

DEFECTS INTRODUCED INTO METALS DURING FABRICATION AND SERVICE

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Contents

1. Introduction
2. Primary Production Defects
 - 2.1. Casting Defects
 - 2.1.1. Pipe and Shrinkage
 - 2.1.2. Inclusions
 - 2.1.3. Segregation
 - 2.1.4. Porosity
 - 2.1.5. Surface Defects
 - 2.1.6. Other Defects
 - 2.2. Forming Defects
 - 2.2.1. Cracks, Laps and Seams
 - 2.2.2. Surface Defects
3. Defects Introduced During Fabrication
 - 3.1. Defects Resulting From Cutting
 - 3.2. Joining Methods
 - 3.2.1. Design Related Defects
 - 3.2.2. Procedure and Process Defects
 - 3.2.3. Metallurgical Factors
 - 3.3. Heat Treatment
 - 3.3.1. Stress relief of machined or welded components
 - 3.3.2. Hardening and quench cracking
 - 3.3.3. Embrittlement
4. Defects Introduced in Service
 - 4.1. Fatigue
 - 4.2. High Temperature Defects
 - 4.2.1. Mechanical property degradation and creep
 - 4.2.2. Environmental interaction
 - 4.2.3. Microstructural Changes
 - 4.3. Wear
 - 4.3.1. Abrasive Wear
 - 4.3.2. Adhesive Wear
 - 4.3.3. Fretting
 - 4.3.4. Erosion
 - 4.3.5. Rolling Contact Wear
 - 4.4. Embrittlement
5. The significance of defects entering service

Glossary

Bibliography

Biographical Sketches

Summary

Defects may be produced during the processing, fabrication and use of metals in service. Those that are introduced early in the processing chain may be carried forward to later stages where they can cause processing problems, or initiate failure. Some of these defects result from complex metallurgical, chemical and physical reactions that metals undergo during these processing operations and are difficult to avoid. They may also be inherent to the process. Whilst it is possible to minimize the effects of these reactions by applying knowledge about a materials behavior, good process and procedural control, it is preferable not to introduce problems that can be avoided by good practice.

Defects introduced during fabrication may arise from either the carry over of defects from earlier stages of processing resulting in the concentration of stresses, a reduction in the load bearing section of the product or changes in the metallurgical structure of the material so that it does not have the properties that the designer intended. Some or all of these can cause the material to fail during fabrication or enter service with defects present that may compromise integrity.

Defects arising during service may result from the presence of defects or features introduced during processing and fabrication, the inadequate specification of materials, or operation outside the intended design criteria.

1. Introduction

All metals contain defects. These can range from faults on an atomic scale that are inherent to crystallographic structures, to larger defects that are introduced during processing. These latter defects may be avoidable, or at least reduced to a level whereby they pose no threat. The complex chemical and physical reactions that take place in the both the molten and solid state can produce effects resulting in both inhomogenities and defects in the material. Non-uniform properties can present problems during the processing, fabrication and subsequent service of metal components. Defects that are introduced during the processing cycle will enter the fabrication route and may cause further problems by either initiating a failure during fabrication, or when the component enters service. The misapplication of the manufacturing process or lack of control at any stage may introduce defects and residual stress that can affect the performance of the structure in service, making it susceptible to failure. Defects that may be produced include holes, cracks, segregation, inclusions, surface marks, notches and undesirable or unintentional metallurgical changes within the material.

Defects may be characterized not only by their origin, but also by their shape. Stresses are concentrated at notches, which occur at sudden changes in geometry. Very high concentrations of stress can develop at sharp notches. This is why planar defects such as cracks, laminations, lack of fusion and lack of penetration type defects are potentially

serious. Three-dimensional (volumetric) defects create a lesser notch effect, but can amplify stresses by reducing the load bearing area. The following characteristics are some that are taken into account when assessing the significance of a defect:

- size
- sharpness
- orientation with respect to both the principle working stress and residual stress
- location with respect to the joints, the exterior surfaces and critical sections of the structure.

2. Primary Production Defects

Defects may be introduced when raw materials are made into a shape suitable for further processing. For convenience, the main defect types may be classified into the following broad descriptions.

Those where the material has started out in the molten state:

- segregation,
- holes and porosity,
- shrinkage and piping,
- inclusions,
- shrinkage and hot tears

and others where the metal is solid and is being processed further:

- cracks,
- surface defects,
- residual stresses,
- embrittlement effects.

The following section describes the broad classification of defects and describes their occurrence in specific processes.

2.1. Casting Defects

2.1.1. Pipe and Shrinkage

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. This is known as secondary pipe. Primary pipe is relatively easy to detect by eye and as it is exposed to the atmosphere it will oxidize and must be removed before further processing takes place. Secondary pipe, on the other hand remains hidden from view and although heavy forging may re-weld the cavities they may not be fully eradicated and remain in the

finished product as areas of potential weakness.

When casting into closed molds, it is important to allow for sufficient feeding to compensate for shrinkage during solidification. In this respect, shrinkage in castings is similar to pipe in ingots. If insufficient molten metal is available to fill the cooling and contracting casting, shrinkage cavities may form. They are commonly found in the center of complex shapes and great thought has to be applied to the provision of an adequate system for continued feeding of molten metal.

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 whilst 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

2.1.2. 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 (typically less than 1 millimeter) 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, resulting from the accidental inclusion of foreign matter such as broken sections of refractory lining and can be several centimeters in size. These can represent a significant threat to component integrity.

Inclusion defects can potentially be encountered in any metal casting process and may have deleterious effects on the material. The formation of films along grain boundaries can result in low ductility at hot working temperatures. In bearings, high levels of inclusions may spall off in-service resulting in poor performance of the bearing and accelerated wear. During further working operations inclusions may become elongated and aligned in the direction of working. In doing so that may be deformed plastically or fracture and fragment. Lines of inclusions result in poor transverse properties, leading to local notch effects, resulting in areas susceptible to fatigue cracking and delamination during welding.

In some cases, inclusions may be deliberately encouraged in order to produce readily machinable materials, as they provide an effective notch or chip starter.

2.1.3. Segregation

The distribution of chemical elements in ingots may not be uniform and some regions may become enriched in certain elements or phases while other regions are impoverished. Segregation is the result of the non-uniform rejection of elements from

the solidifying metal. It 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.

2.1.4. Porosity

Molten metal has a much higher solubility of gas than the solid. 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 ingot or casting. A proportion of the gas may also remain dissolved and cause problems later in the processing cycle or in service. Gas can also be produced by chemical reactions between some of the constituents within the melt. For example, hydrogen dissolved in copper reacts with dissolved oxygen to form steam bubbles. Such gaseous evolution or effervescence is not necessarily detrimental though. It can be utilized to counteract the effects of pipe and shrinkage and may readily weld up on heavy forging provided it is not surface breaking and oxidized.

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 be produced by the walls of the mold by the degradation of resins at high temperature, 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 out-gassing reaction. In these circumstances it is important to allow sufficient time for the reactions to take place prior to casting, whilst 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 than in ingots. In both cases the majority of porosity is sub-surface, but because ingots are worked further, these sub surface defects may be re-welded during heavy deformation processes such as forging and rolling. However, castings are used extensively for pressure or load bearing purposes and unless they are adequately inspected for sub-surface porosity, defects that result in significantly reduced load bearing capacity and leak paths can enter service.

2.1.5. 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 the main problems where the molten material can penetrate the surface of the mold and produce an effect called ‘scabbing’.

2.1.6. Other Defects

During casting operations, the sides of the mold may become splashed with molten metal. The surface of the splash will oxidize in the atmosphere and when the mold fills up, the oxidized surface becomes entrapped within the product.

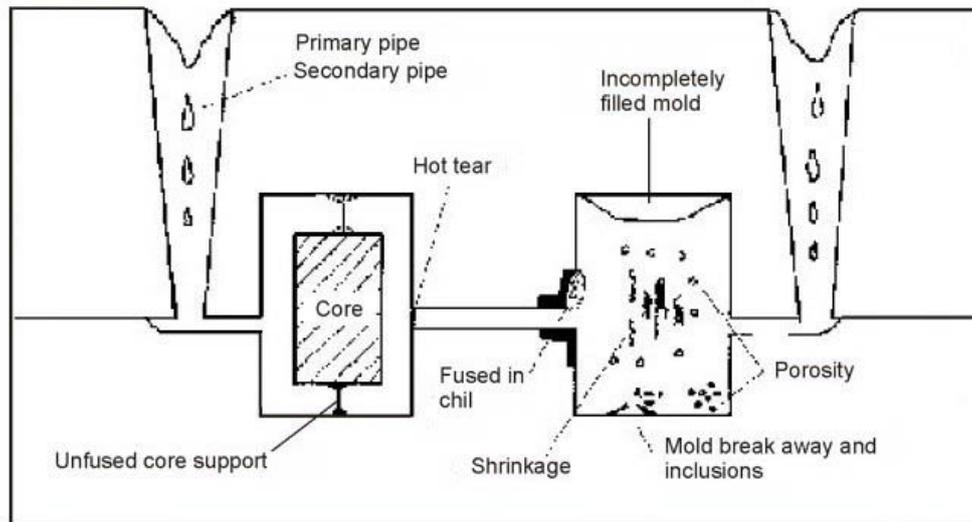


Figure 1: Composite Drawing of Typical Casting Defects

When intricately shaped castings are made, if 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 coming towards it. This “cold shut” can then represent a plane of weakness where the casting is not intimately fused.

When casting molds of complex shapes, it is sometimes necessary to promote rapid cooling to prevent hot tearing. This may be achieved by placing metallic thermal sinks or “chills” within the mold structure alongside the area to be cooled quickly. Occasionally, if the molten metal is particularly hot, these may become fused to the casting. To produce hollow castings, sacrificial “cores” are used that can be held in place by thin metallic pins of a composition similar to or matching that of the casting. The pins should melt and become fully incorporated into the casting, leaving the core in its intended position. If the pins do not melt however, they effectively form a through wall defect.

2.2. Forming Defects

The forming of ingots, or smaller pieces of a larger ingot section, may be carried out by the forging or hot rolling processes. As noted earlier, defects in billets may be carried over into later processes where they can pose a potential problem. Additionally, new

defects can be introduced by the forming process, typically restricted to cracks, and surface shape and size related defects.

2.2.1. Cracks, Laps and Seams

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. Occasionally the cracks can run into the forging and remain when the flash has been removed. The resultant defect is known as a flash crack.

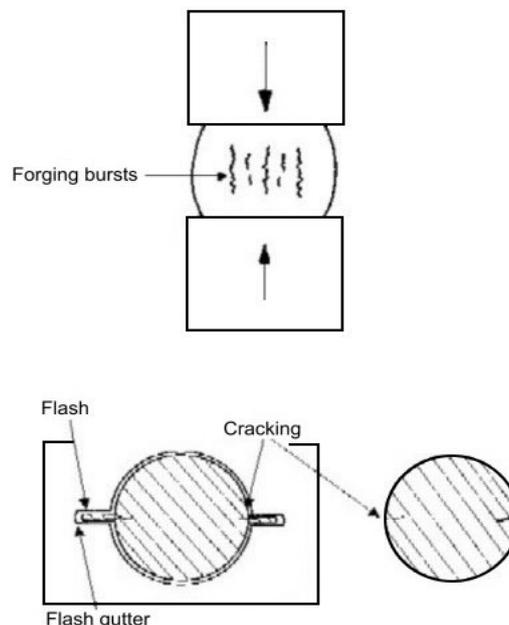


Figure 2: Forging bursts and flash cracks

During the reduction of thick section forgings, high levels of triaxial stress can be set up deep within the sections. If the stress exceeds the tensile strength of the material, fissures can form. These are referred to as forging bursts. Bursts can be surface breaking, but are more often wholly embedded and therefore difficult to detect.

Metals that are quite malleable at room temperature such as aluminum, copper and lead, can be formed either without any additional heat, or with only a modest amount. On the other hand, metals or alloys that have high temperature strength need to be heated to a point where they can be forged. This can then lead to oxidation and surface scaling, which in itself is not necessarily detrimental, but can lead to secondary problems. More specifically, the surface scale can become folded and rolled into the surface in deep channels. This then forms a line of weakness if not removed during subsequent manufacturing operations. These defects are known as laps or seams.

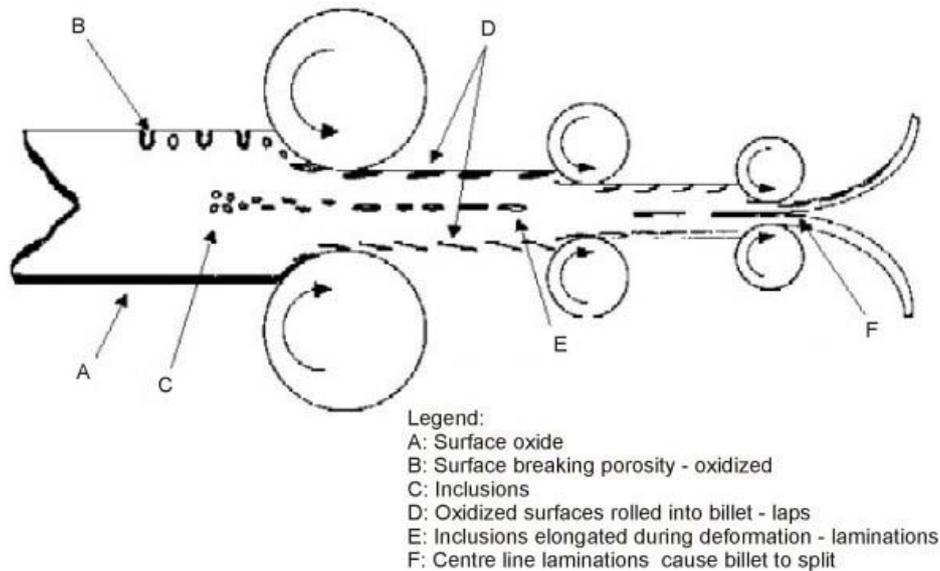


Figure 3: Composite Sketch of Typical Rolling Defects

During direct extrusion, as the billet is forced out through the die, the center sections of the ingot are extruded first, the outer surface moving to the center as the extrusion progresses. Being a hot process, the outer surface will be oxidized and during the latter stages, this oxide is extruded with the metal and enters the extrusion. This effect is eliminated in indirect extrusion. High speed or high temperature extrusion can also result in defects when lubrication becomes difficult. Friction between the product and the dies can result in sticking of the product to the die. As the extrusion breaks away, fissures known as speed cracks are formed.

When forging close to the finished product shape, it is clearly important to ensure that the blank is of adequate size and shape to fill the mold to produce the desired component. If the mold is incompletely filled, then some part of the finished product will be missing. Although this may be obvious during even the simplest of quality control checks, many mass produced products are only sample checked at manufacture and rejectable products may not be detected.

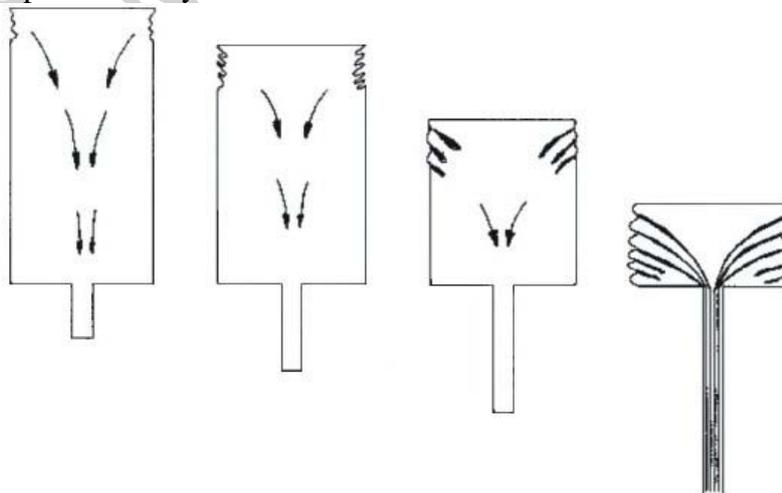


Figure 4: The extrusion defect

If light blows are applied to the surface layers of a material, the interior grain structure will not be sufficiently broken down as to promote recrystallisation. This can lead to a through thickness variation in mechanical properties. If the metal is worked at high temperatures, the presence of micro-segregation or inclusions represents a local weakness and can result in hot shortness and the production of cracks.

2.2.2. Surface Defects

Sheet metal processing has its own set of characteristic defects related to the deep drawing, pressing and cold rolling operations being used. When metal is pressed into a deep die, such as in the production of a kitchen sink or a cup, the amount of plastic deformation that the blank sheet has to undergo may exceed the ductility of the metal. This phenomenon is referred to as cupping. It may only result in excessive thinning of the sidewalls, but can lead to rupture. It can be overcome by lubrication or die re-design, taking account of how the blank pulls itself into the mold, or by a multi stage process where the blank is partially drawn then annealed to restore some ductility and drawn again. ‘Earing’ occurs when highly directional materials are deep drawn, resulting in peaks known as ears and depressions known as troughs. Earing results in a variation in wall thickness, where the wall is thinner below the ears.

Materials that have a grain size of dimensions visible to the naked eye can develop a mottled surface when pressed. As the atom planes within each grain are orientated differently to those of its neighbors, each grain behaves slightly differently in terms of deformation characteristics. Thus the surface does not deform uniformly and takes on a mottled appearance. This phenomenon is known as “orange peel” because of its resemblance to the skin texture of an orange. This is more of an aesthetic than a structural problem, but is significant for materials used to manufacture items where surface finish is important.

If a material with a well-defined yield point, such as mild steel, is lightly pressed, an effect known as “stretcher strains” or “Luders lines” can be encountered. Although it is not normally structurally significant, it can be unsightly, and takes the form of elongated patches or lines, stretched out along the direction of deformation. It is caused when a small element of material locally exceeds the elastic limit and yields, resulting in a slight drop in tensile strength. As deformation continues, this small element deforms in preference to its neighbors, until it work-hardens back up to its pre-yield strength, at which point a different element then undergoes the same process. Thus deformation does not take place in a uniform manner and patterns emerge on the finished product. This can be avoided by using materials that do not exhibit a yield point, or by rolling the sheet with a “pinch pass” first to exceed yield compressively, before pressing.

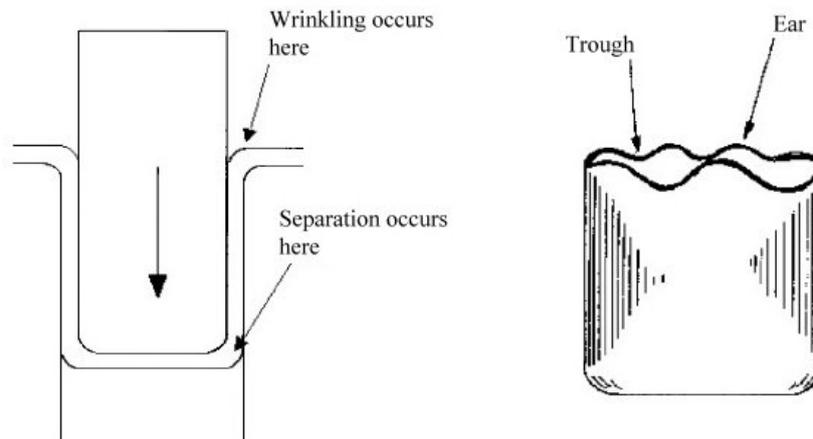


Figure 5: Typical deep drawing defects

Marks on the press tooling or rollers can also be transferred in negative onto the surface of the sheet, again with varying effect on surface finish.

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Biographical Sketches

Andy Wilby has had wide experience of welded fabrication over 22 years, starting in the power generation component manufacturing industry. This involved the fabrication of components for heat exchange equipment by many varied processes from casting and tube making through to welding.

Subsequently, he has worked within the Structural Integrity Branch, Materials Group of British Energy for the last 14 years. He specialises in the field of welding metallurgy but is also responsible for a number of other areas including forensic metallurgy, inspection planning and implementation on working power station sites. This has led to the involvement in a number of large-scale maintenance programmes utilising both manual and automated welding techniques.

David Neale has over twenty years experience in forensic metallurgy gained in manufacturing industry, aerospace and power generation. He is currently employed in the Structural Integrity Branch of British Energy, the principle nuclear generator in the United Kingdom. He specialises in the development and implementation of inspection strategies to detect defects in power station components. David is a graduate of the Open University and an advocate of life long learning.