Case depth measurements on induction hardened crankshafts by using ultrasonic backscattering method

Sebastian Sirén
Abstract

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Induction hardening is a complex process that requires regular verification of the case depth and the microstructure. Today this verification is done by destructive testing where a cross section is analysed. The case depth is measured by several Vickers hardness impressions and the microstructure is analysed by a light optic microscope. This master thesis was performed in collaboration with Volvo GTO in Skövde, with the target to find out if an ultrasonic backscattering method is usable for analysing the case depths on induction hardened crankshafts. This was done by verifying the results provided by ultrasonic testing with the results provided by destructive testing. The measurements were done on several crankshafts with different case depths and steel composition.

The result, for crankshafts with normal case depths, shows a good correlation between the destructive testing (DT) and the ultrasonic testing (UT). The mean value for the discrepancy was 0.39 mm with a standard deviation of 0.20 mm. The reproducibility of the method has a standard deviation of 0.074 mm.


Mätningar gjordes på vevaxlar med normala härddjup, vevaxel med ett grundare härddjup, vevaxel med ett djupare härddjup och även på en vevaxel med en annan stålsammanfattning. Vevaxlarna med det normala härddjupet användes som data för att bestämma korrelationen mellan ultraljudsmetoden och den förstörande metoden. Vevaxeln med det grundare och det djupare härddjupet användes för att undersöka begränsningar med apparaten och med metoden i sig. Vevaxeln med den andra stålsammanfattningen användes för att undersöka om nya korrelationsmätningar måste ske vid användning för andra vevaxletyper.

Studien visar att ultraljud är en lämplig metod för mätningar av härddjupet på induktionshärdade vevaxlar med ett härddjup över 2 mm. Resultaten visar en standardavvikelse på 0,20 mm vilket är noggrannare än metoden som tillämpas idag.
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1. Introduction

The Volvo Group (AB Volvo) is a Swedish multinational manufacturing company that produces trucks, busses, construction equipment and marine- and industrial engines. The powertrain production in Skövde, that is part of the Volvo Group Trucks Operations (Volvo GTO), offers casting, machining and assembly of engines for different customers that are part of the Volvo group. In 2016 about 89,000 engines were assembled and delivered at the plant in Skövde.

Approximately 170,000 crankshafts are being induction hardened annually at Volvo GTO in Skövde to increase the hardness and the strength of the bearings and to protect the surface against wear. The hardening process is performed by inductive heating of the surface above the austenising temperature and subsequent cooling of the parts. This hardening process will lead to a martensitic microstructure near the surface, see figure 1.1, separated by a transition zone, see figure 1.2, from the bulk material consisting of ferrite-pearlite, see figure 1.3. The hardening process will give the material a hard surface with a tough core. The induction hardening of the crankshafts is a complex process that requires regular verification of the case depth and the microstructure.

Today the verification is done by destructive testing where a cross section of the crankshafts has to be sawed out and then mounted in Bakelite. A hardening profile is analyzed by taking several Vickers hardness impressions to be able to determine the case depth in mm. This is a time consuming method that takes about 6-8 h to perform and therefore a quick nondestructive method like ultrasonic testing is of interest.

The target with this project is to find out if ultrasonic backscattering testing (UT) is a reliable method to analyze the case depth on induction hardened crankshaft. If the UT is a reliable method, then it will lead to decreasing the amount of destructive testing and that will minimize the production stop time.
Figure 1.1: A cross section image of the martensitic structure in the hardened zone taken with a light optical microscope, Olympus BH-2 with a Leica DFC295 camera.

Figure 1.2: A cross section image of the transition zone taken with a light optical microscope, Olympus BH-2 with a Leica DFC295 camera.

Figure 1.3: A cross section image of the ferrite-pearlite structure in the hardened zone taken with a light optical microscope, Olympus BH-2 with a Leica DFC295 camera.
2. Theory

Sound travels through a medium by the vibrations of the atoms and molecules. The propagation of the sound waves is therefore dependent on the resistance of the atoms of the solid to vibrate when a force is applied. This means that the sound velocity is dependent on the mechanical properties of the medium and varies from about 300 to 6000 m/s. If the material is homogenous then the sound velocity will be constant through the entire material. Scattering of the sound waves occurs by imperfections and inclusions in the solid material, and will lead to echoes and dampening of the sound wave. [1, 2]

The human ear can hear sound within the frequency interval 20 to 20,000 Hz, which is called the acoustic region. Ultrasound, or ultrasonic, is the term used to describe mechanical vibrations with a frequency above the audible range, i.e. above 20,000 Hz, see figure 2.1. [1, 2]

![Figure 2.1: An illustration of the frequency intervals for different types of sound.](image)

There are different modes of propagation for ultrasonic waves that are determined by the particles oscillation with respect to the direction of the propagation. In ultrasonic testing the most widely used modes of propagation are longitudinal and transverse waves. For the longitudinal waves the particles oscillate in the same direction as the wave propagates, see figure 2.2. The energy travels through the medium by series of compressions and expansions of the atomic structure. The longitudinal waves can propagate in liquids, solids and gaseous materials. The speed propagation of a longitudinal wave is given by:

\[ v_l = \sqrt{\frac{E_d}{\rho \left(1+\nu_d\right)\left(1-2\nu_d\right)}} \text{[m/s]} \]

where \(E_d\) is the dynamic Young’s modulus [Pa], \(\rho\) is the density [kg/m^3] and \(\nu_d\) is the dynamic Poisson’s ratio. [2]

For the transverse waves the particles oscillate at a right angle to the direction of propagation, see figure 2.3. These waves require solid materials for effective propagation. They are
therefore not effectively propagated in liquid or gaseous materials as the longitudinal waves are. These waves are relatively weak and have slower speed propagation than the longitudinal waves. The propagation speed of a transverse wave is given by:

$$v_t = \sqrt{\frac{E_d}{\rho} \frac{1}{2(1+\nu_d)}} \text{ [m/s]}$$

The transverse waves have about half the wavelength of longitudinal waves and are therefore suitable for detection of smaller discontinuities.

![Figure 2.2: An illustration of particles oscillation with respect to the direction of the propagation for a longitudinal wave.](image)

![](image)

**Figure 2.2:** An illustration of particles oscillation with respect to the direction of the propagation for a longitudinal wave. [2]

![Figure 2.3: An illustration of particles oscillation with respect to the direction of the propagation for a transverse wave.](image)

**Figure 2.3:** An illustration of particles oscillation with respect to the direction of the propagation for a transverse wave. [2]

### 2.1 Interfaces

When a longitudinal ultrasonic wave travels through a material consisting of two media, and hits the interface separating these two media, it’s partly reflected and partly transmitted. Both the reflected and the transmitted waves are split into a longitudinal and a transverse wave. According to Snell’s law, the reflected longitudinal wave is inclined by the same angle as the incident wave, see figure 2.4. The angles of the transmitted waves are depending of the impedances and therefore by the transmission speed of the two media. The angles to the normal $\alpha_1$ and $\alpha_2$ are given by:

$$\frac{\sin \alpha_2}{\sin \alpha_1} = \frac{v_{t2}}{v_{t1}}$$
The angles $\beta_1$ and $\beta_2$ for the transverse waves are given by:

$$\frac{\sin \beta_1}{\sin \beta_2} = \frac{\nu_{t1}}{\nu_{t2}}$$

![Figure 2.4: An illustration of a longitudinal wave that hits an interface. Shear wave= transverse wave. [2]](image)

The larger the difference is of the acoustic impedance between the two media, the higher the intensity of the reflected wave is. As can be seen in figure 2.4 the angle of reflection and transmission $\beta_i$ is smaller than those of $\alpha_i$. This because the longitudinal waves travels faster than the transverse waves. The relationship between reflectance, $R$, and the acoustic impedance of the two media, $Z_1$ and $Z_2$ is given by:

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

Compared to solids, the acoustic impedance for gas is very low. This will result in very high values for the reflection coefficient at the solid-gas interface. Due to this aspect the ultrasonic waves will not propagate in the air after they have gone through a solid material. It’s also because of this aspect why a layer of a coupling medium, such as grease or oil, is needed between the transducer and the surface of the solid. [2]

When an ultrasonic wave travels through a material, it will be affected by four different mechanisms: heat conduction, viscous friction, elastic hysteresis and scattering. Adiabatic compression and rarefaction, caused by the sound waves, will release thermal energy due to rise and fall of the temperature, which will decrease the energy of the wave. Scattering at grain boundaries will also contribute to the loss of energy. This occurs because of elastic
discontinuity. These four mechanisms will lead to a distortion and an attenuation of the ultrasonic waves. The reduction of the intensity of an ultrasonic wave, for a path length $z$, in a given material can be expressed using:

$$I_z = I_0 e^{-\mu z}$$

where $I_z$ is the intensity of sound after distance $z$, $I_0$ is the intensity of sound initially, $\mu$ is the absorption coefficient and $z$ is the path length. The absorption coefficient depends on the frequency of the incident wave and by the scattering which is depending on the particle size of the medium. [2]

When a signal increases compared to the first, the comparison is called gain. This feature is used because the backscattered signal is very low compared to the first surface echo. This is a function in the instrumentation and the unit is in dB.

$$Gain = 20 \log \frac{A_1}{A_2} [\text{dB}]$$

$A_2$ and $A_1$ are signal amplitudes. [2]

The sound field of a transducer is divided into two zones: the near field and the far field, as can be seen in figure 2.5. The near field is the region closest to the transducer. In this field the sound pressure is irregularly distributed, as in turbulence. In the far field, the area beyond $N$ in figure 2.5, the sound pressure gradually drops to zero. In this area the sound pressure is distributed more regularly and therefore is optimal as working distance. The near field distance $N$ is given by:

$$N = \frac{D^2}{4\lambda}$$

where $D$ is the diameter of the transducer source and $\lambda$ is the wavelength. Therefore you can control the working distance by choosing the frequency $f$, because the frequency is related to the wavelength by:

$$f = \frac{v}{\lambda}.$$
Due to the energy losses of the ultrasonic waves, the emission cone of the signal source has to be as less divergent as possible. The angle of the ultrasonic beam spread depends on both wavelength and the diameter of the transducer. The angle is given by:

\[ \sin \alpha = \frac{1.2\lambda}{D} \]

The divergence of the wave is contained if \( D \gg \lambda \), therefore if the wavelength approaches the diameter of the transducer then the waves are sent out in all directions. The frequency is in inverse proportion of the wavelength which means that high frequency signals are more directional than the low frequency signals. [2]

### 2.2 Defects

Defects in the test sample can be observed by ultrasonic waves if the amplitude of the reflected waves is strong enough. The characteristics of the defect, to reflect waves with high enough amplitude, are: the geometry, the orientation, the roughness and the size. If the defect is much larger than the wavelength a well-defined reflected beam is created, but also a shadow zone in the transmission. If the defect has the size of the same order as the wavelength then both the reflected beam and the shadow zone will become blurred and not well defined. If the defect is much smaller than the wavelength then the defect will be invisible due to reflects in all directions. [2]

### 2.3 Case depth

Ultrasonic backscattering techniques can be used to measure case depth on induction hardened steel. This is possible due to the change in microstructure of the hardened layer compared to the base material. The hardened layer consists of a martensitic structure and it has a more fine grain structure than the base material and is therefore almost transparent to
ultrasonic waves. The transition in the microstructure should be as sharp as possible to be able to get a good signal with as high accuracy as possible. No scattering takes place when the ultrasonic wave passes the hardened layer, due to the fine microstructure. When the ultrasonic wave passes through the transition zone, significant scattering takes place due to the changes in microstructure, see figure 2.6. By measuring the time of flight between the surface echo and the backscattering signal, the thickness of the hardened layer can be calculated by using the following equation:

\[ Rht = \frac{v \cdot t \cdot \cos \beta}{2} \]

where \( v \) is the velocity in the carbon steel, \( t \) is the time of flight of the ultrasonic beam and \( \beta \) is the angle of incidence. [3-5]

![Figure 2.6](image)

Figure 2.6: The figure to the left shows the scattering of the ultrasonic signal that occurs when it hits the transition zone. The figure to the right shows a typical ultrasonic signal with a surface echo and the echo that occurs due to the backscattered signal. [6]

When measuring the case depth by an ultrasonic backscattering technique there are several advantages in using shear waves instead of longitudinal waves. Shear waves are much more scattered than longitudinal waves and the axial resolution is higher due to the smaller wave length and the longer time of flight. [3]

A study, where the comparison between the hardening depths determined destructively and evaluated from ultrasonic backscattering measurements, shows an accuracy better than \( \pm 10\% \) [3]. Another study shows that the correlation coefficient between the values from UT and from the destructive testing was 0.997[7, 8].
2.4 Microstructure

The propagation rate of sound waves in steel is affected by grain size, relative amounts of phases and lattice distortions. The wave velocity in the structure varies from grain to grain due to changes in the elastic modulus that comes from the individual orientation of each grain. Generally there is an inverse relationship between ultrasonic velocity and hardness. Martensite is the phase with maximum randomness, and a very high dislocation density, which will give a lower sound velocity. When martensite is tempered, a formation of carbide particles will occur with a reduction of dislocation density, which will lead to a higher sound velocity. The sound velocity has an inverse relation with the density and therefore the increase in the sound velocity is related to increasing elastic moduli rather than increasing density. [9]

The attenuation coefficient is also related to the grain size. The larger the grains are the higher the attenuation coefficient is. The attenuation coefficient is related to the frequency of the sound waves as well. A relationship between the grain size, frequency and the attenuation coefficient can be seen in figure 2.7, where the material presented is AISI 304 stainless steel. [9]

![Figure 2.7: The attenuation coefficient is plotted against grain size for different frequencies. The larger the grains are the higher the attenuation coefficient is. [9]](image)

A study was made where different microstructures of SAE 1040 and SAE 4140 steel were analyzed by ultrasonic measurement. Figure 2.8 illustrates the result of percent change of the measured longitudinal wave velocities for various phases on these both steels. The phases were martensite, martensite tempered at 600°C, fine pearlite-ferrite and coarse perlite-ferrite.
This result confirms that the sound velocity has an inverse relation with hardness, since the hardness of the phases increases in the order of ferrite, coarse pearlite, fine pearlite, cementite and martensite. [10]

![Graph showing the percentage change of the measured longitudinal wave velocity plotted against various phases of SAE 1040- and SAE 4140 steel. M stands for martensite, TM-600 stands for tempered martensite at 600°C, FP-F stands for fine pearlite-ferrite, and CP-F stands for coarse pearlite-ferrite. As can be seen from the data, the sound velocity has an inverse relation with hardness.](image)

In another study, the changes in attenuation of longitudinal waves and velocity of shear wave modes were investigated for assessing variations in the microstructure of thermally degraded 2205 duplex stainless steel samples that were aged isothermally at 700°C and 900°C for different time intervals. The study presents that the attenuation coefficient of the longitudinal wave is sensitive to gradual microstructure changes produced by the aging process, see figure 2.9. The attenuation coefficient decreases as aging time increases and it is sensitive to the initial formation of grain boundaries in the ferrite phase. [11]
Figure 2.9: Absorbed impact energy for a longitudinal wave is plotted against aging time. The data shows that the attenuation coefficient decreases as aging time increases. [11]

The fast mode for the shear wave velocity decreases with aging time, but the slow mode remains unchanged for the different aging times, see figure 2.10. [11]

Figure 2.10: Shear wave velocity is plotted against aging time. The fast mode for the shear wave velocity decreases with aging time while the slow mode remains unchanged. [11]
3. Methodology

3.1 Destructive testing
The destructive testing is very time consuming as it takes several hours to perform on each sample. In this section the procedure for the destructive testing is presented.

3.1.1 Sample preparation
The sample preparation, to be able to take several Vickers hardness impressions for the hardness profile, consists of several steps. The first step was to saw the crankshaft into smaller pieces, this to be able to get a cross section of the desired measurement point. The cutting speed of the band saw was set to be 60 m/min with a cutting feed rate of 2 mm/min. A cutting fluid was used both as lubrication and as coolant.

When the cross sections were sawed out then the pieces were mounted in Bakelite into pellets. The pellets were grinded on a grindstone to form a plane surface. The pellets were then polished as followed: 6 min on a diamond polishing pad consisting of 6 µm diamond paste, 3 min on 3 µm diamond paste and lastly 1 min on 1 µm diamond paste.

3.1.2 Vickers hardness profile
The case depth is estimated by measuring Vickers hardness on different depths. This to be able to find out at which depth the hardness has a value below 400 HV. The apparatus used for the Vickers hardness impressions was a Q30 A+ by Qness GmbH, which is a fully automatic micro hardness tester.

3.1.3 Cross section images
The cross section samples were etched in 4% Nital to be able to study the hardened zone and the microstructure. A stereo microscope, Leica M205 C with a Leica DFC295 camera, was used for the images of the cross sections.

3.2 Ultrasonic testing
The apparatus that is implemented at Volvo GTO in Skövde is a Case Depth Tester P3121 by Quality Network, Inc. The ultrasonic search unit consists of a polystyrene wedge with an ultrasonic transducer mounted on it. The ultrasonic sound wave propagates through the surface with an angle of 28.3° and it uses a fixed frequency of 20 MHz. The apparatus is suited for case depths ranging from 1.5 mm up to approximately 12.0 mm. [5, 6]
The position of the first cursor is set where the surface reflectance signal has its maximum. This is because the ultrasonic beam has a certain diameter at the interface between the wedge and the material. The ultrasonic wave propagation through the interface can be seen as a round slice with a certain diameter. This round slice propagates obliquely through the interface step by step and will hit the interface with its lower boundary first. This lower boundary will engender only a small echo which will grow consequently with further propagation. The middle part of the slice has the largest diameter and will therefore engender the biggest echo and this will occur at the same time as the transducer axis hits the surface. [12]

The position of the second cursor is set at the depth where the hardness is 80% of the surface hardness. The case depth is defined as 20% increase of the signal amplitude from the minimum between surface and the back scatter echo to the maximum of the back scatter echo, see figure 3.1. [12]

The sound velocity for the steel was set to be 3.23 mm/µs and the sound velocity for the polystyrene wedge was set to be 2.3 mm/µs. The averaging variable was chosen as a value of 256, which means that it will present an average of all the collected data to get smoother peaks. The gain was set to 62 dB to get a good relation between the surface echo and the backscattered echo.

![Figure 3.1](image.png)

*Figure 3.1: The position of the second cursor, red line, is set at a 20% increase of the signal amplitude from the back scatter echo. The y-axis is in percentage and the x-axis is in µs.*
3.2.1 Ultrasonic transducers
Two different wedges were used for the measurements: one that is designed to fit the crankshaft bearings and one that is designed to fit the crankpin journals of the HDE-11 crankshaft. Two transducers were mounted in each wedge. The first transducer was used to measure the surface of the bearing and the second was used to measure the radius of the bearing.

3.2.2 Measurement points
Measurements with the ultrasonic tester were done on HDE-11 crankshafts made of C38 steel. The crankshaft consists of six crankpin journals and seven main bearings. Figure 3.2 illustrates a HDE-13 crankshaft with the crankpin journals and the main bearings numbered and pointed out. The same order was used for the HDE-11 crankshaft. The first main bearing and crankpin journal are the ones nearest to the pinion side (TS), while the last main bearing and crankpin journal are the ones nearest to the flange side (FS).

Figure 3.2: An illustration of a HDE-13 crankshaft with the crankpin journals and the main bearings numbered and pointed out. The bearings are numbered from the pinion side (TS) to the flange side (FS).

Four measurement points were chosen on each crankpin journal and on each main bearing. The measurement points were chosen on the top, right, bottom and the left side of the crankshaft. Figure 3.3 illustrates the measurement points upper side (blue color) and right side (green color). The bottom side is on the opposite side of the upper side and the left side is on the opposite side of the right side. The same procedure goes for every single crankpin journal and main bearing. The upper side of each crankpin journal is always on the highest point and the upper side of each main bearing is always on the same side as for the nearest crankpin journal pointed to the middle.
For each measurement point, the radius to both side and the bearing/journal surface were analyzed, see figure 3.4. The bearing/journal surface was analyzed with the ultrasonic transducer pointed to both the crank pinion side and to the flange side, this because of the transducer’s 28.3° angle. The total number of measurements for each crankpin journal and for each main bearing was then 16.

### 3.3 Selection of crankshafts for measurements

One HDE-11 crankshaft with a normal case depth was selected for the main part of measurements. This was done to be able to get a large number of measurements at the required case depth of minimum 2 mm. These measurements are used as the base for the correlation between the UT (ultrasonic testing) and the DT (destructive testing).
An additional HDE-11 crankshaft, with a normal case depth, was chosen for measurements. This to be able to determine the reproducibility of the method. These measurement points are listed with an R at the beginning. These measurements are also used as data for the correlation.

Crankpin journal 3 on a HDE-11 crankshaft with longer hardening time was chosen for measurements. The hardening time was extended by 50 % to be able to get a deeper hardening depth. This crankpin journal is listed as “HD+ CJ3”.

Crankpin journal 6 on a HDE-11 crankshaft with a smaller case depth was also chosen for measurements. This crankshaft was chosen due to a problem with the induction hardener which caused the smaller case depth on crankpin journal 6. This may have caused a slightly abnormal microstructure in the hardened zone that may affect the ultrasonic signal. The UT was done on four different measurement points, which can be seen in figure 3.5-3.8. For each measurement point, the both sides radius and the journal surface were analysed by UT. The journal surface was analysed with the ultrasonic transducer pointed to both the crank pinion side and to the flange side. This crankpin journal is listed as “HD- CJ6”.

![Figure 3.5: Measurement point HD- CJ6 M1](image1)
![Figure 3.6: HD- CJ6 M1 to the left and measurement point HD- CJ6 M2 to the right.](image2)
![Figure 3.7: Measurement point HD- CJ6 M3](image3)
![Figure 3.8: Measurement point HD- CJ6 M4](image4)
Measurements on the main bearing 2 on a HDE-13 crankshaft with another steel composition were done to see if the correlation will change with different steel composition. The main bearing on this crankshaft is listed as “13 MB2”.

4 Results

4.1 The method

4.1.1 The ultrasonic signal

The ultrasonic measurements on crankpin journal 1 and main bearing 1 were done without moving the probe. This can be seen in the ultrasonic signals, see appendix B, where the signals from CJ1 and MB1 are less smooth than those where the probe was slightly moved during measurement. An example of an ultrasonic signal where the probe was not moved can be seen in figure 4.1. Figure 4.2 illustrates a signal where the probe was slightly moved during measurement. The difference between those signals is significant and comes as a result of the averaging variable of 256 mentioned in section 3.2. The adjustment of moving the probe during measurements was applied after a mail conversation with Tobias Müller at Q-net.

The time of flight, in figure 4.1 and 4.2, is the distance between the blue and the red line and is in µs. The blue line is centered at the surface echo and the red line is positioned at the slope of the back scattered signal.

![Figure 4.1: An ultrasonic signal for the measurement point MB1 USFS where the ultrasonic probe was static during measurement. The y-axis is in percentage and the x-axis is in µs.](image1)

![Figure 4.2: An ultrasonic signal for the measurement point MB2 USFS where the ultrasonic probe was slightly moved during measurement. The y-axis is in percentage and the x-axis is in µs.](image2)

All ultrasonic signals that were received for the radius have a small peak between the surface echo and the back scattered signal, see figure 4.3. These small peaks might occur because of
an echo from a longitudinal wave. The longitudinal wave is much faster than the transverse wave and should appear at the position of those peaks.

The ultrasonic signals, for the HDE-11 crankshaft with a normal case depth, can be seen in appendix B.

![Figure 4.3: An ultrasonic signal for the measurement point CJ2 UTS. A small peak can be observed between the surface echo and the back scattered signal. The y-axis is in percentage and the x-axis is in µs.](image)

4.1.2 Effect of case depth variation

The cross sections show a large variation of the case depth, see figure 4.4. A slight error in the penetration angle will drastically change the result for the measured case depth by UT. It’s also problematic to choose the exact same penetration line for the DT (destructive testing) as for the UT (ultrasonic testing), which results in a less good correlation.

![Figure 4.4: A cross section image for the measurement point CJ4 UFS with an inhomogeneous hardening zone.](image)
An example of a cross section of a bearing surface can be seen in figure 4.5. The hardened zone is deeper in the middle than at the edges. Because of the fixed angle of 28.3° the measured hardening depth, by UT, is slight offset from the middle part of the bearing surface, see figure 4.6. The cross section images for HDE-11 crankshaft with the normal case depth can be seen in appendix D.

Figure 4.5: A cross section image for the measurement point MB2 BS with an inhomogeneous hardening zone.

Figure 4.6: A schematic figure for a measurement by UT on a sample with inhomogeneous hardening zone. The measured case depth by UT will not have the same order as the measured case depth by DT.
4.2 Measurements

The results from the UT and the DT are described in this section. All data are listed in appendix A and the Vickers hardness profiles are found in appendix C. A summary of the mean values, of the differences between DT and UT, is shown in table 4.1.

Table 4.1: A summary for the mean values for the differences between DT and UT for the standard HDE-11 crankshaft, the crankshaft for reproducibility measurements, the crankshaft with increased case depth, the crankshaft with decreased case depth and the HDE-13 crankshaft.

<table>
<thead>
<tr>
<th>Crankshaft</th>
<th>Standard HDE-11</th>
<th>Reproducibility</th>
<th>HD+</th>
<th>HD-</th>
<th>HDE-13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean difference [mm]</td>
<td>0.39</td>
<td>0.37</td>
<td>-0.08</td>
<td>0.11</td>
<td>-0.13</td>
</tr>
</tbody>
</table>

4.2.1 Crankshafts with normal case depth

The results for the case depth from UT and DT are listed in appendix A. The main bearing is shortened as MB and the crankpin journal is shortened as CJ. The upper side is shortened as U, the right side as R, the bottom side as B and the left side as L. As an example, the flange side upper radius on main bearing 1 is therefore listed as MB1 UFS. The data points, from tables A1, A2 and A3, are plotted in figure 4.7 and the trend from those data points can be seen to be orientated along a straight line, with some spread, slightly offset against the destructive testing. The differences between the DT and the UT have a mean value of 0.39 mm and a standard deviation of 0.20 mm, see table 4.2.

Table 4.2: The mean value of the differences between DT and UT and the standard deviation for the differences. These values are for the standard HDE-11 crankshaft.

<table>
<thead>
<tr>
<th>Crankshaft</th>
<th>Mean value difference (DT-UT)</th>
<th>Standard deviation for the differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard HDE-11</td>
<td>0.39 mm</td>
<td>0.20 mm</td>
</tr>
</tbody>
</table>

Figure 4.8 illustrates the corrected values from the UT, i.e. where the average difference of 0.39 mm is added. The red line is the 1:1 ratio and as can be seen the corrected case depth values are oriented along that straight line. This correction can be arranged by the software by moving the second cursor.
Figure 4.7: Measured case depth by both DT and UT. The differences between the values for the DT and UT have a mean value of 0.39 mm and a standard deviation of 0.20 mm. The data is collected from tables A1, A2 and A3.

Figure 4.8: Corrected case depth values for the UT.
The case depth measured by UT was also plotted against the measured depth of the hardened zone determined by DT, see figure 4.9. This was done by using the Vickers hardness profiles where the depth of the hardened zone is determined as the depth where the hardness has come to a static value. For the Vickers hardness profile in figure 4.10 the depth for the hardened zone is determined to be 4.0 mm. This procedure was done for all the measurement points in A1, A2 and A3. The mean value for the differences between the depth of the hardened zone and the case depth determined by UT is 0.80 mm and the standard deviation for the differences is 0.20 mm.

Figure 4.9: The depths for the hardened zones are plotted against the case depths measured by UT. The mean value for the differences between these values is 0.80 mm.
4.2.2 Crankshaft with increased induction hardening time

Results from the crankshaft with increased induction hardening time can be seen in appendix A, table A4. The mean value for the difference deviates from the value for the standard measurements in section 4.2.1. An explanation for this deviation is the much greater transition zone consisting of some bainite. The transition zone for sample HD+ CJ3 BTS can be seen in figure 4.11, where the darker stripes are areas consisting of bainite. The martensite structure is harder than bainite and as can be seen in figure 4.12 some of the Vickers hardness impressions are at the bainite structure and will therefore engender a lower hardness value.
Figure 4.11: The transition zone for sample HD+ CJ3 BTS. The dark stripes consist of bainite and will engender a lower hardness value for the Vickers impressions.

Figure 4.12: Some of the Vickers impressions are at the bainite structure and will therefore engender a lower hardness value.
4.2.3 Crankshaft with decreased case depth

Results for the measurements on the crankshaft with decreased case depth can be seen in appendix A, table A5. The mean value for the difference between the DT and the UT is 0.11 mm. Some of the values are less than 1.5 mm which is the lowest case depth that the manufacturing company for the case depth tester promises high accuracy. The samples also contain significant values of bainite, which will give a lower accuracy between the UT and the DT.

4.2.4 Reproducibility measurements

Results for the reproducibility measurements can be seen in appendix A, table A3. The mean value for the difference is 0.37 mm, which is in the same order as for the standard measurements. The standard deviation for the reproducibility for this ultrasonic method is 0.074 mm.

4.2.5 HDE-13 Crankshaft

Results for the measurements on HDE-13 crankshaft, which contains a different steel composition, can be seen in appendix A, table A6. The mean value for the difference between the DT and the UT is -0.13 mm. This steel composition has a much larger transition zone which will affect the position for the backscattered echo for the ultrasonic signal. Therefore if this ultrasonic method will be used on the HDE-13 crankshaft then it will require the same type of correlation measurements as has been done for the HDE-11 crankshaft in this project.

5 Discussion

5.1 Correlation between the DT and UT methods

The correlation data for the measurements presented in section 4.2.1 show that this ultrasonic method is a reliable method for case depth measurements on C38 crankshafts. The standard deviation of 0.20 mm is more precise than the current settings for the destructive testing used today. The distance between the Vickers hardness impressions is 0.20 mm, and a smaller distance between those impressions could make the value for the standard deviation to be smaller.

As can be seen in figure 4.6, the correlation line is slightly above the ideal 1:1 ratio. This can be seen as an advantage due to the fact that then the major part of the ultrasonic measurements
shows a slightly lower value than for the real case depth. This will mean that fewer crankshafts will be wrongly approved.

When the ultrasonic measurements are plotted against the measured depths of the hardened zone, see figure 4.8, then the standard deviation for the difference between those two measurement methods has, as expected, the same value, 0.20 mm, as when plotted against the case depth. This means that the distance from the bulk material, where the hardness has a value of 400 HV, is constant.

5.2 The method

5.2.1 Drawbacks
One drawback with this method is the fixed 45° angle, on the transducer, for the radius measurements. As can be seen in figure 4.12 the radius doesn’t have a constant case depth and the lowest value is at a smaller angle than 45°. This can be a problem because you will only get a value for the case depth at a 45° angle and not where the lowest value for the case depth is located. Therefore, the crankshaft can have a lower flexural strength than perceived by the UT.

![Figure 4.12: An example of a crankpin journal radius with an inhomogeneous hardening zone.](image)
Another drawback is the fixed frequency. The frequency is optimized for the signal to be backscattered when entering the bulk material consisting of ferrite-pearlite. Because of this no structure defects, such as bainite, in the hardened layer can be observed using the UT. If the hardened layer consists of some bainite, instead of pure martensitic structure, then it will have a lower surface hardness and it’s therefor crucial to also check the microstructure of some of the crankshafts.

5.2.2 Benefits
The UT is a production friendly method that is suitable to measure case depth on induction hardened parts. It’s a fast method that is precise enough when used on crankshafts made of C38 steel. One major benefit with the UT versus the DT is that you can scan the whole surface and therefor you are not locked on a specific measurement point.

The accuracy for the UT on the C38 crankshaft is also high enough when compared to the DT that is used today where the Vickers impressions is taken with a distance of 0.5 mm from each other.

6. Conclusions
Measurements on HDE-11 crankshafts have been done by using an ultrasonic backscattering method. This to be able to determine if it’s a reliable method to measure the case depth on induction hardened crankshafts instead of the time consuming destructive testing. The apparatus that was used was a Case Depth Tester P3121 by Quality Network, Inc, which uses shear waves with a frequency of 20 MHz. This method with this apparatus is suitable for case depths larger than 1.5 mm.

The following conclusions can be drawn:

- The correlation between the DT and the UT methods is good for determining the case depth on crankshafts with a C38 steel composition. The mean value for the discrepancy was 0.39 mm with a standard deviation of 0.20 mm. The reproducibility of the method is quite high and has a standard deviation of 0.074 mm.
- For larger case depths the correlation between the DT and UT methods became less good. The reason for this was found to be a presence of bainite, which will make the steel less hard, and also because the increased transition zone will displace the correlation line.
• The ultrasonic method with P3121 is suitable for case depths above 1.5 mm, which will make measurements on case depths smaller than 1.5 mm less accurate. The correlation between the DT and the UT will then not be fully applicable for such small case depths.

• A drawback with this method is that when measuring the case depths on the radius of the crankshaft, then the case depth is measured at a 45º angle. Some of the hardening zones is geometrically inhomogeneous and may have a smaller case depth at a different angle than 45º. This can lead to that crankshafts that have been approved with the ultrasonic method should in reality be rejected.

• The ultrasonic method can be used as a complement for the destructive testing but not entirely replace it. This is because the microstructure cannot be analyzed by using the P3121 apparatus.
References

5. Fraunhofer Document No: STR 01-09, P3121 Manual V3.05.
6. Training Materials v1.09, Case Depth Tester P3121.
Appendix

Appendix A – tables of measured case depths

This appendix contains data from both the ultrasonic- and destructive testing. The standard measurements on HDE-11 crankshaft are listed in table A1 where the main bearing is shortened as MB and the crankpin journal is shortened as CJ. The upper side is shortened as U, right side as R, bottom side as B and the left side as L. The pinion side is shortened as TS, surface as S and the flange side as FS.

The measurements to determine the reproducibility of the method are listed in table A2. The same procedure for shortening the measurement points was used as for the standard measurements but with an R at the beginning.

Table A3 contains the data for the measurements on a crankpin journal 3 on a HDE-11 crankshaft produced with a longer hardening time. This crankpin journal is listed as “HD+ CJ3”.

Table A4 contains data for the measurements on a crankpin journal 6, on a HDE-11 crankshaft, with smaller case depth. This crankpin journal is listed as “HD- CJ6”.

Table A5 contains data for the measurements on a HDE-13 crankshaft with a different steel composition. This crankshaft is listed with 13 at the beginning.

Table A1: Data from the UT and the DT for the standard HDE-11 crankshafts main bearings.

<table>
<thead>
<tr>
<th>Measurement point</th>
<th>Case depth, UT [mm]</th>
<th>Case depth, DT [mm]</th>
<th>Differens (DT-UT) [mm]</th>
<th>Ratio</th>
<th>Percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB1 UTS</td>
<td>3.69</td>
<td>3.90</td>
<td>0.21</td>
<td>0.05</td>
<td>5</td>
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<tr>
<td>MB1 US</td>
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<td>4.08</td>
<td>0.30</td>
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<td>MB1 UFS</td>
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<td>3.56</td>
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<td>11</td>
</tr>
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<td>0.14</td>
<td>14</td>
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<td>0.33</td>
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Table A2: Data from the UT and the DT for the standard HDE-11 crankshafts crankpin journals.
Table A3: Data from the UT and the DT for the reproducibility measurements.

<table>
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<tr>
<th>Measurement point</th>
<th>Case depth, UT [mm]</th>
<th>Case depth, DT [mm]</th>
<th>Difference (DT-UT) [mm]</th>
<th>Ratio</th>
<th>Percentage [%]</th>
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<td>R CJ1 USFS(2)</td>
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<td>R CJ1 USFS(3)</td>
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<td>R CJ1 BS(3)</td>
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<td>R CJ1 BSTS(2)</td>
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<td>4.64</td>
<td>0.48</td>
<td>0.10</td>
<td>10</td>
</tr>
<tr>
<td>R CJ1 BSTS(3)</td>
<td>4.08</td>
<td>4.64</td>
<td>0.56</td>
<td>0.12</td>
<td>12</td>
</tr>
<tr>
<td>R CJ1 BSTS(4)</td>
<td>4.02</td>
<td>4.64</td>
<td>0.62</td>
<td>0.13</td>
<td>13</td>
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<tr>
<td>R CJ1 BSFS(1)</td>
<td>4.22</td>
<td>4.64</td>
<td>0.42</td>
<td>0.09</td>
<td>9</td>
</tr>
<tr>
<td>R CJ1 BSFS(2)</td>
<td>4.11</td>
<td>4.64</td>
<td>0.53</td>
<td>0.11</td>
<td>11</td>
</tr>
<tr>
<td>R CJ1 BSFS(3)</td>
<td>4.22</td>
<td>4.64</td>
<td>0.42</td>
<td>0.09</td>
<td>9</td>
</tr>
<tr>
<td>Measurement point</td>
<td>Case depth, UT [mm]</td>
<td>Case depth, DT [mm]</td>
<td>Difference (DT-UT) [mm]</td>
<td>Ratio</td>
<td>Percentage [%]</td>
</tr>
<tr>
<td>------------------</td>
<td>---------------------</td>
<td>---------------------</td>
<td>-------------------------</td>
<td>-------</td>
<td>----------------</td>
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<tr>
<td>HD+ CJ3 UTS</td>
<td>7.73</td>
<td>7.03</td>
<td>-0.70</td>
<td>-0.10</td>
<td>-10</td>
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<tr>
<td>HD+ CJ3 UFS</td>
<td>8.57</td>
<td>7.68</td>
<td>-0.89</td>
<td>-0.12</td>
<td>-12</td>
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<tr>
<td>HD+ CJ3 RTS</td>
<td>4.90</td>
<td>5.22</td>
<td>0.32</td>
<td>0.06</td>
<td>6</td>
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<tr>
<td>HD+ CJ3 RS</td>
<td>7.76</td>
<td>7.63</td>
<td>-0.13</td>
<td>0.02</td>
<td>2</td>
</tr>
<tr>
<td>HD+ CJ3 RFS</td>
<td>4.67</td>
<td>5.11</td>
<td>0.44</td>
<td>0.09</td>
<td>9</td>
</tr>
<tr>
<td>HD+ CJ3 BTS</td>
<td>4.93</td>
<td>4.94</td>
<td>0.01</td>
<td>0.00</td>
<td>0</td>
</tr>
<tr>
<td>HD+ CJ3 BS</td>
<td>8.51</td>
<td>7.44</td>
<td>-1.08</td>
<td>-0.14</td>
<td>-14</td>
</tr>
<tr>
<td>HD+ CJ3 BFS</td>
<td>4.96</td>
<td>4.75</td>
<td>-0.22</td>
<td>-0.05</td>
<td>-5</td>
</tr>
<tr>
<td>HD+ CJ3 LTS</td>
<td>4.44</td>
<td>5.12</td>
<td>0.68</td>
<td>0.13</td>
<td>13</td>
</tr>
<tr>
<td>HD+ CJ3 LS</td>
<td>7.16</td>
<td>7.44</td>
<td>0.28</td>
<td>0.04</td>
<td>4</td>
</tr>
<tr>
<td>HD+ CJ3 LFS</td>
<td>4.41</td>
<td>4.77</td>
<td>0.36</td>
<td>0.07</td>
<td>7</td>
</tr>
<tr>
<td>Mean value</td>
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<td></td>
<td>-0.08</td>
<td>0.00</td>
<td>0</td>
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</table>

Table A4: Data from the UT and the DT for the crankpin journal 3 with increased hardening time.
Table A5: Data from the UT and the DT for the crankpin journal 6 with a smaller hardening depth.

<table>
<thead>
<tr>
<th>Measurement point</th>
<th>Case depth, UT [mm]</th>
<th>Case depth, DT [mm]</th>
<th>Differens (DT-UT) [mm]</th>
<th>Ratio</th>
<th>Percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD- CJ6 M1TS</td>
<td>1.24</td>
<td>1.19</td>
<td>-0.05</td>
<td>-0.04</td>
<td>-4</td>
</tr>
<tr>
<td>HD- CJ6 M1S</td>
<td>3.27</td>
<td>3.55</td>
<td>0.29</td>
<td>0.08</td>
<td>8</td>
</tr>
<tr>
<td>HD- CJ6 M1FS</td>
<td>1.76</td>
<td>1.69</td>
<td>-0.07</td>
<td>-0.04</td>
<td>-4</td>
</tr>
<tr>
<td>HD- CJ6 M2TS</td>
<td>1.36</td>
<td>1.20</td>
<td>-0.16</td>
<td>-0.14</td>
<td>-14</td>
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<tr>
<td>HD- CJ6 M2S</td>
<td>1.44</td>
<td>1.65</td>
<td>0.21</td>
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<td>HD- CJ6 M3S</td>
<td>1.55</td>
<td>1.51</td>
<td>-0.04</td>
<td>-0.02</td>
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</tr>
<tr>
<td>HD- CJ6 M2FS</td>
<td>3.27</td>
<td>3.33</td>
<td>0.06</td>
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<tr>
<td>HD- CJ6 M3FS</td>
<td>2.57</td>
<td>3.11</td>
<td>0.54</td>
<td>0.17</td>
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</tr>
<tr>
<td>HD- CJ6 M4TS</td>
<td>3.77</td>
<td>3.67</td>
<td>0.10</td>
<td>-0.03</td>
<td>-3</td>
</tr>
<tr>
<td>HD- CJ6 M4S</td>
<td>2.95</td>
<td>2.89</td>
<td>-0.06</td>
<td>-0.02</td>
<td>-2</td>
</tr>
<tr>
<td>HD- CJ6 M4FS</td>
<td>3.12</td>
<td>3.66</td>
<td>0.54</td>
<td>0.15</td>
<td>15</td>
</tr>
<tr>
<td>HD- CJ6 M4FS</td>
<td>2.82</td>
<td>2.97</td>
<td>0.15</td>
<td>0.05</td>
<td>5</td>
</tr>
<tr>
<td><strong>Mean value</strong></td>
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<td></td>
<td><strong>0.11</strong></td>
<td><strong>0.03</strong></td>
<td><strong>3</strong></td>
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</table>

Table A6: Data from the UT and the DT for the HDE-13 crankshaft.

<table>
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<th>Measurement point</th>
<th>Case depth, UT [mm]</th>
<th>Case depth, DT [mm]</th>
<th>Differens (DT-UT) [mm]</th>
<th>Ratio</th>
<th>Percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 MB2 UTS</td>
<td>4.05</td>
<td>3.68</td>
<td>-0.37</td>
<td>-0.10</td>
<td>-10</td>
</tr>
<tr>
<td>13 MB2 US</td>
<td>4.38</td>
<td>3.99</td>
<td>-0.39</td>
<td>-0.10</td>
<td>-10</td>
</tr>
<tr>
<td>13 MB2 UFS</td>
<td>3.65</td>
<td>3.49</td>
<td>-0.16</td>
<td>-0.05</td>
<td>-5</td>
</tr>
<tr>
<td>13 MB2 RTS</td>
<td>3.86</td>
<td>3.85</td>
<td>-0.01</td>
<td>0.00</td>
<td>0</td>
</tr>
<tr>
<td>13 MB2 RS</td>
<td>3.91</td>
<td>4.25</td>
<td>0.34</td>
<td>0.08</td>
<td>8</td>
</tr>
<tr>
<td>13 MB2 RFS</td>
<td>3.72</td>
<td>3.66</td>
<td>0.06</td>
<td>-0.02</td>
<td>-2</td>
</tr>
<tr>
<td>13 MB2 BTS</td>
<td>3.57</td>
<td>3.68</td>
<td>0.11</td>
<td>0.03</td>
<td>3</td>
</tr>
<tr>
<td>13 MB2 BS</td>
<td>4.02</td>
<td>4.19</td>
<td>0.17</td>
<td>0.04</td>
<td>4</td>
</tr>
<tr>
<td>13 MB2 BFS</td>
<td>6.46</td>
<td>5.74</td>
<td>-0.72</td>
<td>-0.12</td>
<td>-12</td>
</tr>
<tr>
<td>13 MB2 LTS</td>
<td>4.99</td>
<td>4.5</td>
<td>-0.49</td>
<td>-0.11</td>
<td>-11</td>
</tr>
<tr>
<td>13 MB2 LS</td>
<td>4.09</td>
<td>4.06</td>
<td>-0.03</td>
<td>-0.01</td>
<td>-1</td>
</tr>
<tr>
<td>13 MB2 LFS</td>
<td>3.66</td>
<td>3.69</td>
<td>0.03</td>
<td>0.01</td>
<td>1</td>
</tr>
<tr>
<td><strong>Mean value</strong></td>
<td></td>
<td></td>
<td><strong>-0.13</strong></td>
<td><strong>-0.03</strong></td>
<td><strong>-3</strong></td>
</tr>
</tbody>
</table>
Appendix B – ultrasonic signals

This appendix contains all of the ultrasonic signals for the standard measurements on the HDE-11 crankshaft consisting C38 steel, mentioned in section 4.2.1. The y-axis is in percentage and the x-axis is in μs.
Figure B23: MB2 R5FS
Figure B24: MB2 RFS
Figure B25: MB2 BTS
Figure B26: MB2 BSTS
Figure B27: MB2 BSFS
Figure B28: MB2 BFS
Figure B29: MB2 LTS
Figure B30: MB2 LSTS
Figure B79: CJ1 LSFS
Figure B80: CJ1 LFS
Figure B81: CJ2 UTS
Figure B82: CJ2 USTS
Figure B83: CJ2 USFS
Figure B84: CJ2 UFS
Figure B85: CJ2 RTS
Figure B86: CJ2 RSTS
Figure B119: CJ4 RSFS
Figure B120: CJ4 RFS
Figure B121: CJ4 BTS
Figure B122: CJ4 BSTS
Figure B123: CJ4 BSFS
Figure B124: CJ4 BFS
Figure B125: CJ4 LTS
Figure B126: CJ4 LSTS
Figure B127: CJ4 L5FS

Figure B128: CJ4 LFS
Appendix C – Vickers hardness profiles

This appendix contains the hardness profiles for the standard measurements on the HDE-11 crankshaft mentioned in section 4.2.1.

Figure C1: MB1 UTS

Figure C2: MB1 US

Figure C3: MB1 UFS

Figure C4: MB1 RTS

Figure C5: MB1 RS

Figure C6: MB1 RFS
Figure C13: MB2 UFS
Figure C14: MB2 RTS
Figure C15: MB2 RS
Figure C16: MB2 RFS
Figure C17: MB2 BTS
Figure C18: MB2 BS
Figure C19: MB2 BFS
Figure C20: MB2 LTS
Figure C21: MB2 LS
Figure C22: MB2 LFS
Figure C23: MB3 UTS
Figure C24: MB3 US
Figure C25: MB3 UFS
Figure C26: MB3 RTS
Figure C27: MB3 RS
Figure C28: MB3 RFS
Appendix D – cross section images

This appendix contains the cross section images for the normal crankshaft mentioned in section 4.2.1.
Figure D2: MB1 US

Figure D3: MB1 UFS
Figure D4: MB1 RTS

Figure D5: MB1 RS
Figure D10: MB1 LTS

Figure D11: MB1 LS
Figure D2: MB1 LFS

Figure D13: MB2 UTS
Figure D14: MB2 US

Figure D15: MB2 UFS
Figure D18: MB2 RFS

Figure D19: MB2 BTS
Figure D22: MB2 LTS

Figure D23: MB2 LS
Figure D30: MB3 RFS

Figure D31: MB3 BTS
Figure D34: MB3 LTS

Figure D35: MB3 LS
Figure D36: MB3 LFS

Figure D37: MB4 UTS
Figure D38: MB4 US

Figure D39: MB4 UFS
Figure D44: MB4 BS

Figure D45: MB4 BFS
Figure D50: CJ1 US

Figure D51: CJ1 UFS
Figure D52: CJ1 RTS

Figure D53: CJ1 RS
Figure D58: CJ1 LTS

Figure D59: CJ1 LS
Figure D62: CJ2 US

Figure D62: CJ2 UFS
Figure D63: CJ2 RT5

Figure D64: CJ2 RS
Figure D72: CJ2 LFS

Figure D73: CJ3 UTS
Figure D74: CJ3 US

Figure D75: CJ3 UFS
Figure D76: CJ3 RTS

Figure D77: CJ3 RS
Figure D90: CJ3 BS

Figure D81: CJ3 BFS
Figure D82: CJ3 LTS

Figure D83: CJ3 LS
Figure D90: CJ4 RFS

Figure D91: CJ4 BTS
Figure D96: CJ4 LFS