NON-DESTRUCTIVE TESTING AND EVALUATION OF METALS

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Keywords: Castings, coatings, eddy current, forgings, in-service, inspection, liquid penetrant, magnetic particle, NDE, NDT, parent material, radiography, testing, thermography, ultrasound, visual, welds

Contents

Summary

The overall objective of this article is to describe the application of the main NDT (Non-Destructive Testing) methods associated with the inspection of metals during manufacture. However, some information is also provided on in-service inspection.

The NDT of metals is a vast subject covering a large number of NDT methods and a wide range of defects. Within the scope and length of this article the defects highlighted are limited to those that are most common and associated with NDT standards. A brief description is provided for a selected set of metal processes including the parent material, forgings, castings, welds, and coatings. Each defect associated with each metal process is described briefly along with the most suitable NDT method. A range of dedicated and special NDT methods are also discussed for certain defects that are

difficult to detect by conventional methods.

The defects and NDT methods discussed are summarized in tables for each manufacturing process.

1. Introduction

The Non-Destructive Testing (NDT) of metals worldwide experienced a significant change in the last half of the twentieth century. During the 1950s, the NDT of metals dominated the proportion of NDT carried out by end users and totaled as much as all the other industrial sectors put together (i.e. aerospace, utilities, petrochemical, automotive, and other sectors). However, since then there has been a significant decline in the NDT of metals, which has generally been attributed to the decline in heavy industry. Aerospace and other sectors, such as the food industry and civil engineering, dominate the NDT market by end users. However, this decline notwithstanding, the NDT of metals is still a large and varied market worldwide. To cover this subject properly for this article it has been necessary to focus on the main NDT methods such as visual, X-ray radiography, ultrasonics, liquid penetrant, magnetic particle, and electrical methods, but where necessary other NDT methods have also been introduced.

In national, European, and international NDT standards, the scope of the main NDT methods are usually written with carbon steels and ferritic steels in mind, but in many cases NDT methods are also applicable to other metals. For some metals, specific NDT methods procedures are necessary, but in many cases it is usually sufficient to calibrate the NDT instrumentation to suit the particular metal of concern and then follow essentially the same NDT method as used for steels.

The NDT methods for metals are considered here in the context of the main defects associated with both the manufacturing (or fabrication) processes and with in-service defects. It is important to realize first of all that not every possible defect can be detected by NDT. Moreover, it is often not the defect that is detected but the resulting effect on the material (i.e. the physical properties have been modified, such as the attenuation to ultrasound or the electrical conductivity).

Published NDT standards are invariably written for manufactured components and are aimed principally at ensuring the quality of manufacture (e.g., the quality of the welding or casting) and that the components are fit-for-purpose. For in-service defects, ad-hoc NDT procedures are usually necessary, which are often based on national NDT standards, but the nature of the in-service defect, the component accessibility, and the material preparation are just a few of the additional considerations that are critical in the choice of method and procedure. These ad-hoc NDT procedures are often company specific and while it is difficult to make generalized statements about them in the way that is possible with the NDT of manufacturing defects, some consideration will be given to the NDT of in-service defects.

This article begins by identifying briefly the main type of defects that are relevant and that can occur at the manufacturing stage in five principal areas: parent material, forgings, castings, welds, and coatings. These five areas are considered to represent the

largest percentage of metal components and products. A section is also devoted to the principle categories of in-service defects. For each defect identified and its likely cause, the most appropriate NDT methods are discussed and why they are the most suitable. The article finishes by discussing how the data collected in connection with the defects are interpreted and how this information is used to assess and sentence the defects.

2. Defects in Metals

The importance of detecting even small defects at the manufacturing stage cannot be overstated. Such small defects can develop into fatigue or stress-corrosion cracks in-service, which can be notoriously difficult to detect until it is too late and the component (or product) suffers catastrophic failure.

The term "defect" is just one of many terms used by industry to describe an imperfect material or component. In some texts and NDT standards, the term "defect" is taken to mean that the defect is out of specification with the manufacturing code and a repair is necessary. Other terms such as "imperfections," "discontinuities," or "flaws," are often used as more generic terms to describe that something is present (or missing) that could compromise the integrity of the material or component. In this article the term "defect" is used generically to mean that the component is imperfect in some way and does not automatically imply that a repair is necessary.

It is important to have an appreciation of the important types of manufacturing and in-service defects in metals (see *Defects Introduced in Metals During Fabrication and Service*) and equally important of the names that are used for these defects in the context of NDT. This section begins by describing in brief a variety of defects and covers the vast majority of practical areas of interest: parent material, processes, and in-service. The processes include forgings, castings, welds, and coatings. There are many occasions where the same defect name is used in each of the manufacturing processes, but has occurred for quite different reasons and is peculiar to that process.

2.1. Defects in Parent Material

The term "parent material" is used here to represent the nature of the material as it leaves the mill or the machine shop. It could be in the form of ingots (i.e. large rectangular casts, weighing several tons), or billets (i.e. much smaller rectangular pieces, usually produced from ingots by some additional casting process), or the part of the component that has not been welded.

The types of defects considered in the parent material are as follows:

- Surface Irregularities comprise rust, loose scale, weld spatter, notches, and grooves. These may have arisen because of the casting process itself, the general conditions under which the material is kept, or even from NDT methods such as Magnetic Particle Inspection (see Detection of Defects and Assessment of Serviceability), which can leave particles behind or damage the material at the contact points.
- Surface Roughness refers to the general surface condition, which is measured in

µm.

- Porosity occurs when small bubbles of gas get trapped in the hot metal as it cools and solidifies. These bubbles become elongated and distributed within the metal.
- Inclusions, both metallic and nonmetallic, can occur because of impurities in the base metal, through the refining process, where oxides and silicates are produced, or through additives to improve the machining properties of the material.
- Laminations can occur during the pouring process of the metal where splashes can become trapped in the material.
- Pipe is a defect associated with shrinkage in the upper portion of the ingot during cooling and solidification. There is usually insufficient molten metal to feed the ingot and a cavity is formed, typically in the shape of a cone or cylinder. Pipe can sometimes extend significantly along the length of the ingot (Figure 1).
- High Hydrogen Content can arise when water vapor reacts with the molten metal to form hydrogen, which subsequently gets trapped in the metal grain boundaries. This can cause flaking, which is the appearance of small cracks at the grain boundaries with highly reflective and faceted properties.
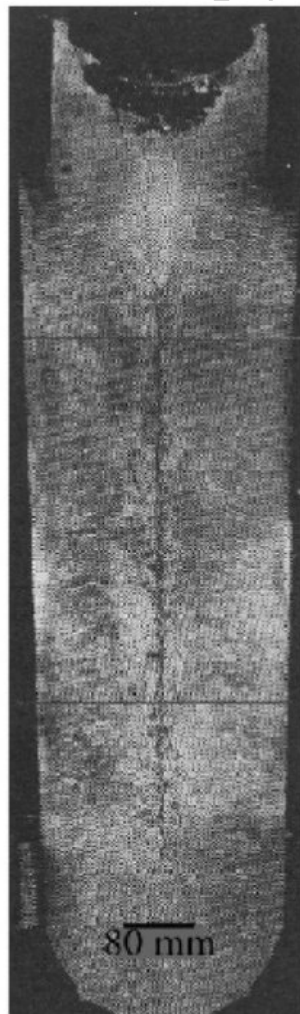

80 mm

Figure 1. A longitudinal section through an ingot, showing extensive centerline shrinkage
(from *ASM Handbook*, **Vol. 17**, 1989, p. 492)

2.2. Defects in Forgings

Forgings are formed from ingots or billets, which are then shaped using hammers or presses by forcing the solid metal into a die cavity (see *Material Processing and Manufacturing Technologies*).

The defects that occur in forgings may have originated from when the ingot (or billet) was first cast (see section 2.1), or through the initial process of reducing the ingot (or billet) before forging, or through the forging process itself. The main types of defects associated with forgings are as follows:

- Surface Defects can arise because of the working of the ingot (or billet). For example, loose pieces of metal getting rolled onto the surface, discontinuities (or "laps") occurring when the hot metal is folded over but not bonding because of oxides on the surface.
- Bursts are internal tears or ruptures, which are a result of some further process on an already weakened ingot (or billet) because of any of the defects already mentioned. During forging these defects may occur because the temperature is too low.
- Burning can occur when some of the metal constituents, with lower melting points, get re-melted because of significant overheating. This type of defect reduces significantly the mechanical properties of the component and is an irreparable defect.
- Internal Cracks can occur for a number of reasons: poor design of the die, sudden change in the rate of heating or cooling, the metal is too cold, the hammer is too light. High hydrogen content in the ingot, already mentioned, can manifest itself at this stage as hydrogen flaking.

2.3. Defects in Castings

A casting is formed when the molten metal is poured into a mold and then solidifies (see *Processing from the Liquid State*). For most steel components the mold has the final desired shape, and so after casting there are usually just the finishing operations to manufacture the final product.

Some casting defects have no influence on the service life of the component, but affect the cosmetic appearance and increase the cost of machining and finishing the component. The International Committee of Foundry Technical Association has a classification of nearly 100 common casting defects. It is inappropriate to consider all these defects in this article. Here, only those defects critical to the integrity of the component and relevant to NDT are considered and are grouped more generally as follows:

- Surface Defects can arise for a whole host of reasons, but are mostly associated

with the condition of the mold, and they include shrinkage, cracks, and dross.

- Cavities or shrinkage defects are formed when the liquid metal solidifies and contracts. They often occur in regions where there is a local change in section thickness or acute angle changes. At these positions, hot spots develop and cannot be fed adequately and lead to local shrinkage (Figure 2).
- Hot Cracking or Tearing are associated with stresses that develop when the contracting and cooling metal is restrained by the mold or by a thinner section that has already cooled (Figure 2).
- Airlocks may appear as a cavity or several cavities and occur when air is entrapped as the molten metal is poured into the mold. Airlocks usually appear just below the surface.
- Gas Holes are normally discrete defects that arise from the evolution of dissolved gases from the metal.
- Blowholes are gas holes that arise specifically from the mold and not from the metal. These are also usually close to the surface.
- Inclusions, metallic and nonmetallic, can occur from the presence of foreign elements, products of metal treatment, and sand from the mold.
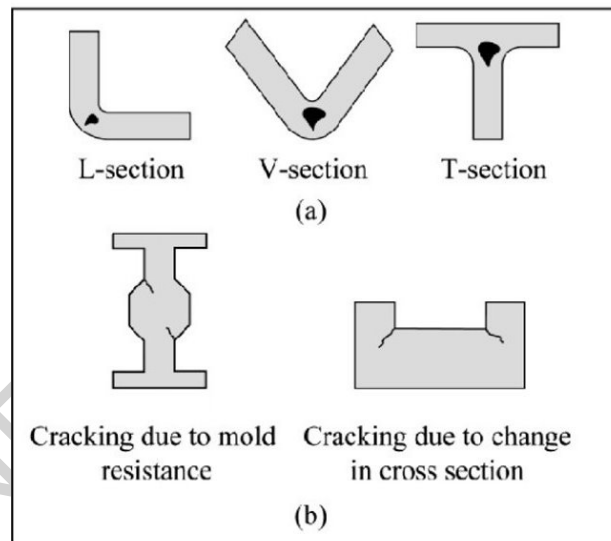

Figure 2. Illustrations of: (a) cavities, and (b) hot cracking in castings

2.4. Defects in Welds

There are numerous welding processes used in industry (see *Joining of Advanced Materials*), and each process produces its own characteristic defects. This section will focus on defects characteristic of arc welding processes (i.e. manual metal arc, submerged arc, gas metal arc, gas tungsten arc, and submerged arc) but will briefly discuss other welding processes (e.g., electron beam, resistance). The specific defects considered are the main ones that are associated with national NDT standards and are described as follows:

- Cracks are fracture-type defects, which have sharp tips, and a small crack opening displacement (COD) compared with the length and width. They can be

longitudinal (i.e. along the weld direction) or transverse to the weld (see *Defects Introduced in Metals During Fabrication and Service*).

- Lack of Side Wall/Root Fusion is when the fusion is incomplete on the wall and root of the weld preparation, respectively (Figure 3a). This is usually caused by poor electrode manipulation.
- Lack of Penetration is when the weld penetration is less than that specified (Figure 3d).
- Porosity (Isolated/Linear/Wormhole/Cluster) represents the different ways that porosity (see section 2.1) appears in arc welds. The particular type of porosity is consistent with its shape and distribution (e.g., wormhole porosity is a term for elongated voids with a clear worm-like shape and texture). Cluster of porosity is a grouping of isolated porosity (Figure 3b).
- Linear Inclusions are linearly distributed and can be nonmetallic and metallic. For example, slag inclusions are a fairly common form of linear inclusion. With each pass of the welding rod, some slag (or scale) is formed at the surface. If this is not removed, the next pass of the welding rod will entrap the slag. Typically, for metal inclusions bits of copper or tungsten drop off the welding electrode into the weld.
- Root Undercut is when a groove is melted in the parent metal either side of the weld root and is not filled by the weld metal (Figure 3e). The integrity of the weld root is extremely important and in most NDT standards there is a specific method of inspection.
- Excess penetration is when too much weld metal is produced at the root end of the weld.
- Misalignment is when two parts of the parent material are not set or aligned properly before welding. This manifests itself through an unusually wide weld cap. While a misalignment may not compromise the integrity of the weld, it can interfere with subsequent inspection (Figure 3c).
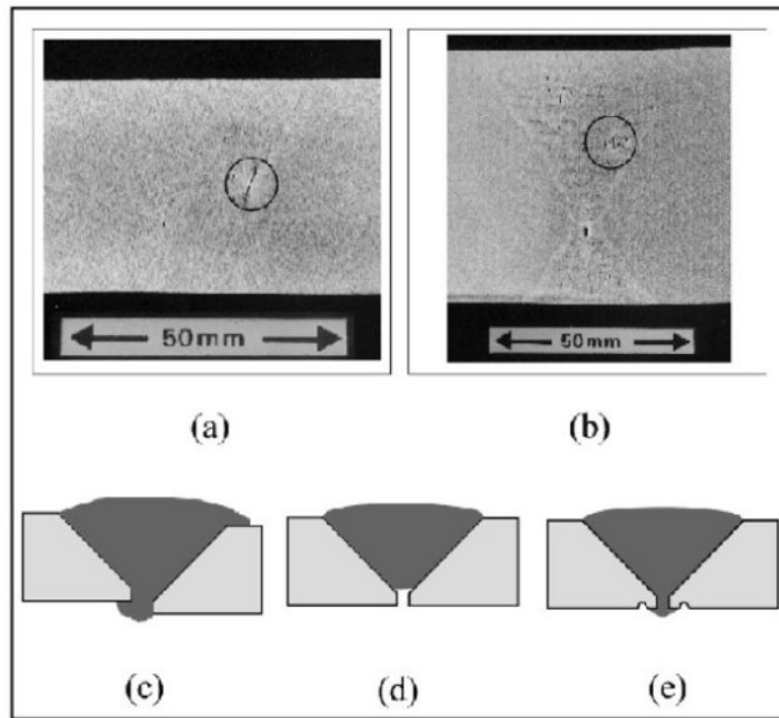
Figure 3. Different cross sections of welds showing a range of weld defects: (a) lack of side wall fusion (©TWI Ltd.), (b) cluster of porosity (©TWI Ltd.), (c) misalignment, (d) lack of penetration, (e) root undercut

In electron beam welding, similar defects occur as in arc welding processes. Typical surface defects include weld root and weld cap undercut, lack of penetration, misalignment, and missed seams (i.e. seams not welded). In electron beam welding, the parent materials have straight edge preparation in contact (seams) and are not prepared as in say a single V-butt weld for arc welding processes.

Resistance welding (also called "spot" welding) involves passing a current from one side of the joint to the other side. Spot welding is commonly used for welding thin components, for example in the automotive and aerospace industries. Typical defects include porosity, lack of fusion, and cracks that can all be caused by overheating and inadequate pressure at the joint.

Other processes for joining metals include friction welding, diffusion bonding, brazing, and soldering.

2.5. Defects in Coatings

The coatings considered here are thermal sprayed coatings, in which melted or semi-melted particles are sprayed with high velocity onto a prepared substrate (e.g., by grit blasting). There is rapid solidification as the nearly spherical particles impact and flatten when striking a much colder surface. The desired thickness and evenness of the coating is built up by passing the spraying gun repeatedly over the substrate (Figure 4).
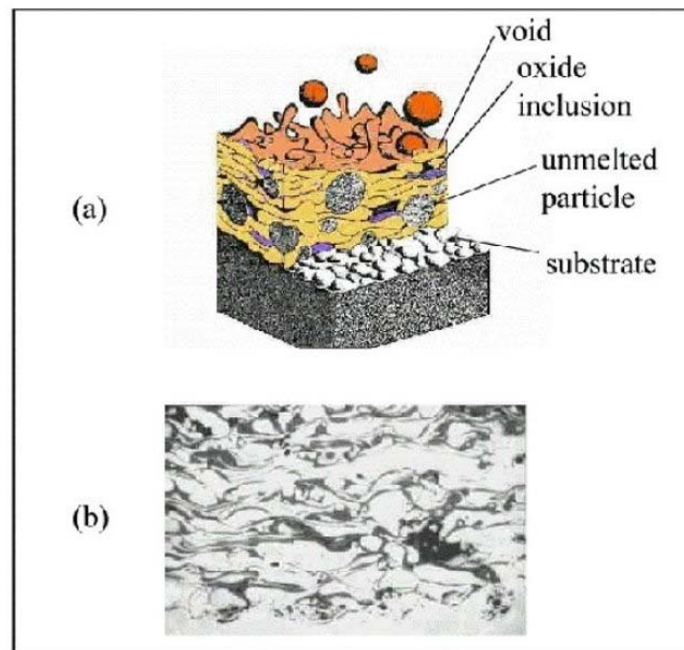
Figure 4. (a) schematic diagram of a thermally sprayed metal coating, (b) typical microstructure of a metallic spray coating (from <www.gordonengland.co.uk>)

Coatings are used to improve both the wear and corrosion resistance properties of the substrate. They can also be used to provide thermal barriers between the component and the operating environment. Coatings that are termed "biologically compatible" are used for metal alloy implants to encourage more efficient growth of new bone into the prosthetic.

Ceramic coatings are used principally as thermal barrier coatings.

The bonding mechanism at the coating/substrate interface is generally accepted to be a combination of mechanical interlocking and diffusion bonding. The strength of this bonding is principally a function of the particle velocities on impact and the residual stress at the coating/substrate interface. In general, the higher the particle velocity the better the bonding, but another important feature is the degree of roughness of the substrate surface.

There are a number of thermal spraying processes, and the main five are listed here in order of increasing particle velocity:

- Flame
- Arc
- Plasma
- High Velocity Oxy-Fuel (HVOF)
- Detonation Flame Spraying (D-Gun)

The most important defects associated with thermal spraying processes for metallic coatings include:

- Uneven Coating Thickness occurs where there is overspraying or underspraying of particular areas and when there is poorly controlled relative movement of component and gun.
- Disbonding is an interfacial defect where the coating can become detached. Poor cleaning and preparation before spraying can result in disbonding.
- Delamination is when there is disbonding between layers of the coating and can be caused by the inappropriate speed of the particles during the spraying process and the rate of cooling of each particle.
- Interfacial Cracking occurs at the coating/substrate interface and can be caused by residual stresses and the different rates of cooling of the coating and substrate.
- Porosity is inherent in most thermally sprayed coatings as the atmospheric gases become trapped in the spray stream. It can have desirable effects (e.g., increased efficiency of a thermal barrier) and detrimental effects (e.g., poor wear characteristics). It can also be caused by contaminants in the coating burning off or by particles not melting properly.
- Near Vertical Cracking can be caused by the different rates of cooling and solidification of the coating and substrate.
- Residual Stress occurs because of the rapid cooling and solidification process, which results in shrinkage and gives rise to tensile and compressive stresses in the coating and substrate, respectively.

2.6. In-Service Defects

The problem of in-service defects and the various mechanisms that cause them (e.g., fatigue, high temperature, wear, and embrittlement) have been dealt with in detail elsewhere (see *Defects Introduced in Metals During Fabrication and Service*). In a number of cases the defects appear typically as cracks, changes in the mechanical and physical properties of the material (e.g., density, hardness, attenuation, reduction in thickness), and reduction in thickness. This makes it possible to apply well-known and established NDT methods (see section 3.6).

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Biographical Sketch

George Georgiou graduated from Imperial College in Mathematics in 1972. He became a Mathematics lecturer at Tottenham College of Technology until 1983. He gained his Ph.D. in 1982, as a part-time student at City University London, on theoretical fluid dynamics. From 1983–1985 he was a research assistant at University College London working on numerical methods for elastic wave scattering problems. From 1985 to 1990 he was a scientist at Topexpress Ltd. in Cambridge and worked on a variety of mathematical models, including internal waves in the ocean and ultrasonic Non-Destructive Testing (NDT). At Topexpress he worked extensively on the elastodynamic Geometrical Theory of Diffraction (GTD). From 1990–1998 he was at The Welding Institute (TWI) as Manager of the Inspection Section and worked on a wide range of NDT related problems, in particular, long-range ultrasonic NDT, radiographic and ultrasonic codes of practice, the NDT of plastics and adhesives, the mathematical modeling of ultrasonic guided waves, and thermography. He has published more than 90 technical papers and project reports, reviewed numerous technical papers and books on mathematics, engineering, and NDT, and has presented many papers at national and international conferences. He received the John Grimwade medal from the British Institute of NDT (BINDT) for best paper in 1989 on GTD, and was the joint winner of the Ron Halmshaw Award for the best paper on Radiology in 1997. He has served as a National expert on the British (BSI) and European (CEN) committees responsible for the ultrasonic inspection of welds since 1990.

He was chairman of the BINDT Technical Committee (1998–2000), which coordinates overall policy for the Institute's technical issues, and was an elected member of the BINDT council (1998−2001), and is Vice−President of the British Institute of NDT. His other activities within BINDT from January 2003 include chairman of the Membership, Education and Qualification (MQ&E) Committee. He is Director of Jacobi Consulting Ltd., offering independent consultancy on a range of mathematical, engineering, and NDT topics.