Prediction of tooth root failure under static loading condition for EN353 steel spur gear

N Gnanasekar¹*, Rama Thirumurugan², A Arun Muthukumar³ and M Azmal Khan⁴

¹Assistant Professor, Department of Mechanical Engineering, P.A College of Engineering and Technology, Pollachi, Coimbatore-642002, Tamilnadu, India.
²Associate Professor, Department of Mechanical Engineering, Dr Mahalingam College of Engineering & Technology, Pollachi, Coimbatore-642003, Tamilnadu, India.
³,⁴UG Student, Department of Mechanical, P.A. College of Engineering and Technology, Pollachi, Coimbatore-642002, Tamilnadu, India.

*Corresponding author: sekarfea@gmail.com

Abstract. Gears are commonly used as mechanical components in power transmissions system. The spur gears are usually subjected to fluctuating loads during power transmitting applications. Gear failures have been identified due to these loads, e.g. Fatigue, impact, wear or plastic deformation. To reduce the failures so much of importance is given to choose suitable material and heat treatment process for reliable design of spur gear. The hardness of the EN353 steel can be improved by austempering heat treatment process. In this paper, the spur gear was investigated for EN353 steel properties with carburizing and austempering heat treatment. Also a gear test rig was designed to analyze the spur gear tooth root for different bending load condition until the tooth root failure in universal testing machine.

1. Introduction

Spur Gears are mostly used to transmit the power in mechanical system. The spur gears are mostly failed due to these following failure modes such as fatigue, impact fracture, wear and stress rupture. The primary modes of failure appeared in spur gears tooth region by bending fatigue, bending impact, and tooth wear, of which the most common failure mode is the bending fatigue. The spur gear tooth damage mostly will be occurred by two ways due to pitting at the surface of spur gear and tooth breakage in the tooth root area. Tooth breakage made destructive damage in tooth root region, since the study of failures in the tooth root should always be looked carefully in all practical gear applications. The different standard procedures were adopted for proper verification of the maximum stress in the tooth root region like (AGMA, DIN, and ISO etc.) [1-2].
Several source of failure will be identified in the spur gear which may be poor design of the gear set, inaccurate assembly or misalignment of the gears, overloads, internal cracks in critical regions, and not proper selection of materials and heat treatments process. In this paper, an importance is given to selection of materials, heat treatments and finds various aspects of failure in spur gear to some aspect. The different mechanical properties of steel can be improved by proper heat treatment technique. In this paper, An En353 steel was selected with 0.2%C which is subjected to different heat treatment process as carburizing and austempering.

Gear failure can occur in various modes. The failure of spur gear can be prevent by making proper care during design stage. The prediction of failures will be more difficult in the spur gear by developing a mathematical model due to interaction of many parameters [3-5]. As the spur gear pair exceeds its load carrying capacity, the different failures will occur in spur gear such as pitting, tooth failure, scuffing, excessive wear, etc., [6]. Since a suitable gear test rig will be needed to predict the gear failure for tooth bending loads. The initiation of crack takes place at the maximum principle stress region, normally at the root of the tooth or from the surface defects [7]. Therefore, a gear test rig which allows the testing the gears under controlled environment is needed. Then crack propagates quick results in fracture of the tooth. In this paper, the failure of spur gear was studied for bending load in tooth root region before and after crack initiation with angle of 45°.

2. Objectives
- The tooth root was mostly loaded region of the spur gear pair and subsequently the tooth flank also. In this work, the failure of tooth root was analyzed in spur gear which is loaded by tangential bending force.
- Normally, the geometry and the kinematics of the gear pair transmit the maximum load to one gear only. So that the tooth root of the pinion is comparatively more loaded than the tooth root of gear or vice versa.
- The effect of EN353 steel materials was studied for different heat treatment process for spur gear application.
- Based on the reviews the new gear test rig was developed for the application of tangential load to predict the failure of tooth root in the spur gear [8].

3. Methodology
The following steps are used to predict the tooth root failure in spur gear by proper designing of gear test rig is shown in Figure 1. The gear test rig was developed based on the methodologies as follows:

4. Gear Design
The following gear nomenclature was used in this paper as shown in table 1. The spur gear and test rig was prepared for based on given parameters as shown in table 2.
Table 1. Gear Nomenclature

| Gear nomenclature       |
|-------------------------|
| $a_{cent}$              | Centre distance          |
| a                       | Crack length             |
| B                       | Tooth width              |
| M                       | Module                   |
| E                       | Young’s modulus          |
| Z                       | Number of teeth          |
| m                       | Poison’s ratio           |
| h                       | Crack propagation angle  |
| $\alpha$                | Pressure angle           |

Figure 1. Methodology
Table 2. Design calculation of spur gear

| Design calculation of spur gear |
|--------------------------------|
| Total number of teeth, N = 20 |
| Module, M = 3 mm               |
| Outer diameter, D₀ = 66 mm    |
| Pitch circle diameter, D = 60 mm |
| Diametrical pitch, P = 0.3333 mm |
| Tooth Width, B = 15 mm        |

5. Material selection

The materials played a main role in the spur gear manufacturing in both common mechanical engineering and automotive industry. The spur gears are manufactured after surface heat treated steels, so it’s called as surface hardened steels [9]. The flank of the spur gear should be hard in order to withstand the slider contact loading by increasing residual stress at the surfaces. Firstly, the gears are cut out to get the teeth over the circumference. After the finished mechanical handling the gears are thermally treated in order to give the material the final strength. The result of such treatment is a hard surface and a tough core. Hard surface extends over the whole gear body. Hard surface layer behave excellently when they are loaded by pressure [10].

The weight percentage of alloy elements will be played important role in the selection of Plain carbon steel as shown in table 3. When the carbon content was increased in plain carbon steel, the metal will have more hardness and strength but it becomes less ductile, lowers the temperature resistance and steel melting point.

Normally these steels have iron with less than two percentage of carbon with small amounts of chromium, cobalt, columbium [niobium], molybdenum, nickel, sulphur, and silicon. Also some other elements are present after removing of some elements in plain carbon steel such as manganese, sulphur, phosphorus which make some changes into the properties of steel. In plain carbon steel, the some residual elements are present like Mn (Max 1.650%) and Si (Max 0.601%).

Table 3. Weight Percentage of Residual Elements in Plain Carbon Steel

| Elements | Maximum weight % |
|----------|-----------------|
| C        | 1.00            |
| Mn       | 1.65            |
| P        | 0.40            |
| Si       | 0.60            |
| S        | 0.05            |

The elements of sulphur, phosphorus and silicon make more impacts on deriving of mechanical properties of plain carbon steel. Then several other residual elements are present in plain carbon steel but it does not make any significant effects on the properties. When the plain carbon steel was heat treated like quenching and tempering, it has a propensity to form a compound with iron which is brittle. So, the absence of phosphorus will increase the ductility [11].
The important properties of plain carbon steel are found after presence of above mentioned elements as shown in table 4. The hardness and toughness was improved after adding the elements of manganese and silicon, when used in a correct proportion. The reason was mentioned as; they can dissolve in austenite and make a significant decrease in the austenite phase transformation rate to pearlite or upper bainite.

| Materials  | Density $x10^3$ kg/m$^3$ | Thermal conductivity Jm$^1$K$^{-1}$s$^{-1}$ | Thermal expansion $10^6$K$^{-1}$ | Young’s Modulus in MPa | Tensile strength in MPa | % Elongation |
|-----------|---------------------------|---------------------------------------------|----------------------------------|------------------------|------------------------|-------------|
| 0.2%c steel | 7.860 | 50 | 11.7 | 210 | 350 | 30 |
| 0.4%c steel | 7.850 | 48 | 11.3 | 210 | 600 | 20 |
| 0.8%c steel | 7.840 | 46 | 10.8 | 210 | 800 | 8 |

The heat treatment process was done on the spur gear specimen and then it was cooled into water, oil and brine water. After heat treatment was done, surface of gear flank is got soften surface and the grain size was changed to modify the structure face of the gear and relive the residual stress set up in the gear flank surfaces. Case hardening was used to harden the flank of spur gear for depth of 0.9 mm by adding the suitable elements which form a residual stress and also wear resistance [12]. The following elements are presented in the tested EN353 steel spur gear specimen as shown in table 5.

| Carbon | Silicon | Manganese | Phosphorous | Sulphur | Molybdenum | Nickel | Chromium | Iron | Rest |
|--------|---------|-----------|-------------|---------|------------|--------|----------|------|------|
| 0.191  | 0.191   | 0.670     | 0.018       | 0.013   | 0.121      | .090   | 0.961    |      | Rest |

6. Failures in gears

The behaviour of spur gear after crack initiation was discussed in many research works for different application with static and dynamic loading cases during service life. A fracture is a separation of parts of an object or material into two or more pieces under the action of stresses. The fracture usually occurs in the tooth root region of spur gear due to certain displacement discontinuity development at its surfaces. The crack is initiated due to the level of stress intensity factor. Crack initiation is a process that forms cracks on the surface of a material [13-14].

The primary reason for the formation of cracks on any surface is static. Static leads to progressive and localised structural damage when any material experience continues loading. Fracture mechanics is concerned with the study of crack initiation and propagation of cracks in the spur gear [15-16]. The special gear test rig was used to find the driving force of crack experimentally under the static loading conditions.

7. Fabrication of Gear Test Rig

While designing a gear it is very important to analyse stress under maximum loading for safety operation. For this prediction of failure in spur gears, there is a need for such test rig. To determine the maximum loading on teeth this test rig assembly used. The static analysis can be performed in UTM machine.
7.1 Assembly of test rig
Assembly of test rig is carried by angle plate column for driver shaft and angle plate column for tested gear are. Standard bearing are fixed in the angle plate column. Test gear shaft and driver gear shaft are fixed in their respective angle plate column then loading clamp is mounded in the test gear shaft. The angle plates are mounted on the base plates at the desired positions the shaft. The entire assemble setup is modelled by the solid works software as shown in figure 2. After that the whole assembly of fixture is need to be fixed in the UTM machine for further loading and testing procedures.

![Figure 2. Assembly of gear test rig and its components.](image)

7.2 Fabrication of test rig
Fabrication of test rig is done using EN24 steel with proper heat treatment as shown in figure 3. Test rig components are Base plate, Angle plate column for driver gear, Angle plate column for test gear, test gear shaft, Driver gear shaft and Loading clamp up & down part. These components are designed and fabricated as per the dimensions.

![Figure 3. The fabricated gear test rig](image)

8. Working principle

8.1 Crack initiation in spur gear
Crack is initiated in a spur gear by using the wire cut EDM (electrode discharge machining) process. In this process the crack is initiated in 45 degree angle as shown in figure 4. In EDM machine the guide is held between upper and lower guides. The guide's moves in the X-Y plane movements to cut a tapered and transitioning shape which was controlled by a CNC to control the axis movement. The crack was initiated at 45° as shown in figure 5.

![Figure 4](image1.jpg) Crack initiation in spur gear by using Wire cut EDM process.  
![Figure 5](image2.jpg) Spur gear tooth with crack initiation for 1 mm in Wire cut EDM

### 8.2 Fixture Set up and Loading in UTM Machine

The base plate is fixed to the UTM machine bed and the test gear and driver gear is rigidly fixed to the angle plate. Test gear is fixed in the small shaft and then driver gear is fixed in the long shaft. The loading clamp is mounted on the end of the driver gear shaft. The static load is applied in the test gear through the loading clamp of driver gear shaft by using hydraulic actuators in vertical direction as shown in figure 6. The load is applied on the clamp by using loading unit or crosshead, the load transfer from rotating gear to fixed gear. During the testing, the single tooth is subjected to bending static load in test gear. The strength of the gear is predicted based on the failure of spur gear for given maximum loading condition. Also crack
growth will be predicted during the testing when the ultimate load is reached for cracked tooth which undergoes the plastic deformation or failure.

9. Result and Discussion

Heat treatment like carburizing and austempering was done in the EN353 steel specimen. The carburizing is done with the case depth of 0.9 mm, while austempering treatment is done at a temperature of 945°C. Hardness test is conducted using Rockwell hardness testing machine. It shows that the comparison of hardness among the green specimen and carburized and austempered specimen of EN353 steel. This comparative graph clearly shows that the austempering process produces the most surface hardened material among the taken treatments.

Fatigue test is carried out using multi-axial fatigue testing machine on treated and non-treated EN353 steel specimen. Totally ten number of specimen was tested on EN353 steel for carburized, austempered treatment specimen, and green specimen. The consecutive results of fatigue test on treated and green EN353 steel specimen were compared in figure 7. The above diagram clearly shows that the comparison among the tested specimen with stress in x-coordinates and No of cycles in y-coordinates and proving that the carburizing and austempered EN353 steel specimen has the utmost highest fatigue strength as compared to green EN353 steel specimen.

The tooth failure was predicted at the root region under static bending load. The tangential load was applied at the highest single tooth point contact which is varies from 800 N/mm to 3900 N/mm in UTM Machine is shown in table 6. The respective stress values are calculated by using Lewis Equation for the given loading conditions. The failure was predicted in spur gear for both green EN353 steel and carburizing heat treatment for without crack initiation as shown in table 6. The crack initiation was started at gear tooth root region for green EN353 steel when the tangential load is greater than the 2400 N/mm.

![Figure 7. S-N Curve for Heat treated and non-treated EN353 steel.](image-url)
Table 6. Prediction of tooth root failure in spur gear without crack initiation

| Load (N/mm) | Stress for respective Loads(Mpa) | Failure on gear for Green EN353 steel Without crack | Failure on gear for EN353 steel after carburizing treatment Without crack |
|-------------|----------------------------------|-----------------------------------------------------|---------------------------------------------------------------|
| 400         | 416.66                           | No Failure                                          | No Failure                                                   |
| 800         | 833.33                           | No Failure                                          | No Failure                                                   |
| 1100        | 1145.83                          | No Failure                                          | No Failure                                                   |
| 1200        | 1250.00                          | No Failure                                          | No Failure                                                   |
| 1400        | 1458.33                          | No Failure                                          | No Failure                                                   |
| 1600        | 1666.66                          | No Failure                                          | No Failure                                                   |
| 1800        | 1875.00                          | No Failure                                          | No Failure                                                   |
| 2000        | 2083.33                          | No Failure                                          | No Failure                                                   |
| 2200        | 2291.66                          | No Failure                                          | No Failure                                                   |
| 2300        | 2395.83                          | No Failure                                          | No Failure                                                   |
| 2425        | 2526.04                          | Failure                                             | No Failure                                                   |
| 2600        | 2708.33                          | -                                                   | No Failure                                                   |
| 2800        | 2916.66                          | -                                                   | No Failure                                                   |
| 3900        | 4062.50                          | -                                                   | Failure                                                      |

Table 7. Prediction of tooth root failure in spur gear with initial crack length of 1 mm

| Load (N/mm) | Failure on gear for Green EN353 steel With 1 mm initial crack | Failure on gear for EN353 steel after carburizing treatment with 1 mm initial crack length |
|-------------|---------------------------------------------------------------|-----------------------------------------------------------------------------------------|
| 400         | No Failure                                                   | No Failure                                                                           |
| 800         | No Failure                                                   | No Failure                                                                           |
| 1100        | No Failure                                                   | No Failure                                                                           |
| 1200        | No Failure                                                   | No Failure                                                                           |
| 1400        | No Failure                                                   | No Failure                                                                           |
| 1480        | Failure                                                      | No Failure                                                                           |
| 1600        | -                                                            | No Failure                                                                           |
| 1650        | -                                                            | Failure                                                                              |

After carburizing treatment on EN353 steel spur gear, the crack initiation in tooth root is identified at the tangential load of 3900 N/mm. After crack was initiated for 1mm length in tooth root region, the failure was predicted in spur gear for both green EN353 steel and carburizing heat treatment for different loads is shown in table 7. From the results, the failure rate of spur gear is reduced after carburizing treatment at the surface of tooth root region with improving strength of tooth. The crack initiation was predicted where maximum principle stress at tooth root region. After crack initiation, the load withstanding capacity of spur gear is reduced for both green and carburized heat treatments.
10. Conclusion
In this paper, the experimental investigation was done for the determination of failure in spur gear tooth root under static loading condition. The fabricated test rig was used to predict the failure of the spur gear by tooth root region for bending load under static load condition. When the gear was tested without crack, the crack was initiated at the gear tooth root near the centre of width where principle stresses was maximum. After that crack was introduced in tooth root for 1mm, the fracture was occurred quickly in gear root area as compared without presence of crack. The actual loading condition was determined in the failure of spur gear for with and without presence of crack at tooth root for further crack propagation path studies.

11. References

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