Potential Quality Issues with Castings and Forgings

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Castings

Castings are integral to manufacturing industry and can be used to create complex geometric parts with relative ease, irrespective of the size of part. Cast metal products are found in a majority of manufactured goods and equipment including critical components for aircraft and automobiles to home appliances and surgical equipment. Also, the process is economical and generates little waste, which can be recycled and used again. While castings have an advantage in that the mechanical properties tend to be isotropic, particularly if solidification has been controlled to avoid coarse columnar grains, the mechanical properties tend to be lower than those of an equivalent wrought product. Additionally, it is common for the mechanical test specimens to be taken from separately cast keel bars from the same heat. These may represent material capability rather than the actual properties of the casting itself.

Under practical conditions castings contain voids, inclusions and other imperfections, which result in quality problems. However, such imperfections may only be regarded as true defects or flaws when the satisfactory function or appearance of the product is in question: consideration must then be given to the possibility of salvage or, in more serious cases, to rejection. This type of decision is dependent not only upon the type of defect itself but upon its significance in relation to the service function of the casting and, in turn, to the quality and inspection standards being applied.

A rough defect classification may be made as follows by grouping them under certain broad types:

1. Shape related defects
2. Inclusions
3. Gas porosity
4. Shrinkage voids
5. Hot tears
6. Segregation
7. Surface defects

Shape related defects:

When liquid metal enters the mold, the first requirement is that it should satisfactorily fill the mold cavity and develop a smooth skin through intimate contact with the mold surface. Failure to meet these conditions produces the most serious defect in this group, the misrun or short run casting, in which the metal solidifies prematurely and some limb or section of the casting is omitted. Cold laps are a less severe manifestation of the same fault. These arise when the metal fails to flow freely over the mold surface; the intermittent flow pattern is retained on solidification due to lack of coalescence of liquid streams. In castings where the molten metal fills a mold from several different directions simultaneously, one advancing front may oxidize and form a skin that becomes entrapped when it meets another stream flowing towards it. This “cold shut” can then represent a plane of weakness where the casting is not intimately fused.

These defects are most generally associated with metal temperature, cold metal being the usual cause in castings for which the production method is normally satisfactory. A further cause can be excessive chill from the mold face; this may arise from heavy chilling or from too high a moisture content in greensand. A contributing cause to these defects can be an inadequate rate of mold filling relative to the freezing rate of the casting: especially susceptible, therefore, are extended casting of high surface area to volume ratio. Slow mold filling may result from low pouring speed, from an inadequate gating system, or as a result of back-pressure of gases in a badly vented mold cavity.

Shift:

A common defect in sand castings is mold shift where a step develops in the cast product at the parting line because of sidewise relative displacement of cope and drag. Core shift is similar to mold shift, but it is the core that is displaced caused by the buoyancy of the molten metal.

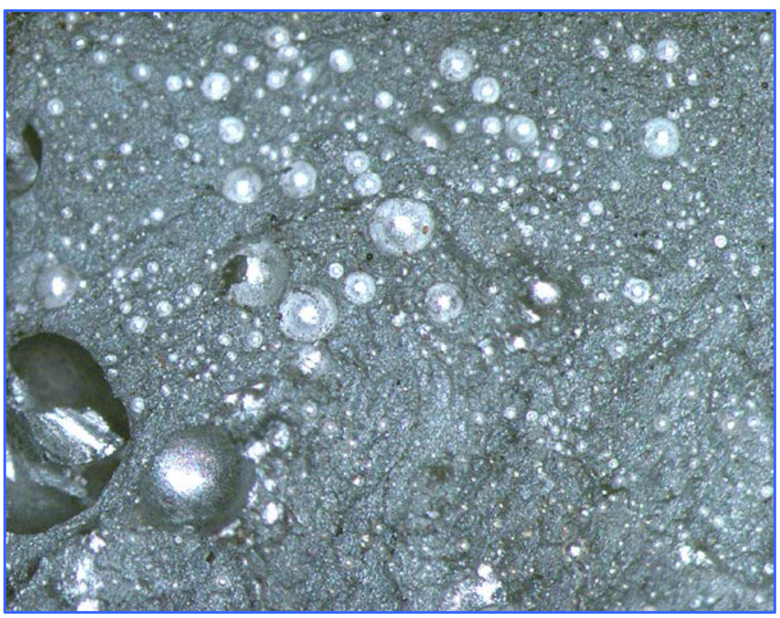
Inclusions:

There are two different types of inclusion, indigenous and exogenous. Indigenous inclusions are small intermetallic particles such as sulfides, oxides and silicates formed by chemical reactions between the various constituents of the alloy and also with the atmosphere. They are usually small and do not normally represent much of a problem if they are well distributed throughout an ingot or casting. They can represent a threat however, if a substantial proportion are concentrated in one place such as the centerline of the ingot.

Exogenous inclusions are larger and result from accidental entrapment of foreign matter during pouring. These vary widely in size and type and include dross, slag and flux residues, formed and separated in the melting furnace but carried over with the metal stream; other sources are refractory fragments from furnace and ladle linings. They can best be prevented by retention in the furnace and by careful skimming at the pouring stage along with the use of a bottom-pouring ladle. A further group of exogenous inclusions originates in the mold itself, consisting of molding material dislodged during closing or pouring. Avoiding defects arising from molding materials involves careful selection, proper ramming during mold making, maintenance of mold properties, and proper design of the gating system to prevent impingement of metal against mold and core surfaces and incorporate smooth curves rather than sharp corners and abrupt changes in direction.

Gas porosity:

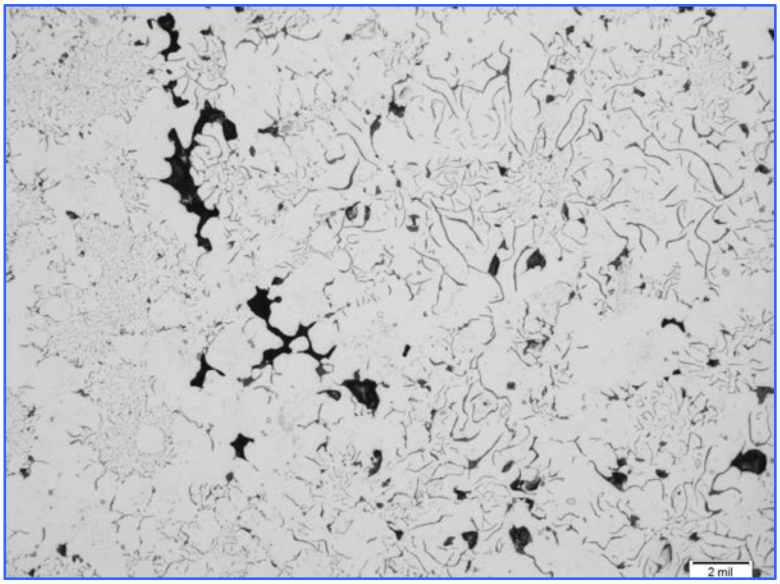
Molten metal has a much higher solubility of gas than the solid phase. As a result, a proportion of the gas that becomes dissolved in the molten state becomes ejected and trapped on solidification. This gives a wide dispersion of gas throughout the casting. A proportion of the gas may also remain dissolved and cause problems later in the processing cycle or in service. Adequate provision has to be made to allow any air in the mold to escape. In casting, the formation of air pockets can prevent full filling of the mold. Sand castings are less susceptible to air entrapment than permanent mold systems as the sand is porous. However, gas can also be produced by the walls of the mold by the degradation of resins at high temperature, inadequate gas permeability of the molding sand or from excessive moisture in the mold material. This can lead to the formation of porosity, which may be several millimeters in size, in the surface layers of the casting. Turbulence within the molten stream can lead to air entrapment and the air may not have time to rise to the surface and escape prior to solidification. In some casting processes, chemical additions are made just before casting, which cause an outgassing reaction. In these circumstances it is important to allow sufficient time for the reactions to take place prior to casting, while ensuring the metal does not cool and remains hot enough to prevent solidification taking place before the mold is filled completely. The effect of porosity is potentially more serious in castings used extensively for pressure or load bearing purposes and they should be adequately inspected for sub-surface porosity.



Macrograph showing gas porosity

Shrinkage voids and pipe:

When molten metal is poured into an ingot mold it cools, starts to solidify and contracts. The outer surfaces solidify first and become fixed, while the center remains molten and, as it in turn cools and contracts, a depression is formed in the top. If a source of molten metal is not maintained at the top of the ingot this depression can be quite deep. It is known as primary pipe. As the last of the ingot solidifies while isolated from any extra source of feeding, contraction cavities form at the core. These defects result from failure to compensate for liquid and solidification contraction, so their occurrence is usually a symptom of inadequate gating and risering techniques.



Micrograph showing shrinkage voids in cast iron

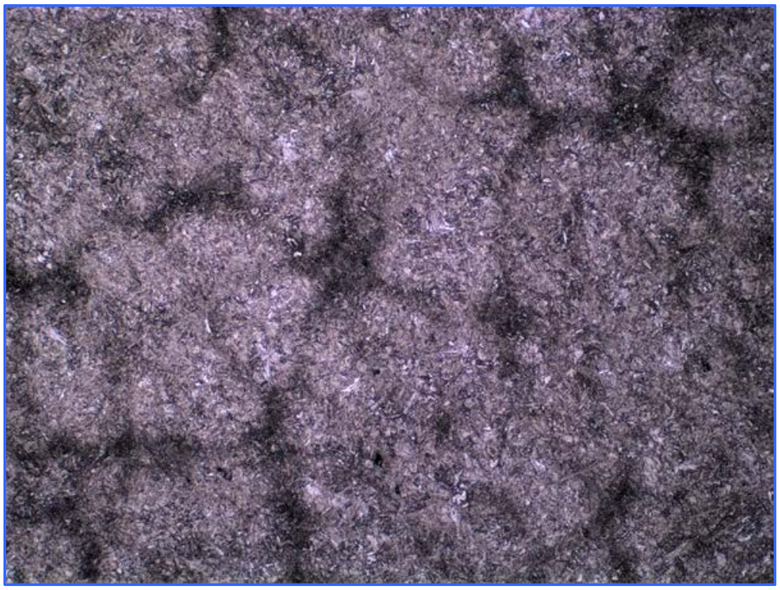
Hot tears:

Another shrinkage related defect is the formation of hot tears. In this case the mold has fully filled prior to solidification, but contraction during cooling is in some way prevented by the geometry of the product. This occurs while the metal is still hot but has little strength. Tearing is often encountered at changes in section and where relatively thin sections join several large masses. In ingots with sharp corners, tearing may occur in the planes of weakness resulting from the two adjacent systems of columnar grains growing perpendicular to the ingot wall.

Alloys with very short freezing range are comparatively free from tearing tendency whereas alloys with a comparatively large temperature range of freezing are more vulnerable. Susceptibility to hot tearing is also influenced by segregation of alloying elements and impurities.

Segregation:

The distribution of chemical elements may not be uniform and some regions may become enriched in certain elements or phases while other regions are impoverished during solidification. Segregation can be microscopic or macroscopic in nature. In the former, the segregation occurs within individual grains, between dendrite arms. Macroscopic segregation on the other hand results in concentration gradients over large distances. This latter type may cause problems in the processing chain due to unexpected ductility differences, and if it remains until later stages may cause non-uniform properties, local differences in composition leading to corrosion problems, embrittlement, and sections of the material that are out of specification.


Micrograph showing chemical segregation in a steel casting

Surface defects:

For certain products, such as those that will have no machining after casting, the surface finish is important and the mold surface texture is reflected in that of the casting surface. Any blemishes or high and low spots will be carried over onto the product. For permanent molds, this means great attention to detail must be paid to cleanliness and wear of the mold surfaces. For non-permanent molds, loose material and surface discontinuities present opportunities for the molten material to penetrate the surface of the mold and produce an effect called "scabbing". Also, inadequate sand packing will result in the molten metal to flow between the sand particles for a distance into the mold wall and solidify. When the casting is removed, this lump of metal remains attached to the casting. This condition is named penetration.

Forgings

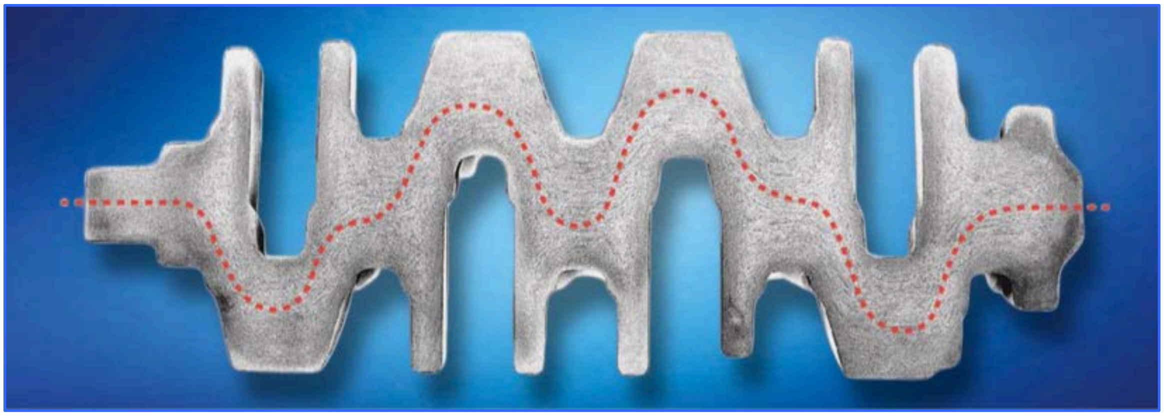
Steel forging is the product of a substantially compressive plastic working operation that has the ability to form the material to the desired component shape, while refining the cast structure of the ingot material, healing shrinkage voids, and improving the mechanical properties. The amount of subsequent machining is also generally reduced, although this depends on the geometry of the finished part and the forging processes used.

The plastic working may be performed by a hammer, press, forging machine, or ring-rolling machine, and must deform the material to produce an essentially wrought structure. Forgings may be subdivided into three classes on the basis of their forging temperatures.

- Hot-worked forgings are produced by working at temperatures above the recrystallization temperature for the material.
- Hot-cold-worked forgings are worked at elevated temperatures slightly below the recrystallization temperature to increase mechanical strength.
- Cold-worked forgings are produced by plastic working well below the temperature range at which recrystallization of the material occurs.

An important criterion for making forgings is the degree of hot working that goes into transforming the ingot material into the forged product. This is measured as a Reduction Ratio obtained by dividing the original ingot cross-sectional area by the maximum cross -sectional area of the forging. Commonly stated as a requirement, this can vary appreciably depending on the application, but a forging reduction ratio of 3:1 is commonly used.

Metal that is rolled, forged, or extruded develops and retains a fiber like grain structure that is aligned in the principal working direction. In wrought products the direction of grain flow is also evidenced by measurement of mechanical properties, as strength and ductility are almost always greater in the direction parallel to the working direction. Therefore, certain components can benefit from the grain flow produced in a forging as opposed to a cast part with no grain flow, or a machined product from a wrought material having interrupted grain flow due to machining operations. A forged part on the contrary will achieve improved properties as a result of optimum grain flow developed during the forging process. Because of these advantages, forgings are the manufacturing method of choice for critically loaded items, such as turbine and generator rotors, crankshafts, high strength pressure vessels, marine propeller shafts, ordnance components, pressure containing nozzles, pump housings, and piping fittings to name a few.



Section of a crankshaft showing the desirable grain flow pattern produced during forging

While there are many advantages to forgings, the large amount of material movement during the operation can also introduce discontinuities that are potential defects.

Inclusions:

Frequently, forging applications involve fatigue (cyclic) loading and for this steel cleanliness, or freedom from nonmetallic inclusions, is very important, since these can and do act as fatigue crack initiation sites. Reduction in the quantity of nonmetallic inclusions also assists materially in improving transverse ductility. This is particularly true when dealing with forgings that have received high forging reductions in the longitudinal direction, and where demanding transverse properties are required. As part of clean steel production, especially for the ordnance and power generation industries, it is necessary to reduce the sulfur content to levels appreciably less than 0.010%, or in other words, well below the maximum limits allowed in many material specifications. A steel making technique that is worthy of mentioning for forgings is inclusion shape control. The object here is to have the inclusions adopt a spherical shape instead of being elongated in the direction of working, as is typically the case for manganese sulfides. This is achieved by the introduction of an element such as calcium in powder or wire form into the ladle after deoxidation has been completed. The resulting inclusions resist deformation during forging and resemble globular oxides. This change leads to improvement in transverse ductility and toughness.

Surface defects:

Underfill may not appear like a flow related defect, but aside from simple insufficient starting mass, the reasons include, improper fill sequence, insufficient forging pressure, insufficient preheat temperature, lubricant buildup in die corners, poor or uneven lubrication, and cold die. An improper fill sequence may result in excessive flash loss, or it may be the result of extraordinary pressure requirements to fill a particular section. Sometimes venting may eliminate the problem but most often a change in the starting workpiece shape is required.

Laps are surface irregularities that appear as linear defects and are caused by folding over of the hot metal at the surface. These folds are worked into the surface but are not metallurgically bonded/fused because of the oxide present between the surfaces. Normally a lap or fold is associated with flow around a die corner, so this critical dimension should be as generous as possible. A lap acts as a sharp notch from which a quench or a fatigue crack can initiate.

Micrograph of a forging lap

Hydrogen flakes:

Flakes or fish-eyes are internal fissures seen in large forgings that have the form of silver-colored spots on fracture surfaces or thin, hair-like cracks on a polished and etched section. These defects manifest themselves after an incubation period, and are contained within the section usually located at about mid-radius to one-third thickness from the surface. Hydrogen has some solubility in steel and is present during all steel making operations (except those done under vacuum). While some is lost on solidification, some amount is retained in the austenitic phase. This hydrogen then segregates at internal voids and inclusions and leads to pressure buildups. Flakes appear and grow after a considerable incubation period, often during the operation of the part. Not being able to detect them during the pre-service inspections makes them a dangerous defect. Depending on the dimensions, number and position in the metal, flakes can decrease the toughness and ductility of steel and markedly reduce the service life of steel forgings, causing unexpected failures.

Fish eyes are bright patches named for their appearance on fracture surfaces

Bursts:

During the reduction of thick section forgings, high levels of triaxial stress can be set up deep within the sections. The stress can exceed the tensile strength of the material and tear it apart internally, particularly if the forging temperature is too high. These are referred to as forging bursts. Bursts can be surface breaking, but are more often wholly embedded and therefore difficult to detect.

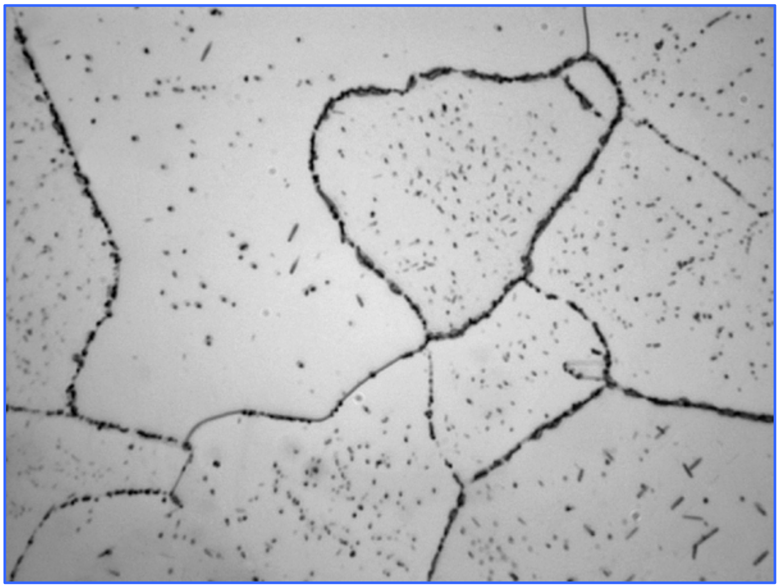
Macrograph of a forging burst

Flash cracks:

Closed-die forging produces a sliver of material, which is forced out between the dies. This is known as “flash”. The flash is removed after forging, but if the strain experienced during extrusion of the flash is excessive, the flash may crack. Furthermore, if the trimming of the flash is performed very close to the geometry of the part, it can produce tearing along the parting line during the trimming operation. Occasionally these cracks can run into the forging and remain after the flash has been removed. The resultant defect is known as a flash crack.

Overheating/Burning:

Heating the ingot to forging temperature is a critical step. The choice of forging temperature must be approached carefully as "hotter is better" is a misconception, although it may reduce forging time and be financially rewarding. The appropriate forging temperature will vary depending on the type of steel involved, and the hot working that has to be performed. Heating of the material before it is forged can be done in various ways, in a furnace or by induction heating. By definition, hot working is carried out above the recrystallization temperature for the steel, and it is desirable to finish it close to this temperature. Although the power needed and time spent to do the work can be reduced when higher forging temperatures are used, serious or even permanent damage can be done to the material if an upper limit is exceeded. Use of higher temperatures increases scale formation and results in excessive grain growth. Since larger grains affect the mechanical properties, additional grain-refining heat treating operations may be needed to restore properties. A step beyond overheating can cause permanent damage with the formation of extremely large grains and incipient melting of lower melting constituents, typically at the grain boundaries. This condition, which severely impairs the mechanical properties, is known as "burning" and is irreversible.



Microstructure showing the onset of incipient melting at the grain boundaries