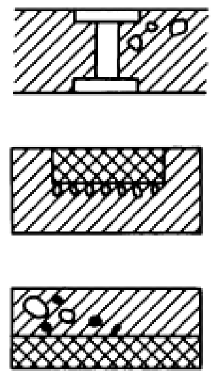
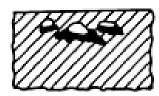
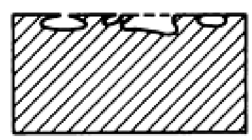
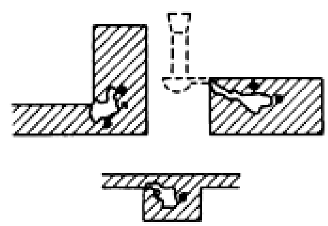
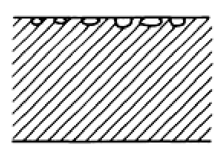
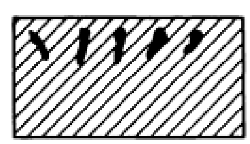
Table 1 presents some of the common defects in each category. In general, defects that can serve as stress raisers or crack promoters are the most serious. These include preexisting cracks, internal voids, and nonmetallic inclusions. The causes of these defects and their correction and prevention are discussed in the Section "Design Considerations" in this Volume.

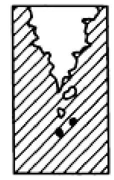
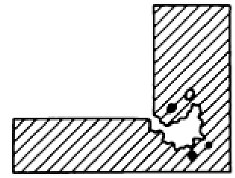
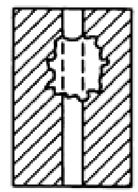
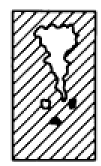
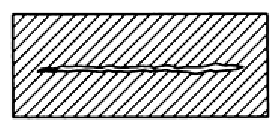
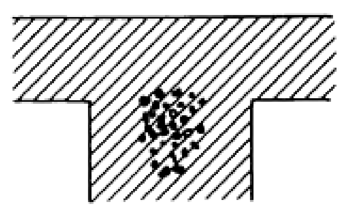
Table 1 International classification of common casting defects

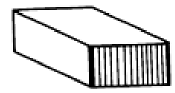
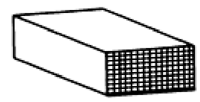
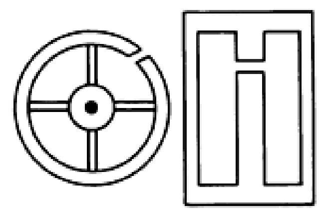
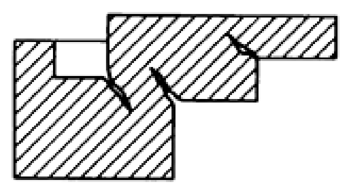
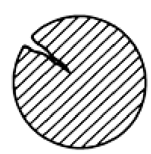
No.	**Description**	**Common name**	Sketch
Metallic Projections			
A 100:	Metallic projections in the form of fins or flash		
A 110:	Metallic projections in the form of fins (or flash) without change in principal casting dimensions		

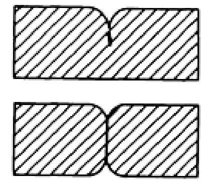
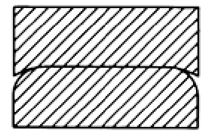
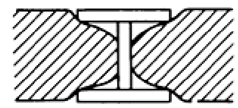
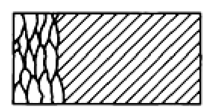
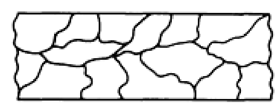
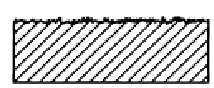
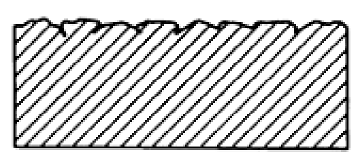
A 111	Thin fins (or flash) at the parting line or at core prints	Joint flash or fins	
A 112	Projections in the form of veins on the casting surface	Veining or finning	
A 113	Network of projections on the surface of die castings	Heat-checked die	
A 114[a]	Thin projection parallel to a casting surface, in re-entrant angles	Fillet scab	
A 115	Thin metallic projection located at a re-entrant angle and dividing the angle in two parts	Fillet vein	
A 120:	Metallic projections in the form of fins with changes in principal casting dimensions		
A 123[a]	Formation of fins in planes related to direction of mold assembly (precision casting with waste pattern); principal casting dimensions change	Cracked or broken mold	
A 200:	Massive projections		
A 210:	Swells		
A 212[a]	Excess metal in the vicinity of the gate or beneath the sprue	Erosion, cut, or wash	

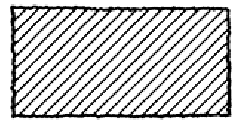
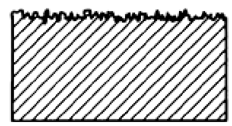
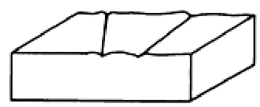
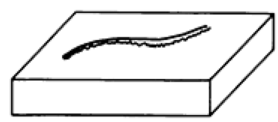
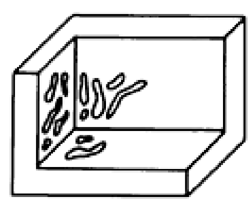
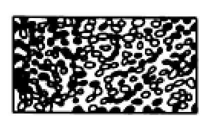
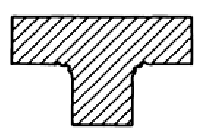
A 213[(a)]	Metal projections in the form of elongated areas in the direction of mold assembly	Crush	
A 220:	Projections with rough surfaces		
A 221[(a)]	Projections with rough surfaces on the cope surface of the casting	Mold drop or sticker	
A 222[(a)]	Projections with rough surfaces on the drag surface of the casting (massive projections)	Raised core or mold element cutoff	
A 223[(a)]	Projections with rough surfaces on the drag surface of the casting (in dispersed areas)	Raised sand	
A 224[(a)]	Projections with rough surfaces on other parts of the casting	Mold drop	
A 225[(a)]	Projections with rough surfaces over extensive areas of the casting	Corner scab	
A 226[(a)]	Projections with rough surfaces in an area formed by a core	Broken or crushed core	
Cavities			
B 100:	Cavities with generally rounded, smooth walls perceptible to the naked eye (blowholes, pinholes)		
B 110:	Class B 100 cavities internal to the casting, not extending to the surface, discernible only by special methods, machining, or fracture of the casting		

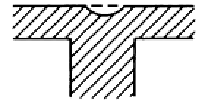
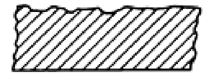
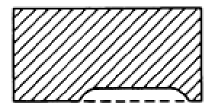
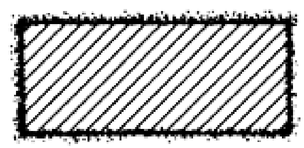
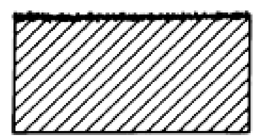
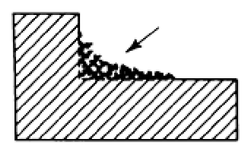
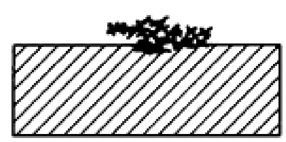
B 111[a]	Internal, rounded cavities, usually smooth-walled, of varied size, isolated or grouped irregularly in all areas of the casting	Blowholes, pinholes	
B 112[a]	As above, but limited to the vicinity of metallic pieces placed in the mold (chills, inserts, chaplets, etc.)	Blowholes, adjacent to inserts, chills, chaplets, etc.	
B 113[a]	Like B 111, but accompanied by slag inclusions (G 122)	Slag blowholes	
B 120:	Class B 100 cavities located at or near the casting surface, largely exposed or at least connected with the exterior		
B 121[a]	Exposed cavities of various sizes, isolated or grouped, usually at or near the surface, with shiny walls	Surface or subsurface blowholes	
B 122[a]	Exposed cavities, in re-entrant angles of the casting, often extending deeply within	Corner blowholes, draws	
B 123	Fine porosity (cavities) at the casting surface, appearing over more or less extended areas	Surface pinholes	
B 124[a]	Small, narrow cavities in the form of cracks, appearing on the faces or along edges, generally only after machining	Dispersed shrinkage	
B 200:	Cavities with generally rough walls, shrinkage		

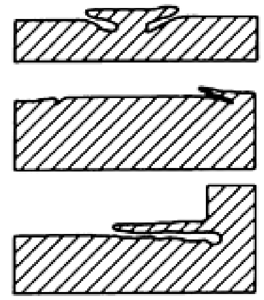
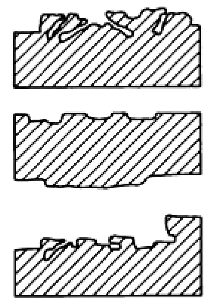
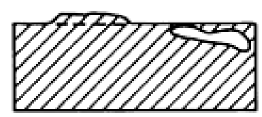
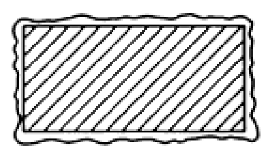
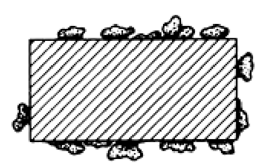
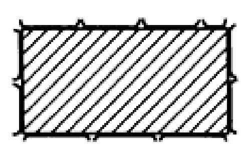
B 210:	Open cavity of Class B 200, sometimes penetrating deeply into the casting		
B 211(a)	Open, funnel-shaped cavity; wall usually covered with dendrites	Open or external shrinkage	
B 212(a)	Open, sharp-edged cavity in fillets of thick castings or at gate locations	Corner or fillet shrinkage	
B 213(a)	Open cavity extending from a core	Core shrinkage	
B 220:	Class B 200 cavity located completely internal to the casting		
B 221(a)	Internal, irregularly shaped cavity; wall often dendritic	Internal or blind shrinkage	
B 222(a)	Internal cavity or porous area along central axis	Centerline or axial shrinkage	
B 300:	Porous structures caused by numerous small cavities		
B 310:	Cavities according to B 300, scarcely perceptible to the naked eye		
B 311(a)	Dispersed, spongy dendritic shrinkage within walls of casting; barely perceptible to the naked eye	Macro- or micro-shrinkage, shrinkage porosity, leakers	
Discontinuities			

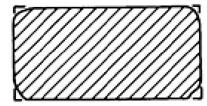
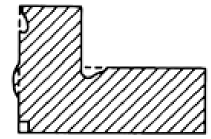
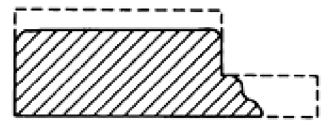
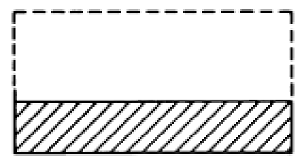
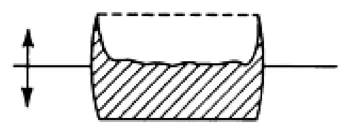
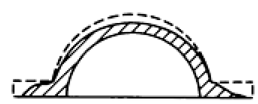
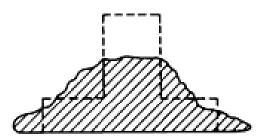
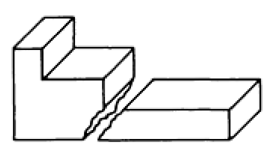
C 100:	Discontinuities, generally at intersections, caused by mechanical effects (rupture)		
C 110:	Normal cracking		
C 111[(a)]	Normal fracture appearance, sometimes with adjacent indentation marks	Breakage (cold)	
C 120:	Cracking with oxidation		
C 121[(a)]	Fracture surface oxidized completely around edges	Hot cracking	
C 200:	Discontinuities caused by internal tension and restraints to contraction (cracks and tears)		
C 210:	Cold cracking or tearing		
C 211[(a)]	Discontinuities with squared edges in areas susceptible to tensile stresses during cooling; surface not oxidized	Cold tearing	
C 220:	Hot cracking and tearing		
C 221[(a)]	Irregularly shaped discontinuities in areas susceptible to tension; oxidized fracture surface showing dendritic pattern	Hot tearing	
C 222[(a)]	Rupture after complete solidification, either during cooling or heat treatment	Quench cracking	
C 300:	Discontinuities caused by lack of fusion (cold shuts); edges generally rounded, indicating poor contact between various metal streams during filling of the mold		
C 310:	Lack of complete fusion in the last portion of the casting to fill		

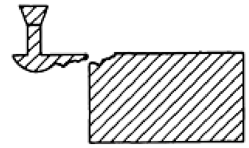
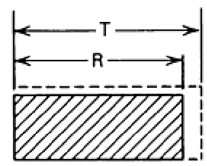
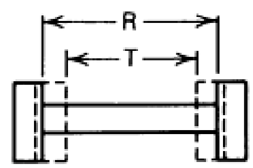
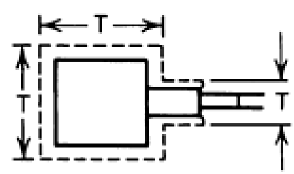
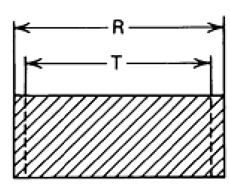
C 311[a]	Complete or partial separation of casting wall, often in a vertical plane	Cold shut or cold lap	
C 320:	Lack of fusion between two parts of casting		
C 321[a]	Separation of the casting in a horizontal plane	Interrupted pour	
C 330:	Lack of fusion around chaplets, internal chills, and inserts		
C 331[a]	Local discontinuity in vicinity of metallic insert	Chaplet or insert cold shut, unfused chaplet	
C 400:	Discontinuities caused by metallurgical defects		
C 410:	Separation along grain boundaries		
C 411[a]	Separation along grain boundaries of primary crystallization	Conchoidal or "rock candy" fracture	
C 412[a]	Network of cracks over entire cross section	Intergranular corrosion	
Defective Surface			
D 100:	Casting surface irregularities		
D 110:	Fold markings on the skin of the casting		
D 111	Fold markings over rather large areas of the casting	Surface folds, gas runs	
D 112	Surface shows a network of jagged folds or wrinkles (ductile iron)	Cope defect, elephant skin, laps	

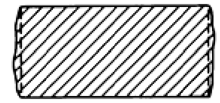
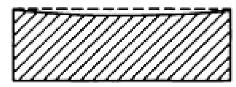
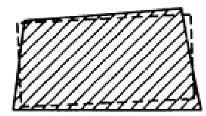
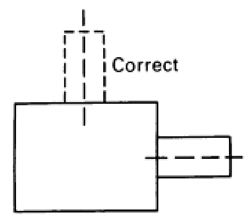
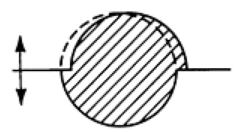
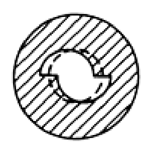
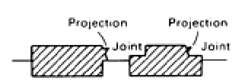
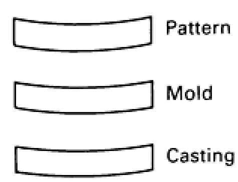
D 113	Wavy fold markings without discontinuities; edges of folds at same level, casting surface is smooth	Seams or scars	
D 114	Casting surface markings showing direction of liquid metal flow (light alloys)	Flow marks	
D 120:	Surface roughness		
D 121	Depth of surface roughness is approximately that of the dimensions of the sand grains	Rough casting surface	
D 122	Depth of surface roughness is greater than that of the sand grain dimensions	Severe roughness, high pressure molding defect	
D 130:	Grooves on the casting surface		
D 131	Grooves of various lengths, often branched, with smooth bottoms and edges	Buckle	
D 132	Grooves up to 5.1 mm (0.2 in.) in depth, one edge forming a fold which more or less completely covers the groove	Rat tail	
D 133	Irregularly distributed depressions of various dimensions extending over the casting surface, usually along the path of metal flow (cast steel)	Flow marks, crow's feet	
D 134	Casting surface entirely pitted or pock-marked	Orange peel, metal mold reaction, alligator skin	
D 135	Grooves and roughness in the vicinity of re-entrant angles on die castings	Soldering, die erosion	
D 140:	Depressions in the casting surface		

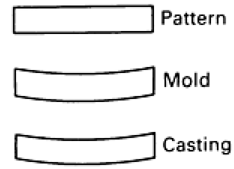
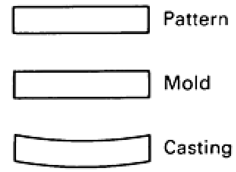
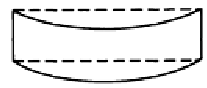
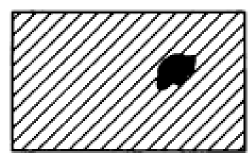
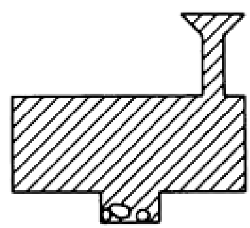
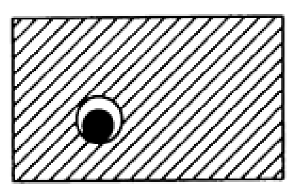
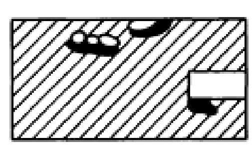
D 141	Casting surface depressions in the vicinity of a hot spot	Sink marks, draw or suck-in	
D 142	Small, superficial cavities in the form of droplets of shallow spots, generally gray-green in color	Slag inclusions	
D 200:	Serious surface defects		
D 210:	Deep indentation of the casting surface		
D 211	Deep indentation, often over large area of drag half of casting	Push-up, clamp-off	
D 220:	Adherence of sand, more or less vitrified		
D 221	Sand layer strongly adhering to the casting surface	Burn on	
D 222	Very adherent layer of partially fused sand	Burn in	
D 223	Conglomeration of strongly adhering sand and metal at the hottest points of the casting (re-entrant angles and cores)	Metal penetration	
D 224	Fragment of mold material embedded in casting surface	Dip coat spall, scab	
D 230:	Plate-like metallic projections with rough surfaces, usually parallel to casting surface		

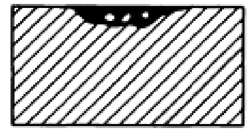
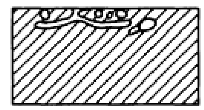
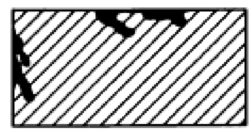
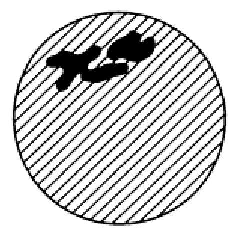
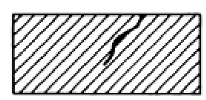
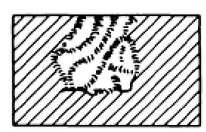
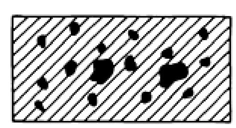
D 231[a]	Plate-like metallic projections with rough surfaces parallel to casting surface; removable by burr or chisel	Scabs, expansion scabs	
D 232[a]	As above, but impossible to eliminate except by machining or grinding	Cope spall, boil scab, erosion scab	
D 233[a]	Flat, metallic projections on the casting where mold or core washes or dressings are used	Blacking scab, wash scab	
D 240:	Oxides adhering after heat treatment (annealing, tempering, malleablizing) by decarburization		
D 241	Adherence of oxide after annealing	Oxide scale	
D 242	Adherence of ore after malleablizing (white heart malleable	Adherent packing material	
D 243	Scaling after anneal	Scaling	
Incomplete Casting			
E 100:	Missing portion of casting (no fracture)		
E 110:	Superficial variations from pattern shape		

E 111	Casting is essentially complete except for more or less rounded edges and corners	Misrun	
E 112	Deformed edges or contours due to poor mold repair or careless application of wash coatings	Defective coating (tear-dropping) or poor mold repair	
E 120:	Serious variations from pattern shape		
E 121	Casting incomplete due to premature solidification	Misrun	
E 122	Casting incomplete due to insufficient metal poured	Poured short	
E 123	Casting incomplete due to loss of metal from mold after pouring	Runout	
E 124	Significant lack of material due to excessive shot-blasting	Excessive cleaning	
E 125	Casting partially melted or seriously deformed during annealing	Fusion or melting during heat treatment	
E 200:	Missing portion of casting (with fracture)		
E 210:	Fractured casting		
E 211	Casting broken, large piece missing; fractured surface not oxidized	Fractured casting	
E 220:	Piece broken from casting		

E 221	Fracture dimensions correspond to those of gates, vents, etc.	Broken casting (at gate, riser, or vent)	
E 230:	Fractured casting with oxidized fracture		
E 231	Fracture appearance indicates exposure to oxidation while hot	Early shakeout	
Incorrect Dimensions or Shape			
F 100:	Incorrect dimensions; correct shape		
F 110:	All casting dimensions incorrect		
F 111	All casting dimensions incorrect in the same proportions	Improper shrinkage allowance	
F 120:	Certain casting dimensions incorrect		
F 121	Distance too great between extended projections	Hindered contraction	
F 122	Certain dimensions inexact	Irregular contraction	
F 123	Dimensions too great in the direction of rapping of pattern	Excess rapping of pattern	

F 125	Excessive metal thickness at irregular locations on casting exterior	Soft or insufficient ramming, mold-wall movement	
F 126	Thin casting walls over general area, especially on horizontal surfaces	Distorted casting	
F 200:	Casting shape incorrect overall or in certain locations		
F 210:	Pattern incorrect		
F 211	Casting does not conform to the drawing shape in some or many respects; same is true of pattern	Pattern error	
F 212	Casting shape is different from drawing in a particular area; pattern is correct	Pattern mounting error	
F 220:	Shift or Mismatch		
F 221	Casting appears to have been subjected to a shearling action in the plane of the parting line	Shift	
F 222	Variation in shape of an internal casting cavity along the parting line of the core	Shifted core	
F 223	Irregular projections on vertical surfaces, generally on one side only in the vicinity of the parting line	Ramoff, ramaway	
F 230:	Deformations from correct shape		
F 231	Deformation with respect to drawing proportional for casting, mold, and pattern	Deformed pattern	

F 232	Deformation with respect to drawing proportional for casting and mold; pattern conforms to drawing	Deformed mold, mold creep, springback	
F 233	Casting deformed with respect to drawing; pattern and mold conform to drawing	Casting distortion	
F 234	Casting deformed with respect to drawing after storage, annealing, machining	Warped casting	
Inclusions or Structural Anomalies			
G 100:	Inclusions		
G 110:	Metallic inclusions		
G 111[(a)]	Metallic inclusions whose appearance, chemical analysis or structural examination show to be caused by an element foreign to the alloy	Metallic inclusions	
G 112[(a)]	Metallic inclusions of the same chemical composition as the base metal; generally spherical and often coated with oxide	Cold shot	
G 113	Spherical metallic inclusions inside blowholes or other cavities or in surface depressions (see A 311). Composition approximates that of the alloy cast but nearer to that of a eutectic	Internal sweating, phosphide sweat	
G 120:	Nonmetallic inclusions; slag, dross, flux		
G 121[(a)]	Nonmetallic inclusions whose appearance or analysis shows they arise from melting slags, products of metal treatment or fluxes	Slag, dross or flux inclusions, ceroxides	

G 122[a]	Nonmetallic inclusions generally impregnated with gas and accompanied by blowholes (B 113)	Slag blowhole defect	
G 130:	Nonmetallic inclusions; mold or core materials		
G 131[a]	Sand inclusions, generally very close to the surface of the casting	Sand inclusions	
G 132[a]	Inclusions of mold blacking or dressing, generally very close to the casting surface	Blacking or refractory coating inclusions	
G 140:	Nonmetallic inclusions; oxides and reaction products		
G 141	Clearly defined, irregular black spots on the fractured surface of ductile cast iron	Black spots	
G 142[a]	Inclusions in the form of oxide skins, most often causing a localized seam	Oxide inclusion or skins, seams	
G 143[a]	Folded films of graphitic luster in the wall of the casting	Lustrous carbon films, or kish tracks	
G 144	**Hard inclusions in permanent molded and die cast aluminum alloys**	**Hard spots**	

(a) Defects that under some circumstances could contribute, either directly or indirectly, to casting failures. Adapted from *International Atlas of Casting Defects,* American Foundrymen's Society, Des Plaines, IL

Common Inspection Procedures

Inspection of castings is most often limited to visual and dimensional inspections, weight testing, and hardness testing. However, for castings that are to be used in critical applications, such as in aerospace components, additional methods of nondestructive inspection are used to determine and to control casting quality.

Visual inspection of each casting ensures that none of its features has been omitted or malformed by molding errors, short running, or mistakes in cleaning. Most surface defects and roughness can be observed at this stage.

Initial sample castings from new pattern equipment should be carefully inspected for obvious defects. Liquid penetrant inspection can be used to detect surface defects. Such casting imperfections as shrinks, cracks, blows, or dross usually indicate the need for adjustment in the gating or foundry techniques. If the casting appears to be satisfactory upon visual inspection, internal quality can be checked by radiographic and ultrasonic inspection.

The first visual inspection operation on the production casting is usually performed immediately after shakeout or knockout of the casting. This ensures that major visible imperfections are detected as quickly as possible. This information, promptly relayed to the foundry, permits early corrective action to be taken with a minimum of scrap loss. The size and complexity of some sand castings require that the gates and risers be removed to permit proper inspection of the casting. Many castings that contain numerous internal cores or have close dimensional tolerances require a rapid but fairly accurate check of critical wall dimensions. In some cases, an indicating-type caliper gage is suitable for this work, and special types are available for casting shapes that do not lend themselves to the standard types. Ultrasonic inspection is also used to determine wall thickness in such components as cored turbine blades made by investment casting (see the article "Investment Casting" in this Volume).

Dimensional Inspection. Dimensional deviations on machined surfaces are relatively simple to evaluate and can be accurately specified. However, it is not so simple to determine the acceptability of dimensions that involve one or more unmachined surfaces. Dimensional inspection can be carried out with the aid of gages, jigs, and templates.

Most initial machining operations on castings use a cast surface as a datum; the exceptions are those large castings that are laid out, before machining, to give the required datum. Therefore, it is important that the cast surface used as a datum be reasonably true and that it be in the correct position relative to other critical machined or unmachined surfaces on the same casting, within clearly defined limits.

The cast surface used as a datum can be a mold surface, and variations can occur because of mold movement. The cast surface can be produced by a core; movement of cores is a frequent cause of casting inaccuracy. Errors involving these surfaces can produce consequential errors or inadequate machining stock elsewhere on the casting.

Where dimensional errors are detected in relation to general drawing tolerances, their true significance must be determined. A particular dimension may be of vital importance, but may have been included in blanket tolerances. This situation stresses the desirability of stating functional dimensions on drawings so that tolerances are not restricted unnecessarily.

Weight Testing. Many intricately cored castings are extremely difficult to measure accurately, particularly the internal sections. It is important to ensure that these sections are correct in thickness for three main reasons:

- There should be no additional weight that would make the finished product heavier than permissible
- Sections must not be thinner than designed to prevent detracting from the strength of the casting
- If hollow cavities have been reduced in area by increasing the metal thickness of the sections, any flow of liquid or gases is reduced

A ready means of testing for these discrepancies is by accurately weighing each casting or by measuring the displacement caused by immersing the casting in a liquid-filled measuring jar or vessel. In certain cases in which extreme accuracy is demanded, a tolerance of only ±1% of a given weight may be allowed.

Hardness testing is often used to verify the effectiveness of heat treatment applied to actual castings. Its general correlation with the tensile strength of many ferrous alloys enables a rough prediction of tensile strength to be made.

The Brinell hardness test is most frequently used for casting alloys. A combination of large-diameter ball (5 or 10 mm) and heavy load (500 to 3000 kgf) is preferred for the most effective representation because a deep impression minimizes the influence of the immediate surface layer and of the relatively coarse microstructure. The Brinell hardness test is unsuitable for use at high hardness levels (above ~600 HB), because distortion of the ball indenter can affect the shape of the indentation.

Either the Rockwell or the Vickers (136° diamond pyramid) hardness test is used for alloys of extreme hardness or for high-quality and precision castings in which the large Brinell indentation cannot be tolerated. Because of the very small indentations produced in Rockwell and Vickers tests, which use loads of 150 kg or less, results must be based on the average of a number of determinations. Portable hardness testers or ultrasonic microhardness testers can be used on large castings that cannot be placed on the platform of a bench-type machine. More detailed information on hardness testing is available in *Mechanical Testing*, Volume 8 of *ASM Handbook*, formerly 9th Edition *Metals Handbook.*

The hardness of ferrous castings can be related to the sonic velocity of the metal and determined from it if all other test conditions remain constant. This has been demonstrated on chilled rolls in determining the average hardness of the core.

Liquid Penetrant Inspection

Liquid penetrant inspection essentially involves a liquid wetting the surface of a workpiece, flowing over that surface to form a continuous and uniform coating, and migrating into cracks or cavities that are open to the surface. After a few minutes, the liquid coating is washed off the surface of the casting and a developer is placed on the surface. The developer is stained by the liquid penetrant as it is drawn out of the cracks and cavities. Liquid penetrants will highlight surface defects so that detection is more certain.

Liquid penetrant inspection should not be confined to as-cast surfaces. For example, it is not unusual for castings of various alloys to exhibit cracks, frequently intergranular, on machined surfaces. A pattern of cracks of this type may be the result of intergranular cracking throughout the material because of an error in composition or heat treatment, or the cracks may be on the surface only as a result of machining or grinding. Surface cracking may result from insufficient machining allowance, which does not allow for complete removal of imperfections produced on the as-cast surface, or it may result from faulty machining techniques. If imperfections of this type are detected by visual inspection, liquid penetrant inspection will show the full extent of such imperfections, will give some indication of the depth and size of the defect below the surface by the amount of penetrant absorbed, and will indicate whether cracking is present throughout the section.

Magnetic Particle Inspection

Magnetic particle inspection is a highly effective and sensitive technique for revealing cracks and similar defects at or just beneath the surface of castings made of ferromagnetic metals. The capability of detecting discontinuities just beneath the surface is important because such cleaning methods as shot or abrasive blasting tend to close a surface break that might go undetected in visual or liquid penetrant inspection.

When a magnetic field is generated in and around a casting made of a ferromagnetic metal and the lines of magnetic flux are intersected by a defect such as a crack, magnetic poles are induced on either side of the defect. The resulting local flux disturbance can be detected by its effect on the particles of a ferromagnetic material, which become attracted to the region of the defect as they are dusted on the casting. Maximum sensitivity of indication is obtained when a defect is oriented in a direction perpendicular to the applied magnetic field and when the strength of this field is just enough to saturate the casting being inspected.

Equipment for magnetic particle inspection uses direct or alternating current to generate the necessary magnetic fields. The current can be applied in a variety of ways to control the direction and magnitude of the magnetic field.

In one method of magnetization, a heavy current is passed directly through the casting placed between two solid contacts. The induced magnetic field then runs in the transverse or circumferential direction, producing conditions favorable to the detection of longitudinally oriented defects. A coil encircling the casting will induce a magnetic field that runs in the longitudinal direction, producing conditions favorable to the detection of circumferentially (or transversely) oriented defects. Alternatively, a longitudinal magnetic field can be conveniently generated by passing current through a flexible cable conductor, which can be coiled around any metal section. This method is particularly adaptable to castings of irregular shape. Circumferential magnetic fields can be induced in hollow cylindrical castings by using an axially disposed central conductor threaded through the casting.

Small castings can be magnetic particle inspected directly on bench-type equipment that incorporates both coils and solid contacts. Critical regions of larger castings can be inspected by the use of yokes, coils, or contact probes carried on flexible cables connected to the source of current this setup enables most regions of castings to be inspected.

Eddy Current Inspection

Eddy current inspection consists of observing the interaction between electromagnetic fields and metals. In a basic system, currents are induced to flow in the testpiece by a coil of wire that carries an alternating current. As the part enters the coil, or as the coil in the form of a probe or yoke is placed on the testpiece, electromagnetic energy produced by the coils is partly absorbed and converted into heat by the effects of resistivity and hysteresis. Part of the remaining energy is reflected back to the test coil, its electrical characteristics having been changed in a manner determined by the properties of the testpiece. Consequently, the currents flowing through the probe coil are the source of information describing the characteristics of the testpiece. These currents can be analyzed and compared with currents flowing through a reference specimen.

Eddy current methods of inspection are effective with both ferromagnetic and nonferromagnetic metals. Eddy current methods are not as sensitive to small, open defects as liquid penetrant or magnetic particle methods are. Because of the skin effect, eddy current inspection is generally restricted to depths less than 6 mm ($\frac{1}{4}$ in.). The results of inspecting ferromagnetic materials can be obscured by changes in the magnetic permeability of the testpiece. Changes in temperature must be avoided to prevent erroneous results if electrical conductivity or other properties, including metallurgical properties, are being determined.

Applications of eddy current and electromagnetic methods of inspection to castings can be divided into the following three categories:

- Detecting near-surface flaws such as cracks, voids, inclusions, blowholes, and pinholes (eddy current inspection)
- Sorting according to alloy, temper, electrical conductivity, hardness, and other metallurgical factors (primarily electromagnetic inspection)
- Gaging according to size, shape, plating thickness, or insulation thickness (eddy current or electromagnetic inspection)

Radiographic Inspection**

Radiographic inspection is a process of testing materials using penetrating radiation from an x-ray generator or a radioactive source and an imaging medium, such as x-ray film or an electronic device. In passing through the material, some of the radiation is attenuated, depending on the thickness and the radiographic density of the material, while the radiation that passes through the material forms an image. The radiographic image is generated by variations in the intensity of the emerging beam.

Internal flaws, such as gas entrapment or nonmetallic inclusions, have a direct effect on the attenuation. These flaws create variations in material thickness, resulting in localized dark or light spots on the image.

The term radiography usually implies a radiographic process that produces a permanent image on film (conventional radiography) or paper (paper radiography or xeroradiography), although in a broad sense it refers to all forms of radiographic inspection. When inspection involves viewing an image on a fluorescent screen or image intensifier, the radiographic process is termed filmless or real time inspection (Fig. 1). When electronic nonimaging instruments are used to measure the intensity of radiation, the process is termed radiation gaging. Tomography, a radiation inspection method adapted from the medical computerized axial tomography scanner, provides a cross-sectional view of a testpiece. All of the above terms are primarily used in connection with inspection that involves penetrating electromagnetic radiation in the form of x-rays or γ-rays. Neutron radiography refers to radiographic inspection using neutrons rather than electromagnetic radiation.