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Failure Analysis of Front Axle Wheel Studs in Small Commercial Vehicles

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ABSTRACT

Irrespective of specific applications, the Small Commercial Vehicles (SCV) are always subjected to severe working conditions, especially the front wheels experience higher loads than design intended due to higher overloading by customers, driver abuse and frequent brake applications. The front axle wheels fasten system plays a key role for safety of the vehicle and pedestrian.

The wheel separation can lead to serious injuries to passengers of the vehicle and pedestrian or from another vehicle maneuvering including fatalities. In this project investigation, the causes that promote failure of front axle wheels fasten system and subsequent wheels separation of SCV is analyzed carefully. Metallurgical analysis of the failed fasten system shows that it is characterized by a series of synergetic steps that include plastic deformation of nuts and studs caused due to disproportionate torque tightening practices. Also, the effect of other external factors that lead to deterioration of stud fatigue life such as road camber and driver abuse are analyzed. Based on this promise, the present investigation deals with detailed analysis of the root causes contributing such failures are analyzed and discussed in this paper. This study would help the fellow designers to select optimized fastening system considering all the parameters influencing wheel separation due to stud failures for SCV, passenger vehicles and heavy duty trucks.

KEYWORDS: Wheel stud failure, wheel fastener, wheel separation, deformation, fatigue life, optimized fastening system, stud clamping load, metallurgical analysis, chemical composition, microstructural analysis, fractographic analysis, hardness test, road camber, fracture surface, SEM, torsional load, tempered martensite, design load, thread section.

Introduction

The ever increasing demand for SCVs to move logistics such ecommerce goods and groceries has led to the operation of SCVs all round the clock. Revenue generation and profitabality of SCV owners have improved significantly owing to this increased running hours. It is important that safety critical components of SCVs are robust such that they ensure safety of drivers and others.

The wheel being a safety critical component, must satisfactorily perform its function for the intended design life. The design of wheels have become more complicated due to the demand for lighter weight and aesthetic wheel configuration coupled with vehicle overloading practices by the customers operating SCVs. Thus, it is paramount to perform rigorous assessment of wheel elements design on the strength and durability perspective. Strength and durability of the wheel elements are underpinned on well-designed wheel studs. Since, failure of them could cause huge risk of accidents.

The wheels poise the complete load of vehicle through vertical reaction from the road. wheel studs clamp wheel rim and hub securely with sufficient clamping load so that vertical load transfer happens from tyre through wheel rim to the hub. The wheel studs while clamping wheel rim and hub may undergoe radial load due to vertical reaction forces exerted during vehicle operation. During vehicle operation, any relaxation in clamping load on the wheel studs could them to cyclic radial loads compromising fatigue reliability of the wheel studs.

To keep up with the market trend, a new SCV with higher payload carrying capacity and superior engine was developed. In general proto build vehicles will be subjected to extensive durability trials simulating customer road and load conditions preceding to the release of production vehicles to the market. In-addition to conducting performance and endurance trials, the proto vehicle drivers would themselves do wheel retrofitments when in need using vehicle tool kit during endurance trials. The intention of this activity was to capture customer abusive behaviour on vehicles pertaining to retrofitment activities and improve design if necessary. Therefore, during the endurance trials proto vehicle drivers used wheel spanners for removing and fastening the front wheel studs without following any defined torque tightening procedure or torque wrenches.

During this extensive endurance trials, all the front axle parts were performing good except front wheel studs.Considerable number of the proto vehicles started exhibiting wheel stud failures only on the front RHS wheels (Right Hand Side of vehicle) after covering 70,000km in Highway as shown in Figure 1. Details of the failures are shown in Table.1

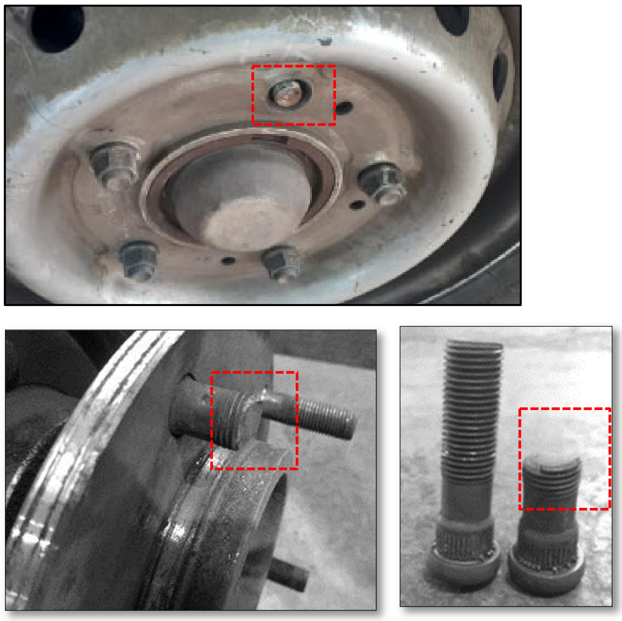

Fig. 1. Photographs of wheel stud failures.

The authors in this paper had attempted to analyse the causes that promoted the failure of front axle RHS wheel studs and proposed a solution that would be useful for the fellow design engineers to select an optimized fastening system for the wheel elements.

TABLE 1

Proto vehicle wheel stud failure km status

Sl. No.	Vehicles	Application	Failure km	REMARKS
1	Proto Vehicle - 01	Highway	71522	1 RHS wheel stud got failed
2	Proto Vehicle - 02	Highway	72435	1 RHS wheel stud got failed
3	Proto Vehicle - 03	Highway	82289	1 RHS wheel stud got failed

As a primary step, visual inspection of the failed wheel studs was done to understand the mode of failure. Design calculations were revisited to check for any fallacy in design. Since the effect of road camber on load acting on the wheel studs were overlooked during the initial phase of design, it was done to understand its consequences on the wheel stud loads. A metallurgical analysis viz. Chemical composition study, Microstructural analysis, Fractographic analysis and hardness test were conducted on the failed samples to get clear picture on the failure and to propose a design solution. Finally, the proposed design solution was validated through bench level and vehicle level tests to proceed for implementation.

Visual Inspection

As a part of failure study, the failed sections of the failed hub studs shown in Figure. 2 were visually inspected.

Figure. 2 (a) & (f) confirms that, the failure has happened between hub and wheel rim interface joints. Figure.2 (b) shows the grade identity of 10.9 on wheel stud which confirms to the specification. The failure mode is not obvious in Figure.2 (c) & (e). The section in Figure.2(d) reveals fatigue mode of failure.

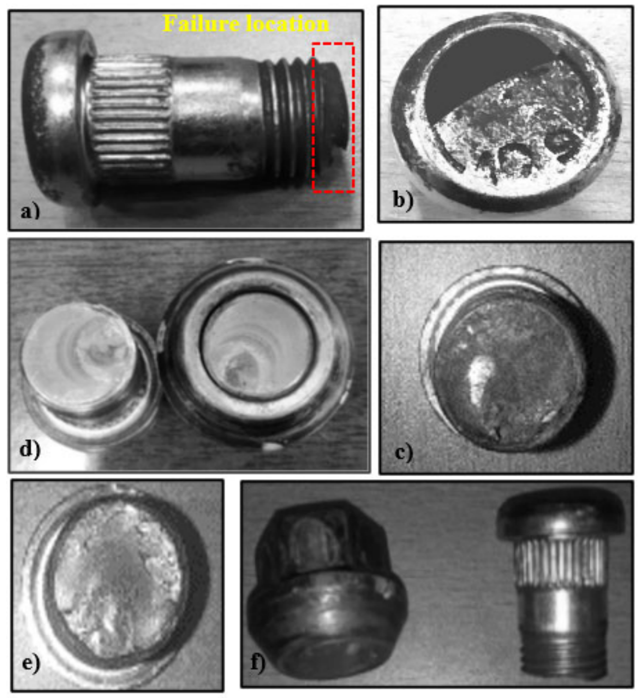

Fig. 2. Visual Inspection of Failed Wheel Studs.

Design Calculation

During a vehicle's life cycle, the wheels are exposed to large variation in load and road conditions. The bench-marked operating load conditions were taken into account for the design calculations. For this SCV, the design calculations were considered for M14 X 1.5mm wheel stud.

$$Fv = \frac{T}{K * D}$$

$$T = Fv[(0.16 * p) + (0.58 * \mu m * d2) + (0.5 * \mu n * du)]$$

$$Fv = \frac{170000}{[(0.16 * 1.5) + (0.58 * 0.2 * 13.025) + (0.5 * 0.18 * 17.5)]}$$

$$Fv = 51kN$$

Where,

Fv - Stud clamping force;

T - Tightening torque

P - Thread pitch=1.5mm

µm – Thread friction co-efficient

µn – Under head co-efficient

d2 – major diameter

du – head diameter

For M14 × 1.5mm wheel stud, theoretical clamping load calculated was 51kN with tightening torque of 170 Nm. With five studs being used, the total clamp load of 256kN was considered to ensure the integrity between wheel rim and hub.

$$Le = \frac{(d - 0.938)^2}{(d - 0.649 * p)}$$

$$Le = \frac{(14 - 0.938)^2}{(14 - 0.649 * p)} = 13.097mm$$

$$As = 0.5 * \pi * do * Le = 273mm^2$$

$$Fs = \lambda * As = 275kN$$

$$At = \frac{\pi}{4} * do^2 = 138mm^2$$

$$\sigma = \frac{Fs}{At} = 1332Mpa$$

$$Fs\sigma = \frac{\pi * \left(\frac{d2}{2}\right)^2}{4 * 9.81} = 5227kg$$

Where,

Le – Effective length of engagement

As - Shear area

Fs – Shear force

λ – Shear strength = 675Mpa

At – Tensile stress area

do –Pitch diameter = 13.26mm

σ – Tensile stress

Fsσ – Stripping strength of stud

Influence of Road Camber on Wheel Stud Failures

Road Camber is the slope gradient of road surface set in transverse direction to discharge precipitation from the road. Camber on straight roads are provided by raising the centre of the road known as crown with respect to the road edges as shown in Figure.3. Usually slope camber of up to 3% is provided for highway roads. This camber on road surface would prevent damage of the roads due to percolation of rain water. Since left hand traffic is practised in India, the vehicles plying on the straight roads have their LHS wheels bearing more load than their RH counterpart owing to road camber. In such instance, LHS wheel studs should experience fairly higher load than its RH counterpart. This phenomenon was evaluated in FEA for road camber with 3% slope.

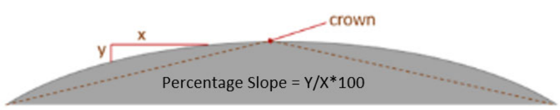

Fig. 3. Road camber.

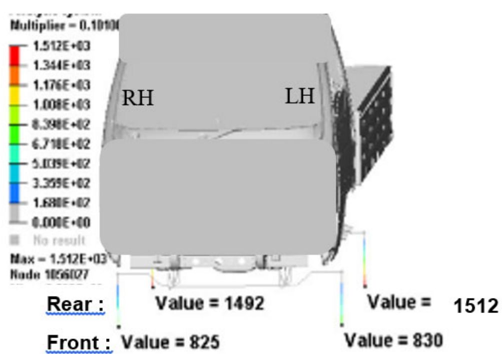

Fig. 4. Flat Road - Zero Camber (load values in kg).

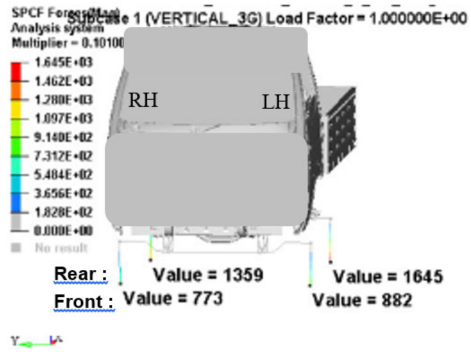

Fig. 5. LH Road Camber – 3% slope (load values in kg).

By referring Figure.4 & 5, it can be observed that due to LH road camber with slope 3%, RHS front wheel load had decreased from 825kg at Zero camber to 773kg i.e Load on RHS heel decreased by 6%. Thus road camber conditions at India have no influence on RHS wheel stud failures.

Chemical Composition Study of Failed Samples

Chemical composition analysis for a pair of failed wheel stud samples were conducted by optical emission spectroscopy. The results of which are shown in Table 2. It had been observed that the chemical composition of the failed wheel stud samples satisfies the nominal composition of steel 15B41/ Grade 10.9.

TABLE 2

Chemical Composition of Failed Samples

Description	Drawing Specification	Observation %	
		Sample 1	Sample 2
C	0.28 - 0.55	0.39	0.40
Si	-	0.22	0.21
Mn	-	1.49	1.47
S	0.045 max	0.01	0.01
P	0.040 max	0.006	0.006
Cr	-	0.12	0.12
B	-	0.003	0.003
Material Grade	STEEL PER SAE J1199 PROPERTY CLASS 10.9/15B41	Conforms to drawing specification with respect to chemical composition and hardness	Conforms to drawing specification with respect to chemical composition and hardness
Hardness (HRc)	33 - 39	34 - 37	33 - 36
Microstructure	-	Tempered martensite with no decarb on surface	Tempered martensite with no decarb on surface

Microstructural Analysis of Failed Samples

The failed samples were then subjected to metallurgical analysis to study their microstructure. The samples were prepared for inspection by various grade of SiC paper polishing under colloidal solution for refinement. Post polishing it was etched with 3% of nitric acid. With the sections in place as shown in Figure.6 the microstructural properties were analysed under optical microscopy. The corresponding microstructures were obtained in the samples. Figure.7 shows Sample-1 results, where-in the microstructure on the surface of the stud is basically tempered martensite at the case and core, no decarburization was found on the thread. It can be observed from Figure.8 that the core of the section sample-2 & 3 presents tempered martensite in core together with bainite. Microstructures indicate that hardened & tempered process were done properly.

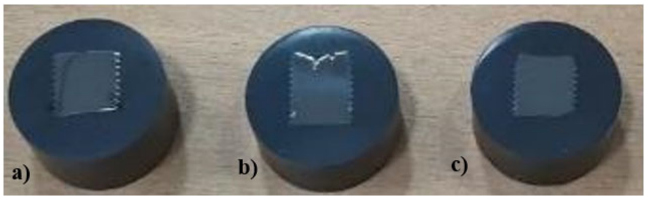

Fig. 6. Microstructure analysis – Cut Sections (a) Sample-1, (b) Sample-2, (c) Sample-3.

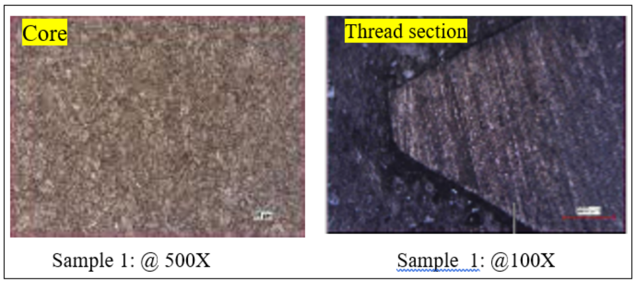

Fig. 7. Microstructure shows Tempered martensite in core & no decarb seen in thread.

No microstructure defects were found in both failed samples. Hydrogen embrittlement was not observed in all the stud samples. These test results conclude that failed stud samples are in agreement with the material specification and no abnormalities were observed.

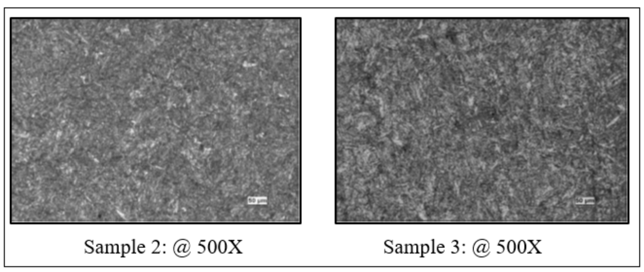

Fig. 8. Microstructure shows Tempered martensite together with bainite.

Hardness Test on Failed Samples

Hardness is defined as the resistance of the subject material to penetration by another harder material. Hardness measurements were made on segmented M14 stud specimen to determine the hardness gradient from the thread surface to the core of failed stud. The sectioning was carefully prepared using diamond disc and abundant amount of coolant were used to mitigate heat generated during cutting process. The hardness test was carried out by using Rockwell hardness tester. In Rockwell hardness test method, the hardness of the specimen was mesured by means of measured indentation depth. As shown in Figure. 9, the test specimen thickness was kept at 12 times the depth of indentation and secured on the support table. A diamond cone with 120° apical angle was used as an indenter. With the help of a handwheel, the specimen was pressed against the indenter until preliminary test force F0 of 10kgf for 3 seconds .Then an additional test force F1 of 90kgf was applied for 6 seconds. Permanent increase in depth of penetration 'e'under preliminary test force after removal of additional force was recorded. The Rockwell hardness value HRC was read from the machine directly after withdrawing force F1.

The Formula for determining Rockwell Hardness number is

$$\mathrm{HRc} = \mathrm{N} - \mathrm{e}/\mathrm{S}$$

Where,

e = Remaining indentation depth in mm

HRc = Rockwell hardness value on the C scale with diamond cone as indenter

N = Numerical value tied to S;

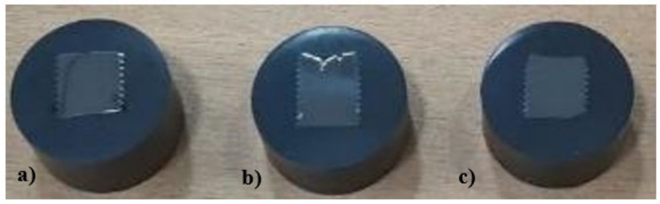

Fig. 9. Hardness Measurements - Test Specimen - Sections (a) Sample-1, (b) Sample-2, (c) Sample-3.

Multiple indentations were done at different positions at a distance of 2.5 times the indentation diameter from the test specimen edge to determine the variation in hardness from surface to the core. Core and surface hardness values were observed to be in the range from 33HRC to 37HRC which are in-line with the specification

Fractographic Analysis of Failed Samples

Fractographic analysis was carried out on three failed studs to identify the failure mode and sequence of failure. The analysis was done using Scanning Electron Microscope (SEM). Figure.10 depicts the images of areas pertaining to fracture surfaces of failed Stud sample-1. The most significant observation is that failure has initiated from thread root under torsional load. The SEM image reveals that, crack which had originated at the thread root had undergone propagation prior to final fracture. From Figure. 10, beach marks can be clearly seen indicating fatigue failure.Unsuitable wheel installation with deficient torqueing practice have allowed for the possibility of very higher preloads on the studs leading to crack intiation at thread root. This crack couldt have propagated under the influence of service loads. The slackening of the stud might have then set in allowing for unidirectional bending fatigue failure.

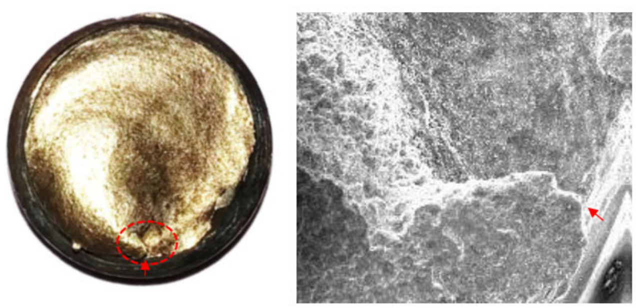

Fig. 10. Failed Stud Sample-1 & its fracture surface.

Figure 11. depicts failed stud sample-2 and fracture surface. It can be seen that mode of failure was unrecognizable by observing both failed sample and SEM

image. However this failure can be attributed to over-torqueing of studs to some extent.

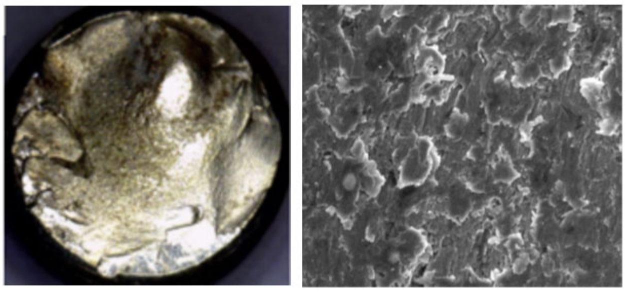

Fig. 11. Failed Stud Sample-2 & its fracture surface.

In Figure.12, failed stud sample-3 exhibits some significant results. Cracks are observed at the thread root of studs, with multiple initiation points. The adjacent SEM image corresponds to an area with the important presence of ductility fracture.

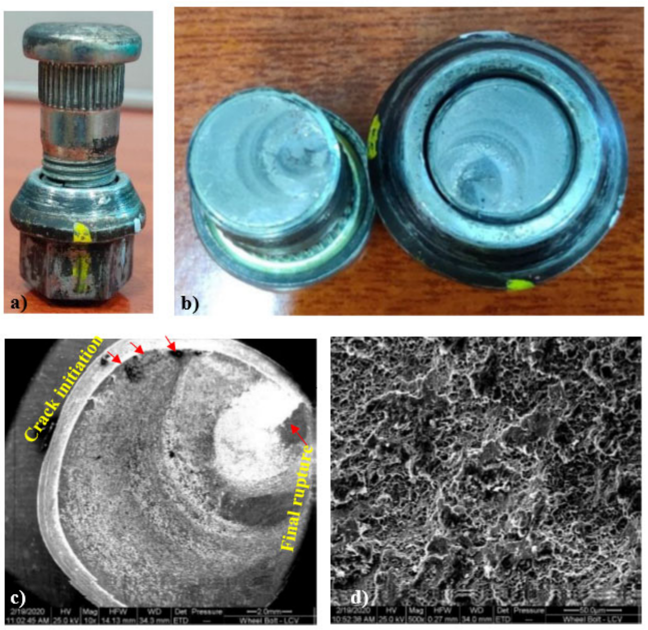

Fig.12. Failed Stud Sample-3 and its fracture surface & SEM image.

Metallurgical analysis of presented failed wheel studs reveals that all the wheel studs failed due to over tightening of wheel nuts causing too high pre-load to the wheel studs. The excessive tension in studs had resulted in yielding of the stud causing relaxation in tension. This pre-load relaxation in studs subjected them to cyclic loads during vehicle operation resulting in fatigue failure at the end. Since the design load calculations were intact, it was decided to go with a superior stud of same grade with improved fatigue properties which also should withstand the abusive torque tightening practices of the customers.

With the help of fastener suppliers and along with our Metallurgical experts opinion, M14 stud of material SAE4140, Grade 10.9 was chosen. SAE4140 wheel studs possesses improved hardenability, tougness and fatigue properties due to additional alloying of Chromium and Molybdenum as shown in Table 3.

TABLE 3
Chemical Composition comparison of SAE4140 and SAE15B41

Grade/Elements %	SAE 4140	SAE 15B41
C	0.38 / 0.43	0.35 / 0.45
Mn	0.75 / 1.00	1.25 / 1.75
Si	0.15 / 0.35	0.15 / 0.35
Cr	0.80 / 1.10	0.040 Max.
Ni	-	0.035 Max.
Mo	0.15 / 0.25	-
S	0.04 Max.	-
P	0.035 Max.	-

A comparison study on hardenibility of materials SAE15B41 and SAE4140 was made and the results were plotted as shown in Figure 13. The graph clearly shows that SAE4140 has better hardenability compared to SAE15B41 owing to its additional composition of molybdenum and chromium. Bench level tests were conducted for abusive torqueing conditions to corroborate the material analysis of SAE4140 wheel studs and are discussed futher.

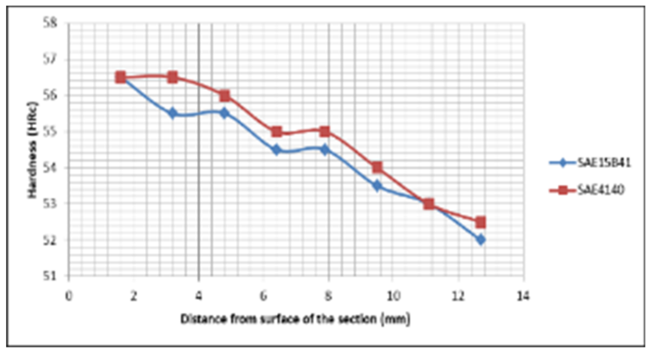

Fig. 13. Hardenability comparison of SAE4140 & SAE15B41.

Bench Level Abusive Torqueing Test on Existing - SAE15B41 and Proposed - SAE4140 Wheel Studs

The vehicle during operation are subjected for regular service tyre change, brake pad change and similar services which may lead to high torque application by the vehicle driver and service mechanic while reassembly. In order to capture this scenario, bench level abusive torqueing test was conducted on existing studs - SAE 15B41 & proposed studs – SAE4140.

Set of five new studs of material SAE 15B41 were assembled to a wheel hub. The wheel hub was then clamped tightly to a fixture table and wheel rim was carefully placed over the wheel hub with the guidance of wheel studs. Wheel nuts of grade class 10 were hand-tightened all over the studs. Using a calibrated torque wrench of capacity 980NM, torque was gradually applied over the all the nuts in clockwise sequence as shown in Figure 14(a) and the readings were noted.

Among the five studs, four were torqued until failure and one was torqued till crack initiation by gradually increasing the torque as shown in Figure 14(b). Failed studs of material - SAE 15B41 is shown in Figure.15(a),(b) & (e).

Fig. 14. Bench Level Abusive Torqueing Test: (a) Fixture setup for torque test, (b) Bolts failed due to abusive torqueing.

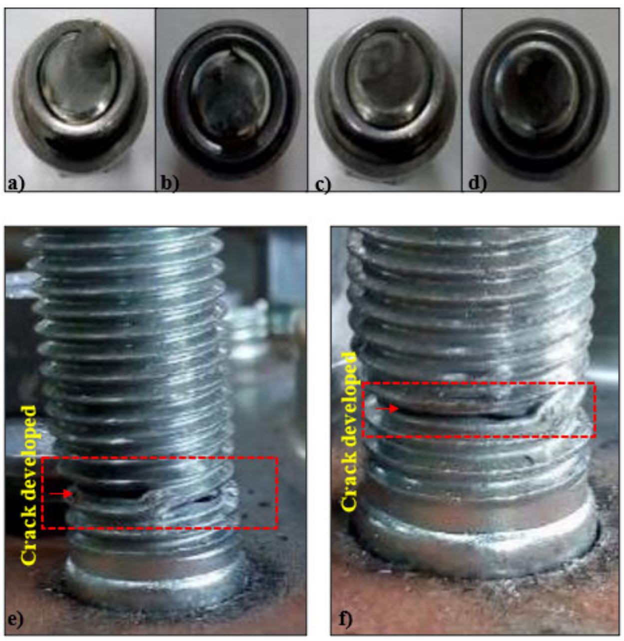

Fig. 15. Studs failed abusive torqueing test: (a),(b) &(e) – SAE 15B41; (c),(d) & (f) – SAE 4140.

The abusive torqueing test was repeated with the studs of proposed material-SAE4140 using the same setup as explained above. Failed studs of material - SAE4140 is shown in Figure.15(c),(d) & (f). By physical observation, it can confirmed that, failure have originated from the thread root under torsional load.

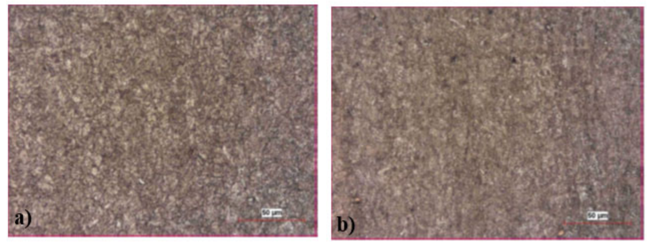

Fig.16. Microstructure analysis @500x: (a) – SAE 4140 showing tempered martensite, (b) – SAE 15B41 showing tempered martensite.

The samples failed by bench test were subjected to metallurgical and fractography analysis for study. By microstructural analysis, there observed no abnormalities in terms of decarburization or internal oxidation in both SAE5B41 & SAE4140 bolts as shown in Figure.16. The surface and core microstrures were observed to be temepered martensite.

The fractography study which is shown in Figure.17&18 reveals that, failure had been initiated from thread root and progressed towards the core section. The fracture surface reveals dimple mode failure, which indicates ductile failure by excess torsional load.

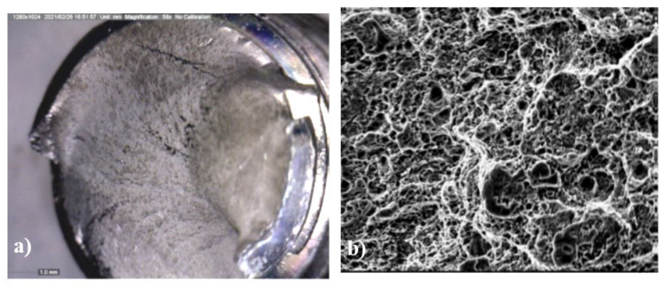

Fig. 17. Fractography analysis of SAE 4140 studs failed by bench level abusive torqueing test (a) - Dino image shows fracture surface at stud thread, (b) - SEM image @ 1000x magnification shows dimples indicating ductile mode of failure.

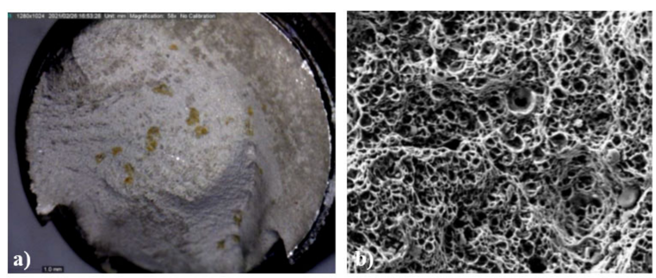

Fig. 18. Fractography analysis of SAE15B41 studs failed by bench level abusive torqueing test (a) - Dino image shows fracture surface at stud thread, (b) - SEM image @ 1000x magnification shows dimples indicating ductile mode of failure.

From abusive torqueing test, it is evident that, proposed SAE 4140 wheel stud is capable of withstanding higher abusive torque of 750Nm(avg.) than existing SAE15B41 wheel stud which was able to wtihstand only 591Nm(avg.). The comparison of abusive torque test results are in shown in Figure. 19.

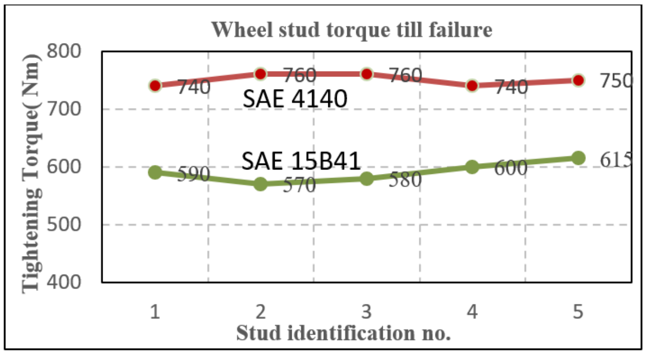

Fig. 19. Abusive torque test results comparison between SAE4140 & SAE15B1.

Vehicle Level Endurance Trials with Proposed - SAE4140 Wheel Studs

Based on the confidence from bench level tests and metallurgical analysis results, new proto-built vehicles as well as proto vehicles which had SAE15B41 wheel stud failures were assembled with proposed SAE4140 wheel studs and endurance trials were carried out. Similar to earlier validation practice, the proto vehicle drivers followed removal/refitment of front wheel studs using wheel end spanners at service intervals/as required during endurance trials. The endurance trials on the three proto vehicles (which had SAE15B41 stud failures) were stopped upon they covering 49,000 to 64,000km without any wheel stud failures since most of the other proto-built vehicles crossed highest failure km of 82,289km without any issues. More than 14,000 vehicles were sold with SAE4140 wheel studs assembled to them. Many customer vehicles have crossed 90,000km without any wheel stud failure issues. Few customer vehicles have crossed 1.2 lakh km without any front axle wheel stud failures till date as shown Table.4.

TABLE 4

Details on km coverage of few customer vehicles & proto vehicle (which had SAE15B41 stud failures) endurance trials fitted with SAE4140 wheel studs

Sl. No.	Vehicle ID	Application	Covered km	Remarks
1	Customer Vehicle - 01	Highway	119,858	As on 08.07.21 Guttapalli, AP
2	Customer Vehicle – 02	Highway	100,581	As on 10.07.21 Guntur, AP
3	Customer Vehicle - 03	Highway	94,236	As on 20.07.21 Undi, AP
4	Customer Vehicle - 03	Highway & Intracity	90,100	As on 12.07.21 Guntur, AP
5	Customer Vehicle - 04	Highway & Intracity	81,782	As on 12.07.21 Krishnagiri, TN
6	Proto Vehicle - 01	Highway	54,782	Failure - 71,522 km ODO - 126,304 km
7	Proto Vehicle - 02	Highway	49,916	Failure - 72,435 km ODO - 122,351 km
8	Proto Vehicle - 03	Highway	64,230	Failure – 82,289 km ODO - 146,519

Summary

A thorough analysis was done in identifying the causes that promoted the failure of front axle RHS wheel studs at 70,000+ km and a design solution is proposed.

Design calculations were revisited to check for any fallacy in design and concluded that original design specification holds good for this SCV. Load shift from RHS wheel to LHS wheel due to road camber was studied. It was observed that due to LH road camber with slope 3%, RHS front wheel load had decreased by 6% thus confirming that Indian road camber conditions didn't have any influence on RHS wheel stud failures. However, for wheel stud failures on LHS wheels, influence of Indian road camber conditions should be taken into account while analyzing such failures. Because, LHS road camber causes increase in load on LHS wheels by 6% on front axles and 9% on rear axles which is significant.

Metallurgical analysis of presented failed wheel studs reveals that all the wheel studs failed due to over tightening of wheel nuts causing too high pre-load to the wheel studs. The excessive tension in studs had resulted in yielding of the stud causing relaxation in tension. This pre-load relaxation in studs subjected them to cyclic loads during vehicle operation resulting in eventual fatigue failure.

Since the design load calculations were intact and metallurrgical results confirmed that the failure of studs were due to excessive torqueing, it was decided use a superior wheel stud of same grade with improved fatigue properties and can withstand the abusive torque tightening practices.

With the help from metallurgical experts and fastener suppliers, SAE 4140 stud of grade 10.9 was proposed which is superior to SAE 15B41 stud. SAE 4140 studs have improved mechnical properties due to its additional composition of molybdenum and chromium. Bench level tests were performed to confirm whether SAE4140 wheel studs would withstand excessive torque while tightening. The test results reveled that, SAE 4140 wheel stud was capable of withstanding higher abusive torque of 750Nm than existing SAE15B41 wheel stud which was able to wtihstand torque only upto 591Nm on average.

Endurance trials conducted on proto vehicles with SAE4140 wheel studs and crossed highest failure km without any issues. Based on the above confidence, SAE4140 wheel studs were sucessfully applicated on SCV front axle wheels. More than 14,000 vehicles were sold with SAE4140 wheel studs till date and many customer vehicles have crossed 90,000 km. Some of them covered 1.2 lakh km without any front axle wheel stud failures.

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