INVESTIGATION ON INFLUENCE OF CIRCUMFERENTIAL VELOCITY AND LUBRICATION OIL GRADES ON SCUFFING AND THERMAL EFFICIENCY OF GEARBOX

Vaidhyanathan D1, Pushparaj A2, Mahendran K3, Ragunathan V4
1,2,3,4 – New Product Development., Shanthi Gears Ltd, Coimbatore, India
E-mail: vaidhyanathand@shanthigears.murugappa.com

Abstract. Lubrication oil grades plays major role in reducing the friction to prevent scuffing in gears. Gears transmit power through rolling/sliding contacts between teeth, which must operate reliably for designed life with reduced friction so that there will be minimum wear. Lubrication of tooth contacts, both as a means of minimizing scuffing and as a means of reducing friction due to sliding, is therefore of crucial importance. The circumferential velocity of high speed gearboxes and oil grades plays major role in thermal efficiency of gearboxes. In gearboxes with oil sumps, churning losses contribute for significant portion of the total power loss. Present empirical approaches for examining the churning losses are often limited to certain constraints and operating conditions. Furthermore, they do not provide any information about the oil distribution in the gearbox. In order to overcome these shortcomings, we investigated a steel mill gearbox failure with analytical tools and simulations with the help of renowned software packages and predicted the thermal behavior of the gearbox as function of oil grade and circumferential velocity, also validated later at application.

1. Introduction
The gear fatigue failures like pitting, tooth breakage will take time to happen, whereas a single overloading of gear can lead to scuffing failure immediately. Scuffing is defined as localized failure caused by solid - phase welding that occurs between surfaces in relative motion. Scuffing most commonly occurs at one of the two extreme end regions of the contact path or near the points of single tooth contact where sliding is maximum. Circumferential velocity between the mating gears determines the contact time between gear teeth. The type of lubrication (splash, fully oil immersed and forced lubrication) depends on the range of operating speed and oil grade selection also vital to have better thermal rating.

Thermal rating of the gearbox (torque /power) is considered as the torque level at which the system establishes the oil temperature at 95 degrees, during the full load test. It depends on several factors like oil parameters, casing surface area exposed to external environment, air velocity, altitude, free space available in the gearbox surrounding, etc.

The scuffing is caused by the high frictional heat generated by high hertizan stress and high sliding velocity. This increased temperature with minimal film thickness at the areas of tooth contact surface along with the higher loads and thin lubrication film leads to welding of surfaces. The following are the factors that influences scuffing.
1. Sliding velocity
2. Lubrication film thickness
3. Load sharing factor
4. Temperature
5. Effective tip relief

1.1. Sliding Velocity

The sliding velocity of gear tooth is defined as a difference between the rolling velocities of gear and pinion in mesh. Pure rolling is present only at the pitch point where the pitch circle intersects the line of action. The amount of sliding increases when the gear tooth contact point moves away from the pitch point. The sliding velocity of a gear mesh can be determined using the following equation:

\[ v_s = v_{Rp} - v_{RG} \]

Where:
- \( v_s \) – Sliding velocity (m/s)
- \( v_{Rp} \) – Rolling velocity at pinion
- \( v_{RG} \) – Rolling velocity at gear
- \( v_T \) – Tangential velocity
- \( \alpha \) – Pressure angle

Figure 1. Tooth Mesh Sliding

In reference to figure 1, the driver connects the mating gear initially near root, and contact rolls up towards tip. In this motion the sliding is happening always from pitch line. In contrast, the initial contact happens near to tip for the driven gear. In driven gear the contact rolls down towards root and sliding is happening towards pitch line. Crack grows opposite direction of sliding and converges at pitch line.

For optimum specific sliding, the value suggested in KISSsoft [1] shows the profile shift for a cylindrical gear pair that has been balanced for a specific sliding between the pinion and the wheel.

Influence of Profile Shift coefficient in Scuffing Safety

Figure 2. Specific Sliding influence on Flash Temperature
1.2. Lubrication film thickness

When the gear mesh occurs, the lubricant between the mesh surface will experience the hertzian pressure which in turn increases the viscosity of the oil. The lubricant with increase in the viscosity behaves as a solid phase, thus increasing the temperature.

When the lubricant thickness reduces asperity contact increases. As shown in the figure 3, there will be no scuffing, when a thick lubricant film separates the gear teeth by minimizing the surface asperities. As lubricant film thickness decreases, asperity contact increases and scuffing becomes more probable.

![Figure 3. Effect of lubricant on scuffing](image)

The poor surface roughness of the gear tooth causes the lubrication film thickness to increase the bulk temperature, thus results in scuffing. The adequate care has been take to have smooth profiles with profile grinding Ra<0.8, and tooth gap with the recommended specifications of DIN 3967.

1.3. Load Sharing Factor

The scuffing usually occurs when a single tooth contact happens to transfer the load at specified speed. The figure 4, shows the gear tooth load sharing factor from Lowest Point of Single Tooth Contact (LPSTC) to Highest Point of Single Tooth Contact (HPSTC). The load sharing factor is highly influenced by Tip relief and profile modifications for high load capacity and smooth contact. The Loaded tooth contact analysis has been computed for optimal combination of profile modification values.

![Figure 4. Load sharing factor Xgam](image)

1.4. Temperature

1.4.1. Flash temperature: The flash temperature is the calculated increase in gear tooth surface temperature at a given point along the line of action resulting from the combined effects of gear tooth geometry, load, friction, velocity and material properties during operation.

1.4.2. Integral temperature: The integral temperature method has been proposed as an alternative to the flash temperature method by which the influence of the gear geometry imposes a critical energy level based on the integrated temperature distribution along the path of contact and adopting a steady gear tooth temperature. The safety factors for scuffing is calculated according to ISO TR 13989 [2,3] and values are compared.
1.5. **Effective Tip Relief**

As the scuffing occurs the most two end region of the gear pair, providing a tip relief at the gear tooth reduces the risk of occurrence of scuffing. The tip relief reduces the entry impact & exit impact of the driven gear and driving gear respectively. Usually, tip relief is applied to both the gear and pinion as specified in the ISO 15144.

2. **Methodology**

The gearbox failed under scuffing at the application has been analyzed for the Macro Geometry [4] parameters and found absolutely OK for pitting and root strength [5] for the rated capacity. However, it has lower service factors on starting torque which is higher than rated capacity and reaches peak while application is preloaded. Further investigation with detailed calculations throws light on the gaps in micro-geometry parameters. Hence the study has been extended with three zones of different tip relief conditions and the respective scuffing safety is analyzed using KISSsoft to choose the best parameters for profile modification.

![Investigated Gearbox Layout](image5)

![Tip Relief -Profile modified](image6)

2.1. **Effect of Tip Relief and oil quantity on Scuffing**

Table 1 represents the scuffing safety factors [6] against integral temperature and flash temperature. Case 1 data has been computed without tip relief in an oil bath system and Case 2 results are obtained with an optimum tip relief value in a gear system where as gears are completely immersed in lubrication oil.

| Profile Modification: (Ca) in microns | Caa=66 | Lubrication Type | Safety Against Scuffing (Integral Temperature) | Safety Against Scuffing (Flash Temperature) |
|--------------------------------------|--------|-----------------|-----------------------------------------------|---------------------------------------------|
| Scuffing temperature                 | $[\theta_S]$ °C | Oil bath Lubrication 296 | Fully immersed in oil 296 |
| Tooth Temperature                    | $[\theta_M]$ °C | 146.2 | 89.5 |
| Maximum Flash Temperature            | $[\theta_{flmax}]$ °C | 136.09 | 134.85 |
| Maximum contact Temperature          | $[\theta_{Bmax}]$ °C | 282.3 | 224.36 |
| Probability of Scuffing              | $[P_{scuff}]$ % | 38 | 5.33 |

| Result : Risk of Scuffing (AGMA 925, Table 5) |
|-----------------------------------------------|--------|--------|
| Safety Against Scuffing (Integral Temperature) | 2.171 | 2.628 |
| Safety Against Scuffing (Flash Temperature)   | 1.817 | 2.275 |

As the tooth temperature decreases in immersed condition with higher tip relief, the chances of scuffing are reduced, thus improving the scuffing safety.
2.2. Effect of Lubrication on scuffing

The gear pair is tested with two types of approved oils - Brand A & Brand B, to check which one has better properties against scuffing safeties using the KISSsoft calculations.

| Table 2. Lubrication oil specifications |
|----------------------------------------|
| **Brand A**                          | **Brand B** |
| Relative Density at 15.6°C            | 0.87        | 0.86       |
| Flash Point                           | °C          | 226        | 240        |
| Pour Point                            | °C          | -36        | -39        |
| Kinematic Viscosity oil at 40°C [μν40]| mm²/s       | 320.8      | 334.4      |
| Kinematic Viscosity oil at 100°C [μν100]| mm²/s      | 34.2       | 37.4       |
| Lower limit service temperature       | °C          | -30        | -30        |
| Upper limit service temperature       | °C          | 95         | 95         |
| Lubricant base – synthetic (Polyalphaolefin – PAO) | PAO | PAO |
| Scuffing test – FZG TEST A/8.3/90;ISO 14635-1 (normal) (stage passed) | 14 | 12 |
| Micropitting test -C-GF/8.3/90 with Ra=0.50 theta = 90deg. (FZG) | 10 | 10 |

Brand A has better in scuffing parameters due to its higher load stage in FZG scuffing test [7]. The table shows the technical specifications of the lubricant oil which are selected for the comparison.

| Table 3. Lubrication oil specifications |
|----------------------------------------|
| **Safety for**                         | **Brand A** | **Brand B** | **% diff** |
| Scuffing (integral temp.)              | 2.628       | 1.903       | 27%        |
| Scuffing (flash temp.)                 | 2.275       | 1.732       | 24%        |

Since the circumferential velocity of the gearbox which is under investigation has not exceeded beyond the recommended limit of 15m/s, there is no influence of circumferential velocity in this gearbox.

2.3. Thermal Efficiency

The previous supply gearbox housing was analysed for thermal rating [8] to determine the power that can be continuously transmitted under the operating temperature without resulting any damage to the internals. The FEA [9] done with ANSYS software and found that the housing bottom portion is subjected to higher temperature than standard practice (85°C) values.

![a) OLD CASING b) NEW CASING](image-url)

**Figure 7.** FEA thermal analysis in ANSYS. a) Old casing vs b) New casing with Ribs

A new gearbox housing was made with additional ribs and fins and FEA shows significant reduction in temperature (73°C) within the same boundary dimensions. The thermal efficiency improved 14% with the new housing.
3. Result and Discussion

1. Providing Optimum Specific sliding of profile shift coefficient gives better scuffing safety on the gears thereby ensuring the reliability of the gears. (figure 2)

2. As the tooth temperature decreases in immersed condition with higher tip relief, the chances of scuffing are reduced, thus improving the scuffing safety. (table 1)

3. If the circumferential velocity increases above 15 m/s care has to be taken to ensure that the gears are well lubricated by either external forced lubrication system or in such a way that the gears are not immersed in oil. The lubrication is done with the help of shaft driven pump. [1]

4. Housings made with more ribs and fins gives significant reduction in oil sump temperature. (figure 7)

5. Lubrication oil parameters and their influence is tabulated below

| Oil Parameter                          | Scuffing Safety factor for Integral | Scuffing Safety factor for Flash |
|----------------------------------------|-------------------------------------|----------------------------------|
| Density of oil - increased             | increased                           | increased                        |
| Upper limit of kinematic viscosity - increased | increased                           | increased                        |
| Lower limit of kinematic viscosity - increased | increased                           | increased                        |
| Load stage scuffing -increased        | increased                           | increased                        |
| Load stage micro pitting -increased   | no change                           | no change                        |

It is observed from the above table that when kinematic viscosity of the oil is increased, it has better scuffing safety. So oil grade ISO VG-320 has better scuffing safety than ISO VG-220 and so on.

6. The higher the stage passed in FZG scuffing test A/8.3/90, ISO 14635-1, will have better scuffing rating. (table 3)

4. Conclusion

With calculations we conclude that gearboxes with pitch line velocities closer or higher than 15 m/s are to be provided with forced lubrication system with suitable oil viscosity grades (low viscosity oil for light load) based on lubrication film thickness calculations. While gears are loaded higher torque with low pitch line velocities, we have to use high viscous oils to negotiate high loads and long contact times. It is also realised that the higher kinematic viscosity oil has better scuffing safety. While gearbox housing designed with higher number of ribs exposed to external atmosphere, the sump oil temperature gets reduced and thermal rating increased. This research has ample scope for validating all the results with FEA tools later compared with Highly Accelerated Load Tests (HALT).

References
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