Failure analysis of S50C carbon steel applied for fine boring transmission system

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Abstract. The purpose of this research was to analyze the failure of the axle of fine boring transmission system shaft engine which was subjected to JIS G4051 S50C carbon steel. In industrial machinery, fatigue failure is often found on the work machine. The transmission system uses a bearing on each side of the shaft so that the shaft rotation becomes smoother and the shock load at the beginning of the rotation becomes smaller. This analysis was carry out by comparison of metallographic results such as fractography by SEM, identification of chemical composition by OES, mechanical properties by tensile and Rockwell test with loading 150 kgf, and calculation of fracture toughness. The analysis obtained from the research showed that, the average of fracture toughness evaluated by hardness and tensile crack were 26 and 77 MPa.m$^{1/2}$, respectively. Therefore, by fracture toughness calculation results and crack propagation in microstructure results, it is confirmed that that the shaft does not meet the JIS Key Slot standard, and these factors would contribute to the occurrence of failures on the transmission shaft.

1. Introduction

Failure of the work system on the transmission is often due to the magnitude of the rotational speed that is passed from the main motor drive [1–3]. The transmission system serves as the successor of power and rotation from the main motor to the other transmission shafts to get the spindle rotation speed as desired [4, 5]. During the operation process, transmission components such as shafts, bearings, gears, and pegs are often damaged by corrosion and fatigue failures. To prevent failures such as fatigue, the transmission system uses pads on each side of the shaft so that the shaft rotation becomes smoother and the shock load at the beginning of the turn becomes smaller. The main causes of failure are the high coefficient of friction on the rotating component, heat transfer, and corrosion, among others [6–8]. The torque load that occurs in the transmission system exceeds the permitted torque load so that the failure happens on the components transmission system [7]. This research was conducted to determine the mechanism and causes of failure in the transmission system based on failure theory. The failure analysis on the transmission system components is done by testing the mechanical properties of the material. The results of this research are expected to reduce the failure rate of transmission system components and can determine preventive maintenance on the machine so that the breakdown maintenance does not occur in the production process.

A transmission system acts as a successor and converts the rotation of the main motor to the successor shafts of rotation by using several main components to work such as shaft, gear, pegs, and bearings [9]. Because the components are a constituent part of a transmission system, the load due to the rotation that occurs in the component is very high. The components of this transmission system often encounter several problems such as failure [9]. The failure that occurs in the transmission system breaks the shaft. The analysis performed is from the results of the hole being processed to be very coarse and the result of the measurement of roughness exceeds the expected roughness tolerance. So that the machine is must stop its production for inspection and repair. The examination found that there was a fault that occurred in the axis precisely on the stake house (keyway). With the fracture at the stake house, the rotation of the main motor could not be continued to the maximum and cause imperfect spindle rotation until the roughness of the results of the process. The objectives of this research are to analyze the failure that occurs on the broken transmission shaft, to analyze the main causes of failure, the forces and stresses that occur on the shaft, also the type of fracture, and the fault mechanisms that occur.

The failure analysis was subjected to S50C carbon steel which is equivalent to JIS G 4051. The composition standard of S50C carbon steel is shown on the following Table 1.

Table 1. Composition standard of S50C.

Steel	C	Mn	P (%)	S (%)	Si	Cr (%)	Ni (%)	Cu (%)
			max	max		max	max	max
S50C	0,47–0,53	0,5-0,8	0,035	0,035	0,17 0,37	0,25	0,25	0,25

2. Experimental method

As the preparation, before the surface fractographic observation of the fracture on the shaft was cleaned by blowing method to avoid the dirt on the fault surface such as dust, oil, and others. The observation of this fractography used a Zeiss EVO MA10 scanning electron microscope (SEM). This microscopic test was divided into several stages of the process, namely the preparation stages. At this stages, specimens to be tested were cut first to facilitate the test. The part to be observed was in the core area of the material so that the cutting of the material is done perpendicular to the broken post plot. The hardness testing used Rockwell test with indenter in the form of diamond cone with angle 120° with 150 kgf loading in accordance with the standard test on JIS Z 2245. The specimens for hardness test were cut into spherical bars with each specimen’s size measuring 25 mm. Afterward, the specimens were mounted on test machine with maximal firmness at both end of specimens. The tensile testing used the Intron 3328. In order to confirm the repeatability of results, as many as seven pieces of specimens were prepared for each hardness and tensile test.

Figure 1. Specimens and its dimension.

3. Results and discussion

The testing of the material composition used a spectrometer test device with OES (optical emission spectroscopy) system as shown in Table 2. The requirements of the specimens to be tested was that it should have a flat surface wherein the test specimen would pass through the surface combustion stage resulting in complete combustion. In the A001 transmission axle system, the part that received the largest load was located at the bottom corner of the stake home. Due to the large load obtained from the torque of the main motor rotation, a high concentration of stress on that part would occur. This caused the beginning of cracks because the shaft material could not resist or absorb the high stress or tension that occurs repeatedly.

Table 2. Spectrometer test result of S50C.

Item		C	Si	Mn	P	S	Cr
Std S50C JIS G4051		0.47-0.53	0.15-0.35	0.6-0.9	0.030 max	0.035 max	0.2 max
Gear shaft	Act spark 1	0.51	0.21	0.62	0.027	0.0010	0.136
	Act spark 2	0.51	0.21	0.63	0.026	0.0015	0.137
	Act spark 3	0.51	0.21	0.63	0.027	0.0013	0.136

Figure 2. Direction of shaft loading.

In the stake home area, the shaft was flowed with a certain depth so that the shaft part which holds the load from the initial spin that occur less than half the diameter of the shaft. Then the next step was to observe on the part of the shaft that has broken failure to analyze the initial part of the crack that causes the fracture, the pattern of the fracture propagation and the final area of the fault. In Figure 2, some formation that occurs due to fracture can be seen, that is: Sign machine on the post groove, cracking origin, fatigue propagation zone, plastic deformation in the zone of final fracture, and longitudinal sign. An observation by using scanning electron microscope was done on the surface fracture pattern from the beginning of crack initiation, propagation from crack and final rupture to surface of the broken shaft can be seen. The observations were performed with an enlargement of less than 20× in order to obtain an overall breaking surface. The beginning of the crack was affected in the machining process signals. In asddition, the longitudinal marks on the post-plot that exist prior to the occurrence of the fracture were caused by the events occurring when the peg was inserted into the stake groove, thus leaving small scratches on the stake. In addition, there was also a ratchet mark and beach mark that showed high stress at the angle of the stake groove.

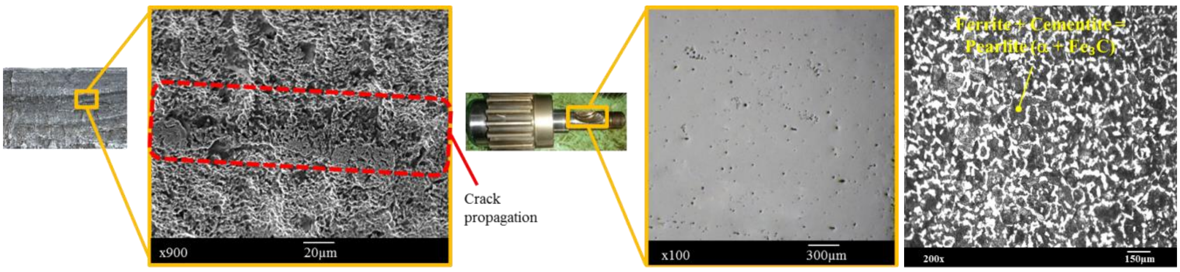

Figure 3. Direction of shaft loading and its microstructure.

The microstructure testing evaluated conformity with the material standard JIS G 4051 S50C also the initial formation process of the material whether the material gets heat treatment during the manufacturing process can be also be known. This test was conducted to obtain an overview of the material structure using etchants of 5 g $CuCl_2$, 40 ml HCl, 30 ml ethanol, and 30 ml of aquadest. Examination of samples on microstructure observation is found in three parts of the specimens which can be in broken transmission porous material with 200× phase enlargement of the material in the form of pearlite which is a combination of two ferrite (α) and cementite (Fe_3C) phases. The pearlite phase was formed by the heating process of the material followed by slow cooling to the room temperature.

Hardness testing on S50C shaft material was performed to determine the hardness of the material itself and the toughness value of the shaft that has breakage failure. The test was carried out on the postal cutter piece of the post which had failed. The test was performed on the surface of the shaft piece and was loaded perpendicularly from the cut surface of the shaft. The test was performed by using Rockwell C hardness test tool with a loading of 150 kgf. The result of hardness testing can be seen in the table where the average test result obtained is 22 HRC, which means the hardness value of the shaft material is uniform and the surface hardening process was absent. From Figure 3, the results of surface observation after a hardness testing can be seen where, on each side of the indenter, cracks occurred; the results can later be used to analyze toughness of the material based on the length of cracks that occurred. The experiment used a S50C shaft material formed from an A001 transmission shaft spare part and latched in accordance with JIS Z 2201 specification standard.

Fracture toughness is an indication to determine what value of maximum stress is allowed to minimize the propagation of pre-existing defects. According to T.L. Anderson [10–13], existing cracks will spread when the elastic strain energy released is at least equal to the energy required to create a new surface crack. Therefore, if the stress that occurs on the shaft exceeds the toughness value of the shaft material, then it can cause a new crack, thus leading to the breakage of the shaft. Based on hardness and tensile tests, there are several equations [14–17] for calculating the value of the fracture toughness. From the several equations obtained, the standard fracture toughness, K_{Ic}, of the S50C medium carbon steel range from 12 – 92 MPa.m$^{1/2}$.

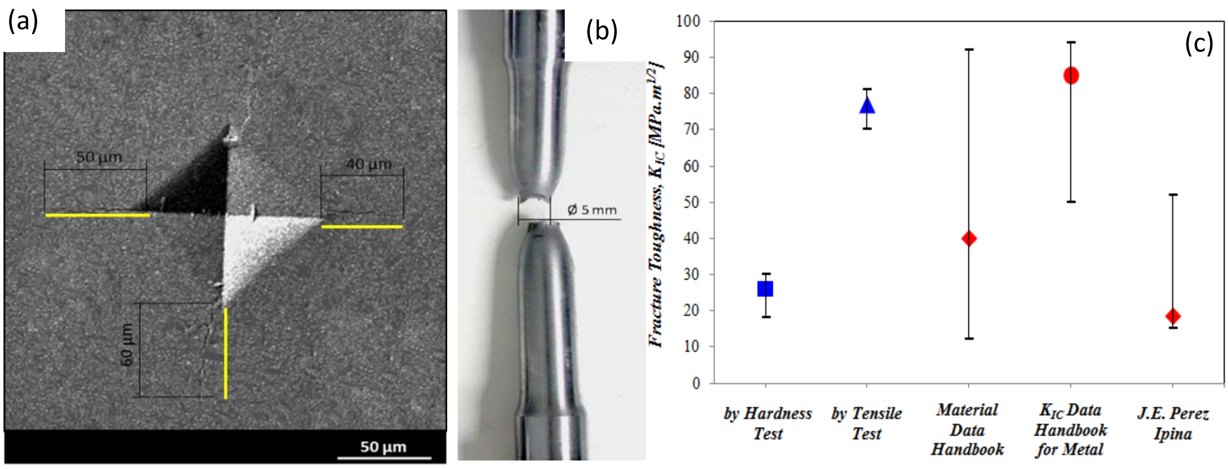

Figure 4. Crack length obtained by (a) hardness indentation and (b) tensile test (c) graph of fracture toughness obtained from calculation compared by some references [14–20].

The average of fracture toughness obtained by hardness and tensile crack are 26 and 77 MPa.m$^{1/2}$, respectively, as shown in Figure 4. The error bars indicate the minimum and maximum for both K_{Ic} obtained by hardness and tensile test, which are 18 – 30 MPa.m$^{1/2}$ and 70 – 81 MPa.m$^{1/2}$, respectively. The differences of fracture toughness obtained by hardness and tensile test are considerable because of the crack length. Based on the macrostructure, it was found that the failure that occurred was a fatigue failure due to the form of propagation from the fracture. The resultant criterion of the fracture surface occurring satisfies from the fatigue of the form because of the high-stress concentration at the stakeholder in the beginning of the fracture. The stages of fracture in the transmission shaft began from the occurrence of plastic deformation or deformation of the post home and the initial crack initiation at the point of the stake home, followed by the crack propagation due to repeated loading, and after the material was not able to resist and reduce the stress that occurred then the material would be broken (final rupture). This is evidenced by the results of microscopic material testing through visual observation or by using an SEM. The fractography evaluation also found similar results on the surface of the shaft that indicate a final rupture. The fracture surface observed that there are fracture propagation and the initial failure occurring due to the stress from the rotation passed by the shaft through the stake housing.

From the microstructure evaluation, the formation of pearlite structure shown, consisting of two phases consists of ferrite (α) and cementite (Fe_3C), was obtained. This explains the fact that the occurrence of heat treatment at the stage of material formation by heating and then gradually cooling at room temperature so that carbon bonds form pearlite structure. In the test results of the chemical composition of the transmission, shaft material meets the standards of the JIS G 4051 S50C material. With the resultant chemical composition of the three tests being within the limits of the percentage composition tolerance standard are C (0.47 – 0.53), Si (0.15 – 0.35), Mn (0.6 – 0.9), P (0.03 max), S (0.035 max) and Cr (0.2 max). All material compositions fall within the standard range of JIS G 4051 S50C material.

Mechanical testing of the material by conducting hardness testing found that the material received a uniform heat treatment as evidenced by the result of the hardness of the shaft material with the loading perpendicular to the shaft diameter obtained a hardness of 22 HRC at all test points. From tensile test sample formed in accordance with JIS Z 2201 standard with 10 mm diameter, it was found that the maximum material stress was 74 kg/mm^2 at 5832 kg with a yield point 62 kg/mm^2 at 4800 kg loading and 24% material length increase. From the test and analysis obtained, it was showed that the shaft failure was in the form of final rupture. As previously mentioned, the main cause of failure was fatigue fracture caused by high stress concentrations at one point and repeated loading. The area that experienced the highest stress was at the stake part of the house, the stake home area is the part that gets high stress at the angle of the stake groove. From the three methods that have been done in the form of analysis on the transmission component material, the design analysis of the transmission components and also of the forces acting on the transmission of shaft material should not fail because the force and the load acting on the shaft do not exceed the yield stress and permit stress axis. In the material, changes due to the environment that affect the structure of the material are also found. Deviations are occurs at the stake home portion where the size of the stake home exceeds the allowed tolerance.

4. Conclusions

The fine boring transmission shaft system of S50C carbon steel has been analyzed the failure experienced by the axle component is caused by fatigue failure. Mechanism of failure of the shaft started with the beginning of crack initiation, crack propagation, and the occurrence of final rupture. Fracture type in the form of a ductile where the material undergoes plastic deformation first then cracks occur until the occurrence of fracture. The occurrence of fracture was cause by the high-stress concentrations in the post hole home that receive a large load. Material transmission shaft components are in accordance with JIS G 4051 S50C standard. However, the size of the post groove formed on the shaft does not meet the JIS Key Slot standard (JIS1301-1976). Therefore, these factors would contribute to the failure occurs on the transmission shaft.

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