Journal of Materials Science & Surface Engineering Vol. 3 (1), 2015, pp 171-176

Contents lists available at http://www.jmsse.org/

Journal of Materials Science & Surface Engineering

Fatigue Life Prediction and Durability test of passenger car Rheocast Aluminium Steering Knuckle

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Article history

Received: 02-May-2015
Revised: 10-June-2015
Available online: 01 July, 2015

Keywords:
Rheocasting,
Aluminium knuckle,
Strain gauging,
Road Load Data Acquisition(RLDA),
Fatigue life prediction,
Durability lab test,
Block program generation

Abstract

Ride and Handling of any passenger car is one of the most selling parameter in today's automotive industry. Keeping the un-sprung mass as low as possible without compromising the required strength and stiffness is one of the most challenging problems today as the un-sprung mass directly effects the ride and handling of the car. Steering knuckle which is one of the most critical parts of the un-sprung system of a car significantly contributes to the un-sprung mass of a car and thus forms an important opportunity to reduce its mass. For this, an aluminium knuckle developed by a recent manufacturing technique called rheocasting is chosen. Very limited data is available on fatigue strength and durability of Rheocast aluminium knuckle as on today.

In this paper, an attempt is made to calculate fatigue life using measured strain data through RLDA and test data for the durability strength of a passenger car's Rheocast Aluminium knuckle. Strain and Stress based Fatigue life prediction techniques are then applied with different mean stress correction schemes to calculate life of the knuckle using measured strain data. Rheocast aluminium knuckle was tested using servo hydraulic actuator for its static and durability strength. Strain comparison was made between track and lab and established rig level durability test. Predicted life from different models are compared with actual failure cycles from physical test to establish the prediction model suitable for knuckle life calculation.

The work had been presented *at an* international conference ***Fatigue Durability India 2015****, 28-30th May 2015, JN TATA AUDITORIUM, Indian Institute of Science, Bangalore.*

Introduction

Since 1990, the steady increase in the mass of the typical family vehicles due to safety and luxury has challenged the automakers ability to comply with the fuel efficiency standards, other than causing significant mass problems. The strive for original equipment manufacturer (OEMs) to comply with current and future fuel efficiency standards and emissions legislation has been the critical path for the reversal of this mass spiral. The use of lighter components in the suspension system (un-sprung mass) helps to improve ride quality and handling, as well.[1-2]

In today's automobile, the mass of the un-sprung components is normally 13 to 15 percent of the vehicle curb mass. In the case of a 1750 kilograms vehicle, un-sprung mass may be as high as 250kilograms. A 250 kilograms mass reacting directly to roadway irregularities at high speeds can generate significant vertical acceleration forces[3]. These forces degrade the ride, and they also have a detrimental effect on handling. [2]

As the knuckle has a greater mass compared to the other parts, it has a greater impact in reducing the overall mass of the un-sprung mass. Hence, this study aims at reducing the mass of the steering knuckle and validating it through its durability testing.

Presently, most of the passenger car manufacturers use either steel forged or ductile iron casted knuckle, which are bulky and heavy.[1] Aluminium alloys were found to be a feasible alternative option because of its high strength to weight ratio, corrosion resistance, ductile nature, mainly light weight properties and economic feasibility.

Experimental

Material Properties

Aluminium Alloy A356 was used to manufacture the steering knuckle. The chemical composition of the material used in this study is given in table 1. The typical mechanical properties of Al A356-T6 is presented in table 2.

Table 1: Chemical composition of Aluminium A356-T6

Cu %	Mg %	Si %	Ti %	Mn %	Zn %	Fe %	Others %	Al %
0.2	0.2 - 0.4	6.5 - 7.5	0.25	0.1	0.1	0.2	0.15	91.1 – 92.3

Table 2: Tensile properties of Al A356-T6[8]

	Tensile Strength (MPa)	Elongation %
A356-T6	250	8.6 - 13.2

Manufacturing Process involved

The manufacturing process chosen for the development of the steering knuckle is Rheocasting for its advantages over the conventional methods discussed later.

Rheocasting is a form of Semi solid metal casting (SSM) technology as shown in figure 1. SSM is done at a temperature that puts the metal between its liquidus and solidus temperature. Ideally, the metal should be 30 to 65% solid. The metal must have a low viscosity to be usable. The temperature range at the slurry state required for aluminium alloys is 5–10 °C. Rheocasting

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develops the semi-solid slurry from the molten metal produced in a typical die casting furnace/machine. This is a big advantage because it results in less expensive feedstock, in the form of typical die casting alloys, and allows for direct recycling.[5]

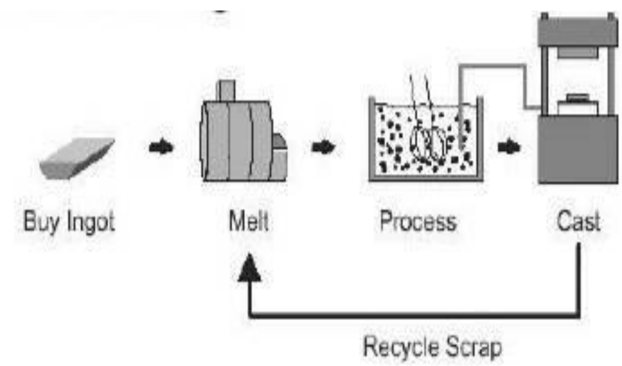


Figure 1: Description of the Rheocasting process

Advantages of SSM:

- Energy efficiency: metal is not being held in the liquid state over long periods of time;
- Production rates are similar to pressure die casting or better;
- Smooth filling of the die with no air entrapment and low shrinkage porosity gives parts of high integrity (including thin-walled sections) and allows application of the process to higher-strength heat-treatable alloys;
- Fine, uniform microstructures give enhanced properties;
- Reduced solidification shrinkage gives dimensions closer to near net shape and justifies the elimination of machining steps;

Limitations of SSM:

- The cost of raw material for rheocasting can be high and the number of suppliers small;
- Initially at least, personnel requires a higher level of training and skill than with more traditional processes;
- Temperature control: the solid fraction and viscosity in the semi-solid state are very dependent on temperature.
- Alloys with a narrow temperature range in the semi-solid region require accurate control of the temperature;

Service Loads

Steering knuckle as shown in figure 3 has three arms for mounting; the lower strut arm, mounted to the sprung mass through the strut assembly; this arm takes up the most of the vehicle's weight and all the vertical reaction forces. The second, steering arm connects the steering rack to the wheel for manoeuvrability and also takes all the side forces of the vehicle. The lower arm is mounted to the lower control arm and acts like a guide to the wheel.[7]

Static Strength Test

Based on the generic 3-2-1g load cases, the stiffness plots were plotted. The knuckle was clamped to a rigid member using appropriate fixtures and the loads were applied using a servo-hydraulic actuator. Loads were measured using a load cell and deflections through an LVDT sensor as shown in figure 4.

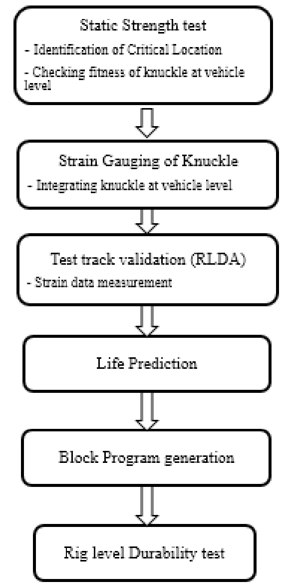


Figure 2: Project process Flow

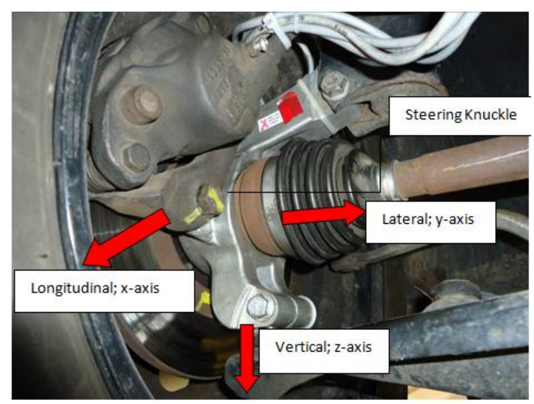


Figure 3: SAE co-ordinate system

Table 3: Vehicle load cases

S.No.	Force Direction	Load	Physical Condition
1.	Vertical Force (Z-axis)	3g	Jounce/Rebound
2	Longitudinal Force (X-axis)	2g	Sudden Braking/ Acceleration
3.	Lateral Force (Y-axis)	1g	Hard Cornering

Figure 4: Fixture setup for static strength test

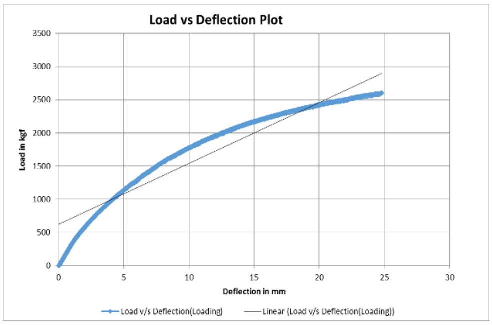


Figure 5: Stiffness plot of steering knuckle

The stiffness plot as shown in figure 5 determines the behaviour of the component while loading as compared to the standard specimen of the same material. Test results showed that the ultimate strength of the knuckle is beyond the maximum service loads acting (as per generic 3-2-1g load cases). Also, the critical zones as shown in figure 6 were identified which were used in the later part of the project.

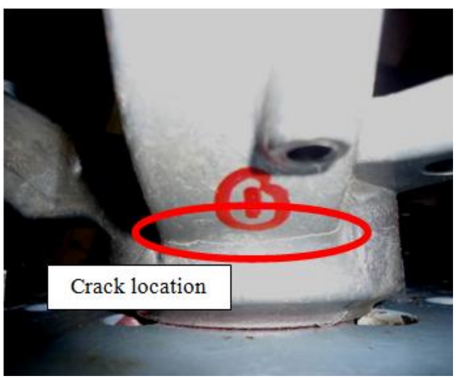


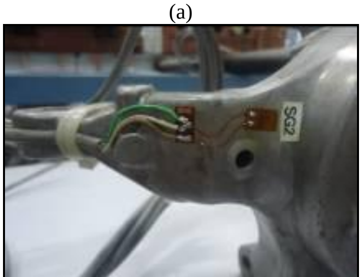
Figure 6: Fracture location of the knuckle

Results and Discussion

Strain gauging

Strain gauges were pasted at all the identified critical locations of the knuckle as shown in figure 7a, 7b & 7c. Strain data from RLDA of these locations was used to predict the life of the knuckle later.

(a)



(b)

(c)

Figure 7: Strain gauged knuckle at different locations

Gauges with 350Ω resistance and Quarter bridge connection scheme have been used.

The lower strut mount (Figure 7a) and steering arm rear (Figure 7b) are mounted with uniaxial strain gauges while a Rosette on the forward side of steering arm (Figure 7c)

Customer Utilization Pattern of the Vehicle

Vehicle with the strain gauged knuckle was run on the torture tracks like Belgian pave, high frequency, twist tracks and others to measure the strain data at the strain gauged locations using an appropriate data acquisition system.

The choice of the tracks and the weightage for each track was based on the Customer Utilization pattern as shown in figure 8 & 9. It is the study of the vehicle's possible utility catering to its costumer market.

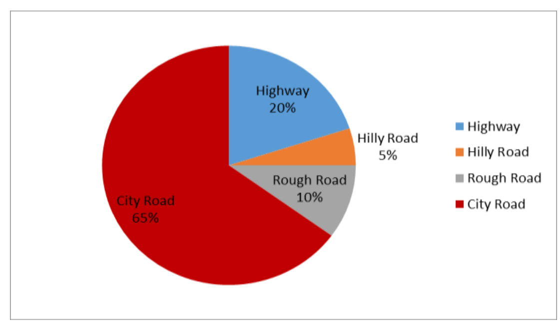


Figure 8: Customer Utilization Pattern of a city drive vehicle

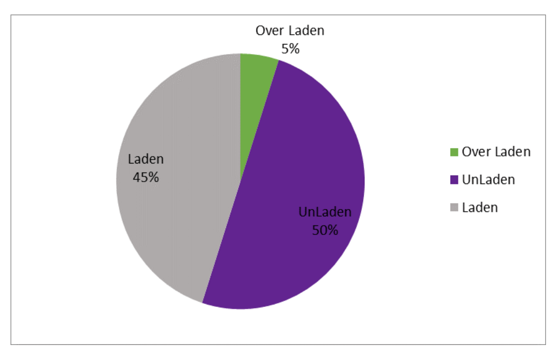


Figure 9: Weight distribution conditions for testing

Strain data of pave1, pave 2, twist track, high frequency and long wave pitch was recorded.

Data Processing

The next step involved the filtering and extraction of the raw data from RLDA. Major steps in filtering include Spike detection, Running mean removal and elimination of unwanted frequencies. Discarding the unwanted data to get the test track data only is Extraction.

The outcome (Figure 10) illustrates only the filtered track strain data after snipping the complete unwanted data.

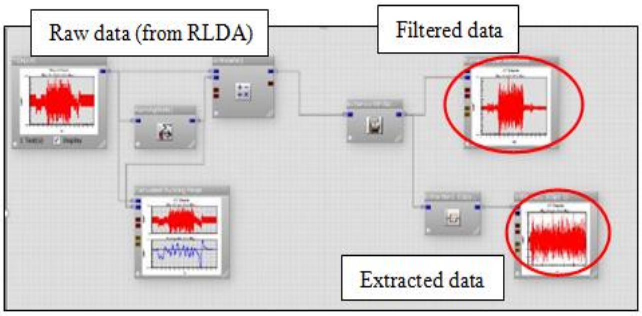


Figure 10: Program for filtering of data

Life Prediction

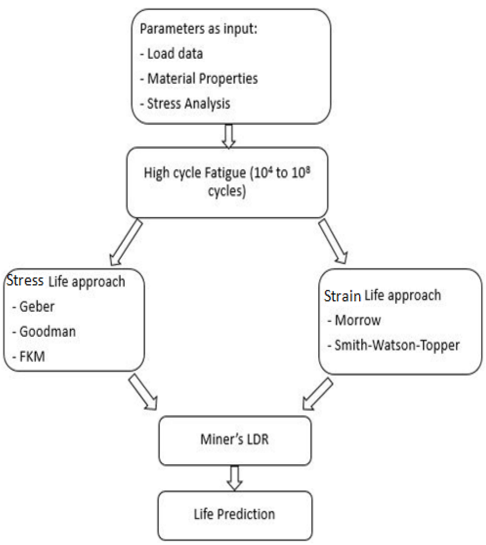


Figure 11: Life prediction techniques

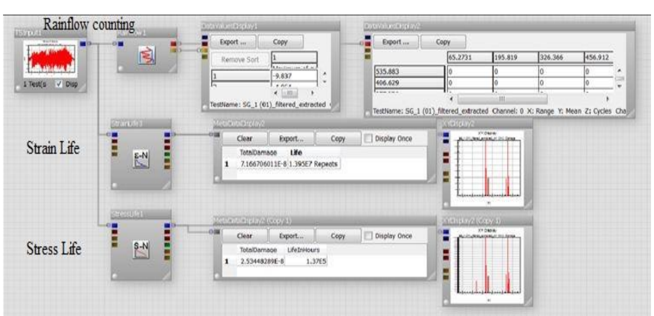


Figure 12: Life prediction using stress life and strain life approach

Fatigue life prediction technique (Figure 11 & 12) is a crucial integral of the durability test of that component as it helps in predicting the life and behaviour of the component at early stages of the testing. This acts as a development stage to predict the failure of the part before the commencement of the test. The damage caused by each strain signal as shown in table 4 & 5 was calculated and the corresponding life was derived. The predicted fatigue life depends on the mechanism used (Stress life and strain life) as well as the mean correction scheme input (Goodman, Geber, SWT, Morrow and FKM) while calculating the damage.

Strain Life Approach:

Table 4: Damage caused due to strain life approach

	Damage caused		
Tracks	No Correction	Morrow	SWT
Track 1	1.2E-5	1.27E-5	1.45E-5
Track 2	1.42E-5	1.24E-5	9.98E-6
Track 3	7.79E-6	7.767E-6	7.99E-6
Track 4	0	0	0

Stress Life Approach:

Table 5: Damage caused due to stress life approach

	Damage caused			
Tracks	No Correction	Geber	Goodman	FKM
Track 1	1.73E-6	1.73E-6	1.78E-6	1.85E-6
Track 2	1.93E-6	1.95E-6	1.81E-6	1.69E-6
Track 3	1.19E-6	1.19E-6	1.20E-6	1.20E-6
Track 4	0	0	0	0

Block program generation for part level testing:

Block program (Figure 13) which is a set of various load cases is used to program the servo-hydraulic actuators for real time durability testing of the component

Rainflow counting as shown in figure 14 was carried out on the measured strain signal and the range vs. mean matrix was plotted. From the matrix, the damaging and non damaging cycles were identified based on the similar damage calculations. Damaging cycles were converted to constant amplitude sinusoidal cycles and the damage of these cycles was again calculated. Ratio of the damage of the measured strain signal and the derived sinusoidal cycle gave the number of repeats for attaining the equivalent damage.

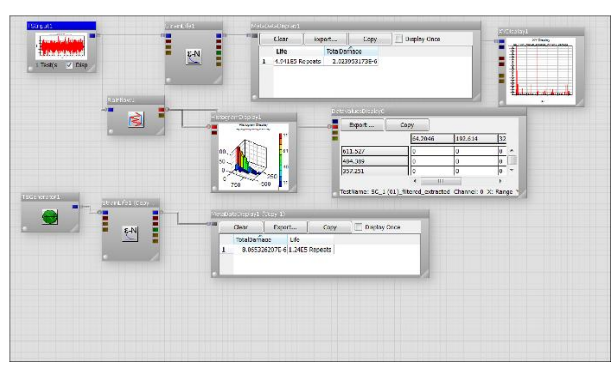


Figure 13: Block program generation

As per Miner's Linear Damage Rule,

$$Total\ Damage = D_{track\ 1} + D_{track\ 2} + D_{track3} + \ldots + D_{track\ n}$$

where $D_{track\ n}$ represents the damage of the strain signal (Table 6) of the corresponding track[6]

$$Total\ no.\ of\ cycles = \frac{Damage\ of\ the\ measured\ strain\ signal}{Damage\ for\ one\ pass\ of\ sinusoidal\ signal} \times Predicted\ life$$

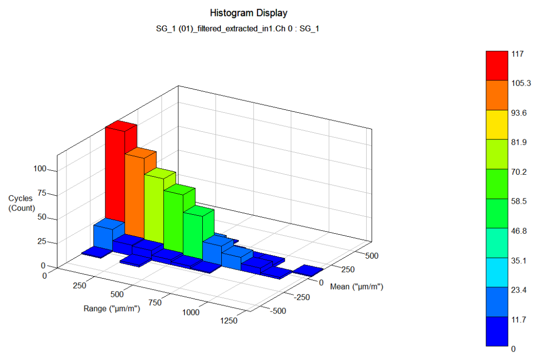


Figure 14: Rainflow counting of input strain data

Table 6: Damaging strain values

Track	Range (µe)	Mean (µe)
Track 1	1084	6
	1228	6
Track 2	1054	-91
	1195	-91
Track 3	1109	19

Strain Calibration

The strain gauged knuckle was mounted onto the test rig as shown in figure 17. Loads had been applied to the knuckle and the load vs. strain data was plotted as shown in figure 15.

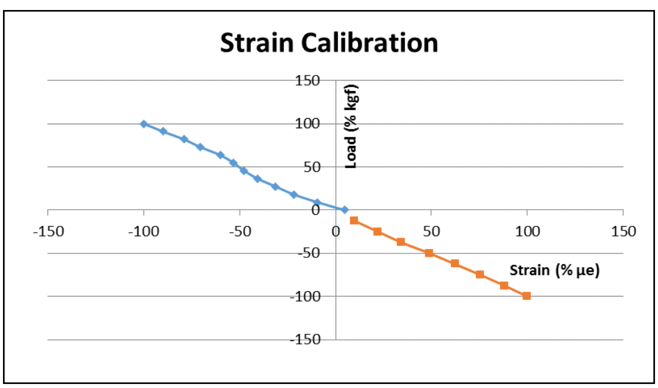


Figure 15: Strain calibration for load controlled actuator

Using the load vs. strain plot, load cases for block program generation were calculated for corresponding strain values at different tracks as shown in table 7.

Table 7: Block program generation for rig level testing

Track	Range (µe)	Mean (µe)	Load Range (kgf)	
			Compression	Tensile
Track 1	1084	6	219	464
	1228	6	246	527
Track 2	1054	-91	177	535
	1195	-91	204	598
Track 3	1109	19	229	463

Rig Level Testing & Correlation

The block program generated (Figure 16) from the strain vs. load cases was fed to a load controlled servo hydraulic actuators for the durability test of the knuckle. The block program and its number of repeats was finalized using the rainflow counting of the RLDA strain data and the cycle count weightage given to each track.

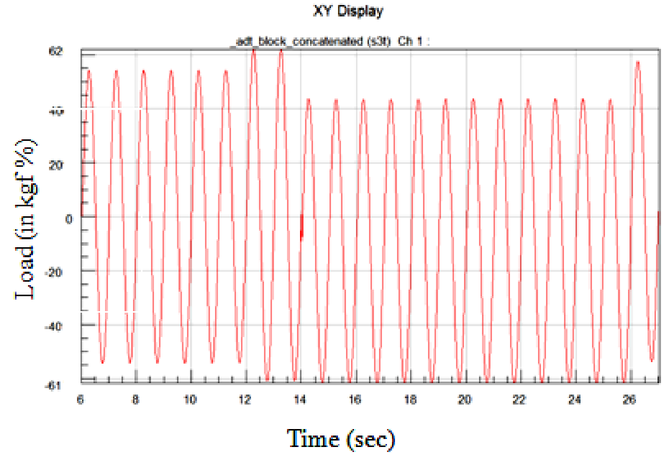


Figure 16: Block program of sinusoidal range of damaging cycles

Figure 17: Rig level setup for durability test

Correlation Techniques

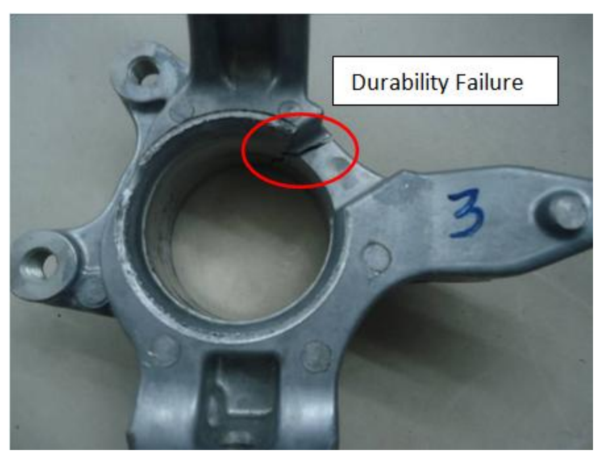


Figure 18: Steering knuckle failure post durability test

Table 8: Predicted vs. Actual fatigue life of knuckle

Predicted Life (no. of repeats)	Actual Life (no. of repeats)		
	Sample 1	Sample 2	Sample 3
1.53*10^5	1.12*10^5	1.14*10^5	1.15*10^5
Correlation %	73.2%	74.5%	75.16%

The block program generated durability life of the knuckle was correlated with all the life prediction approaches and mean corrections as shown in table 8. The best correlation among the given techniques was achieved for **No correction scheme** in the **strain life approach.**
Lab to rig level correlation (in %) = 74.5%

Failure mode of the knuckle post the durability test is shown in figure 18.

More number samples to be tested to get very accurate results and to conclude precisely on the life prediction models with better correlation results

Conclusion

1. Further research into the Semi solid metal casting will help advantageous processes like Rheocasting improve the output quality of manufacturing processes.
2. The developed strain bound fatigue prediction model has been validated and can be used as an effective tool in product development stage to minimize rig level physical testing.
3. Fatigue time series block program with removal of non-damaging cycles from the measured strain, helps to predict fatigue life closer to test at the physical level.
4. Predicted life with no mean stress correction approach is closer to rig level test result for the selected part and material.

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