

Ultrasonic Inspection of Sub-Surface Defects In Aluminium Die-Castings

by

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Abstract

Non-destructive testing using ultrasonic measurement is used to ensure the quality of the die-casting products. The quality of a casting depends on the presence of discontinuities such as porosity and on the final metallurgical structure. Discontinuities occurring in the sub-surface of the cast structure mostly have irregular surfaces which scatter the ultrasound waves and make ultrasonic testing more difficult. The effective use of ultrasonic testing for inspection of castings depends greatly upon the skills and expertise of the operator. However, the initial experimental set-up is important to develop a proper inspection procedure that is easily understood by the operators. The aim of the present work is to investigate and develop an automated ultrasonic inspection system for detecting sub-surface defects in aluminium die-casting parts. Two sample test cases were selected from the industrial partners. Ultrasonic immersion testing was carried out on the sample parts using different probes situated at different water path distances to obtain the best possible signal from the defect. The results obtained from the experiments have demonstrated the feasibility of developing an online automatic inspection system to detect sub-surface defects in aluminium die-casting components.

1. Introduction

Many die-casting organisations are concerned with internal porosity problems in their castings. Much of the porosity is simply air entrained as the liquid metal flows through the shot sleeve and runner. Porosity in aluminium alloy castings generally appears as rounded pores associated with air or as elongated inter-dendritic pores. Although the level of sub-surface casting imperfections is not always pre-determinable, it is generally unwanted (Gupta, et al., 1992) because it might weaken the strength of the casting and also might cause leak if the defect is opened to the surface.

At present, Ultrasonics, X-ray, Liquid Penetration, Eddy Current and Magnetic Particle testing are used in different areas of the casting industry mostly with finished products (Long, 1998). Castings can be ultrasonically inspected to detect manufacturing defects such as shrinkage cavities, blowholes, pores and porosity, inclusions, segregation and cracks. Ultrasonic inspection provides qualitative indications of discontinuities and is useful in the inspection of castings of simple design where the echo pattern is reliably interpreted. Either pulse echo or through transmission techniques are used to determine the presence, location, relative size or severity of flaws.

The major limitations on the use of ultrasonics for inspection of castings are size, shape, thickness, surface roughness and orientation of defects. Metallurgical characteristics of castings such as coarse grain structure cause strong attenuation of the sound beam. Both contact and immersion methods are used to detect defects in castings. The immersion method is preferred for castings having rough and irregular shape. Hence, in this case, due to the sample part having a rough surface the immersion test system was used. In addition, contact inspection, using different frequencies, is carried out on the sample castings. This was carried out to prove that it is not a viable technique for inspecting rough surface die-castings.

The objectives of this research program emphasised the necessity of obtaining an understanding of the casting process and use of ultrasonic inspection. Once the components of casting and non-destructive testing are understood then it is possible to duplicate the expertise of a human inspector in the inspection area through an automated system. The experimental set-up and results obtained from ultrasonic immersion testing of the test cases are discussed in the later part of this paper.

2. Ultrasonics Testing

Ultrasonic non-destructive testing, which utilises sound waves at frequencies beyond human hearing (more than 20KHz), is a widely accepted technique for flaw detection. Ultrasonic testing takes a leading role in product quality control inspection compared to other NDT methods for locating and characterising sub-surface defects in the welding industry (Jack, 1996). Notwithstanding the advantages of ultrasonic inspection there are problems in identifying defects such as porosity, inclusions and cracks (Chen et al., 1999).

The ultrasonic inspection method requires a vast amount of knowledge and experience to properly establish inspection techniques and interpret results. The surface roughness of castings and their dimensional variations scatter the sound pulse and make detection of discontinuities difficult. The other major problem with ultrasonic inspection is associated with the grain size of the casting.

There has been much research carried out to increase the reliability of ultrasound testing technology. There have been problems associated with the different heat conductivity of casting materials and the orientation of the grain changes during casting. Between 1985 and 1987, Kuppermar et al. (1985 and 1987) researched the effect of structure orientation on ultrasound propagation. They also examined changes in ultrasound propagation speed and beam skewing in testing the properties of material. Nelligan (1992) has demonstrated that ultrasonic flaw detectors can be used to detect internal flaws in castings. However, for shop floor applications, the operator should be experienced and have reference standards to be able to reliably interpret the echoes. Most of the experiments carried out were related to thickness measurement of castings and material analysis, but he also carried out flaw detection of castings. Nelligan stated that defect detection could be automated in cases where relatively simple casting geometries, smooth surface finish and proper flaw detectors are involved.

3. Sample Parts

A good example of a problem of sub-surface discontinuities is found in the manual transmission case (MTC) housing. The critical areas for inspection are the areas around the bearing and seal bosses where extensive porosity is found. Porosity can cause leaks in parts containing fluids, as well as tool breakage, and both result in rejects and incur significant cost penalties. Such a casting is complex, costly and often-significant value is added because of the extensive machining required. Also, such castings are often part of a complex assembly, which further adds value.

Another sample casting is the structural oil sump pan (SOSP), which suffers from leakage problems caused by porosity in the in-gate region. The gate area is the last area to solidify, and shrinkage in this zone causes porosity. The porosity problem is further aggravated by the removal of the gate, which is done by breaking the gate off the sump. This exposes any porosity, and causes a rough surface with openings of up to 2-3 mm in depth. If cracks are present and extend through to the other side, a leak(s) will result.

With modern design techniques and aluminium alloys, the mechanical strength of castings is usually not a problem. Few such castings actually break. A more likely problem is that a casting may leak due to the opening of sub-surface discontinuities. Automotive castings are often subject to fluids under pressure, including transmission fluid, engine oil, and coolant. Therefore, detection of porosity and other defects that cause leakage is important.

The material of the two sample parts have more or less the same combination of base Al, Si, Fe, Cu, Mn and Mg elements. In addition to the above elements less than one percentage of Ti, Cr, Ca and P are also present in the alloy.

4. Material Properties

The material properties affect the sensitivity of ultrasound frequencies in inspection applications. The smaller the defect the higher the frequency of ultrasound required for detecting it. Unfortunately, the higher the frequency also means the higher the rate of signal dampening in a material. When testing the selected sample part, the attenuation of the test signal was found to be a major factor due to the coarse grain structure of the material. To reduce the dampening of ultrasound within the test material, lower frequency probes are preferred. However, the testing capability of the probe is compromised if the frequency of the ultrasound is too low (for example less than 2MHz). Furthermore, to be able to increase the amplitude of the ultrasound signal, the probe should not be too small (not less than 5mm diameter). Due to the detrimental effect of surface roughness on the ability of ultrasound to enter the specimen, a couplant is required to facilitate the binding of the probe to the specimen. This allows for better penetration of the ultrasound. In this research the straight beam and angle beam pulse echo methods were employed and the propagation time and amplitude change of the reflected signal were measured to determine the effect of cavities on ultrasonic waves. The equipment and the transducers selected for this research were the EPOCH III flaw detector and 10MHz and 20MHz probes (to compensate for the problems of small

thickness of casting and surface roughness). Once the equipment and the probes were selected ultrasonic immersion testing method was selected. The literature review assisted in the selection of the appropriate inspection method and the experimental results were validated by X-ray inspection of the sample parts.

Adler (1989) and other researchers investigated the ultrasonic immersion technique for evaluation of porosity in smooth surface aluminium cast materials and used volumetric analysis to determine the gas porosity.

5. Experimental Set-up

In automated ultrasonic inspection the technique involving total immersion of the work has become universally accepted, as stated by Banks et al. (1962). This requires the use of an immersion tank where the part is placed under water and the transducer is immersed in the water over the inspection area. The experimental set-up for this research consists of an ultrasonic flaw detector (EPOCH III), immersion probes of 10MHz and 20MHz, a water tank, calibration blocks, probe holding device and probe handling device. A special probe holding device was designed using Pro/Engineer, CAD software. The major factors considered in the design were the total payload that the PUMA robot (probe handling device) can handle, 4.0kg under static and 2.5kg under dynamic conditions and the easy handling of the probe. The final design of the device was found to have a mass of 1.25kg. Two laser pointers were attached to the probe holding device for focusing the ultrasonic probe on the immersed part. The sample part was immersed in the water tank and the PUMA robot was moved on the top of the casting, where inspection was carried out and the reading were stored in the flaw detector. The following paragraphs discuss the results obtained by both contact and immersion testing.

6. Results

In ultrasonic contact testing 5MHz and 10MHz frequency normal beam contact probes were used. The back wall echo (reflected ultrasound signal from the back surface of the casting) was not obtained in certain sections of the sample parts. In the case of angle beam contact probes, different angled wedges (30, 45, 60 and 70 degrees) were used. Due to the rough surface, it was difficult to move the probe along the surface of the casting. The ultrasound contact testing experiments carried out on the test cases supported the view of other researchers that it was quite difficult to obtain satisfactory results with contact inspection. Hence, immersion testing was carried out on the sample castings.

Before starting the ultrasonic immersion testing calibrations were carried out, one on the PUMA robot and other on the ultrasound equipment. These calibration tests were required to confirm the accuracy and repeatability of the test results. The calibration tests on the PUMA robot were carried out by repeatedly moving the robot arm to a particular point a total of 20 times. The variations in the co-ordinate values were recorded using three dial-gauges for three directions (X, Y and Z). The repeatability of the PUMA robot indicates a robot accuracy of $\pm 0.1\text{mm}$ at a particular position.

Similarly, the calibration of the ultrasound signal was carried out on the sample castings N2 without defect and N5 with a defect section. In this experiment ultrasound signals from a particular section were obtained 20 times in three sets. Only at a particular point there was a variation when the robot was moved out of the water column and back to the test case, the air bubbles were formed at the tip of the probe. Hence, there was a drop in the ultrasound signal at this point in the measurement process. Otherwise, there was only a slight variation of ± 1 dB.

The suitable velocity range for the inspection of aluminium castings was determined by carrying out multiple ultrasonic contact testing to maximise the amplitude of the ultrasound signal reflected from the sample parts. The ultrasound velocity was found to be 6256 m/sec in the selected sample die-castings. Then the ultrasonic signal was focused at the back surface of the casting to get the maximum amplitude with the velocity of ultrasound in aluminium. This was to ensure that the probe was perpendicular or normal to the back surface. Since 72% of ultrasound was reflected back at the water-aluminium interface, these experiments ensured maximum amplitude signal was obtained from the remaining 28% transmitted into the aluminium sample part. The distance between the probe and the part (sample casting) was referred to as the water path distance. The water path (WP) distance was obtained from the Equation 1.

$$\text{Water Path Distance} = F - \left[MP \left(\frac{V_m}{V_w} \right) \right] \dots\dots\dots (1)$$

- where F = Focal length in water = 1" = 25.4 mm
- MP = Material Depth (mm)
- V_m = Velocity of ultrasound in material = 6256 m/sec
- V_w = Velocity of ultrasound in water = 1480 m/sec

Immersion testing was carried out on the sample castings by using the experimental rig as described in the previous section. Results were obtained from the optimisation of water path distance and probe frequency at 60 different positions on the sample castings. At 10MHz and 7.5mm water path distance, 85% back wall echo signals were obtained with the remaining 15% being lost due to surface roughness. From Figure 1 it was evident that at 10MHz and 7.5mm water column distance the maximum back wall signal was obtained compared to 20MHz for different water path column distances ranging from 7.5mm to 17mm (calculated using Equation 1).

The results obtained from immersion testing were validated against the X-ray results obtained from radiographic inspection.

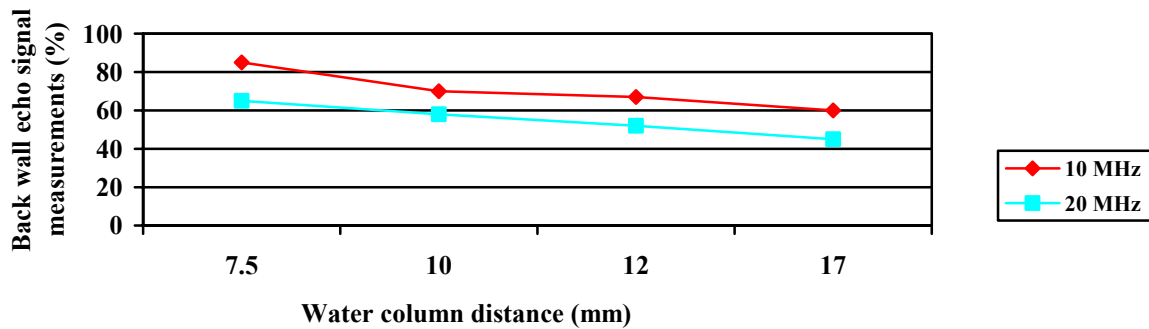


Figure 1. Optimisation of Water Path Distance and Probe frequency (at 60 different positions on the sample castings)

7. Conclusion and Future Work

The literature review revealed that there has been little research on ultrasonic inspection of aluminium die-castings using the immersion technique. The main conclusions that can be drawn from the present research are:

- Calibration of the equipment is necessary to ensure that reliable results are obtained from the inspection system;
- The results of contact inspection tests on the sample parts proved it is difficult to carry out inspection on a rough surface;
- Finally, the velocity of ultrasound in the material, the water path column distance and the frequency have been carefully selected to ensure effective inspection of the sample die-castings.

In future work, investigations will be carried out with the current experimental apparatus, and procedures will be developed for effective inspection of aluminium die-castings. The defect classification is being carried out with the use of feed forward back propagation neural networks.

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