A FRAMEWORK TOWARDS ACHIEVING QUALITY IN CASTING: A REVIEW

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ABSTRACT

This paper gives an idea about the defects and inspection methods of casting which can be fruitful to other researcher for the future work. Casting is the backbone of mechanical manufacturing industry and it is the prime goal of any organization to reduce defects and rejection for revenue generation and survival in the global competitive market for resilience and robustness. Main extract of various researcher in the literature reviewed is to promote higher productivity with least wastage or reduced rejection with good quality by applying various quality tools. As the industries are producing with full capacity to meet varying demands and the conventional quality techniques for maintaining quality of the product is no more contemporary.

Keywords: Contemporary, Conventional Quality Techniques, Resilience, Robustness and Quality Tools

I. LITERATURE REVIEW

Casting is one of the most ancient metal-shaping techniques, and is the process of forming metal objects by melting metal and pouring it into moulds [1]. Discontinuities are a common problem in castings. Discontinuities are irregularities, breaks, or gaps in the material structure. Most types of casting discontinuities are visible to the naked eye and are caused by variation in the casting process. However, some of them are not detectable by visual inspection because they occur below the surface of the material. The sub-surface is the most highly loaded region of the material. Therefore, sub-surface discontinuities such as cracks, inclusions, or pores greatly influence the ability of a component to withstand load. Sub-surface discontinuities must be detected and identified before remedies can be developed to eliminate them [2].

With the emergence of modern design techniques and aluminium alloys, the mechanical strength of castings is usually not a problem. However, automotive castings are often in contact with fluids under pressure, including transmission fluid, engine oil and coolant. Hence, a more likely problem is that, the castings with defects are subjected to leakage under pressure. Therefore, die casting manufacturers inspect their castings for defects that may cause leakage under pressure prior to supplying them to their customers. These defects primarily relate to porosity and cracks. In the 21st century, casting manufacturers need to maintain standards and keep abreast of the latest technologies to be competitive in the international market. George Johnson expressed a similar view in his keynote address on “The people/technology partnership”.

"To survive and prosper in the coming years, successful foundries will have to be leaders in quality, cost, technology and response to customer needs"

Even though this statement was made in the early 1990's, it remains valid for the casting industries. Hence, maintaining an ISO 9000 series certification is not sufficient to maintain a market share of produced goods. Quality assurance programs will often pass or reject the entire production lot based on randomly inspected samples. If a quality system detects a fault in a single sample at customer's site, the whole consignment will be scrapped. Therefore, it is essential that the manufacturer detect every fault, in order to avoid costly delays, ever increasing scrapping cost and customer dissatisfaction. As the cost of scrapping goes up, there is an increasing need for a cost effective advanced inspection system. The new system should emulate the skills, decision making capacity and the supervisory control of the operator. A thorough knowledge of the casting process is an essential requirement for the development of a new quality inspection system [2].

As mentioned above, a casting organization's relationship with a customer is enormously influenced by the quality of castings delivered and the satisfactory quality requirement varies from industry to industry. Thus, the inspection process is an important step in the quality assurance program for most die casting manufacturers [3]. While there are a number of elements that go into the implementation of a Total Quality Management (TQM) system, in this research the focus is on Non-Destructive Testing (NDT), specifically ultrasonic based inspection for detecting sub-surface defects in the aluminium die casting industry.

NDT techniques include ultrasonic, X-ray, liquid penetrant, eddy current, leak and magnetic particle testing. They have been previously used in different areas of the casting industry, mostly on machined casting products [4]. At present, in the automotive industry an operator detects defective castings off-line, using X-ray or leak NDT methods. However, none of these systems provides feedback to the die casting machines in real time. Due to the amount of time required, it is not possible to carry out a 100% inspection of all castings produced using these methods. Hence, there is a compelling need for a reliable high speed inspection system to identify defects.

Rickards and Wickens [3] identified the most important problem areas in the casting inspection process and brought courses of action to the attention of casting industries in their investigation. These were based upon the wider understanding of NDT techniques used, making the best use of the equipment available and ensuring that the correct procedures were employed.

In this investigation, importance of NDT inspection methods has been emphasized for overall casting inspection. However, the ability to test castings using NDT methods is dependent on the type of metal, surface roughness, grain structure and type of defect to be detected. These factors increase the overall complexity involved in identifying quality castings using ultrasonic inspection. Most ultrasonic techniques were developed in the die casting industry to inspect castings with simple geometries and machined surfaces. A technique could not be described as non-destructive if it requires alteration of a surface prior to inspection. Another problem with this method is that it may expose the porosity defects just beneath the rough surface. Defects at greater depth (more than 3 or 4 mm) are not of much consequence in casting inspection [5]. The machining process would also change the substrate structure of the casting and therefore, change the overall properties of the part to be inspected. In the past, ultrasonic inspection of castings was restricted by their metallurgical and physical characteristics.

The research project was undertaken in accordance with the following problem statement: To investigate the possibility of using an ultrasonic inspection technique to detect small sub-surface defects (gas porosity) near the front rough surface of castings with varying grain size, by classifying weak and noisy ultrasonic signals using suitable signal processing techniques.

According to Krautkrämer and Krautkrämer [5], the success of casting inspection generally depends on the selection of a suitable probe frequency. The resolution of the ultrasonic probe, or the smallest defect size that can be detected, is half the wavelength. Therefore, smaller defects can be detected with higher frequencies of ultrasound. Unfortunately, the higher the frequency also means the higher the rate of signal damping in a material, and more scattering at the rough surface. In terms of this project the measurement capability of the probe is compromised if the frequency of the ultrasound is too low (1 MHz or 2 MHz) making it hard to detect defects less than one millimeter in size. Hence, there is a need to obtain a balance between the possibility of ultrasonic inspection and the requirement to detect small gas porosity defects in rough surface castings. A metal casting may be defined as a metal object produced by pouring molten metal into a mould containing a cavity which has the desired shape of the end product, and allowing the molten metal to solidify in the cavity [1]. Historical data indicates that casting began around 4000 B.C. According to Taylor et al. [6], copper was the first metal to be cast – it was used to produce bells for large cathedrals at the beginning of the 13th century. In the 14th through 16th centuries, metal casting evolved from what was an art form to the casting of engineering shaped components [7]. However, the first authenticated casting in aluminium was produced in 1876 [8]. In the present context, die casting involves all processes that are based on use of metallic moulds [9]. The selection of the mould materials depends on the alloy being cast, the number of parts to be produced and the size of the parts. The process is a highly mechanized one, in which dies may be interchanged without making changes to the machine. Metal for die casting is melted in holding pots and transferred to the die casting machine pot as required. Dies are water-cooled so as to maintain them at constant operating temperatures. This prolongs the life of the die and provides the fastest allowable cooling rate for castings so that they develop optimum properties [9]. High Pressure Die Casting (HPDC) differs from permanent mould castings wherein the metal is forced into the mould cavity under high pressure. In HPDC, molten metal is injected into a metal mould (die) at a high velocity. The solidification of the metal results in the end product [10]. Advantages of the HPDC process include the ability to produce thin sections and the short cycle time involved. In comparison with other metal working methods, die casting is carried out with a minimum expansion of metal [11]. In the die casting industry, the major problem is the inability of the die casting process to produce parts without discontinuity [13]. There are a number of factors that cause discontinuities in the castings. Sinha [14] investigated the types of failures in castings arising from manufacturing discontinuities. The discontinuities are regarded as true defects or flaws when the satisfactory function or appearance of the product is affected. Castings with such discontinuities are rejected and scrapped. The logical classification of casting defects presents great difficulties due to a wide range of contributing causes, but grouping the defects in certain broad categories based on origin of defects is an accepted practice. Davies [15] stated that casting design and technique of manufacturing have an influence on the production of sound castings. According to Davies, depending on the location of the casting defects, they can be divided into two major categories, namely surface and subsurface defects.

II. SURFACE DEFECTS

Surface defects are discontinuities occurring on the surface or near to the surface (exposed to surface) of the castings. Surface defects in aluminium die castings can result from deficiencies at any stage of the manufacturing process [16]. The prevention of surface defects is a key requirement when producing most aluminium die castings. The prevention of defects related to the casting process can best be achieved through proper design of the die and feed system and control of the variables associated with the die casting process [16]. Rowley [17] has described in detail the major surface defects of castings – gas run, cope defect, seams, flow marks and slag inclusions. Most of these defects are related to the surface of the die and temperature of the mould, and result from pouring metal that is too cold into the mould. Usually these imperfections occur in castings with relatively light sections where two surfaces of flowing metal meet and do not fuse properly. In cold shuts, small shot-like spheres of metal are almost completely distinct from the casting. This can usually be prevented by using higher pouring temperatures. Surface defects may also be related to the finishing process at the surface. Crack-like defects that emerge on the surface of a material through propagation are possible sources of failure under conditions of either stress or corrosion, or both [6].

III. SUB-SURFACE DEFECTS

Sub-surface defects are not visible to the naked eye due to their occurrence below the surface of the castings. Typical casting sub-surface defects are [17]:

- Shrinkage cavities generated by contraction during solidification and insufficient feed of metal.
- Blowholes and porosity occurring when gas bubbles are released during pouring and cooling.
- Non-metallic inclusions generated by interaction between the molten metal and the mould material, a piece of the mould material itself, or by oxide films swept along with the metal pouring, and
- Hot tears caused by shrinkage during solidification, in combination with restrictive stresses.

Unlike the crack-like defects, all other casting defects are more or less voluminous and globular. For instance, the gas porosity defect is the most common voluminous and globular defect in high pressure die castings [16].

Among the different sub-surface defects presented in this section, porosity type defects may lead to hazardous flaws with regard to the loading capability of a material. These defects can be defined as voids in the material where the cast metal alloy is absent [18]. Much of the porosity is simply air entrapped as the metals move through the shot sleeve and runner. Air will enter the die cavity unless it is removed using a vacuum technique. When such air or gas entrapment is sufficiently large and is located just under the skin of the casting, blistering may result. The air or gas in the void is subjected to the metal injection pressure.

Surface reactions sometimes cause sub-surface porosity or pin holes. In aluminium alloys containing more than 1% magnesium, a reaction tends to occur between the magnesium of the alloy and the water vapour of the mould [6]:

$$\mathbf{Mg + H20 = MgO + H2\ (gas)}$$

Gas porosity defects in aluminium alloy castings generally appear as rounded pores associated with gas, or as elongated inter-dendritic pores referred to as shrinkage porosity [13]. Common causes of excessive air porosity are turbulence in the shot sleeve and in the runner, poor flow patterns in the gating system, low metal temperature, blocked vents and overflows and excessive lubricants.

A large level of porosity, which is located in the centre of the casting may not effect mechanical properties or fatigue performance. A smaller, isolated pore near a surface may have a significant impact on the performance of the castings. However, according to Gupta et al. [21], the level of casting imperfections such as gas porosity is not always pre-determinable and they are generally unwanted in the end product.

IV. NON-DESTRUCTIVE TESTING

Non-destructive testing (NDT) is the branch of engineering concerned with detecting flaws in materials. Flaws can affect the serviceability of the material or structure. Therefore, NDT is important to guarantee safe operation of the components and as well as quality control. NDT is also used for in-service inspection and condition monitoring of an operating plant and measurement of physical properties such as hardness and internal stress. The essential feature of NDT is that the test process itself produces no deleterious effects on the material or structure under test [22]. Raj [23] highlighted the fact that the subject of NDT has no clearly defined boundaries. NDT ranges from simple techniques such as visual examination of surfaces to well-established methods such as radiography, eddy current testing, ultrasonic testing and magnetic particle crack detection. NDT methods can be adapted to integrate with automated production processes. Sattler [24] shared a parallel view that the term NDT is used to describe all methods which make the testing possible, or inspection of a material without impairing its future usefulness. Further, Sattler stated that from the industrial viewpoint, the purpose of NDT is to determine whether a material or part would satisfactorily perform its intended function.

V. NON DESTRUCTIVE EVALUATION

Non-destructive evaluation (NDE) is a term used often interchangeably with NDT. However, technically, NDE is used to describe measurements that are more quantitative in nature. For example, an NDE method would not only locate a defect, but it would also be used to determine characteristics of that defect such as its size, shape, and orientation. NDE may also be used to determine material properties, such as fracture toughness, formability, and other physical characteristics [25].

VI. NDT&E TECHNOLOGIES

At present, five major methods are available for inspecting metal casting. These methods are, Magnetic Particle Testing, Liquid Penetrant Testing, Ultrasonic Testing, Radiographic Testing, and Eddy Current Testing. Other less commonly used methods include Acoustic Emission and Thermal Radiation methods [4]. No single method can provide a complete solution for casting quality inspection. In some cases, a combination of NDT methods is usually used to determine the desired inspection parameters [4]. Presented below is a brief literature review on the five major NDT methods.

6.1 Magnetic Particle Testing

Magnetic Particle Testing (MPT) is a NDT method that detects surface and near surface discontinuity in ferromagnetic materials using the principle of magnetization [26]. Typically, a high current is passed through the casting, which in turn, establishes a magnetic field. If a discontinuity is present, it will disrupt the magnetic flux field from the current flow, resulting in a flux leakage. The inspection medium (iron particles) that is applied simultaneously with the current will be attracted to the areas of flux leakage and provide a visible indication of the discontinuity (i.e., particles will pile up over the area of the discontinuity). The external magnetic field indicates the internal defects. The surface condition of the component plays a vital role in MPT since it affects the flow of the magnetic field on the surface of the component.

The major advantage of this test method is that it is quick and simple in principle and application. It is very sensitive to the detection of very minute (less than 1 mm) shallow surface cracks. On the other hand, it has the disadvantage of being applicable only to ferrous materials. Furthermore, care is required to avoid burning of the casting surface at the points of electrical contact [27].

6.2 Liquid Penetrant Testing

Liquid Penetrant Testing (LPT) can detect surface discontinuity in both ferrous and non-ferrous castings [4]. This method uses the principle of capillary action which is the ability of a liquid to travel to or be drawn into a surface opening. The most critical step in this penetrant process is the pre-cleaning of the casting. Because the penetrant physically enters the discontinuity, the opening of the discontinuity must be free of any material that could inhibit the movement of penetrant.

This method is highly sensitive to fine, tight surface discontinuities such as cracks and cold shut. It is also effective in the detection of rounded indications, such as porosity. The discontinuity indications are viewed on the casting surface. The limitation of LPT is that the discontinuity must be open to the inspection surface. Based on the investigations carried out by Glatz [28], LPT is not always effective in locating small surface flaws in certain complex shaped parts. Further, the LPT method cannot be used detect sub-surface discontinuities.

6.3 Ultrasonic Testing

Ultrasonic testing (UT) methods use high frequency sound waves to detect surface and sub-surface discontinuities in both ferrous and non-ferrous castings [5]. UT can also be used to gauge the thickness of a casting. Because UT enables the investigation of the cross-sectional area of a casting, it is considered a volumetric inspection method.

UT has several advantages in both product quality control and in-service inspection for locating and characterizing sub-surface defects and evaluating the mechanical properties [29]. These advantages include high probability of defect detection, less cost for automation and less hazardous to environment. However, there are problems in identifying defects such as porosity, inclusions and cracks in castings [30]. The major limitations are due to the sensitivity of ultrasonic inspection with respect to the grain size and surface roughness of the castings [31].

6.4 Radiographic Testing

Radiographic Testing (RT) is a method that uses X-ray or gamma energy to pass ionizing radiation through a casting to reveal internal discontinuities on a film medium [32]. Gamma rays are ionizing radiations which are the product of nuclear disintegration from a radioactive isotope. The RT method can be used with both ferrous and non-ferrous castings. This inspection technique utilizes the ionizing radiation to penetrate the cross-sectional area of a casting and expose a piece of radiographic film. When discontinuities such as cracks, gas and shrinkage porosity are present in a casting, less radiation is absorbed and more radiation reaches the film. This increased film exposure to the radiation ultimately produces an image of the discontinuity on film.

Advances in computer technology have led to a CRT screen replacing the film. With this technology internal discontinuities are revealed on the screen in real time. An advantage of radiography is that it can provide a permanent record of the casting quality after inspection. The orientation of the radiation source, the object and the film may cause distortion in the projected discontinuity image. The inspection requires access to both sides and surfaces of the casting. The discontinuity in the casting must be parallel to the radiation beam for the best possible detection. The disadvantage of this technique is that the casting thickness and density limit the possible range of inspection [31, 32].

6.5 Eddy Current Testing

Eddy Current Testing (ECT) utilizes an induced low-energy electrical current in conductive ferrous or non-ferrous materials. The alternating current creates an expanding and collapsing magnetic field in a longitudinal direction across coil windings. The magnetic flux is created, extending into the casting which in turn induces the flow of the eddy current. When a discontinuity is present, it affects the characteristics of the magnetic field associated with the eddy current, which then alters the interaction between the two magnetic fields detected at the surface. This altered interaction is displayed on the eddy current instrument display.

This inspection method is suitable for the detection of surface flaws or material changes that may not be detected by other NDT inspection methods [24]. A major limitation of the ECT inspection method is that it requires considerable knowledge and experience to properly establish inspection techniques and interpret the results. A further disadvantage is that it is only suitable for electrically conductive materials.

VII. FLAW DETECTION IN CASTINGS

In the case of castings, flaw detection is almost exclusively concerned with manufacturing defects rather than with in-service inspection. The requirement for the quality inspection of castings is dictated by the end use of the casting. Each industry has specifications and acceptance criteria developed around each type of product manufactured. The testing of castings is complicated due to several variables such as the surface condition of the metal which are discussed later in this chapter. In an investigative study, Barberis [33] found that NDT had been used in casting industries for more than 50 years. This was mainly due to the customers of die casting manufacturers, who expected castings to be supplied to a defined quality standard. Conformity to this standard usually depends on the quality of the inspection system. NDT of castings provides quality assurance for end products delivered to customers, and involves a combination of physical inspection methods that can be used to determine the integrity of a casting without causing physical damage to it. Bowland [34] provided an extensive analysis of NDT inspection methods for castings in his research work. The importance of quality assurance and training was emphasized for each of the inspection methods used in the casting industry. Liquid penetrant, magnetic particle and visual test techniques have been used extensively for surface defect detection [4]. Radiography and ultrasonic techniques have been used for sub-surface defect detection [33, 35]. In this section, emphasis has been given to inspection techniques that are relevant for sub-surface defect detection.

Leak testing of castings usually involves some form of wet bubble testing, often carried out in hostile environments [36]. Such testing usually has the relatively simple goal of determining whether a part leaks or not. The problem with using a leak test method to find a leak in a casting is the inability to identify the type and location of a defect. Heine [37] noted that evaluation of leak rates is qualitative, and subjective, and is always compared to standardized test procedures. Hence, tests should be conducted, beginning with leak tests and then progressing to more sensitive methods to obtain quantitative results.

Radiography has been the preferred method for testing castings. But radiography has inherent dangers because the radiation produced can have a detrimental effect on operators if they are exposed to it. The other problem with the X-ray image or radiography approach is related to the reliance on human operators to interpret the images produced. Human error in identifying defects in die castings may occur due to operator fatigue, distraction and lack of sufficient experience. There may be circumstances where orienting a casting properly for radiography is impossible due to shape and thickness constraints. In such cases, radiography is not useful in the inspection of castings. However, digital radioscopy has experienced a significant upturn in the past few years as noted by Hanke [38] due to better digital images plus the development of increasingly powerful and complex algorithms for image processing.

Even though radiography is the generally accepted test method for castings, ultrasonic inspection can also be used due to its low environmental impact and its effectiveness with respect to near-surface defect detection and location [35]. However, castings do present a problem in relation to ultrasonic inspection, the parameters affecting propagation of ultrasound in the die castings (test specimens) are discussed. The surface roughness of die castings and their dimensional variations scatter the sound pulse and make discontinuities difficult to detect. Some of the problematic areas of ultrasonic NDT such as surface roughness and grain size variation need to be addressed as suggested by Rickards and Wickens [3]. Lavender [39] has discussed the effects of surface conditions on performance of different methods of NDT. Apart from these problems, the ultrasonic inspection method also requires a vast amount of knowledge and experience to fully establish an inspection methodology and interpret results.

Lavender and Wright [40] discussed some of the advantages of ultrasonic inspection over radiography, including the cost factor. According to their findings, ultrasonic inspection has a large cost benefit ratio compared to radiography due to the ease of automation. Recently, Kleven and Blair [41] presented a comparison of ultrasonic and radiography inspection techniques for the testing of castings. They concluded that a reasonable balance has to be maintained in the inspection of castings. When the defects are oriented parallel to the scan surface, ultrasonic inspection is suitable, and if oriented perpendicular to the inspection surface then X-ray inspection is suitable. In some cases, a combination of both ultrasonic and radiography has to be used. This also confirms the views of Long [4], who concluded that a single inspection technique does not provide a complete solution for casting inspection. Another factor indicated in Table is that near-surface detection and surface roughness are not easily accommodated with ultrasonic inspection.

Characteristic	**Ultrasonic**	**Radiography**
Equipment cost	+	-
Operating training	-	+
Near surface detection	-	+
Portability	+	-
Large part size	=	-
Rough surface	-	=
Need for calibration	-	+
Part attenuation/grains	-	=
Intricacy of part geometry	-	=
Limited plant space	+	-
Discontinuity orientation	=*	=**
Permanent record	-	+

- not advantageous
+ Advantageous
= moderate advantageous
* If oriented parallel to scan surface (planar or crack like)
** If oriented perpendicular to part surface/radiation beam (planar or crack like)

Comparison of ultrasonic and radiography inspection of castings [41]

VIII. CONCLUSION

The organizational culture has been recommended as an illuminating variable for the level to which a company meritoriously implements its quality practices. Literature act as great source of learning. It includes wide variety of quality practices. It concludes that organization should invest on promoting learning and continuous improvement processes.

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