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ORIGINAL ARTICLE

Crankshaft Hardness Quality Evaluation of Passenger Car

R. Firdaus, P. Paryanto* and S. Sulardjaka

Mechanical Engineering Department, Faculty of Engineering, Universitas Diponegoro, 50275, Indonesia

ABSTRACT – A crankshaft is a part of the main engine components and plays a critical role in car performance. The crankshaft component consists of journals, pins, and flange that experience induction hardening treatment to increase their hardness. Hardness case depth represents important hardness criteria achieved by the depth of induction hardening process. This paper aims to evaluate crankshaft hardness quality by analyzing hardness case depth measurement. The control chart shows the results, which presents process stability to indicate abnormal processes. The capability process is also performed to process consideration. Evaluation results show hardness case depth is not at its best performance even though process capability meets product requirements. Affected factors to process stability are manpower, method, material, measurement, machine and environment. Implemented improvements based on the problem root cause to eliminate influenced factors and achieve stable process are delivered.

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INTRODUCTION

The engine is the main vehicle powertrain consisting of five main components: crankshaft, cylinder block, cylinder head, camshaft and connecting rod. The crankshaft is the most important rotary component that plays a critical role in car performance. Crankshaft failure will affect not to the crankshaft itself but also other engine components, including the cylinder block, connecting rods, pistons and bearings [1]. The crankshaft is transforming energy through converting reciprocated motion to rotational motion as the impact of thermal expansion inside the cylinder head [2]. Crankshaft component consists of journal, pin, flange and counterweight. Journal will be installed to the cylinder block, pin is assembled with connecting rod, flange is as flywheel counterpart and counterweight works to balance the crankshaft by compensating centrifugal force from rotational move [3].

The crankshaft is manufactured in a machining line that is dominated by the turning and milling process. Besides that, the machining line provides hardening treatment by induction hardening process. Hardening treatment proposes to increase crankshaft hardness as one of the mechanical properties major. Mechanical properties affect mechanical strength level and material ability to be formed. Mechanical properties show a material capability to resist against mechanical load [4]. Mechanical properties are identified for material standardization or design need. In general, some of the mechanical properties such as strength, toughness and hardness are measured after raw material forming becomes finished product. Material hardness is one of the mechanical properties that show material resistance against plastic deformation by other materials. [5]. The crankshaft especially journal, pin and flange should meet minimum criteria of hardness value to present the best performance and guarantee failure resistance.

Any process that increases the hardness layer level is called surface hardening treatment. Formed hardness layer by surface hardening treatment is called as case that has various depths; in range between 0.0025 to 10 mm [6]. The hardness case depth term is stated to describe the depth of the formed hardness layer after the surface hardening process. Induction hardening treatment is a common method used to increase the material's surface and component layer hardness. During induction hardening treatment, the material microstructure of surface and layer transform becomes more compressive [7]. Journal, pin and flange components are hardened by the induction hardening process. The treatment guarantee journal, pin and flange resist working failure such as cracks. Furthermore, friction force reveals between journal and cylinder block assembly and pin and connecting rod assembly increase wear possibility. Journal and pin should have higher hardness than their counterpart to prevent excessive wear [3].

Induction hardening treatment is usually used to increase the surface hardness of medium carbon steel. Surface hardening is conducted using high-frequency induction coil to fasten the heat treatment time. The frequency level of induction coil depends on the desirable case depth. Heat treatment causes material microstructure to form austenite then, followed by a quenching and tempering process to complete the process and release residual stress [5]. The induction hardening treatment that is used in the machining line consists of three different induction coils for journal, pin and flange components. Induction hardening treatment starts from journal 1 and pin 1, journal 2 and pin 2, journal 3 and pin 3 and last journal 4 and flange consecutively.

Hardness becomes one of the important point aspects to control. Hardness case depth is a part of hardness criteria that contributes to wear and crack failure potential [8]. Hardness case depth is the perpendicular distance from the hardened surface to the deepest point of the hardness layer or in other words, it is a criterion that shows how deep the hardness

*CORRESPONDING AUTHOR | P. Paryanto | ✉ paryanto@ft.undip.ac.id

treatment achieved. There are two kinds of hardness case depth, total case depth and effective case depth. Total case depth describes hardness depth perpendicularly from the surface layer where the hardness value does not decrease and stay on stable condition due to the achieved hardness peak. Total case depth shows the depth condition that carbon composition reaches 0.04% more than core carbon. Effective case depth explains the depth and area that have hardness Vickers value equal to 550 by 9.81 N load [9]. It can also be said that hardness depth reaches HRC 45 minimally. Less hardness value will contribute to overall hardness quality and decrease crankshaft durability against fatigue. A small crack could be a sign of the impact.

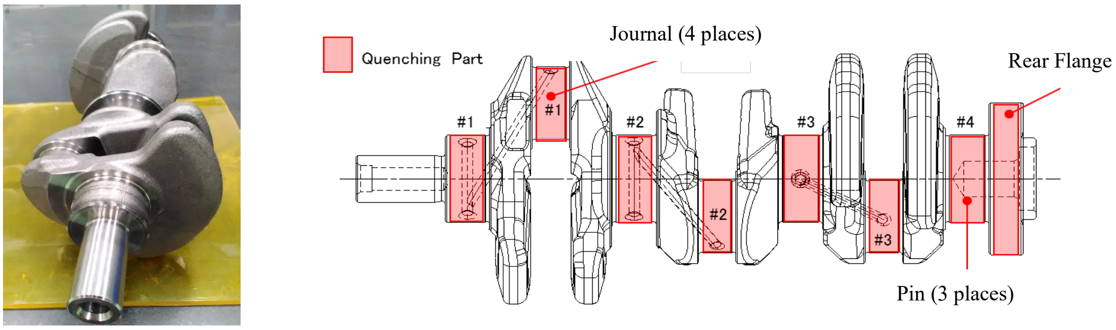
Various researches show the importance of case depth regarding the surface hardness of crankshaft. Xu and Yu [10] conduct failure analysis of a truck diesel engine crankshaft and found the crack occurred is taken place on the lower surface hardness part component area. The component area with corresponding hardness case depth is tougher than other areas. Fonte et al. [11] explain the partial absence of a surface hardening layer decreases fatigue strength and wear resistance of diesel crankshaft. Crack initiation appears in the weaker region and leads to fatigue. Fonte et al. [12] show severe hardening also could contribute to initial crack. Surface hardening by adequate heat treatment is recommended for a better quality crankshafts. Witek et al. [13] found ununiform surface hardening process accelerates crack initiation in diesel engine crankshaft pin. Large hardness is concentrated in the center, so edge area is much smaller.

Hardness case depth faces unachieved minimum hardness concern, which occurs several times. Due to its failure potential, if hardness case depth does not achieve the minimum value, the concern needs more attention to find the problem's root cause and perform countermeasures immediately. This research aims to evaluate crankshaft hardness case depth to measure quality level and find the root cause of hardness case depth value instability. Besides enriching reference to limited research about crankshaft hardness case depth, this research will reveal factors related process instability, provide appropriate countermeasure to tackle the concerns and suggest preventive actions to do.

METHODOLOGY

Materials

The crankshaft evaluated in this research is the passenger car type. The crankshaft material is forged metal that is formed by the forging process at the raw material supplier. The crankshaft is a three-cylinder model that proposes a 1200 cc engine capacity, as shown in Figure 1. The crankshaft is hardened by the induction hardening process where the hardening process was conducted in the middle stage of the machining process. The raw material crankshaft was pre-machined on the front shaft, journals, pin and flange area. Each component of the journal, pin and flange area then experienced induction hardening process. The induction hardening treatment used in the machining line consists of three different induction coils for journal, pin and flange component. Induction hardening treatment starts from processing journal 1 and pin 1, journal 2 and pin 2, journal 3 and pin 3 and last journal 4 and flange consecutively.



(a) crankshaft (b) hardening area

Figure 1. Three-cylinder crankshaft model

Data Collection and Process

Data used in this research is gathered from routine measurement data for one year. Data is measured from the crankshaft that finishes induction hardening process with a focus on hardness case depth point only. Hardness case depth is the measurement point of the induction hardening process that faces unachieved minimum value concern. Hardness case depth is measured once per shift at the beginning shift to determine the crankshaft hardness quality of the production day can go or not. Data processing is started by preparing the data. Data is analyzed by using the control chat method to visualize process conditions. The calculation is conducted to find process stability and capability. Sensitivity analysis is used to recognize abnormal point which represents the abnormal process. Each abnormal point is mapped into six factors by using a cause and effect diagram. Every factor was then analyzed deeper using five whys analysis to find the root cause, as shown in Figure 2.

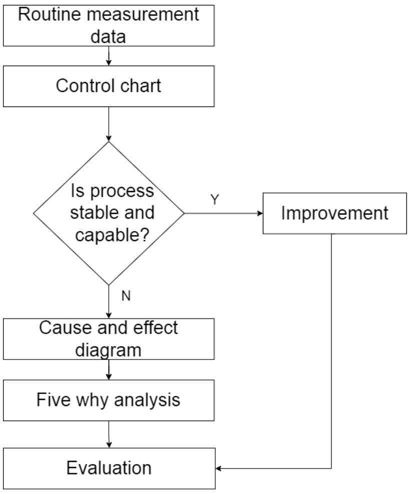


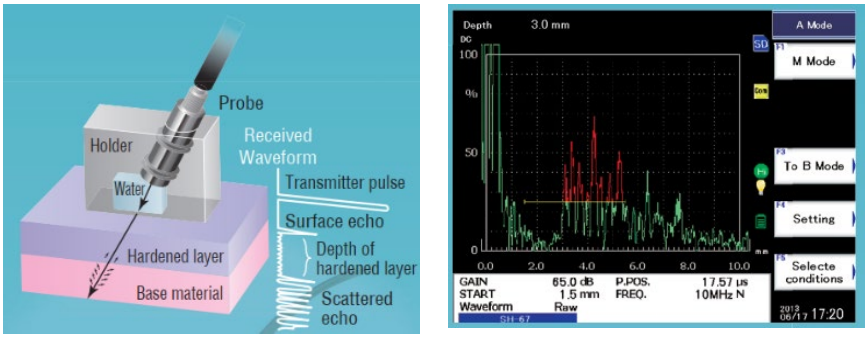
Figure 2. Data processing methodology

Measurement Process

Quality control is an activity carried out to measure the actual performance of an ongoing process, compare actual performance with predetermined criteria, and take corrective action if deviations occur. Quality control is a system that aims to create products that meet consumer needs. So, quality control is an effort made to ensure that the products produced meet the established criteria. Quality is one of the major elements of operation planning in manufacturing industries [18]. Quality is also defined as the suitability of use which consists of two aspects, namely quality of conformance and quality of design [20]. Quality of conformance aspects related to product quality with specifications and tolerances are determined through factors such as the selection of manufacturing processes. The quality of design aspect refers to variations in the design of a product, such as variations in type, size, appearance, and performance. These variations lead to differences in the manufacturing process as well as the tools and machines used.

Quality control begins with the process of identifying the main criteria that can meet customer wants and needs. The process is continued by designing product features from the main criteria, designing processes for making these features to controlling the feature creation process. Offline quality control includes assessment of consumer needs and desires, product characteristic design and manufacturing process design, while online quality control is carried out during the ongoing process through ongoing process control. Product sampling is one of the main factors in controlling and improving product quality. Sampling inspection is closely related to product inspection, which is the earliest quality control method in which statistical quality control is not widely used.

Measurement holds an important role in guaranteeing product quality. Hardness case depth measurement is conducted once per shift by using hard echo ultrasonic wave, namely hard echo, as shown in Figure 3. Measurement results determine required action to keep quality at a desirable level, such as machine setting, maintenance, countermeasure and problem-solving. Trained quality assurance operators measure the crankshaft at the beginning of shift. Hardness case depth is controlled by two inspection methods are Non-Destructive Test (NDT) by using hard echo ultrasonic wave and Destructive Test (DT) through direct measurement using micro Vickers by cutting the crankshaft into pieces. Hard echo is used frequently due to its function as quick measurement for quick judgment. Ultrasonic measurement is widely used today due to rapid technology development and part integrity issue. Besides ultrasonic wave measurement for hardness case depth, there are various research related non-destructive measurement. Mao et al. [14] use nonlinear ultrasonic for carburized case depth measurement. Satoru et al. choose [15] magnetic hysteresis technology for case depth measurement on induction hardened steel rods research. Send et al. [16] use low frequency magnetic field measurement or Barkhausen noise method for case hardening depth measurement. Schneider et al. [17] use laser ultrasonic detection method or surface acoustic wave for hardened steel hardness depth measurement.



GAIN 65.0 dB
START 1.5 mm
Waveform Raw
P.POS. 17.57 µs
FREQ. 10MHz N

Figure 3. Measurement process

The ultrasonic wave of hard echo is obtained by measuring propagation wave time between the sensor and the transition zone. The measurement principal of hard echo is identifying hardened layer characteristics. The hardened layer has a finer microstructure than the non-hardened layer. Ultrasonic waves propagate through the hardened layer and base layer and then create scatter as a result.

The measurement result was used to create a control chart, process stability measurement and process capability measurement. There are eight parts of the crankshaft hardness depth case measurement result, which consist of four journal components, three pin components and one flange component, so the control chart. In the end, the control chart of four journal components will be combined as one control chart named journal, so the control chart of the pin. Process stability and capability consist of three component groups named as journal, pin and journal. The data was calculated using Minitab 19.

Control Chart

Quality is related to variability; a product has good quality if it contains less variability. Product sampling technique is related to product inspection when quality control is known and the statistical method has not been widely developed. Current quality control does not emphasize product sampling as the main method and focuses more on statistical process control and experimental design. Product sampling shows quality as only conformance to specifications but does not provide feedback on the manufacturing process, design or product development that could lead to quality improvement. Quality improvement has the primary objective of reducing variability in important product characteristics. In the early stages of quality control development, product sampling is used as the primary tool, with out-of-spec products dominating the output process. However, statistical process control development could stabilize the process in such a way as to reduce variability.

Statistical process control is a method that aims to obtain stability and improve process capability using statistical techniques to reduce variability [20]. The control chart is part of statistical process control to identify the working process and show process abnormality to analyze. Each process abnormality is checked to figure out the abnormal event that happened at the time. Every event is classified into a common cause and a special cause. The common cause comes from the natural variability of the process is ignored. Even with good process design and machine maintenance, natural variability is inevitable in any production process. Natural variability is a collection of small things that are impossible to avoid. A process that works only with variations due to a common cause is called a statistically controllable process. Another variability that can occur in the production process is a special cause. The special cause of variability comes from external factors such as machine error, human error, and inconsistent material composition.

The control chart shows the process stability, which is restricted by the control limit that is defined based on its process variability. Control limit usually provides stricter criteria than specification limit so it can prevent the product result from exceeding the standard and going to defect product. The specification limit is a criterion determined by the company based on the suitability of the function of a product. If the product is outside the specification limit, the product can be said to be Not Good (NG), but if the product is outside the control limit, the product can still be said to be good but the process is experiencing instability. So, it is necessary to find the cause and make improvements to prevent more severe instability causing instability—product out of specification limit. The cause of this variability has an impact on the process variability, which is very large when compared to the common cause. A process that occurs with a special cause in it is called an uncontrolled process.

A control chart has the main function of detecting special causes that lead to process deviations early [19]. This allows decision-makers to investigate processes and take corrective action before deviations from production standards occur. The goal to be achieved by the control chart is to eliminate process variability, although variability cannot be completely eliminated because there are always undesirable factors that exist naturally. The control chart was developed to reduce variability as much as possible in the hope that the process can be maintained stable.

Statistical methods have an important role in efforts to improve and improve quality because the variability that occurs in the process can only be explained through statistical terms [20]. There are two classifications of data on quality control, namely, attribute data and variable data. Attribute data is discrete data that is commonly used to evaluate processes based on product defects, while variable data is continuous measurement data that is commonly used to evaluate processes through product parameter measurements. In addition, there are two types of control charts, namely variable control charts and attribute control charts. Each of the control charts plays a role in controlling quality based on the type of data applicable to the product.

This research uses the exponentially weighted moving average (EWMA) control chart type due to its ability to proceed with non-normal distribution data. EWMA is a control chart that calculates a weighted average from the results of observations that have been conducted previously; this control chart is not sensitive to the issue of normality [20]. EWMA creates a control chart by using one sample for each observation that meets the measurement method used in the production line. The EWMA is shown as z formula as follows:

$$z_i = \lambda x_i + (1-\lambda) z_{i-1} \tag{1}$$

$$UCL = \mu_0 + L\sigma\sqrt{\frac{\lambda}{2-\lambda}[1-(1-\lambda)^{2i}]} \tag{2}$$

$$CL = \mu_0 \tag{3}$$

$$LCL = \mu_0 - L\sigma\sqrt{\frac{\lambda}{2-\lambda}\left[1-(1-\lambda)^{2i}\right]} \tag{4}$$

where UCL is the upper control limit, CL is control limit, LCL is the lower control limit, i is sample at i order, λ is constant weight in range $0 < \lambda < 1$ and μ is the mean of the process. The control chart increases its sensitivity to detect abnormality process by dividing the chart into three zones based on sigma values called zone rules, as shown in Figure 4. The control chart will be evaluated to identify abnormality by using sensitivity rules [20]. Sensitivity rules provide criteria to find abnormality signals from data patterns, as listed in Table 1.

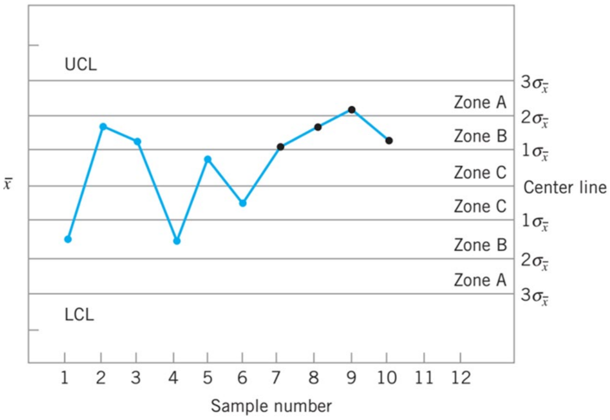


Figure 4. Zone rules

Table 1. Sensitivity rules

No.	Standard action signal
1.	One or more points outside of control limits.
2.	Two of three consecutive points two-sigma warning limits.
3.	Four of five consecutive points beyond one-sigma limits.
4.	A run of eight consecutive points on one side of center line.
5.	Six points in a row steadily increasing or decreasing.
6.	Fifteen points in a row in zone C (both above and below the center line).
7.	Fourteen points in a row alternating up and down.
8.	Eight points in a row on both sides of the center line on both sides of the center line with none in zone C.
9.	An unusual or nonrandom pattern in the data.
10.	One or more points near a warning or control limit.

Cause and Effect Diagram

A cause-and-effect diagram is one statistical process control that is used to identify a problem by classifying based on its group. Causes are put at the edge, and effect is put at the end of the diagram. Causes consist of manpower, machine, material, method, measurement, and environmental factors. Cause and effect are used in this research to connect causes to the effect and find the relation. The cause-and-effect diagram is conducted by following steps [20]:

i. Identify problem to analyze;
ii. Form a team to analyze together;
iii. Draw center and influenced factors;
iv. Specify and classify the root cause based on the category then correlate it to the central line;
v. Analyze the root cause of each factor;
vi. Sort the root cause starting from the most influential factor;
vii. List and execute countermeasures.

Five Whys Analysis

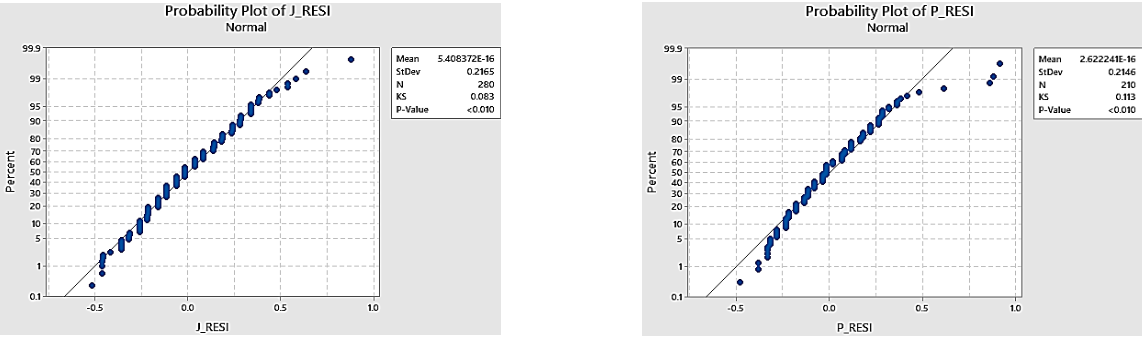
A repeated occurring problem is commonly the only symptom of a more complex problem. Five whys are proposed techniques to explore the knowledge from the problem by asking questions five times [20]. The questions should be asked to the right person with the appropriate background and experience to acquire the best answer. Five whys analysis illustrates the sequence of events that leads to the main incident [21]. The five whys technique can be used independently or combined with another technique. This research combines the five whys technique and cause-and-effect diagram. Defining the problem aspect and category will be assessed by a cause-and-effect diagram then exploring the root cause will be assessed by a five whys analysis. Countermeasure is a complete action taken to solve the problem on the spot and take preventive measures so that similar problems do not happen again. It can be a form of process and tool improvements, making procedures to train users. The team will discuss each root cause to solve.

RESULTS AND DISCUSSION

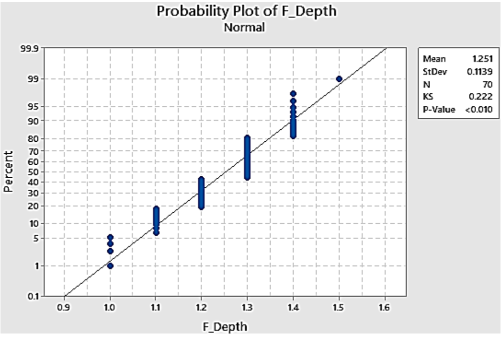
Process Stability

Process stability is assessed by reviewing the control chart. The process is called a stable process if the whole measurement point follows the sensitivity rule. Each violation of the sensitivity rules causes the process to be unstable. Analysis should be conducted to identify the root cause. If the violation point is caused by an assignable cause, it will be ignored. Violation point caused by special cause needs to analyze the root cause.

Commonly, the most control chart is constructed based on normal distribution data assumption. The normal distribution shows the distribution of errors that are owned by the data. The normal distribution also shows how much the sample's ability to represent the actual data. Normal distribution status determines the technique used to process the data further. Data that is not normally distributed will use a different control chart from data that is normally distributed. The control chart that is built based on the assumption of a normal distribution cannot properly process data that is not normally distributed; there can be errors in describing the state of the process. Normal distribution data can be known through a normality test. The Kolmogorov-Smirnov method is used in this normality test, as shown in Figure 5. The hypothesis used is H_0 for data normally distributed (p-value > 0.05) and H_1 for data not normally distributed (p-value < 0.05). Journal, pin, and flange data have p-values < 0.05, where data is not normally distributed. It is also shown in the plot that points spread do not follow the center line.



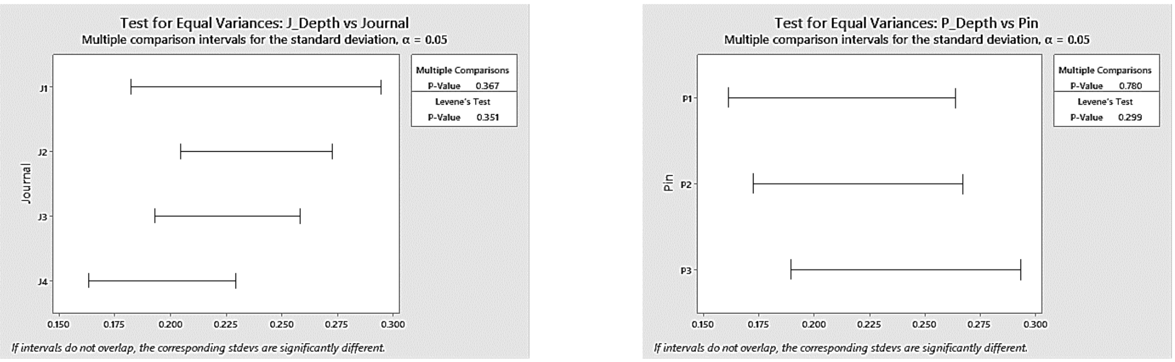
(a) journal (b) pin



(c) flange

Figure 5. Normality test result

An equal variance test is conducted to understand data similarity among whole journals data and pins data. Similarity shows data suitability for combining. The greater the similarity of the data or the smaller the variance that exists between the data, the greater the opportunity for the data to be combined and provide new knowledge. Selection of the right variance similarity test method requires information in the form of normality of data from each component. The Levene test will be used, as shown in Figure 6, due to its ability to process non-normally distributed data. The hypothesis used is H_0 for data that has a similar variance (p-value > 0.05) and H_1 for data that does not has a similar variance (p-value < 0.05). Journals and pins data have p-values > 0.05 where data have similar variance. It is also shown in the plot that data components intersect each other.



(a) journal (b) pin

Figure 6. Equal variance test result

The journal, pin, and flange data owned are not normally distributed; they are not accurate when mapped on the Shewhart control chart. An alternative control chart that can accommodate the non-fulfilment of the assumption of normally distributed data is the EWMA control chart. In addition, the EWMA control chart is intended for data that perform data collection in the form of a single sample. The EWMA control chart is built through two parameters that must be determined, namely the sigma multiplier used at the control limit (L) and the weight value (λ) [20].

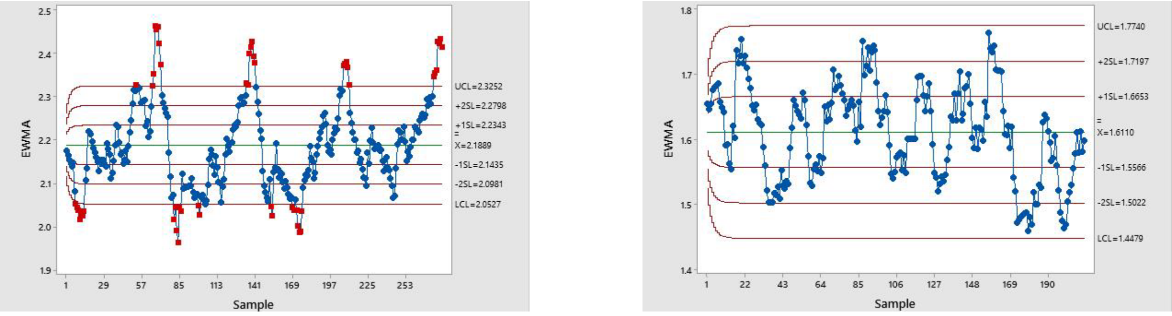
The control limit value used is three as defined by the standard rule and implemented by Minitab. In addition, the weight value used in making this EWMA control chart is 0.15. The weight value has an interval of $0.05 \leq \lambda \leq 0.25$. The smaller the value, the better at detecting small shifts. However, it should also be noted that a small value has an impact on decreasing the speed of the EWMA control chart in detecting shifts. The weighting of a small value has the consequence that the EWMA control chart has to go through more stages to move when detecting data from one side to the other.

At $\lambda=0.05$ or $\lambda=0.10$, the EWMA control chart shows its best performance in detecting small data shifts including data that are normally distributed or data that are not normally distributed [20]. The selection λ of 0.15 is based on the best ability of the EWMA control chart in detecting data that is not normally distributed and considering the optimal speed in detecting shifts. In addition, based on trial and error conducted by the researcher, the use of $\lambda=0.1$ and $\lambda=0.15$ do not provide a significant difference. EWMA control chart shows journal, pin, and flange process conditions, as shown in Figure 7. Journal, pin, and flange EWMA control chart represent process condition is unstable, which is shown by its violation of sensitivity rules.

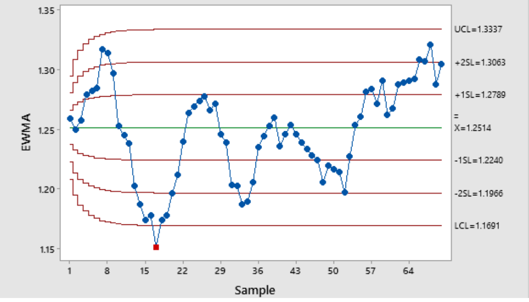
Identification of the process is carried out after making the control chart. The identification process serves to assess the controllability of the process. The identification process seeks to find deviation patterns based on ten sensitivity rules. The process is said to deviate if there are points that are outside the control limit that indicate the variation of the process taking place. However, the product is declared to be a good product if it is still within the specification limit which indicates the criteria based on the specified standard.

Journal EWMA control chart breaks sensitivity rules of one or more points outside of control limits, two of three consecutive points two-sigma warning limits, four of five consecutive points beyond one-sigma limits, six points in a row steadily increasing or decreasing, and one or more points near a warning or control limit. Journal EWMA control chart has the biggest violation among the parts. Pin EWMA control chart breaks sensitivity rules of two of three consecutive points, two-sigma warning limits four of five consecutive points beyond one-sigma limits and six points in a row steadily increasing or decreasing. On the pin control chart, there are no points that go out of the control limit. Flange EWMA control chart breaks sensitivity rules of one point outside of control limits, two of three consecutive points, two-sigma warning limits and four of five consecutive points beyond one-sigma limits.

EWMA control chart results show whole crankshaft component process experiences violation. A good process is a process that has high stability. Stability shows the variability that exists during the production process within a certain period of time. The smaller the level of variability, the more consistent and precise the production process will be. The process requires improvement to achieve stability through the elimination of deviant data. Each violation is analyzed to identify the cause classification which is conducted by comparing problem data points and problem report data on the day. If there is no problem reported at the day in point concern, so the point will be classified as a common cause. A violation that is classified as a common cause will be ignored, and a violation which classified as a special cause will be analyzed further.



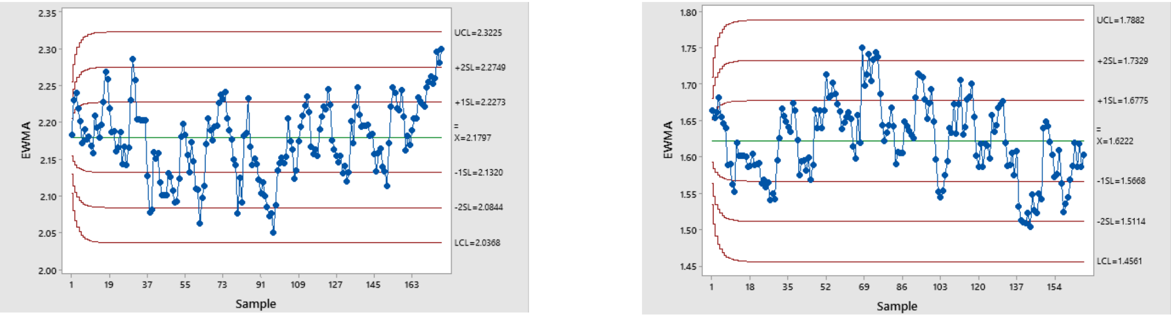
(a) journal (b) pin



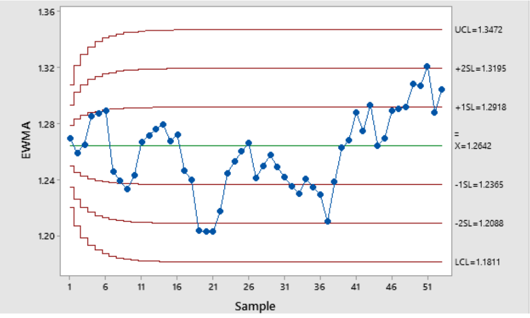
(c) flange

Figure 7. EWMA control chart design

Special cause concerns should be overcome by finding the root cause. Assignable causes are disturbances in the process that cannot be controlled due to unusual activities or non-natural variabilities, such as defective raw materials, machine setting errors, and operator negligence. Assignable cause data can be identified and can be eliminated through improvements so that this data will be eliminated after countermeasure is applied to determine the stability of the process naturally. Control chart deviations are corrected by eliminating deviant points based on the sensitivity rule. The root cause and countermeasure of the concern are explained in the root cause analysis and process improvement parts. The control chart after the countermeasure is shown in Figure 8. The whole data follows sensitivity rules and is within the control limit and specification limit. In other words, a control chart can be stated as a stable process.



(a) journal (b) pin



(c) flange

Figure 8. EWMA control chart design

Process Capability

Process capability is measured after the process is stated as a stable process. Process capability measurement proposes to figure out the process's ability to produce the product within the desired specification. Process capability determines at what level the process is and what actions need to be taken to maintain, keep and improve quality. In addition, the frequency of checking conducted is also determined based on the capability value of a process. Process capability is symbolized by Pp and Ppk. Pp represents process potential that could be reached if the process is at minimally medium performance. Ppk evaluates the process capability through process assessment if it is not in the middle of a performance and compares the shift to the middle-performance process based on the specification limit. Ppk is also called actual process in the line due to its ability to represent better process capability. Pp and Ppk values are minimally 1.00 to state the process on a good capability level and expected more than 1.00. The processing capability can be calculated as follows [20],

$$\mathrm{Pp} = \frac{\mathrm{USL} - \mathrm{LSL}}{6\sigma} \tag{5}$$

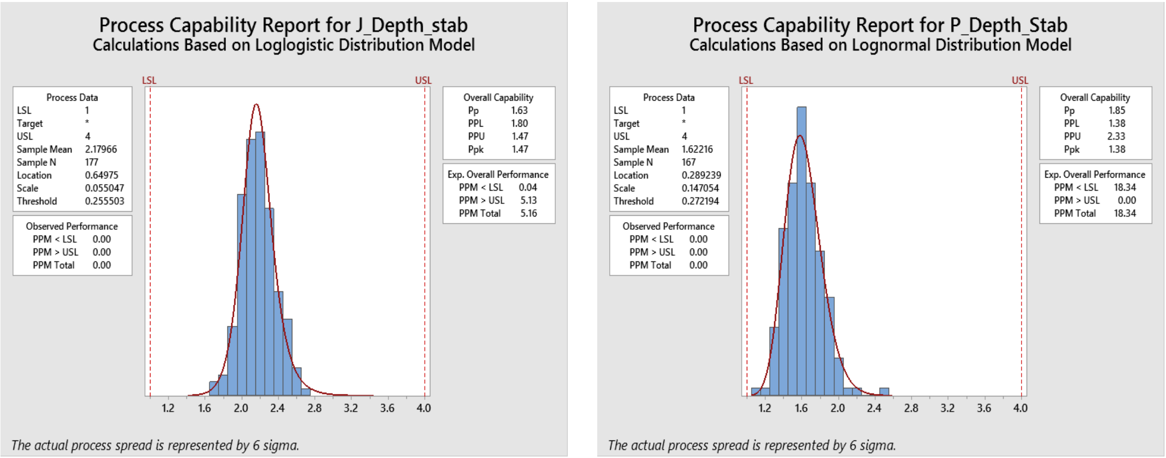
$$\mathrm{P}pk = \min(\mathrm{P}_{pu}, \mathrm{P}_{pl}) \tag{6}$$

where USL is upper specification limit, LSL is lower specification limit, Cpu is Cp upper and Cpl is Cp lower. Pp and Ppk measurements are used to encompass the whole process performance. Due to the data do not meet the normality assumption, the goodness of fit test is performed to obtain the proper model for each capability measurement. Distributions are represented by LRT P-value following the determined hypothesis. The hypothesis used is H_0 for data that follows the model distribution (p-value > 0.05) and H_1 for data that does not follow the model distribution (p-value < 0.05) as shown in Table 2.

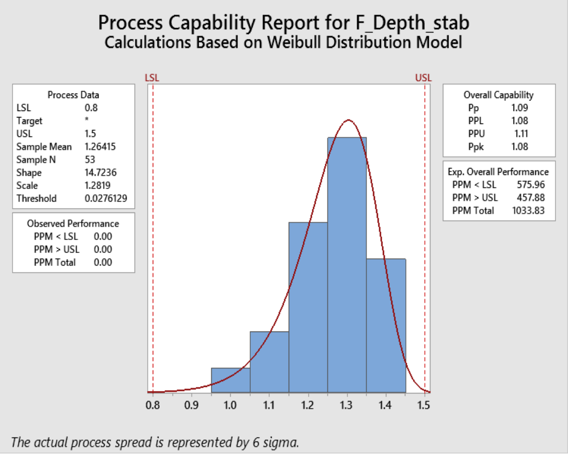
Table 2. Goodness of fit test result

Component	Distribution	LRT P
Journal	3-Parameter Loglogistic	0.892
Pin	3-Parameter Lognormal	0.650
Flange	3-Parameter Weibull	0.990

Data will be measured based on distribution model suitability. The goodness of fit test results shows the different distribution for each component. Then capability process is measured as shown in Figure 9. Based on the Pp Ppk value of a journal, pin, and flange process capability result, there is a good level of capability based on the pp Ppk value > 1.00. All products are within specification limits and can be improved to improve performance. In addition, a reduction in the sample rate can be considered. The best capability result is shown by the journal process. The Pp pin value which is greater than the Pp journal, indicates the potential for pin processing that can be improved. In addition, the pin control chart before repair shows a more stable pin process than the journaling process. The flange process needs more attention due to its process capability result near 1.00, so the natural tolerance is the same as the specification limit. If there is a slight deviation, it can reduce performance and result in points outside the control limit. The Pp and Ppk values of the flange are the lowest among journals and pins, so immediate repairs are needed.



(a) journal (b) pin



(c) flange

Figure 9. Process capability result

Root Cause Analysis

Control charts have a major role in improving processes. It is known that, firstly, running processes are dominated by processes that are not running under statistically controlled conditions. Second, the root cause of the problem comes from a special cause which, if it can be eliminated from the process, the variability can be reduced, and the process can perform better. This identification can be conducted easier by using a control chart. Lastly, an active role from the management level to the operator in the form of corrective actions is very important in an effort to eliminate special causes because the control chart can only identify problems.

Each problem needs proper countermeasures to eliminate the concern. Countermeasures work well when they reach the root cause of the problem. It is essential to analyze each concern to find the root cause. Each concern is analyzed by classifying into six groups which are represented by a cause-and-effect diagram as shown in Figure 10.

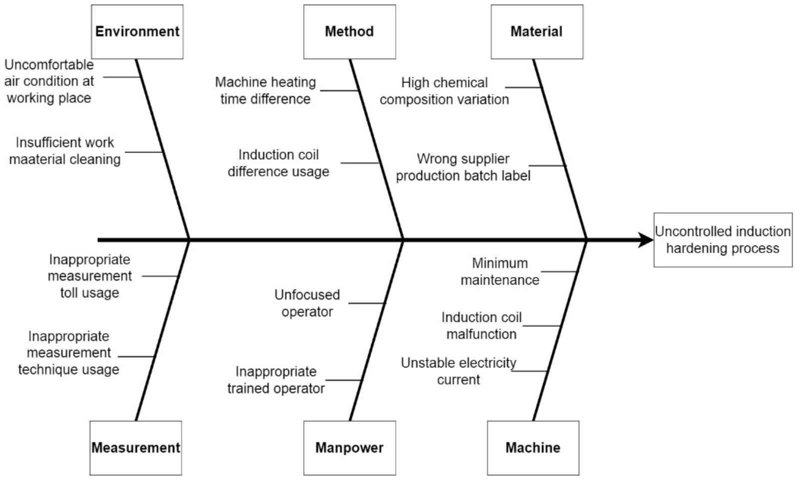


Figure 10. Cause and effect diagram of crankshaft hardness concern

The cause-and-effect diagram classifies concerns based on factors that consist of material, method, manpower, machine, measurement, and environment. Each factor is explored deeper by using a five-whys analysis to reach the root cause, as shown in Table 3. Concern from factors is analyzed into last why to obtain root cause source. A phenomenon from a factor may come from another factor, so it also may affect another factor. A phenomenon from the environmental factor is caused by the machine factor, which is insufficient filter specification. The phenomenon from the measurement factor is affected by the manpower factor which is related to manpower skill and knowledge. Phenomenon form method factor comes from material factor due to its composition and dimension. There needs to be an in-depth and integrated analysis of factors to be able to find the root of the problem and the right solution.

The environmental factor contributes to two phenomena that cause instability. An uncomfortable working environment affects the operator's performance which decreases because it is not focused so there can be negligence in crankshaft processing. An environment that has a lot of smoke comes from a machine with insufficient air filter capability. Poor material cleaning is related to the crankshaft washing process environment. The crankshaft which still has impurities in the journal, pin, and flange components, has the potential for imperfections in the induction hardening process. Therefore, these two phenomena are also related to the condition of other machines, namely washing machines and turning machines. The measurement factor contributes to two phenomena that cause instability. Inappropriate measuring tools and measurement techniques affect the measurement results. Inappropriate measuring tools usage is caused by operator errors in using the jig holder sensor, and inappropriate measurement technique usage is caused by the absence of rules in the measuring position. Therefore, these two phenomena are also related to the manpower and method factors.

Table 3. Five whys analysis

Factor	Phenomenon	Last Why
Environment	Uncomfortable air condition at workplace place	Insufficient filter specification
	Insufficient work material cleaning	Open coolant container Dirty environment
Measurement	Inappropriate measurement tool usage	Incomplete training in measurement tool usage
	Inappropriate measurement technique usage	Minimum product knowledge
Method	Machine heating time difference	Material composition change
	Induction coil difference usage	Component dimension difference
Manpower	Inappropriately trained operator	Existing operator change
	Unfocused operator	Repeated activity for a long time Unfit condition
Machine	Induction coil malfunction	Reach coil usage life Manufacturing defect
	Unstable electricity current	Pest attack to cable
	Minimum maintenance	New machine lack of knowledge
Material	High chemical composition variation	Raw material variation
	Wrong supplier production batch label	Supplier misunderstanding

The method factor contributes to two phenomena that cause instability: machine heating time difference and induction coil difference usage. The difference in heating time affects the hardness case depth results. The initial heating time has a standard from the machine maker and the company but is still returned to each factory to adjust the heating time in order to achieve the expected hardness case depth. The difference in the use of induction coils affects the variation in results because it uses three different induction coils, namely induction coils for journals, pins, and flange. Therefore, these two phenomena are also related to machines and material factors. The manpower factor contributes to two phenomena that cause instability. Operators who are poorly trained usually occur when there are new operators who are still adapting and have not been able to work optimally. This has an impact on work, such as improperly positioning the crankshaft on the engine. An unfocused operator is a common occurrence caused by individual operator factors such as health conditions. The effect of an unfocused operator is also due to the effect of a new operator.

The machine factor contributes to three phenomena that cause instability. The induction coil malfunction causes the hardness case depth results to vary after the induction hardening process or not meet the standards. Induction coil malfunctions are caused by the age of the coil that has reached its age or defects in the coil. An unstable electric current causes the induction process to be disrupted so that the engine cannot reach its optimal performance. This is caused by the wires being chipped by pests. Lack of maintenance causes the machine not to work at its optimal performance. The lack of knowledge of the maintenance team because it is a new machine is a contributing factor. Therefore, these two phenomena are also related to manpower and environmental factors.

The material factor contributes to two phenomena that cause instability. High variations of chemical composition cause high variations resulting in high hardness case depth as well. This is caused by raw material suppliers who cannot control raw material composition properly. There needs to be a notification to the supplier of raw materials to improve the process. Incompatibility of supplier production batches can cause variation in results because each batch of raw crankshaft production has a different level of material concentration, so it is necessary to set the machine if the measurement results due to variations in material concentration differ much from the target. This is due to raw crankshaft suppliers who mix production batches of regular products with hold products which they usually separate for investigation.

Process Improvement

The concern will never appear again if a countermeasure is implemented to the root cause. Moreover, improvement actions prevent similar concerns from occurring. Countermeasure that is conducted based on the standard and experience of the team, as shown in Table 4. Advice from other plant counter partners and machine makers is considered to obtain an appropriate solution. Countermeasures and improvements are implemented for each factor and related factor inside the concern. Environment concerns focus on the environment itself and machine issues. Measurement concerns handle measurement and also manpower issues. Method concerns overcome not only method but also material issues.

Table 4. Process improvement analysis.

Factor	Root Cause	Countermeasure	Improvement
Environment	Insufficient filter specification	Filter change	Upgrade filter specification
	Open coolant container	Coolant change	Coolant container coverage
	Dirty environment	Environment cleaning	Working place cleaning standard
Measurement	Complete training of measurement tool usage	Usage training	Routine usage training and evaluation
	Minimum product knowledge	Knowledge product training	Routine knowledge training and evaluation
Method	Material composition change	Machine setting	Routine material composition information document
Manpower	Existing operator change	Operator training	Skill evaluation control
	Repeated activity for long time	Working area change	Break time resetting
	Unfit condition	Operator change	Routine supplement consumption
Machine	Reach coil usage life	Coil change	Upgrade coil specification
	Manufacturing defect	Coil change	Supplier change
	Pest attack to cable	Cable change	Pest trap
	New machine lack of knowledge	Routine maintenance	Machine study comparison
Material	Raw material variation	Machine setting	Improve raw material variation stability
	Supplier misunderstanding	Raw crankshaft separation	Supplier understanding and standard sharing

CONCLUSIONS

This research delivers process stability and capability of crankshaft hardness processes. The induction hardening process is experiencing instability which is indicated by process deviations based on the journal, pin, and flange control chart. Deviations on the control chart are indicated by points that are outside the control limit, two of three consecutive points outside the two-sigma line, four of five consecutive points outside the one-sigma line, six points consistently increasing or decreasing, or there are points that are near the control limit. Hardness case depth quality is affected by six factors that contribute to instability individually or influence each other. Furthermore, concerns that affect its stability are analyzed to find the root cause. The solution is implemented based on the root cause to guarantee its effectiveness to eliminate the issue. Improvement is conducted to prevent similar concerns from appearing in the future.

The EWMA control chart shows its capability to process non-normal distribution data very well and capable of showing data violation of the process. The sensitivity rules help the control chart identify process abnormalities that appear clearly and potential abnormalities. Cause and effect diagrams classify concerns based on factor cause to help identify the issues easier. The five whys technique does work to find and analyze the root cause based on the cause-and-effect diagram classification problem. The cause-and-effect diagram and the five whys technique are good combinations to find the concern and identify the root cause.

The cause and effect diagram and five-whys analysis find the root cause of the problem which can then be countermeasured directly including replacing the operator immediately if the operator experiences a problem, and changing the coil if the depth of hardness result is not reached the minimum standard or approaching the lower limit and checking the cable condition if the machining process is unstable. In addition, prevention actions can be taken against six factors of elements, including operator training and operator change for labor factor, coil changes, cable changes, and maintenance and repairs for machine factor, machine settings, and crankshaft separation according to production batches for material factor, routine filter changes and routine cleaning of the work area for an environmental factor, usage training, and product knowledge training for measurement factor and machine settings for method factor.

The crankshaft hardness process is unstable, which is shown by its violation of sensitivity rules on a control chart. The capability of the induction hardening process is good enough, which is indicated by the Pp Ppk value. The journal process is worth Pp 1.63 and Ppk 1.47, the pin process is Pp 1.85 and Ppk 1.38, and the flanging process is Pp 1.09 and Ppk 1.08. All products are within the specification limit. In addition, a reduction in the sample rate can be considered. However, the Pp and Ppk flange numbers which are still worth one, indicate that the natural tolerance is the same as the specification limit, so if there is a slight deviation, it can reduce performance and result in points outside the control limit, so it needs to be improved. Implemented countermeasures work effectively to improve process stability.

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REFERENCES

[1] K. Aliakbari, R. M. Nejad, S. K. P. Toroq, W. Macek, R. Branco, “Assessment of unusual failure in crankshaft of heavy-duty truck engine,” *Engineering Failure Analysis,* vol. 134, p. 106085, 2022.

[2] H. Yamagata, “The crankshaft,” In *The Science and Technology of Materials in Automotive Engines,* Woodhead Publishing, pp. 165-206, 2005.

[3] M. Fonte, M. Freitas, L. Reis, “Failure analysis of a damaged diesel motor crankshaft,” *Engineering Failure Analysis*, vol. 102, pp. 1-6, 2019.

[4] S.S. Murugan, “Mechanical Propeties of Materials: Definition, Tesing and Application,” *International Journal of Modern Studies in Mechanical Engineering*, vol 6, pp. 28-38, 2020.

[5] W.D. Callister, *Materials Science and Engineering an Introduction*, 7th ed., New York: John Wiley & Sons Inc, 1940.

[6] S. Santa-aho, M, Vippola, A. Sorsa, K, Leiviskä, M. Lindgren, T. Lepistö, “Utilization of Barkhausen noise magnetizing sweeps for case-depth detection from hardened steel,” *NDT&E International*, vol. 52, pp.95-102, 2012.

[7] G. Fett, “Importance of induction hardened case depth in torsional applications,” *Heat Treating Progress,* vol. 9, no. 7, pp. 15–19, 2009.

[8] J. Mateus, V. Anes, I. Galvão, L. Reis, “Failure mode analysis of a 1.9 turbo diesel engine crankshaft,” *Engineering Failure Analysis,* vol. 101, pp. 394-406, 2019.

[9] K. Genel, “Estimation method for the fatigue limit of case hardened steels,” *Surface and Coating Technology,* vol. 194, Issue 1, pp. 91-95, 2005.

[10] X.l. Xu, Z.w. Yu, “Failure analysis of a truck diesel engine crankshaft,” *Engineering Failure Analysis,* vol. 92, pp. 84-94, 2018.

[11] M. Fonte, V. Anes, P. Duarte, L. Reis, M. Freitas, “Crankshaft failure analysis of a boxer diesel motor,” *Engineering Failure Analysis,* vol. 56, pp.109-115, 2015.

[12] M. Fonte, P. Duarte, L. Reis, M. Freitas, V. Infante, “Failure mode analysis of two crankshafts of a single cylinder diesel engine,” *Engineering Failure Analysis,* vol. 56, pp.185-193, 2015.

[13] L. Witek, M. Sikora, F. Stachowicz, T. Trzepiecinski, “Stress and failure analysis of the crankshaft of diesel engine,” *Engineering Failure Analysis,* vol. 82, pp.703-712, 2017.

[14] H. Mao, Q. Li, H. Mao, Z. Huang, W. Tang *et al.*, “Nonlinear ultrasonic characterization of carburized case depth, *NDT & E International*, vol. 112, p. 102244, 2020.

[15] S. Kobayashi, H. Takahashi, and Y. Kamada, “Evaluation of case depth in induction-hardened steels: Magnetic hysteresis measurements and hardness-depth profiling by differential permeability analysis,” *Journal of Magnetism and Magnetic Materials,* vol. 343, pp. 112-118, 2013.

[16] S. Send, and D. Dapprich, J. Thomas *et al.*, “Non-destructive Case Depth Determination by Means of Low-Frequency Barkhausen Noise Measurements,” *Journal of Nondestructive Evaluation,* vol. 37, p. 82, 2018.

[17] D. Schneider, R. Hofmann, T. Schwarz, T. Grosser, E. Hensel, “Evaluating surface hardened steels by laser-acoustics,” *Surface and Coating Technology,* vol. 206, issues 8–9, pp. 2079-2088, 2012.

[18] P. P. Tambe, and M. S. Kulkarni, “A reliability based integrated model of maintenance planning with quality control and production decision for improving operational performance,” *Reliability Engineering & System Safety,* vol. 226, p. 108681, 2022.

[19] A. Salmasnia, B. Abdzadeh, and M. Namdar, “A joint design of production run length, maintenance policy and control chart with multiple assignable causes,” *Journal of Manufacturing Systems,* vol. 42, pp. 44-56, 2017.

[20] D.C. Montgomery, *Introduction to Statistical Quality Control*, 7th ed, USA: John Wiley & Sons. Inc, 2009.

[21] B. Hoła, T. Nowobilski, I. Szer, and J. Szer, “Identification of factors affecting the accident rate in the construction industry,” *Procedia Engineering,* vol. 208, pp 35-42, 2017.