Defects and Discontinuities

The aim of non-destructive inspection is to determine if the object being inspected is to be accepted or rejected. During the inspection, the inspector looks for discontinuities in the object and identifies their nature and size. Then, those discontiouities are evaluated according to an acceptance criterion to determine if they are considered to be defects (*the presence of defects mans that the object will be rejected*).

A ***Discontinuity*** is defined as an imperfection or interruption in the normal physical characteristics or structure of an object (*crack, porosity, inhomogeneity, etc.*). On the other hand, a ***Defect*** is defined as a flaw or flaws that by nature or accumulated effect render a part or product unable to meet minimum applicable acceptance standards or specifications (*defect designates rejectability*).

It should be clear that a discontinuity is not necessarily a defect. Any imperfection that is found by the inspector is called a discontinuity until it can be identified and evaluated as to the effect it will have on the service of the part or to the requirements of the specification. A certain discontinuity may be considered to be a defect in some cases and not a defect in some other cases because the defenetion of defect changes with the type of component, its construction, its materials and the specifications or codes being used.

Types of Discontinuities

Discontinuities are generally categorized according to the stage of the manufacturing or use in which they initiate.

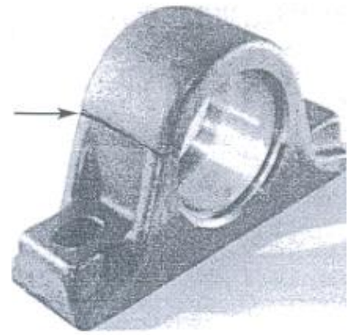
Therefore, discontinuities are categorized in four groups which are:

- Inherent discontinuities
- Primary processing discontinuities
- Secondary procession discontinuities
- Service discontinuities

INHERENT DISCONTINUITIES

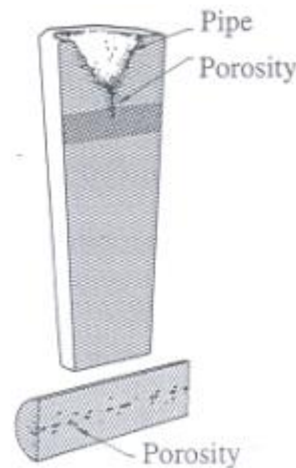
This group refers to the discontinuities that originate during the initial casting process (*when the metal is casted into ingots for further processing*) and also it includes the discontinuities that are produced when metal is casted as parts of any given shape. The initial casting discontinuities are usually removed by chopping the ingots but some of them remain and further change their shape and nature during the subsequent manufacturing operations.

Cold Shut



Cold shut occurs usually during the casting of parts because of imperfect fusion between two streams of molten metal that converged together. It could be on the surface or subsurface. It could be attributed to sluggish molten metal, surging or interruption in pouring, or any factor that prevents the fusion of two meeting streams.

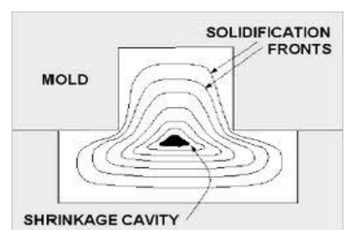
Pipe



Bar rolled from ingot above

During solidification of the molten material it shrinks causing an inverted-cone shaped cavity in the top of the ingot. It could be on the surface or subsurface. If this defected region is not cut out completely before further processing (rolling or forging) it will show up in the final product as an elongated subsurface discontinuity. Also, pipe could occur during extrusion when the oxidized surface of the billet flows inwards toward the center of the extruded bar.

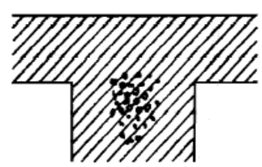
Shrinkage Cavities



Shrinkage cavities are subsurface discontinuities that are found in casted parts. They are caused by the lack of enough molten metal to fill the space created by shrinkage (similar to pipe in an ingot).

Micro-shrinkage Cavities

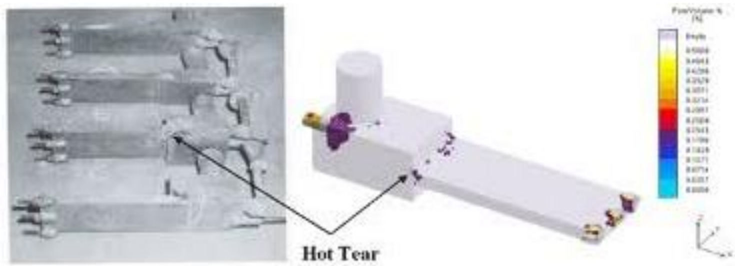
Micro-shrinkage cavities are aggregates of subsurface discontinuities that are found in casted parts. They are usually found close to the gate and they occur if metal at the gate solidifies while some of the metal beneath is still molten. Also, micro-shrinkage could be found deeper in the part when molten metal enters from the light section into heavy section where metal could solidify in the light section before the heavy section.



Hot Tears

Hot tears occurs when low melting point materials segregate during solidification and thus when they try to shrink during solidification cracks and tears will develop because the surrounding material has already solidified.

Also, hot tears occur at the joining of thin sections with larger sections because of the difference of the cooling rate and thus solidification.



Blowholes and Porosity

Blowholes and porosity are small rounded cavities found at the surface or near surface of castings and they are caused by the entrapped gasses that could not escape during solidification. Blowholes are caused by gases released from the mold itself (*external gases*) while porosity is caused by gases entrapped in the molten material (*internal gases*). During subsequent manufacturing operations these gas pockets get flattened or elongated or fused shut.

Nonmetallic Inclusions

Nonmetallic (or slag) inclusions are usually oxides, sulfides or silicates that remained with the molten metal during original casting. The properties of those inclusions are different from the metal and usually they have irregular shapes and discontinuous nature therefore they serve as stress raisers that limit the ability of the material to withstand stresses.

Segregation

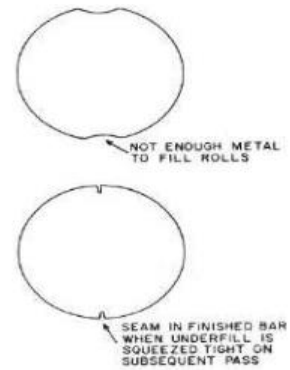
Segregation is localized differences in material composition (and thus mechanical properties) caused by the concentration of some alloying elements in limited areas. These compositional differences may be equalized during subsequent hot working processes but some still remain.

PRIMARY PROCESSING DISCONTINUITIES

This group refers to the discontinuities that originate during hot or cold forming processes (extrusion, forging, rolling, drawing, welding, etc.). Also, some of the inherent discontinuities in the material could propagate and become significant.

Seams

Seams are elongated surface discontinuities that occur in bars during rolling or drawing operations. They result due to under-filled areas that are closed shut during rolling passes. Those under-filled areas may result because of blowholes or cracks in the material. Also seams may result from the use of faulty, poorly lubricated or oversized dies.



Lamination

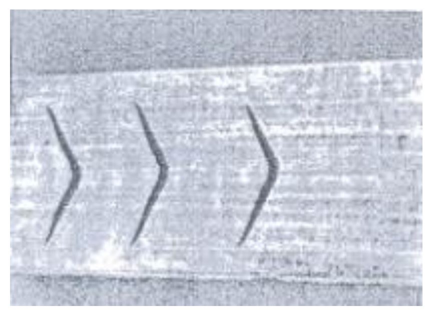
Laminations are thin flat subsurface separations that are parallel to the surface of plates. They may result from inherent discontinuities (pipe, inclusions, porosity, etc.) that are flattened during the rolling process.

Stringers

Stringers are elongated subsurface discontinuities that are found in bars (they run in the axial direction). They result from the flattening and lengthening of nonmetallic inclusions during the rolling process.

Cupping

Cupping is a subsurface discontinuity that may occur in bars during extrusion or sever cold drawing. It is a series of cone-shaped internal ruptures that happen because the interior of the material cannot flow as fast as the surface where that causes stress buildup and thus rupture.

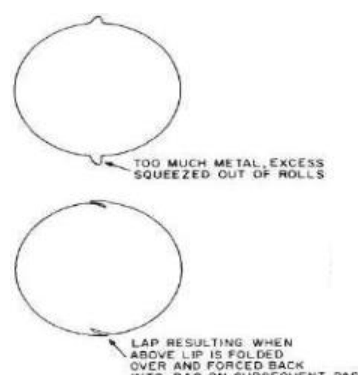


Cooling Cracks

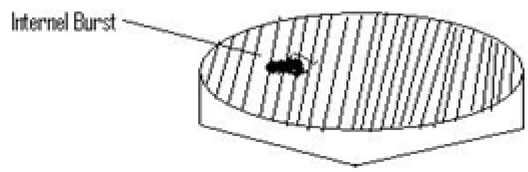
Cooling cracks may occur on the surface of bars after rolling operations due to stresses developed by uneven cooling. They run in the axial direction (similar to seams) but unlike seams, they do not have surface oxidation.

Forging and Rolling Laps

Laps are elongated surface discontinuities that occur during rolling or forging operations due to the presence of some excessive material (fin) that is folded over. They may result because of oversized blanks or improper handling of the material in the die.



Internal or External Bursts



Internal bursts are found in bars and forgings formed at excessive temperatures due to presence of inherent discontinuities that are pulled apart by the tensile forces developed during the forming operation.

External bursts occur when the forming section is too severe or the sections are thin.

Slugs

Slugs are surface discontinuities found on the inner surface of seamless (extruded) tubes. They occur when some metallic pieces that are stuck on the mandrel, are torn and fused back on the inner surface of the tube.

Gouging

Gouging is surface tearing found on the inner surface of seamless (extruded) tubes and it is caused by excessive friction between the mandrel and the inner surface of the tube.

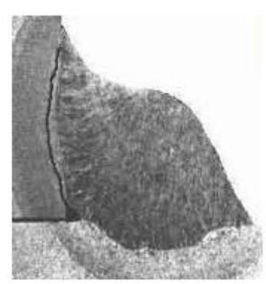
Hydrogen Flakes

Hydrogen is available during manufacturing operations (*from decomposition of water vapor or hydrocarbons "oil", atmosphere, etc.*) and it dissolves in material at temperatures above 200° C. Hydrogen flakes are thin subsurface discontinuities that develop during cooling of large size parts produced by forging or rolling because of the entrapment of hydrogen resulting from rapid cooling.

Welding Discontinuities

Several types of discontinuities result from welding operations. Only the discontinuities associated with fusion welding processes (arc welding, gas welding, etc.) are presented here.

Cold Cracks



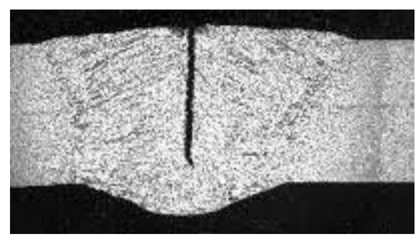
Cold cracks, also known as *delayed cracks*, are hydrogen induced surface or subsurface cracks that appear in the heat affected zone or the weld metal during cooling or after a period of time (hours or even days). The sources of hydrogen which leads to this type of cracks may include moisture in the electrode shielding, the shielding gas or base metal surface, or contamination of the base metal with hydrocarbon (oil or grease).

Hot Cracks

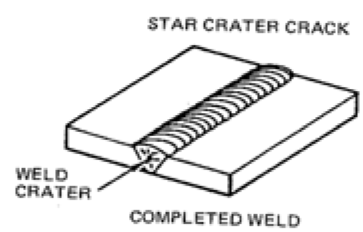
Hot cracks include several types of cracks that occur at elevated temperatures in the weld metal or heat affected zone. In general, hot cracks are usually associated with steels having high sulfur content. The common types of hot cracks include:

Solidification Cracks: This type occurs near the solidification temperature of the weld metal. They are caused by the presence of low melting point constituents (such as iron sulfides) that segregate during solicitation then the shrinkage of the solidified material causes cracks to open up.

- *Centerline Crack* is a longitudinal crack along the centerline of the weld bead. It occurs because the low melting point impurities move to the center of the weld pool as the solidification progresses from the weld toe to the center, then shrinkage stresses of the solidified material causes cracking along the centerline. The likelihood of centerline cracking increases when the travel speed is high or the depth-to-width ratio is high.

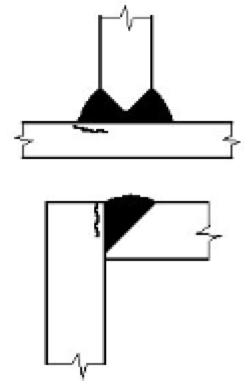


- *Crater Crack* which occurs in the crater formed at the termination of the weld pass. Crater cracks are mostly star shaped and they are caused by three dimensional shrinkage stresses. The likelihood of crater cracks increases when welding is terminated suddenly.



Liquidation Cracks: This type, also known as *hot tearing*, occurs in the heat affected zone when the temperature in that region reaches to the melting temperature of low melting point constituents causing them to liquidate and segregate at grain boundaries. As the weld cools down, shrinkage stresses causes the formation of small micro-scale cracks which later might link up due to applied stresses to form a continuous surface or subsurface crack.

Lamellar Tearing



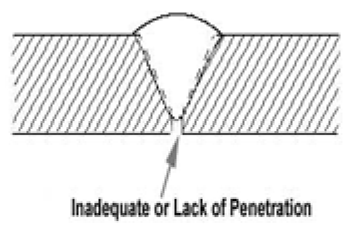
Lamellar tearing is a subsurface discontinuity that occurs in rolled plates having high content of nonmetallic inclusions. Those inclusions have low strength and they are fattened during rolling, thus they can be torn underneath the welds because of shrinkage stresses in the through thickness direction.

Lack of Fusion

Lack of fusion is the failure of the filler metal to fuse with the adjacent base metal (or weld metal from previous pass) because the surface of base metal did not reach to melting temperature during welding. This typically occurs when welding large components that could dissipate heat rapidly especially when it is at a relatively low temperature before welding. Lack of fusion is often seen at the beginning of the first pass and in such case it is commonly called a *cold start*. Also, lack of fusion could occur when the surface a previous pass is not properly cleaned from slag where slag reduces the heating of the under-laying surface.

Lack of Penetration

Lack of penetration is insufficient (less than specified) penetration of the weld metal into the root of the joint. This is mostly caused by improper welding parameters such as; low amperage, oversized electrode or improper angle, high travel speed, or inadequate surface pre-cleaning. Also, lack of penetration could happen when the root face is too large, the root opening is too narrow, or the bevel angle is too small.



Porosity

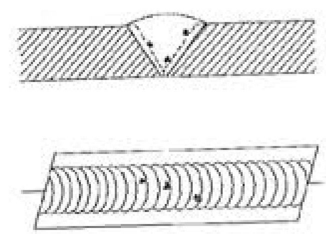
Porosity is small cavities or bores, which mostly have spherical shape, that are found on the surface of the weld or slightly below surface. Porosity occurs when some constituents of the molten metal vaporize causing small gas pockets that get entrapped in the metal as it solidifies. These small bores could have a variety of shapes but mostly they have a spherical shape. The distribution of bores in weld metal could be linear (*linear porosity*) or they could be

clustered together (*cluster porosity*). In general, porosity can result from the presence of dirt, rust or moisture on the surface of base or filler metal. Also, it could result from high sulfur content in the base metal or excessive arc length.

Inclusions

Inclusions refer to the presence of some material, that is not supposed to be present, in the weld metal.

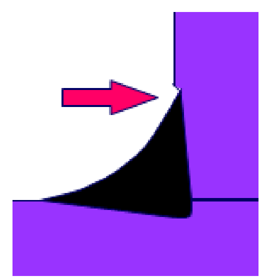
Slag Inclusions: This type of inclusions mostly happens in shielded metal arc welding (SMAW) and it occurs when the slag cannot float to the surface of the molten metal and get entrapped in the weld metal during solidification. This could happen when; the solidification rate is high, the weld pool viscosity is high, an oversized electrode is used, or slag on the previous pass was not properly removed.



Tungsten Inclusions: This type of inclusions can be found in weld metal deposited by gas tungsten arc welding (GTAW) as a result of allowing the tungsten electrode to come in contact with the molten metal.

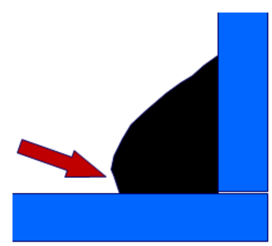
Oxide Inclusions: This type of inclusions results from the presence of high melting point oxides on the base metal which mixes with the molten material during welding.

Undercut



Undercut is a reduction in the base metal thickness at the weld toe. This is caused by an oversized molten weld pool which may result from excessive amperage or oversized electrode.

Overlap



Overlap is the protrusion of the weld metal over the weld toe (due to lack of fusion). This may be caused by insufficient amperage or travel speed.

SECONDARY PROCESSING DISCONTINUITIES

This group refers to the discontinuities that originate during grinding, machining, heat treating, plating and related finishing operations.

Grinding Cracks

Grinding cracks develop at locations where there is a localized heating of the base metal and they are usually shallow and at right angle to the grinding direction. Such cracks might be caused by the use of glazed wheels, inadequate coolant, excessive feed or grinding depth.

Pickling Cracks

Pickling is chemical surface cleaning operation (using acids) used to remove unwanted scale. Picking cracks are hydrogen induced cracks caused by the diffusion of the hydrogen generated at the surface into the base metal. Such cracks mostly occur in materials having high residual stresses such as hardened or cold worked metals.

Heat Treatment (Quenching) Cracks

Heat treatment cracks mostly occur during quenching especially when harsh media is used for quenching (such as cold water, oil quenching is less harsh). During quenching the material at the surface cools immediately upon contacting the liquid while the material inside take relatively longer time. This difference in cooling rate causes residual stresses in the component and could also result in cracks at the surface if the residual tensile stress is higher than the strength of the material. In steels, austenite is transferred into ferrite and martensite upon cooling. This transformation results in volume increase and thus causes tensile stresses at the surface layer since the material at the surface transformed and solidified before material at the core.

Machining Tears

Machining tears result from the use of machining tools having dull or chipped cutting edges. Such discontinuities serve as stress raisers and can lead to premature failure of a component especially when it is subjected to fatigue loading.

Plating Cracks

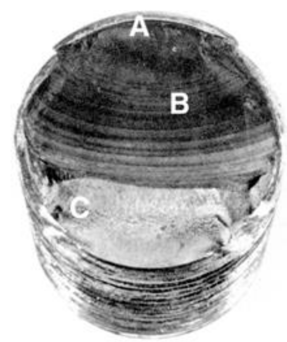
Plating cracks are surface discontinuities that can develop due to the penetration of hydrogen or hot plating material into the base metal. Also, some plating materials (*such as chromium, copper and nickel*) produce residual tensile stress which can reduce the fatigue strength of a component.

SERVICE DISCONTINUITIES

This group refers to the discontinuities that originate or develop while the component is in service. The service conditions (loading, mechanical and chemical environment, maintenance) of a component affect its expected life. Although most of service discontinuities might look somehow similar but they are caused by different failure mechanisms.

Fatigue Cracks

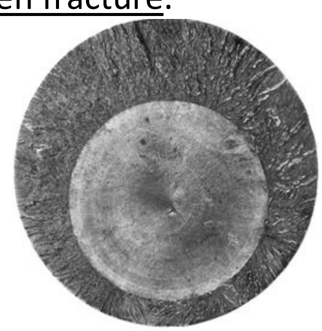
When a component is subjected to fatigue stress (cyclically applied stress), fatigue cracks can develop and grow and that will eventually lead to failure (even if the magnitude of the stress is smaller than the ultimate strength of the material). Fatigue cracks normally originate at the surface but in some cases can also initiate below surface. Fatigue cracks initiate at location with high stresses such as discontinuities (*hole, notch, scratch, sharp corner, porosity, crack, inclusions, etc.*) and can also initiate at surfaces having rough surface finish or due to the presence of tensile residual stresses.



According to Linear-Elastic Fracture Mechanics (LEFM), fatigue failure develops in three stages:

- *Stage 1*: development of one or more micro cracks due to the cyclic local plastic deformation at a location having high stress concentration.
- *Stage 2*: the cracks progress from micro cracks to larger cracks (macro cracks) and keep growing making a smooth plateau-like fracture surfaces which usually have beach marks that result from variation in cyclic loading. The geometry and orientation of the beach marks can help in determining the location where the crack originated and the progress of crack growth. The direction of the crack during this stage is perpendicular to the direction of the maximum principal stress.
- *Stage 3*: occurs during the final stress cycle where the remaining material cannot support the load, thus resulting in a sudden fracture.

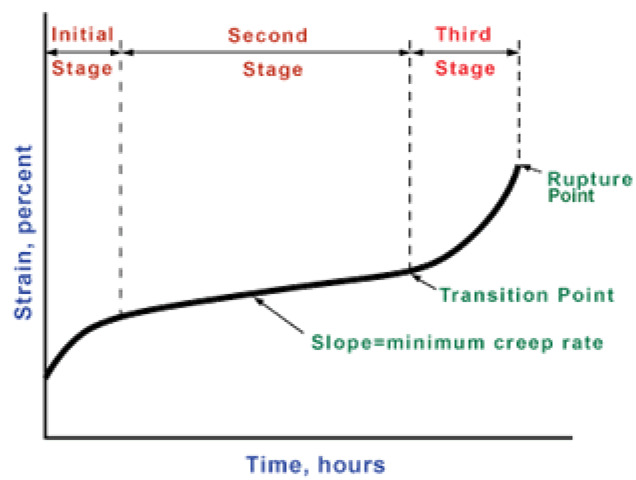
The presence of the crack can (and should) be detected during the crack growth stage (stage 2) before the component suddenly fails.



Creep Cracks

When a metal is at a temperature greater than 0.4 to 0.5 of its absolute melting temperature and is subjected to a high enough value of stress (lower than the yield strength at room temperature but it is actually higher than the yield strength at the elevated temperature), it will keep deforming continuously until it finally fractures. Such type of deformation is called creep and it is caused by the continuous initiation and healing of slipping dislocation inside the grains of the material.

According to the rate of progress of the deformation, three stages of creep deformation can be distinguished:



- *Initial stage (or primary creep)*: the strain rate is relatively high but slows with increasing time due to work hardening.
- *Second stage (or steady-state creep)*: the strain rate reaches a minimum and becomes steady due to the balance between work hardening and annealing (thermal softening). The characterized "creep strain rate" typically refers to the rate in this secondary stage.
- *Third stage (or tertiary creep)*: the strain rate exponentially increases with stress because of necking phenomena and finally the component ruptures.

Creep cracks usually develop at the end of the second stage (the beginning of third stage) and they eventually lead to failure. However, when a component reaches to the third stage, its useful life is over and thus creep should be detected (*by monitoring the deformation*) during the second stage which takes the longest time period of the three stages. For steels, adding some alloying elements such as molybdenum and tungsten can enhance creep resistance. Also, heat treatments that produce coarse grains (such as annealing) can also increase life under creep conditions.

Stress Corrosion Cracks

Stress corrosion cracks are small sharp and usually branched cracks that result from the combined effect of a “static” tensile stress and a corrosive environment. The stress can either be resulting from an applied load or a residual stress. Stress corrosion cracks can lead to a sudden failure of ductile materials without any previous plastic deformation. The cracks usually initiate at the surface due to the presence of preexisting discontinuity or due to corrosive attack on the surface. Once the cracks initiate at the surface, corrosive material enters the cracks and attacks the material inside forming corrosion products. The formation of the corrosion products (*which have a larger volume than original metal*) inside the tight cracks causes a wedging action which increase the stress at the crack tip and causes the crack to grow. The corrosive environment varies from material to material; for example saltwater is corrosive to aluminum and stainless steel, ammonia is corrosive to copper alloys, and sodium hydroxide is corrosive to mild steel. The resistance to corrosion can be improved by plating the surface of a component by appropriate material which does not react with the environment.

Hydrogen Cracks

Hydrogen cracking, also known as hydrogen embrittlement, results from the presence of hydrogen medium and usually occurs in conjunction with the presence of applied tensile stress or residual stress. Hydrogen can be already present in the metal due to previous processes such as electroplating, pickling, welding in moist atmosphere or the melting process itself. Also, hydrogen can come from the presence of hydrogen sulfides, water, methane or ammonia in the work environment of a component. Hydrogen can diffuse in the metal and initiate very small cracks at subsurface cites (usually at the grain boundaries) subjected to high values of stress. The presence of such cracks at several locations causes ductile materials to show brittle fracture behavior.