FAILURE ANALYSIS OF REAR AXLE (BANJO BEAM) HOUSING OF A UTILITY VEHICLE

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ABSTRACT

This paper describes the failure analysis of a rear axle housing used in a utility vehicle. This vehicle had been involved in an accident. The rear axle shaft housing was found broken into two pieces. In present study utility vehicle rear axle housing was selected to study the failure analysis experimentally and numerically. The failed rear axle housing was undertaken to check its integrity which includes visual examination, chemical analysis, photo documentation, micro hardness test, and metallographic tests to evaluate the failure. Failure analysis of a rear axle housing used in a utility vehicle was studied to determine stress concentration area. Based on field study strain gauges are mounted on failed parts to determine stress intensity and joint analysis were validated with Finite Element Analysis results.

SEM (scanning electron microscope) was used to examine the failure zones. The analysis showed that the rear axle housing suffered a fatigue induced fracture. The fracture initiated at the weld joint between back plate and rear axle housing, where a stress concentration was created. This stress concentration was higher than the stress concentration considered at the time of design which results into the breakage of the housing into two parts. Also stress concentration was found more on left side as compared with right side. Hence, all the reported failures were broken on the left side only. So, the causes of the failure of the rear axle housing was due to defective geometric design of the rear axle housing. To avoid this failure in future the axle housing thickness is changed from 3.5 mm to 4 mm. This design change sustained the high stress concentration which was analysed with the help of finite element analysis.

Key words: Failure Analysis, Finite Element Analysis, Rear axle, Rear axle Housing.

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1. INTRODUCTION

An axle is a cross member supporting a vehicle, on which one or more wheels turn. Axle shaft connects the two wheels in a vehicle. Axle shaft usually extends from opposite sides of a differential gear box and provided at their outer wheel ends with integral or otherwise rigid drive flanges which are connected to the wheels for transmission of driving power [1]. An axle assembly on a vehicle is the set of components that allows the wheels to rotate freely. Axle sits inside an axle housing. It is held in place by bearings or bushings that allows it to rotate within the axle housing. Axle housing also supports in lubrication of the rotating axle.

Axle housing is non- rotating member and carry the suspension seats over which the suspension springs are mounted. They are subjected to dynamic inertial loads as the vehicle moves over an uneven road surface and hence are predominantly subjected to bending during service. Bending moment distribution of rear axle housing's schematic diagram, is shown in Fig. 1.

Figure 1 Bending moment distribution on rear axle housing

Research on failure analysis of various components has been carried out over the years. S. P. Raut and L.R. Raut [1] reviewed the various methodology used for failure analysis of shaft used in different application. The researchers discussed various tools and techniques used for analysis such as, non destructive testing, optical microscope, scanning electron microscopy, energy dispersive X-ray spectroscopy, heat affected zone, hardness testing instruments, fatigue testing, tensile testing, etc. Souvik Das et al. [2] carried out failure analysis of axle shaft of a fork lift which was failed at operation within 296 hours of service. They suggested that the fracture was initiated from the martensitic case as brittle mode due to improper heat

treatment process and inclusions along the longitudinal axis made the component more prone to failure.

Khairul Akmal et al. [3] reviewed premature failure that occurred due to the higher loading capacity of the heavy vehicle. New design of rear axle model was developed by increasing the thickness of sheet by 7 mm to increase the fatigue life of the housing to increase the rigidity of the axle housing. F. Mujahidin et al. [4] reviewed the axle shaft. Their findings showed that the failure was not due to material factors but the failure occurred due to a large enough momentary shock load.

G.K. Nanaware, et al. [5] reviewed the rear axle shafts of 575 DI tractors manufactured by Mahindra and Mahindra Ltd, Tractor Division, Mumbai and found that it failed before completion of warranty period. Inadequate spline root radius resulted into the failure of rear axle shafts, which results into subsequent crack growth and crack initiation was by fatigue under the cyclic loading conditions of field operation. Osman Asi [6] has done the failure analysis of a rear axle shaft used in an automobile. Results suggest that the axle shaft fractured while reversed bending fatigue because of improper welding. M.M Topac, et al. [7] reviewed a premature failure that occurs prior to the expected load cycles during the vertical fatigue tests of a rear axle housing prototype.

The objective of this paper is to investigate, analyse the root cause of the sudden failure of a rear axle housing in a running condition and to find the solution to avoid this kind of failures in future. Root cause analysis was carried out using experimental analysis and with combination of experimental and finite element analysis, solution and recommendation is proposed. Fig.2 shows the actual fracture of the rear axle housing.

Figure 2 Fracture of the Rear Axle housing at the left side

2. EXPERIMENTAL ANALYSIS OF REAR AXLE HOUSING

The failed rear axle housing was collected from the field for analysis. The sample was cleaned with acetone to remove dirt to perform visual examination. After that the sample was prepared for metallographic analysis. Transverse specimen was made from the cut section end of the failed rear axle housing for conducting Optical Emission Microscopic examination. The sample was polished by standard metallographic techniques to produce scratch free surface. The polished sample was etched in 3% Nital solution (3ml nitric acid and 97ml ethyl alcohol), and etched as well as un etched samples were examined under an Optical Emission Microscope. The hardness of the different location of rear axle housing was measured in Vickers hardness tester. A 50 kgf of load was applied during testing, and a few numbers of indentations were made to measure the hardness of the rear axle housing.

Experimental investigation includes following analysis of the failed rear axle housing-

- Visual Analysis
- Metallographic & Chemical Analysis
- Hardness measurement.

2.1. Visual Inspection

Beam housing / rear axle housing failed from left side & fractured into two pieces from the end of weld joint of the back plate & beam housing. Fracture initiated from the end of seam weld on back plate at 13 to 14 mm below tube seam weld. At fracture initiation, clear beach marks are observed. No hit or dent mark or other damage were found near fracture initiation. Fracture can be determined as brittle when the surface seen flat, mixture of ductile and brittle when surface has moderate degree of roughness, ductile when surface is more on rough side. Broken component shows moderate degree of roughness, so it must be combination of ductile and brittle type of fracture. As shown in Fig. 3.

Figure 3 Broken piece of rear axle housing

2.2. Metallographic Analysis

Fig. 4 explains in detail about the approximate magnification ranges from instruments used to study the fracture surfaces and microstructure. It shows that till x10 magnification, hand lenses can be used. For x10 to x100, stereo microscope is helpful. To study between x100 to x1000 optical microscope is used. Scanning electron microscope can be used to study from x10 to less than x100000 and transmission electron microscope can give magnification from greater than x100 to x100000. Based on the application and detail requirement, instrument can be selected to do the analysis.

In this paper for the analysis scanning electron microscope is used.

Figure 4 Approximate magnification ranges for instruments used to study the fracture surfaces and microstructure

Table 1 Chemical composition of the rear axle housing

Specification	C%	Mn%	P%	S%	Si%	Al% (min)
BSK-46	0.12	1.4	0.03	1.03	0.1	0.3 max
Actual Percentage	0.11	1.18	0.01	0.02	0.04	0.02

Table 1 Actual chemical composition of the rear axle housing with respect to the specified composition [8]

Table 1 shows, the chemical composition of the failed axle housing containing 0.11% Carbon, 1.18% Manganese, 0.01% Phosphorus, 0.02% Sulphur, 0.04% Silicon and 0.02% Aluminium. Whereas raw material BSK-46 contains 0.12% Carbon, 1.4% Manganese, 0.03% Phosphorous, 1.03% Sulphur, 0.1% Silicon, and 0.3% max Aluminium [8]. Failed component material is BSK-46 only as indicated by the observed values. Hence, no deviation is observed in the raw material. Therefore, the failure is not attributed to improper raw material. According to chemical composition analysis by Optical Emission Spectroscope, the rear axle housing was manufactured using BSK-46[8].

Metallographic microstructure is shown in Fig.5 for the rear axle housing. It shows an element mainly formed by uniformly distributed ferrite & perlite. The presence of uniform perlite indicates that the material suffered a heat treatment of quenching & tempering.

Figure 5 Microstructure of the material. Etched with Nital 3%

Figure 6 Specimen under different magnification under Scanning Electron Microscope (SEM).

SEM (scanning electron microscope) was used to examine the fractured surface in order to characterize the fracture micro mechanism. Fig. 6 shows the specimen at different magnification. The fracture surface contains ratchet marks. The ratchet marks indicate multiple origins and relatively high total stresses. Ratchet marks can result from high stress on the part or from high-stress concentrations. The combination of many ratchet marks and a small overload zone indicates that the load was light, but there were high stress concentrations. From these observations, it is clear that fatigue cracks have initiated at stress concentration points leading to fracturing of the rear axle housing. The badly welded region can lead to a high-stress concentration, but can also cause fatigue crack initiation during short service time. A fatigue crack has possibility to form when the local stress exceeds the material yield strength. Since steel resistance to fatigue initiation, is proportional to its yield strength, the low properties of the steel left it open to fatigue initiation. The area of final overload fracture is small, approximately 15% of total area, indicating that the material was adequate for the applied stresses. Fig. 6 shows specimen under 30X magnification having flat as well as moderate roughness, which indicates material is mixture of both ductile as well as brittle failure.

2.3. Vickers Hardness Study

Vickers hardness study were performed using a 50 kgf load with 13 second dwell time on location back plate to beam housing weld. Table 2 shows Vickers hardness test results.

Table 2 shows, there was no deviation in material thickness, leg length, maximum weld nugget hardness, concavity, maximum heat affected zone hardness. Hence, weld parameter of the components was within specification as per ES-PS-0522[9]. It indicates no issue in weld parameter of components.

Table 2 Vickers hardness test results

Weld Parameters	Beam housing to weld (near fracture initiation)	Backing plate to weld (near fracture initiation)	Specified per ES-PS-0522
Actual wall thickness (mm)	3.5	3.5	Beam Hsg.: 3.5+/-0.127mm Backing plate: 3.5+/-0.127mm
Leg length (mm)	3.7	3.1	2.10 – 7.93 mm (0.6 X Thickness of thinnest member)
Effective Throat (mm)	1.91		2.10 – 7.93 mm (Equal to Minimum Leg Length)
Maximum weld nugget hardness (HV)	295		354 HV Ma
Concavity (mm)	0.39		0.8 mm Max
Maximum heat affected zone hardness (HV)	231	167	446 HV Max
Parent material hardness	211	214	79 – 91 HRB (147 – 190 HV)

2.4. Weld Evaluation Analysis

Weld evaluation analysis study was performed on the component by taking various sections to understand the weld quality. Table 3 shows, backing plate to beam housing weld quality test results and Table 4 shows, backing plate to beam housing cut section analysis results. fig. 7 shows the different sections taken for the analysis with the help of red dotted line.

Fracture shows high cycle bending fatigue type failure along beam axis. Probable cause of premature weld failure seems to be high stresses coming at weld joints during application.

Table 3 Backing plate to beam housing weld quality

Locations	Weld Region Hardness (HV)	
	Beam housing to weld (near fracture initiation)	Back plate to weld (near fracture initiation)
Parent	211	134
	214	139
	-	137
Heat affected zone (HAZ)	227	158
	231	163
	-	167
Weld nugget	288	
	295	
	293	

Table 3 shows detailed analysis of weld quality. It indicates that weld quality is as per specification as the weld region hardness is less than 446 HV [5].

Table 4 Backing plate to beam housing weld quality

Locations	Specification per ES – PS - 0522	Weld quality Case - 1			
		Cut section 2 location A at linear weld beam housing to weld	Cut section 2 location B at back plate to lower half beam housing to weld	Cut section 3 at linear weld beam housing to weld	Cut section 4 at linear weld beam housing to weld
Actual wall thickness (mm)	Beam Hsg.: 3.5+-0.127mm Backing plate: 3.5+-0.127 mm	3.5	3.5	3.5	3.5
Leg length (mm)	2.10 – 7.93 mm (0.6 X Thickness of thinnest member)	5.3	3.16	4.5	4.7
		4.8	2.7	3.9	4.5
Effective throat (mm) max weld nugget hardness (HV)	2.10 – 7.93 mm (Equal to minimum leg length)	2.44	2.6	2.165	2.3
Penetration for seam joint	60% min	69.8	15.1	61.85	64.3
Concavity	0.8 mm max	NA	Not obs	NA	NA
Max heat affected zone hardness (HV)	83 Max (446 HV max.)	193	177	186	179
Parent material hardness	79 – 91 HRB (147 – 190 HV)	193	186	190	179

Locations	Specification per ES – PS - 0522	Weld Quality Case - 2			
		Cut section 1 location A1 at linear weld beam housing to weld	Cut section 1 location A2 at back plate to lower half beam housing to weld	Cut section 1 location B1 at linear weld & back plate beam housing to weld	Cut section 1 location B2 at back plate to lower half beam housing to weld
Actual wall thickness (mm)	Beam Hsg.: 3.5+-0.127mm Backing plate: 3.5+-0.127 mm	3.5	3.5	3.5	3.5
Leg length (mm)	2.10 – 7.93 mm (0.6 X Thickness of thinnest member)	4.8	5.4	5.2	3.2
		5.9	3.5	5.3	2.2
Effective throat (mm) max weld nugget hardness (HV)	2.10 – 7.93 mm (Equal to minimum leg length)	2.4	4.2	3.1	3.43
Penetration for seam joint	60% min	68.4	41.11	87.9	20.74
Concavity	0.8 mm max	NA	Not obs	NA	Not obs
Max heat affected zone hardness (HV)	83 Max (446 HV max.)	168	191	189	186
Parent material hardness	79 – 91 HRB (147 – 190 HV)	178	187	178	187

Table 4 Shows that, weld quality of the failed component was within the specified range as per ES-PS-0522 [5].

Figure 7 Side view of fracture and dotted line in red colour indicate sample section for weld analysis.

2.5. Stress Level Measurements

A Strain gauge is a sensor used to measure applied force. Its resistance varies with applied force. The force, pressure, tension, weight, etc., is converted into an electrical resistance that can then be measured. External forces result in stress and/or strain when applied to an object.

Strain gauges were mounted on the rear axle housing, to calculate the stresses in the rear axle housing Mounting position was shown by the red circles in table 5. Following are the mechanical properties of the base material of rear axle housing (BSK-46) [9].

Table 5 Mechanical properties of base material (BSK-46) [9].

Specification	YS (MPa) (min)	TS (MPa) (min)	Elongation% (min)
BSK-46	451	490-627	21

Contact stresses calculated as ,

Stress = Young's Modulus / Strain.

Therefore, stress at left side as 261.58 MPa and right side as 216 MPa.

Figure 8 Mounting of strain gauges on axle housing to measure contact stresses

Strain gauges mounting position were shown by the red circles in the fig. 8. With this strain gauge arrangement, stress values received in the running condition on the rear axle housing.

3. FINITE ELEMENT ANALYSIS OF REAR AXLE HOUSING

Using Finite Elements Analysis (FEA) it is possible to find the locations of high stresses suffered by the analysed element and their values. Specific conclusions can be drawn in this

way and reach possible solutions to avoid the recurrence of these kinds of failures. In this analysis the rear axle housing was geometrically modelled as shown in Fig. 9. Hexagonal elements with a size of 2 mm were used in the FE mesh. The mesh had a total of 25277 elements. The size of the elements and mesh were selected after performing a series of iterations with the same loads and using different mesh sizes. It was noted from the iterations that the values of the stresses in the element varied considerably, for elements smaller than 2 mm, making it high values related to singularities caused by small elements. For elements bigger than 2 mm the stresses were not representative as the size of the elements were higher than the contact region.

Following are the loading, boundary, and contact conditions of the model:

1. A fixed contact in zone A (end of the rear axle housing)
2. Lateral load B & C, assumed constant in this analysis to simplify the modelling, with a value of 5100N and applied on the back plate.

Figure 9 Loading condition in ANSYS

The analysis and calculations of maximum stresses were performed with and without the back plate, in order to highlight the places of higher stresses in the element. It is observed that there is no major change in the readings after removing the jack mounting plate from the welding joint. After this trial the trial by changing the thickness of the material from 3.5 mm to 3.7 mm, 4 mm and 4.2 mm.

Figure 10 Von Mises stress plot for 3.5 mm thickness

Fig. 10 shows the stress distribution of original rear axle housing with 3.5 mm thickness. Left side stress distribution (250.48MPa) is higher than the right-side stress distribution (206.24 MPa) by 21%.

For analysis increased the thickness from 3.5 mm to 3.7 mm and it was giving following which is shown in Fig. 11

Figure 11 Von Mises stress plot for 3.7 mm thickness

Left side stress distribution reduced up to 217.8 MPa from 250.48 MPa and right side stress distribution reduced up to 180.35 MPa from 206.24 MPa. The thickness from 3.7 mm to 4 mm and it is giving following which are shown in Fig. 12

Figure 12 Von Mises stress plot for 4 mm thickness

Left side stress distribution reduced up to 187.64 MPa from 217.8 MPa and right side stress distribution reduced up to 161.84 MPa from 180.35 MPa. The thickness from 4 mm to 4.2 mm and it was giving which is shown in Fig. 13

Figure 13 Von Mises stress plot for 4.2 mm thickness

Left side stress distribution reduced up to 161.69 MPa from 187.64 MPa and right side stress distribution reduced up to 143.71 MPa from 161.84 MPa.

Table 6 Comparison of experimental and numerical results

S.No.	Contact stresses on rear axle housing with strain gauges (MPa)	Contact stresses on rear axle housing for 3.5 mm thickness with FEA (MPa)	Percent error
1	261.58	250	4.42%
2	216	206.4	4.44%

The comparison of experimental and numerical results is carried out and is shown in Table 6. The FEA results are compared with the physical test results showing 5% error in both results which is negligible.

Table 7 Percent decrease in stress with respect to the original stress based on finite element analysis.

Housing Thickness	Left side Von mises stress	Right side Von mises stress	Percentage decrease in stress with respect to 3.5 mm thickness
3.5	250.48	206.24	NA
3.7	217.8	180.34	13%
4	187.64	161.84	24%
4.2	161.69	143.71	33%

Table 7 shows when thickness was 3.5 mm, left side contact stress was 250.48 MPa and right side contact stress was 206.24 MPa at which axle housing was failed. To avoid the failure, axle housing thickness was increased from 3.5 mm to 3.7 mm, 4 mm & 4.2 mm and get the respective left side and right side contact stress values. When thickness increased to 3.7 mm, contact stresses decreased by 13% but 3.7 mm thickness material is not available in market. Hence, 3.7 mm thickness is not feasible from production point of view. Then thickness increased to 4.2 mm and contact stresses decreased by 33%. If 4.2 mm thickness material used for production it will increase the weight of the axle housing by 20% which will affect the vehicle performance. So, 4.2 mm thickness is not acceptable. Then thickness changed to 4 mm and checked contact stresses, which was decreased by 24% and weight

increased by 14%. 4 mm thick raw material is also available in market. Hence from cost, manufacturing and performance wise 4 mm thickness is the optimized thickness. Therefore, 4 mm thickness for rear axle housing is proposed.

4. CONCLUSION

The failed rear axle housing of a utility vehicle is studied to check its integrity which includes visual examination, chemical analysis, photo documentation, micro hardness test, and metallographic tests to evaluate the failure. Spectrum analysis and micro-hardness measurement revealed that the failed axle housing material was BSK-46 steel. The composition, microstructure, hardness values of the raw metal were found to be satisfactory and within the specification. The fracture initiated at the weld joint between back plate and rear axle housing, where a stress concentration was created.

The material used in the manufacture of the rear axle housing was appropriate for this kind of application. However, less thickness of the rear axle housing element allows the formation of stress concentrators which further reduce the life of the element. Therefore, the causes of the failure of the rear axle housing was due to Defective geometric design of the element thickness.

In order to reduce the contact stresses on the rear axle housing element, a change on the geometric design of the element was proposed. FEA done on 3.7 mm, 4 mm and 4.2 mm thickness. Finally, 4 mm thickness was selected. This was an optimised thickness from manufacturing, cost and vehicle performance. Therefore, in the proposed design, thickness of the rear axle housing beam was increased by 0.5 mm. This element was modelled using the same loading and boundary conditions employed for the failed element. In the proposed case the maximum stresses were found on the section of the element, with a maximum value of 187.64 MPa approximately (24% improved as compared to the original one).

Finally, it is suggested to modify the geometry of the rear axle housing to reduce the contact stresses and avoid such types of failures.

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