Ultrasonic inspection of rough surface aluminium die castings

S Palanisamy, C R Nagarajah and P Iovenitti

Most ultrasonic techniques developed in the die casting industry were to inspect castings with simple geometries and machined surfaces. A technique could not be described as non-destructive if it required alteration of a surface prior to inspection. This paper describes an investigation into the possibility of using an ultrasonic sensing-based non-destructive testing system to detect defects in aluminium die casting parts with rough surfaces. As the signal-to-noise ratio is very important in quantifying sub-surface defects, the major factors relating to noise creation in the ultrasonic signal during ultrasonic immersion testing were identified and addressed. The application of ultrasonic testing to inspect rough surface aluminium die castings with side-drilled holes to simulate porosity type defects is described in detail. Investigations indicate that the scattering from the rough surface of the castings masks the defect signal when the defect was close to the front surface. The results obtained from ultrasonic immersion testing indicated that focused ultrasonic probes operating at frequencies between 5 MHz and 10 MHz were best suited for the inspection of castings with surface roughness R_a values varying between 50 µm and 100 µm.

Introduction

The condition of the surface through which a sound beam enters a material is an important factor in ultrasonic non-destructive testing[1]. Detection of discontinuities such as cracks, voids and porosities in castings is greatly affected by the extent of roughness. Increased roughness reduces the transmitted energy of the sound beam and this, in turn, reduces the amplitude of the received signal, leading to difficultly in measuring the size of the discontinuity[2]. The measurement of back-wall echo amplitude provides a better understanding of the effects of material characteristics on signal attenuation. Appreciation of the problem has led to a large number of studies investigating various aspects of material characteristics on ultrasonic test signals[3-9]. From the literature, it is evident that the results obtained were based on theoretical or model-based studies[9-18].

Thavasimuthu *et al*[9] investigated the effect of front surface roughness on the ultrasonic signal amplitude in samples with various discontinuities using ultrasonic contact testing. They have concluded that the increase in surface roughness results in loss of ultrasonic signal amplitude and selection of equipment and probes are dependent on surface roughness and defects to be inspected. A similar study was carried out by Bilgen[10] in his doctoral research work on the effect of surface roughness on ultrasonic immersion testing in detail using a theoretical model. According to Bilgen[10], only the coherent part of the ultrasonic wave field participates in focusing and it dominates the backscattered signal. Hence, in the focal region, the signal-to-noise ratio is relatively unaffected by surface roughness, as the signal and noise are altered in the same manner. However, for a surface roughness above 25 µm, the coherent part of the ultrasonic beam becomes negligible even in the focal area and a high loss in the signal-to-noise ratio results[10]. Focusing changes the backscattered signal and consequently attention must be given to select a suitable ultrasonic focus probe in order to accommodate the surface roughness variation.

Rose *et al*[12] used an ultrasonic NDT method to identify gas porosity defects in aluminium alloy castings. They also investigated the effects of surface roughness on ultrasonic signals from the castings. Their study concentrated on quantitative assessment of gas porosity defects in die casting aluminium materials of plate-like geometries. Similarly, Adler *et al*[13] investigated porosity defects in aluminium cast materials, and used volumetric analysis to identify gas porosity defects. They studied the effects of backscatter in their work on the ultrasonic inspection of aluminium cast materials. Their theoretical analysis of the attenuation ratio indicated that it was independent of frequency or surface roughness up to 40 µm root mean square value (*ie*, equal to 36 µm R_a).

An extensive literature search has indicated that an ultrasonic inspection system has not been successfully developed to inspect aluminium die castings with surface roughness above 50 µm for sub-surface defects. The lack of previous research for this particular application may be due to the nature of castings and the sensitivity of ultrasound. In this particular research, it was important to inspect the casting in the as-cast state (with surface roughness between 50 µm and 150 µm) because further processing (*ie*, machining) weakens the justification for a non-destructive testing application. Hence, there is a need to determine the limitations of ultrasonic inspection of castings with surface roughness values greater than 50 µm. The initial intention was to obtain ultrasonic signals with the maximum possible amplitude from defects within the rough surface areas of the castings.

Experimental methodology

An ultrasonic inspection rig was designed and constructed to inspect the samples with an ultrasonic immersion testing system. The experimental set-up used in this research work is shown in Figure 1. It consisted of an ultrasonic flaw detector with immersion focus probes, a water tank, a sample casting and a probe-handling device. A sample part was immersed in the water tank and a PUMA type industrial robot (probe handling device) was used to move the transducer. The readings obtained were transferred via the flaw detector, to a personal computer for processing.

The lens in the immersion focus probe enables it to focus the sound energy at the specified focal point within the water column. To achieve a point focus within the castings, a series of experiments

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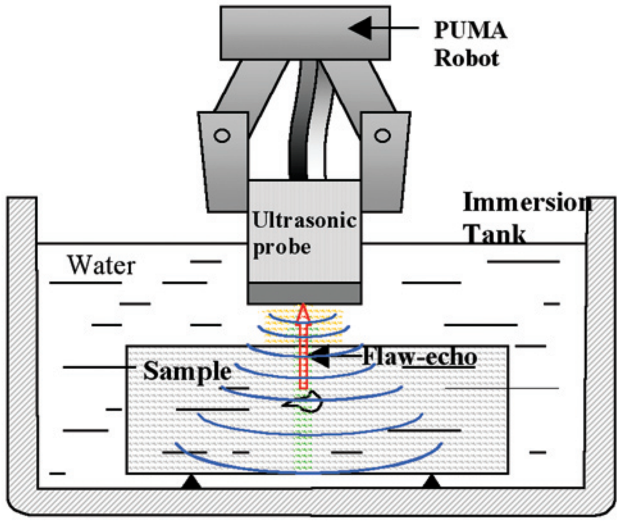

Figure 1. Ultrasonic immersion testing experimental set-up

were carried out with different water path distance (distance between the probe face and casting surface) by varying the focal point[14]. The optimum water path distance of 7.5 mm was obtained to achieve a point focus at approximately 4.5 mm (critical material depth investigated in this research) from the front surface of the casting[14]. This water path distance is kept constant with the aid of a PUMA robot for this investigation. Once the experimental set-up and water path distance were determined, the effects of surface roughness on the ultrasonic signal amplitude at different probe frequencies was investigated as presented in this paper.

Sample castings

The structural oil sump pan castings used in this project are representative of a product having sub-surface discontinuities and material variations and can be described as automotive high pressure die castings. These sample castings suffer from leakage problems caused by discontinuities in the in-gate region. For this investigation, the sample castings were machined into small sections (100 x 15 x 8 mm^3) at the in-gate region as shown in Figure 2. The surface roughness (R_a) was approximately 50 μm to 150 μm in the in-gate region because the gate is sheared off in a trim press operation. For this research, taking into account the impracticability of collecting a sufficiently high number of experimentally representative situations, porosity defects were simulated by 0.5, 0.7 and 1 mm side-drilled holes along the cut section of the sample castings. Only the end section of the side-drilled hole was considered for inspection as it replicated the gas porosity in castings.

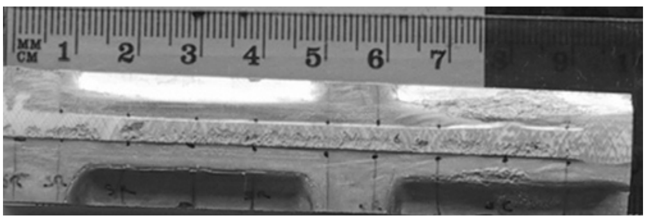

Figure 2. A cut section of the in-gate area of structural oil sump pan casting showing the rough surface area

Prior to inspection, the experimental parameters had to be selected. The initial experimental parameters like water path distance, focusing distance within the part and ultrasonic velocity in the material had been obtained from previous research on ultrasonic inspection of aluminium die castings[14]. The material properties have an effect on the selection of experimental parameters and they affect the influence of various ultrasound frequencies in inspection applications. The frequency of a transducer is a determining factor in its use.

Effects of surface roughness

In order to determine the influence of surface roughness on the defect signal amplitude, experiments were carried out on castings of 8 mm thickness and fine grain size range[14] (grain size less than 25 μm). Then, the amplitude of the defect signal was evaluated as a function of surface roughness and incident frequency. The roughness of the rear side of the casting was ignored because it was less than 5 μm (*ie*, similar to a smooth surface). Similarly, as smooth surfaced side-drilled holes were used in these experiments, the surface roughness associated with the holes was considered to have a negligible effect on the ultrasonic signal. The inspection parameters selected as presented by Palanisamy *et al*[14] were used in the experiments presented in this paper.

Experiments were carried out on five casting sections each with 10 simulated defects of 0.7 mm diameter. The results of this analysis are presented in Figure 3. The defect signal amplitude percentage of the Full Screen Height (FSH) amplitude signal was obtained for each simulated defect. The Full Screen Height amplitude signal was normalised to defect signal amplitude obtained from the smooth surface casting section. It can be seen that the defect signal amplitude decreases with increases in surface roughness (R_a). Negligible defect signal amplitude was observed in the region where surface roughness was 150 μm with all of the selected frequencies (5 to 20 MHz). This was due to the high scattering effect of the ultrasonic signal at the rough surface. The low frequencies (up to 10 MHz) showed larger defect signal amplitude than the high frequencies (15 MHz and 20 MHz) for any surface roughness up to 100 μm. No defect signal amplitude was observed for surface roughness values above 125 μm when 15 MHz and 20 MHz frequency probes were used. These results indicate that both the surface roughness and frequency used have a significant influence on the ability to detect the defects in castings.

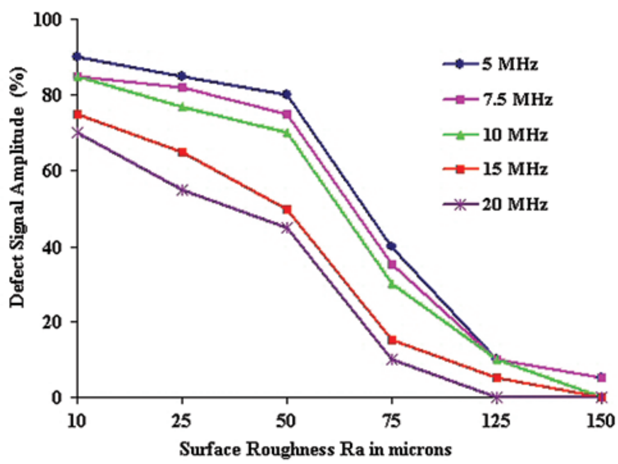

Figure 3. Variation of defect signal amplitude with surface roughness for different frequencies

A frequency of 10 MHz had been selected as an outcome from these experiments to carry out further inspection on the rough surface castings to detect gas porosity defects that are smaller than 1 mm diameter. Figure 4 shows the signals obtained from a non-defect area of the casting. The original rough casting section was analysed to obtain the signal shown in Figure 4(a). Following this, the casting section was machined to obtain the signal shown in Figure 4(b). The Y-axis of the Figure is in decibels (dB) and on the X-axis each division represents 1.6 mm. The defect sections of the casting were also inspected. However, as indicated in

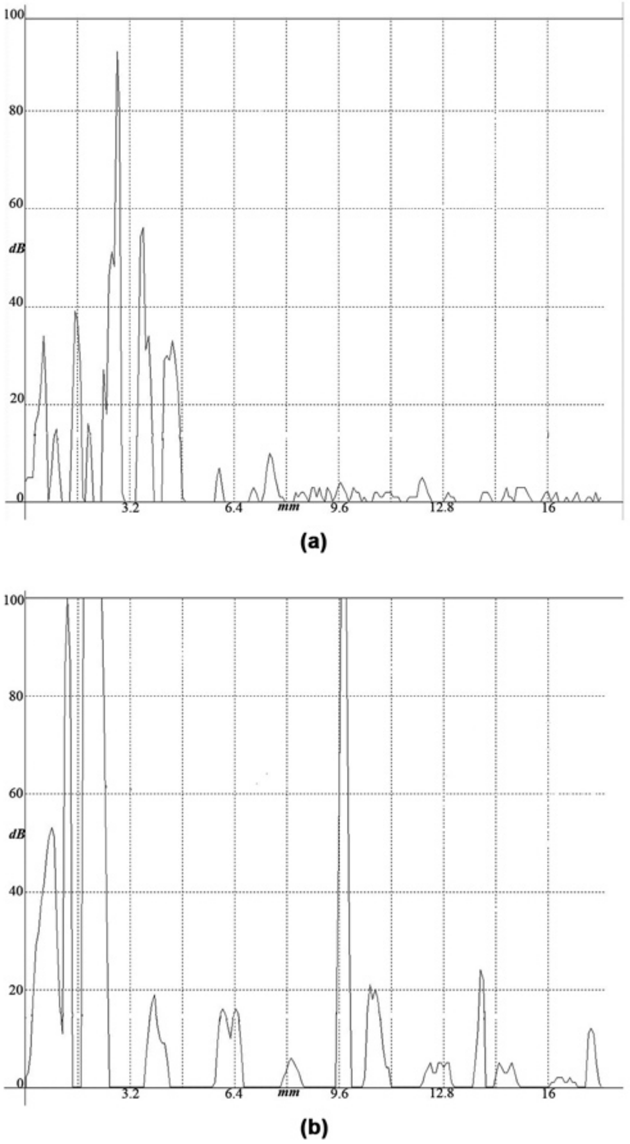

Figure 4. Ultrasonic A-scan signal display from a non-defective casting having (a) rough surface and (b) machined smooth surface using 10 MHz frequency probe

Figure 5(a), it was difficult to identify the defect (0.7 mm diameter side-drilled hole at a depth of around 3.5 mm) from the rough surface by observing the ultrasonic A-scan display. The location of the defect was identified with the aid of X-ray inspection. The horizontal bars in Figures 4 and 5 represent the electronic gates set in the EPOCH III equipment used in these experiments. These electronic gates are used to select the appropriate time base (X-axis in Figures 4 and 5). This section of the time base is displayed across the full width of the A-scan screen. Thus, these electronic gates are used to eliminate the sections of the ultrasonic signal that are not relevant to the investigation (signal from the transducer face up to the front surface of the casting).

At the front rough surface, the defect signal merges with the clustered front-wall echo (FWE) due to the signal scattering effect at the rough surface. A spreading out of the front surface echo due to the rough surface causes the loss of resolving power in the ultrasonic signal. This is seen as a wide front surface echo on the oscilloscope and is caused by reflection of the transducer side lobe energy. Side lobe energy is normally not reflected back into the transducer from smooth surfaces. Some of the side lobe energy returns to the transducer in multiple reflections from the front wall. This is referred to as clustering. This causes loss of resolving power in the transducer and increases the length of the dead zone. This condition masks the discontinuity below the surface. Widening of the beam due to scatter from the rough surface leads to the requirement for a lower frequency to reduce scatter. In the case of machined surfaces, the defect signal and back-wall echo were clearly identified (Figure 5(b)). This was not the case for rough surface castings (Figure 5(a)).

Discussions

The rough surfaces greatly altered the signal-to-noise ratio of the ultrasonic signals. As described earlier, there has been much published research dealing with the analysis of ultrasonic signals from rough surface parts in different applications. However, there is no published evidence of investigation on the variation of ultrasonic signal amplitude with castings having surfaces with roughness values over 50 μm, which is normal for un-machined sheared regions like the gates in high pressure aluminium die castings.

From Figure 3 it is evident that there is an increased loss of defect signal amplitude as the surface roughness increases. Also, it can be seen that there is an increased loss of defect signal amplitude as the ultrasonic frequency increased (within the range of 5 MHz to 20 MHz). Blessing *et al*[4] achieved similar results with steel samples at a frequency range of 1 to 20 MHz, where BWE decreased with increased surface roughness. Their investigations were confined to surfaces with roughness values up to 23 μm.

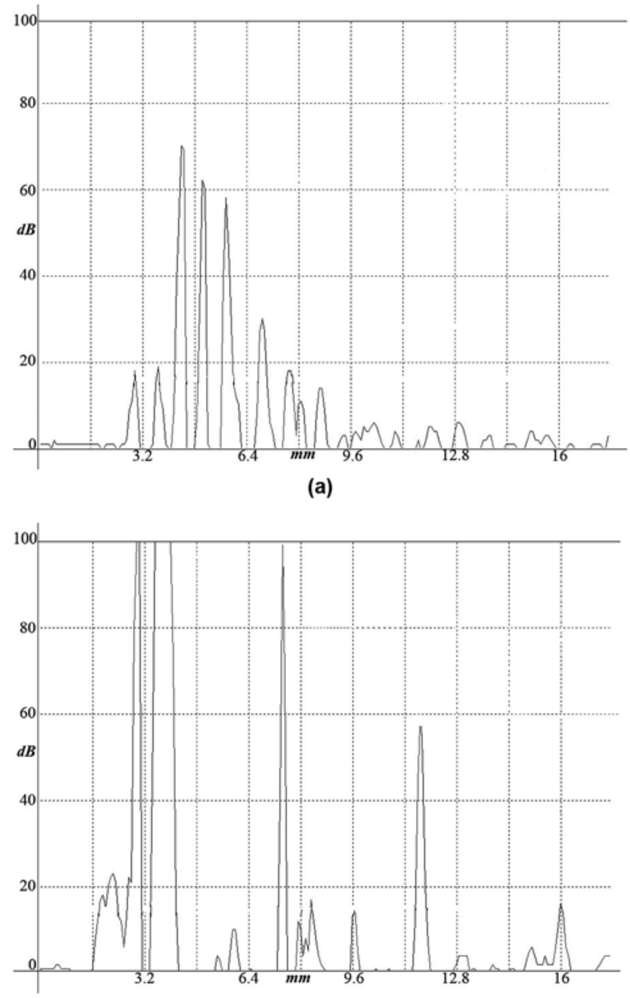

Figure 5. Ultrasonic A-scan signal display from a defective casting having (a) rough surface and (b) machined smooth surface using 10 MHz frequency probe

The main difference between the research undertaken by Blessing *et al*[4] and the work described here is that this work is concerned with castings containing rough surfaces (with R_a values mostly varying between 50 μm and 150 μm). It should be emphasised that in this work even a single BWE could not be obtained when surface roughness values exceeded 100 μm at a frequency of 20 MHz. This was different from the research undertaken by Blessing *et al*[4], who observed multiple BWEs (a total of four) due to multiple reflections within the steel samples at frequencies identical to those used in this research. Investigations have indicated that for surface roughness values up to 50 μm, the effect of surface roughness is minimal when frequencies are kept equivalent to or below 10 MHz.

The inability to detect an ultrasonic defect signal with rough surfaces may be caused by the following factors. For instance, the defect signal amplitude may be reduced due to the general scattering losses of the ultrasonic signal at the rough front surface of the casting. This was illustrated in Figure 3, in which it could be seen that the defect signal amplitude was reduced for large surface roughness (in particular for the R_a value of 150 μm). Next, the defect signal might be difficult to detect due to the noisy backscattered signal in the region of the rough front surface. For example, Figure 5(a) shows the ultrasonic signal obtained from a rough surface casting section with a 0.7 mm diameter side-drilled hole at a depth of approximately 3.5 mm. It could be observed that there is a significant clustered front-wall echo signal which affects the signal up to a depth of approximately 4.5 mm (Figure 4(a)). Therefore, it was difficult to identify the defects located close to the front surface of the particular casting section. Further, the defect signal amplitude, is also dependent upon the defect surface within the castings – when the surface of the defect is rough, more scattering occurs, resulting in lower signal amplitude than for a similar sized defect within a smooth surface. A similar trend in relation to the first back-wall echo amplitude was observed at different frequencies used in this research for castings with surface variation from 100 μm to 150 μm.

Adler *et al*[13] studied the effect of backscatter in their work on the ultrasonic inspection of aluminium cast materials. They also found that the transmitted wave was attenuated in a similar way to the reflected wave at the water-aluminium interface during ultrasonic immersion testing. However, the backscatter effect observed in the current research showed that the ultrasonic signal depended on both the selected frequency range and surface roughness if it was over 10 μm R_a value (as shown in Figure 3). The larger the relative surface roughness when compared to the wavelength of the ultrasonic signal, the greater the energy scattered at the surface interface. This then reduces the amount of ultrasonic energy entering the casting. Further, the reflected echo from a defect and the back surface has to be transmitted via the rough surface interface back to the ultrasonic transducer (probe). Once again, more energy is scattered at the interface, and less ultrasonic energy is detected at the probe. This explains about a significant loss in the back-wall echo after 50 μm R_a for the selected frequency range in this research (as shown in Figure 3). At a surface roughness below 10 μm, the loss of signal amplitude from the back-wall and defect was minimal for any selected frequency. The selection of a frequency range suitable to inspect castings with surface roughness of more than 50 μm has been successfully achieved in this research. The suitable frequency range was identified as being between 5 and 10 MHz. With this frequency range the signal patterns obtained from the castings with surface roughness between 50 μm to 150 μm were suitable for further analysis in relation to defect detection.

It was difficult to detect any back surface or defect echo in the ultrasonic signals obtained from the castings with the naked eye as observed from Figure 5(a). This was due to clustering of the front-wall echo and difficulty in identifying the defect signals close to the front surface of the casting. Even an increase in the electrical gain (dB) in the equipment to offset the effect of attenuation did not assist in identifying the defect echoes. Therefore, to identify the defect signal echoes from the rough surface castings, a suitable signal processing technique was required to be applied to the ultrasonic signals.

Finally, the decision on the selection of a suitable ultrasonic frequency to inspect aluminium die castings depends on the discontinuities to be detected. Since the detectable minimum size of the defect depends on the wavelength of the ultrasonic signal, the frequency of the probe required to inspect these castings should be selected based on the critical defect size to be inspected. The frequency selected is also constrained to be in the range previously determined by the experiments described in this paper.

Conclusions

This research was based on the application of ultrasonic NDT to inspect rough surface aluminium die castings with drilled holes to simulate porosity type defects. The effects of surface roughness on ultrasound signals in inspecting selected die castings were identified and quantified with the experiments described previously. It aided in the selection of a suitable frequency range to detect gas porosity defects in the rough surface sections of the castings. Even though calibration assisted in developing a suitable experimental methodology, near-surface defect detection was still difficult due to the clustered front-wall echo obtained from the rough surface castings. The scattering from the rough surface of the castings masked the defect signal when the defect was close to the front surface.

The frequency range from 5 to 10 MHz was most suitable for inspection of aluminium die castings with surface roughness (R_a) values varying between 50 μm and 100 μm. The experimental results were used as a framework in developing an inspection procedure for aluminium alloy die castings. This procedure also provided guidelines for selecting suitable transducer frequencies that accommodate variations in material properties while taking into account the critical defect size to be detected.

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