Understanding of TIFF and TFF is required at the design stage of transmission systems

Evaluation of TIFF and TFF Load Carrying Capacities and Comparison Against Other Failure Modes

This paper consolidates validation of methodology and comparison of load carrying capacity to allowable loading conditions for bending and pitting fatigue failures.

- Baydu Al, Analyst/Software Engineer, Smart Manufacturing Technology
- Dr Paul Langlois, CAE Products Development Department Manager, Smart Manufacturing Technology

Examples from the open literature have been used to compare results with those obtained by a proposed methodology, as implemented in SMT's MASTA software, for analysis of TIFF and TFF in which loaded tooth contact analysis (LTCA) results have been utilized to determine load boundary conditions at a selected number of points in the gear tooth load cycle. The method is then used to extend existing understanding of TIFF and TFF load capacity and compare to the allowable loading conditions for bending and pitting fatigue failure based on the standard calculation procedures. Possible methods that could be used to mitigate TIFF risk are presented and the effect of these methods on the performance with respect to the other failure modes are quantified.

Overview of Failure Mode

Gears are case hardened to produce compressive residual stresses at and close to the surface, improving wear resistance, bending fatigue, and contact fatigue strength. These beneficial compressive stresses are balanced by tensile stresses within the core. This poses an increased risk of fatigue crack growth below the surface. Both Tooth Interior Fatigue Fracture (TIFF) and Tooth Flank Fracture (TFF, also known as Tooth Flank Breakage (TFB)) describe a failure mode where a subsurface fatigue crack initiates close to the case core boundary, at approximately mid-height of the tooth.

Previous research [1–8] has established that the direction in which the crack propagates and the appearance of the associated fracture is dependent on the flank loading (i.e. single stage loading versus idler usage). Although there does not appear to be total agreement in the literature, TIFF (failure with reverse loading) and TFF (failure with single flank loading) appear to have very similar characteristics and crack initiation mechanisms. However, as shown in Figure 1, the final fracture shape and distribution of total stresses are different, due to TIFF having near-symmetric total stresses along the tooth centreline (with two possible initiation points per tooth). The location of the crack initiation distinguishes this failure mode from other fatigue failure modes, where the crack initiates at or close to the surface.

TIFF and TFF failures can appear at loads below the allowable loading conditions for pitting and bending fatigue failure based on the interna-

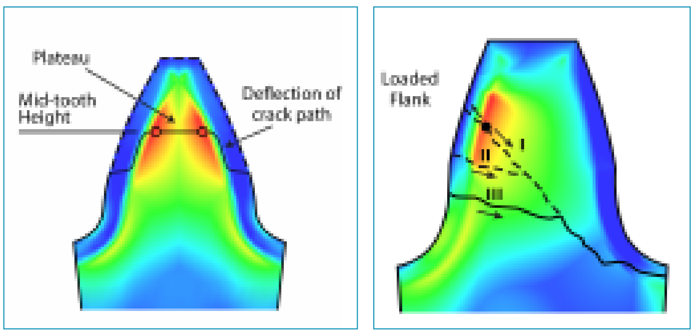

Figure 1 Expected crack propagation paths and intensity of total stresses for TIFF (left, adapted from [1]) and TFF (right, adapted from [4]).

	Author's method	Author's method with Lang [16] for residual stresses
Stress History	Calculated using 2D FE analysis where MASTA's LTCA model [15] has been utilized to obtain the load boundary conditions for the contact.	
Residual Stress State	Calculated using 2D FE with volume expansion specified as in MackAldener.	According to Lang [16] and used by Witzig [8]. Tensile stresses in the core are assumed negligible.
Equivalent Stresses	Calculated using Findley critical plane criterion. Fatigue sensitivity to normal stress assumed to vary continuously in the same manner as the hardness profile. As in MackAldener.	
Initiation Threshold	Calculated by dividing the maximum Findley plane stress by the permissible stress at a given point. Critical plane stress is assumed to vary continuously in the same manner as the hardness profile. As in MackAldener.	

Table 1 Summary of the author's calculation method

tionally accepted calculation procedures (such as ISO 6336 [9] and AGMA 2101-D04 [11]). Therefore, understanding of TIFF and TFF failure modes is required at the design stage to avoid durability issues in the field.

As of the time of writing, there is no accepted standardised method to assess the probability of this type of failure and the relative importance of the influencing factors. It is, however, worth noting that TFF is an active topic within the ISO gearing committee, which is currently working on a draft standard, ISO/DTR 19042, for the calculation of Tooth Flank Fracture performance.

Methodology

A review of existing calculation methods can be found in Al et al. [12]. The methodology used throughout the rest of this paper, and implemented in MASTA, is derived from MackAldener's finite element method and has been described in detail in our previous work [12-14]. Table 1 provides a brief summary of the methodology.

Validation Against TIFF Open Literature [2]

A parametric study initially conducted by MackAldener [2] to investigate which parameters influence the risk of TIFF has been repeated to validate the author's methodology, presented in [12, 13]. This study considered varying critical plane stress within the core (A), fatigue sensitivity to normal stress within the core (B), gear tooth geometry (C), total case depth (D), and torque on the pinion (E). The change in gear design in C is reflected mostly in the "slenderness ratio", defined as the ratio between the height of the involute and the tooth thickness (C- lower ratio, C+ higher slenderness ratio). For each of the designs, the Crack Initiation Risk Factor (CIRF) throughout the tooth was calculated. Al et al. [12] further investigated the effect of using Lang [16] to specify residual stresses, where residual tensile stresses within the core are not considered.

Figure 2 shows a comparison of the calculated maximum CIRF for all 32 designs. From **Figure 2**, it is clear that there is a good overall correlation between CIRF calculated by the author's method and that calculated by MackAldener [2].

Figure 3 displays the average CIRF results for each factor at its low and high level together with the average for some interactions. It can be seen that good agreement exists for factors A, B, D, and E, and reasonable agreement for factor C.

Details regarding these comparisons are discussed in [12]. One interesting observation here comes when examining the cases where the author's method is used with Lang [16] for residual stresses. In these calculations tensile stresses within the core are assumed negligible. As can clearly be seen from **Figure 2**, this approach underestimates the maximum CIRF in all designs investigated. Furthermore, using Lang [16] for residual stresses changes the relationships and some interactions expected from the factors (Figure 3). This change can be attributed to differences in the hardness profiles and/or neglected tensile residual stresses within the core.

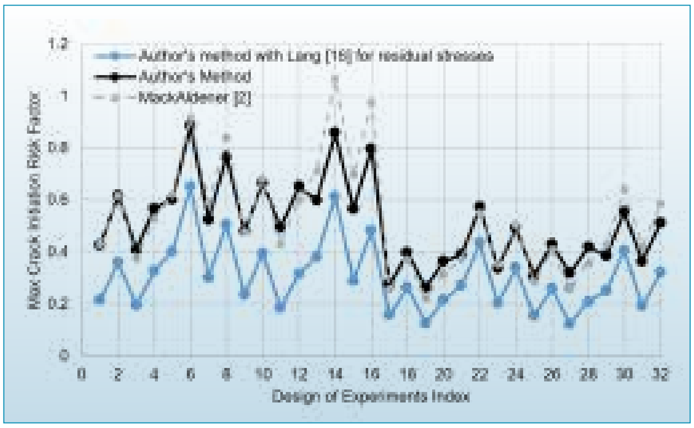

Figure 2 Comparison of the calculated Maximum CIRF's using the author's method, author's method with Lang [16] for residual stresses, and MackAldener's finite element calculations. Index values have been determined by first sorting according to factor (A through E) then sorting the values of each factor in ascending order. As shown in Al et al. [12]

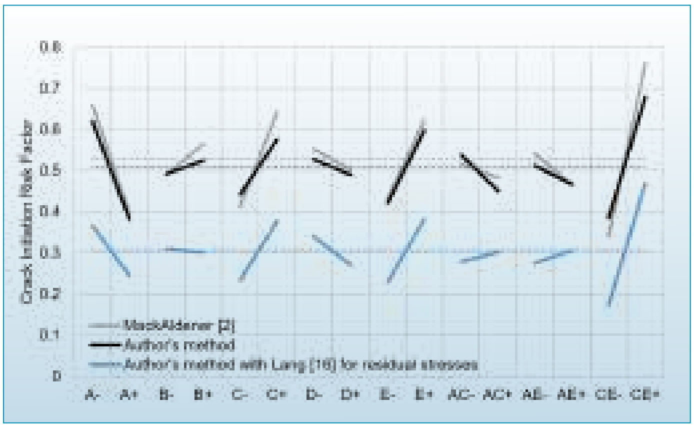

Figure 3 Comparison of the effects of individual factors and their interactions on CIRF response for author's method, author's method with Lang [16] for residual stresses, and MackAldener's FE calculations. The dotted lines represent the mean response from each method. As shown in Al et al. [12]

Effect of Factors on Pitting and Bending Safety Factors

Factor (C) gear design and Factor (E) torque on the pinion are two parameters investigated in the factorial design which would have a direct effect on pitting and bending fatigue calculations according to ISO 6336 [9]. It has been assumed all gears have a flank tolerance class of 5 according to ISO 1328-1 [10] and material quality grade of ME. It should be noted that the other parameters in the study could also potentially have an effect on the pitting and bending safety factors, however they are not directly reflected in the inputs of ISO 6336 which for the material properties has assumptions based on the ISO material type selected.

Figure 4 shows how crack initiation risk factor, bending safety factor, and pitting safety factor vary with the change in the common factors which affect all three calculations. It should be noted that resistance to all three failure types can be improved by reducing the torque. For the cases investigated, slender toothed gears show an improved safety against bending, however reduced safety for TIFF and pitting. As can be seen from Figure 4, both CIRF^{-1} and gear bending fatigue are more sensitive to both geometry and loading compared to pitting.

Validation Against TFF Open Literature [8]

Witzig [8] has run numerous experiments with test gears and validated their calculation model, suggesting a critical threshold of 1.2 for safety factor dependent on material exposure and calibration coefficient. These gear sets were designed to fail due to Tooth Flank Fracture and results were reproducible. It is important to note that failure analysis of these gear sets showed that, in the majority of cases, initial crack initiation occurred at an inclusion near the case-core boundary. However, the size and the effect of these inclusions are not included within the analysis (i.e. material is considered homogeneous).

Figure 5 summarizes the results from Witzig [8] for spur gear set 67/69 spur gear set. It should be noted that the y-axis on the right, for the TFF safety factor, is shifted to give comparable results (i.e. the critical value for the CIRF^{-1} is expected to be 1 while for Witzig TFF safety factor this critical value is 1.2).

Given the assumptions made, including the assumption that a critical CIRF^{-1} of 1 can be compared with a Witzig's TFF safety factor of 1.2,

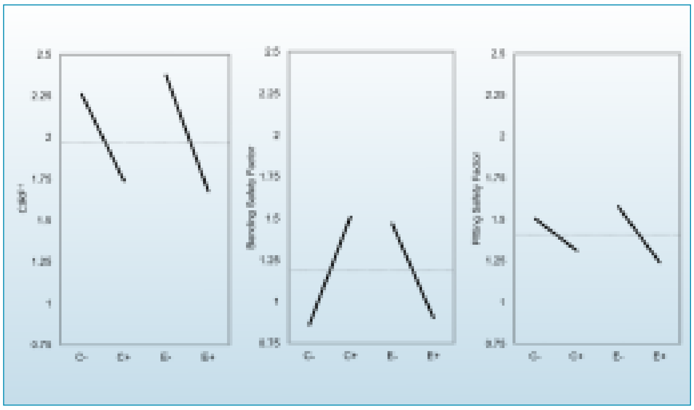

Figure 4 Comparison of geometry and load effects on CIRF, Bending Safety Factor, and Pitting Safety Factor. As shown in Al et al. [12]

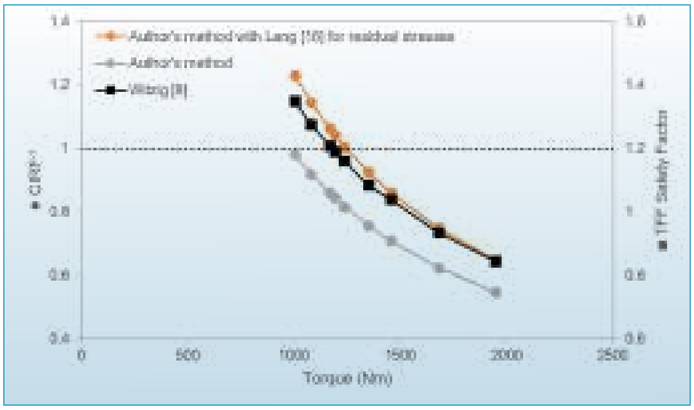

Figure 5 Comparison of calculated CIRF^{-1} and Witzig's method for 67/69 Spur Gear. It should be noted that y-axis of the TFF safety factor is shifted to give comparable results (i.e. threshold value for CIRF^{-1} is expected to be 1 and for TFF safety factor is 1.2 [8]). Adapted from Al, et al. [14]

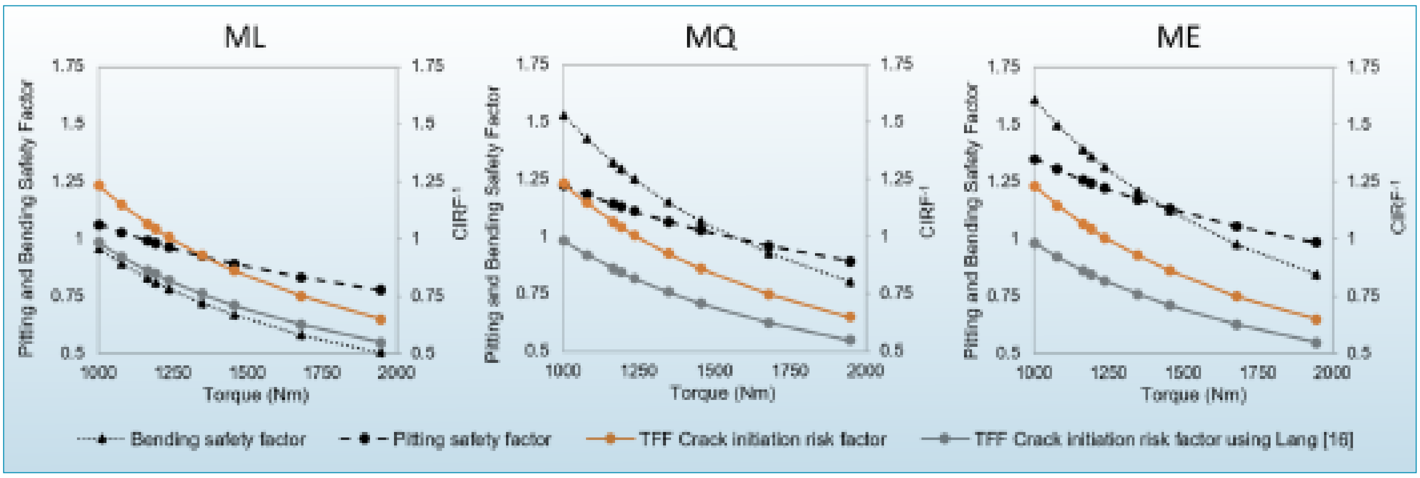

Figure 6 Comparison of TFF load capacity with safety factors for bending and pitting fatigue failures based on ISO 6336 [9], for 67/69 spur gear with different material qualities, from left to right ML, MQ, ME. As shown in Al et al. [12].

the results obtained show similar qualitative behaviour but some significant difference in the torque which leads to the critical metric values ($CIRF^{-1}$ or TFF Safety Factor) for different designs. Further investigation is required to understand whether this difference is down to the assumptions made in our inputs or a more fundamental difference in the formalism of the methods. The results in Figure 5 for the author's method with and without the use of Lang for residual stresses give some indication that differences relate to the inclusion or not of residual tensile stresses in the core.

Comparison of Load Carrying Capacity with Other Failure Mode

Calculated $CIRF^{-1}$ using the author's method with both residual stress calculation methods are extracted from Figure 5 and plotted together with pitting and bending fatigue safety factors in Figure 6. The figure shows results for the three different ISO 6336 material quality classes. As can be seen in Figure 6, according to the calculations the torque range over which TFF failure could occur changes, in comparison to pitting and bending failure. However, it should be noted that TIFF and TFF calculations, at present, do not take material quality into account. This is a significant shortcoming of the current procedures given the indications in the field that TIFF failures are often associated with crack initiation at material inclusions. Utilizing MackAldener's approach, this parameter could be included within the critical fatigue strength.

Conclusions

This paper aimed to consolidate the existing understanding of TIFF and TFF load capacity and its comparison to allowable loading conditions for bending and pitting fatigue based on standard calculation procedures.

The key conclusions from this study are:

- It is possible to replace a computationally expensive explicitly modelled FE-based contact analysis e.g.[2] with simple load boundary conditions obtained by a separate specialized gear Loaded Tooth Contact Analysis (LTCA), in order to apply MackAldener's methodology for the analysis of TIFF.
- It is possible to analyse the risk of TFF by applying a methodology based on MackAldener. However, as is to be expected, thresholds obtained from Witzig's method and Findley are different. The critical value has been found to be close to 1, but requires further investigation.
- The calculated CIRF is higher when tensile residual stresses are considered within the core compared to Lang. It has been found that for the cases investigated the effect of residual stresses increases with torque. It should be also noted that neglecting tensile stresses within the core modifies the expected relationships between factors resulting from the factorial design.
- The torque range across which TFF failure can be seen could be relatively small compared to the operating range.

Further understanding of residual tensile stresses within the core of a gear loaded on a single flank is required to determine the suitability of Lang[16] to these applications.

It is the author's opinion that the critical effect of material quality and inclusions is the key factor missing in the type of analyses presented. We would expect that this could be addressed as a factor applied to e.g. the material thresholds (utilizing MackAldener's approach, this parameter could be included within the critical fatigue strength), however significant field experience and further experimental studies are required to address this point.

More Information

The contents of this paper are consolidated from papers presented at British Gears Association (BGA) Gears 2015, Car Training Institute (CTI) Symposium USA 2016 and American Gear Manufacturers Association (AGMA) Fall Technical Meeting 2016.
For more information, see www.smartmt.com/Downloads/

References

[1] MackAldener, M. and Olsson, M. (2000) Interior Fatigue Fracture of Gear Teeth, Fatigue & Fracture of Engineering Materials & Structures, 23 (4), pp. 283–292.
[2] MackAldener, M. and Olsson, M. (2000) Design Against Tooth Interior Fatigue Fracture, Gear Technology, Nov/Dec 2000, pp.18–24.
[3] MackAldener, M. and Olsson, M. (2001) Tooth Interior Fatigue Fracture, International Journal of Fatigue, 23, pp. 329–340.
[4] Bauer, E. and Bohl, A. (2011) Flank Breakage on Gears for Energy Systems, VDI International Conference on Gears, October 2010. Also Gear Technology. November/December 2011.
[5] Ghribi, D. and Octrue, M. (2014) Some theoretical and simulation results on the study of the tooth flank breakage in cylindrical gears, International Gear Conference, Lyon, France, 26–28 August 2014.
[6] Tobie, T.; Höhn, B. R. and Stahl, K. (2013) Tooth Flank Breakage – Influences on Subsurface Initiated Fatigue Failures of Case Hardened Gears. Proceedings of the ASME 2013 Power Transmission and Gearing Conference, Portland, OR, 4–7 August 2014.
[7] Boiadjiev, I.; Witzig, J.; Tobie, T. and Stahl, K. (2014) Tooth flank fracture – basic principles and calculation model for a sub-surface initiated fatigue mode of case hardened gears, International Gear Conference, Lyon, France 26–28 August 2014. Also Gear Technology. August 2015.
[8] Witzig, J. (2012) Flankenbruch Eine Grenze der Zahnradtragfähigkeit in der Werkstofftiefe. PhD Thesis, Technical University of Munich.
[9] BS ISO 6336-1: 2006 Calculation of load capacity of spur and helical gears – Part 1: Basic Principles, Introduction and General Influence Factors.
[10] BS ISO 1328-1:2013 Cylindrical gears – ISO system of flank tolerance classification – Part 1: Definitions and allowable values of deviations relevent to flanks of gear teeth.
[11] ANSI/AGMA 2101-D04 (2004), Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth.
[12] Al, B. Patel, R. and Langlois, P. (2016) Comparison of Tooth Interior Fatigue Fracture Load Capacity to Standardized Gear Failure Modes. AGMA Fall Technical Meeting, Pittsburgh, PA, 2-4 October 2016.
[13] Al, B. and Langlois, P. (2015) Analysis of Tooth Interior Fatigue Fracture Using Boundary Conditions form an Efficient and Accurate Loaded Tooth Contact Analysis, British Gears Association (BGA) Gears 2015 Technical Awareness Seminar, 12th of November 2015, Nottingham, UK. Also Gear Solutions February 2016.
[14] Al, B., Patel, R. and Langlois, P. (2016) Finite Element Analysis of Tooth Flank Fracture Using Boundary Conditions From LTCA. CTI Symposium USA, Novi, MI, 11–12 May 2016. Also Gear Technology September/October 2016.
[15] Langlois, P., Al, B., Harris, O. (2016) Hybrid Hertzian and FE-Based Helical Gear-Lonaded Tooth Contact Analysis and Comparison with FE, Gear Technology, July 2016, pp. 54–63.
[16] Lang, O. R. (1979) The dimensioning of complex steel members in the range of endurance strength and fatigue life, Zeitschrift fuer Werkstofftechnik, Vol. 10, p.24–29.