

INFLUENCE OF DIFFERENT GEAR FLANK DEVIATION TOLERANCE CLASSES ON THE CONTACT PATTERN

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Abstract. *The mobility electrification advent, mainly driven by the regulations for the reduction of greenhouse gases emission, has directly affected the vehicle systems' new design requirements, especially for the powertrain components. The current literature already cites that among the critical fields affecting the functional performance of future powertrain components is their geometrical accuracy. In the case of gears, the necessity of tighter manufacturing tolerances is related to the much higher rotational speeds involved in the electric motor operation than the internal combustion engine, besides being simultaneously quieter, torque-efficient, and operating with higher power densities. Although the gear flank tolerance classification system establishes the limits of tolerable gear pitch, profile, and helix deviations, there is no treatment in this system regarding how different deviation factors can differently influence the dynamic behavior of gears. Therefore, when gear standards suggest that high-speed gears require improved tolerance classes, all deviation factors are considered a group. In the case of mobility industries like the automotive, where high productivity rates and cost-reduction policies are crucial, tightening tolerance classes represent a challenge. In this context, the objective of the present study was the assessment of the influence of different gear deviation factors in tooth contact patterns to identify possible different effects among them. So, tooth contact analyses were performed by computational simulations for an ITA Geometry gear sample. The influence of gear manufacturing profile and helix slope deviation parameters of different gear tolerance classes in the flank contact pattern was investigated. The results have demonstrated that a tolerance class modification in helix slope deviation has a higher impact on the maximum Hertzian contact pressure than a class modification in profile slope deviation. When gear pair assembly deviations are also considered, the distinct influences are intensified. By identifying the most influential deviation parameters, it is intended to emphasize that the gear manufacturing sector does not have to tighten all tolerances to guarantee an adequate e-mobility gear operation. Concentrating the efforts only on the most impacting parameters may allow a good trade-off between operation behavior and manufacturing costs.*

Keywords: *gears; manufacturing deviations; contact stress; electric mobility*

1. INTRODUCTION

The mobility sector is facing a transformation, primer influenced by incorporating the so-called "green technologies" as one of the aspects of the ESG Agenda (ISS ESG, 2020). The new regulations for the reduction of greenhouse gases emission have evidenced electric and hybrid vehicles as some of the candidates to replace internal combustion-powered ones. This tendency of mobility electrification is highly noticeable when looking at the recent European Union (EU) approved bans on the sale of new combustion vehicles after 2035. It is expected that over 55% of all new cars will already be fully electrified by 2030 in the EU, while 40% of new vehicles will include hybrid drive technologies combined with combustion engines (PWC, 2017).

Among all the vehicle systems impacted by the electrification advent, the powertrain is undoubtedly one of those with the most significant trade-offs to be solved, particularly in the case of gears. While internal combustion engines commonly operate at speeds up to 8,000 rpm, the electric motor speeds can easily overcome 15,000 rpm, potentially increasing to 30,000 rpm up to the next decade (Reichert *et al.*, 2016; Mileti *et al.*, 2018; Stadtfeld, 2020). Although there are no standards directly addressing the impact of e-mobility on gear design, an AGMA (2014a) specification for high-speed helical gears has some suggestions about the impacts of the high speeds on gear quality requirements.

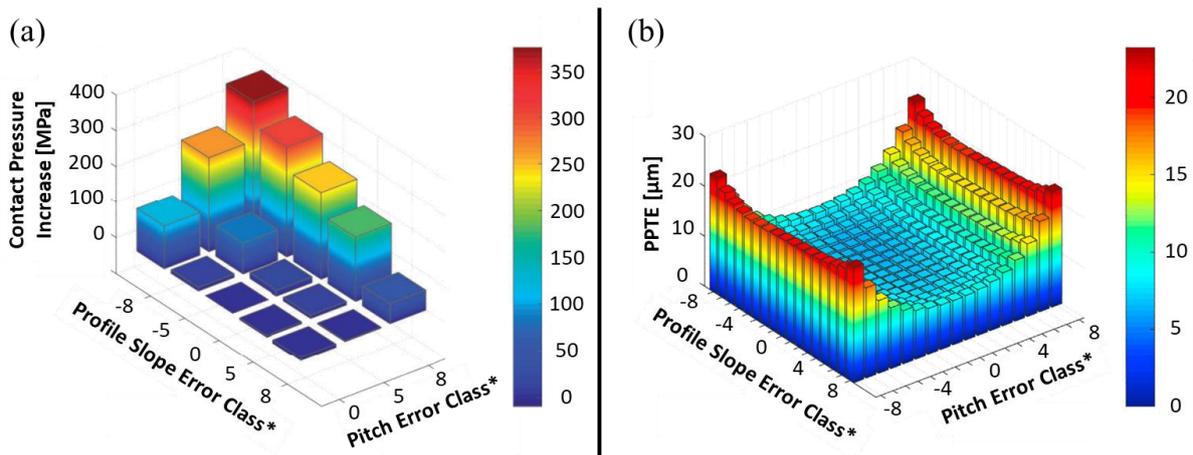
DIN 3962-1 (1978) and AGMA (2014b) standardize the magnitude of the gear deviations between designers and manufacturers with a system of accuracy. The system has 11 accuracy grades, from 1 to 11, of which grade 1 is the highest

degree of accuracy and grade 11 is the lowest, so the lower the class number, the tighter the limits of tolerable gear pitch, profile, and helix deviations. As seen in Tab.1, AGMA 6011-J14 (2014) establishes flank class 5 as the minimum acceptable for high-speed helical gears. As the current automotive sector hardly works with flank classes better than 7 (sometimes 6, in the case of ground gears), the tighter manufacturing tolerances required for high-speed applications such as e-mobility represents an increase in manufacturing costs and times (Dizdar *et al.*, 2003).

Table 1. Suggested flank tolerance classes for high-speed helical gears (AGMA, 2014a).

Pitch Line Velocity [m/s]	Flank Tolerance Class
35 – 100	5
100 – 150	4
Over 150	3

High control of the gear flank tolerance classes becomes essential for the electric mobility case since they impact other demands of this application. Hjelm *et al.* (2021a) studied the influence of manufacturing error tolerances on gear contact pressure, focusing on the pitch and profile slope errors of ISO 1328 (1995) tolerance classes 5-8, typically used in the automotive industry. By simulating the gear meshing and calculating the contact pressure, their results, evidenced in Fig. 1a, showed that the error class is important and whether the error signal is positive or negative. As the higher torque levels and the reduced number of gears involved in the operation of electric vehicles lead to a higher power density necessity, which directly influences the gears' fatigue life, the actuating contact pressures assessment in the design phase requires even more attention (AGMA, 2021).



*Negative class indicates opposite error direction, and class 0 is the nominal gear condition (with no manufacturing errors).

Figure 1. Effect of gear profile slope error and pitch error class in (a) maximum contact pressure increase relative to the nominal condition and (b) peak-to-peak transmission error (Hjelm *et al.*, 2021a; Hjelm *et al.*, 2021b)

Hjelm *et al.* (2021b) expanded the investigation of Hjelm *et al.* (2021a), finding links between static transmission error, contact pressure, and manufacturing error tolerances of gears, as shown in Fig. 1b. Due to the elimination of the internal combustion engine, which is the primary Noise, Vibration, and Harshness (NVH) source in vehicles, the transmission noise is unmasked and becomes more easily perceived in electric vehicles, being amplified by the higher rotational speeds (AGMA, 2021). As the peak-to-peak transmission error (PPTE) is closely related to NVH generation in gearing, the tighter control of the tooth distortions during manufacturing can also contribute to transmission noise reduction.

The referred flank tolerance classification system establishes ranges of tolerable gear pitch, profile, and helix manufacturing deviations for each class number. There is no straightforward treatment regarding how different deviation factors can differently influence the dynamic behavior of gears. If the AGMA 6011-J14 (2014) suggestion for the tolerance classes of high-speed gears is rigidly met, all deviation factors tolerances are considered a single group and have to go through tight tolerance control. However, in case the deviation types have distinct levels of influence in the efforts involved during gearing, a manufacturing process focused on meeting the tightened tolerance range only for the most influential factors can prevent unnecessary cost increases. Therefore, there is an urgent need to rethink not only the gear design stage but also the manufacturing aspects of the transmission systems themselves.

Given all the above mentioned, the objective of the present study was the assessment of the influence of different gear deviation factors in tooth contact patterns to identify possible different effects among them. Based on this understanding, the concept of design for manufacturing is discussed for the e-mobility gears case.

2. METHODOLOGY

2.1 Gear geometry selection

Given the strong motivation related to the automotive industry challenges, the gear geometry used for the investigations of the manufacturing deviations impacts in gearing contact pressures was selected to adequately represents this sector. In that way, the *ITA Geometry* was chosen, as its design considers the automotive gears application of both vehicles with internal combustion engines and accompanies the electric vehicle trends in increasing loading conditions.

For the development of the cited geometry, Carvalho (2020) mapped the loading operation conditions of the current Brazilian automotive scenario, considering values for maximum power and maximum torque representative of almost 70% percent of all vehicles sold in 2018 (FENABRAVE, 2019). With this procedure, *ITA Geometry's* nominal power and torque were defined as 110 hp and 240 N.m, respectively (Carvalho *et al.*, 2021). Its main macrogeometry and microgeometry parameters are presented in Tab. 2 for pinion and gear.

Table 2. *ITA Geometry's* main parameters (Carvalho, 2020).

	Normal module [mm]	Number of teeth	Normal pressure angle [°]	Helix angle [°]	Reference diameter [mm]	Face width [mm]	Tip relief [μm]	Lead crowning [μm]	Profile crowning [μm]
Pinion	2.85	21	17.5	0	59.85	24	25	6	15
Gear	2.85	28	17.5	0	79.80	27	25	6	15

2.2 Flank tolerance classes selection

Two classes were selected to evaluate the effects of a flank tolerance class variation of distinct gear tooth manufacturing deviations in the flank contact loads. Based on the current automotive sector's regular classes, the first class to be considered was 7. The second class was chosen to represent the e-mobility demands for tighter tolerance control in gears. For a rotational speed of 15,000 rpm, among the operating range for electric motors applications, the pitch line velocity for the *ITA Geometry* is approximately 47 m/s. Accordingly to AGMA 6011-J14 (2014), the recommended flank tolerance class is 5. So, the ISO 1328-1 (1995) flank classes 7 and 5 were defined for the analysis.

Among the various gear flank deviation factors, profile (f_{Ha}) and helix slope deviation ($f_{H\beta}$) parameters were chosen to represent, respectively, the involute profile direction and the tooth width direction along the gear flank. By comparing their impact in the contact loads due to a tolerance class variation, it is possible to induce the direction with higher impacts in the stresses involved in tooth contact.

Profile deviations are related to the amount by which an actual profile deviates from the designed one, assessed along with the profile evaluation range (L_a). This range corresponds to the one where the specified accuracy grade is applied. A mean profile of a measured flank, obtained by the least-squares method, aids the evaluation of the deviations in the profile direction (ISO, 1995). The profile slope deviation (f_{Ha}) represents the difference between the actual and the designed pressure angle difference. It is verified as the distance between the mean profile and the theoretical involute within L_a , as represented in Fig. 2.

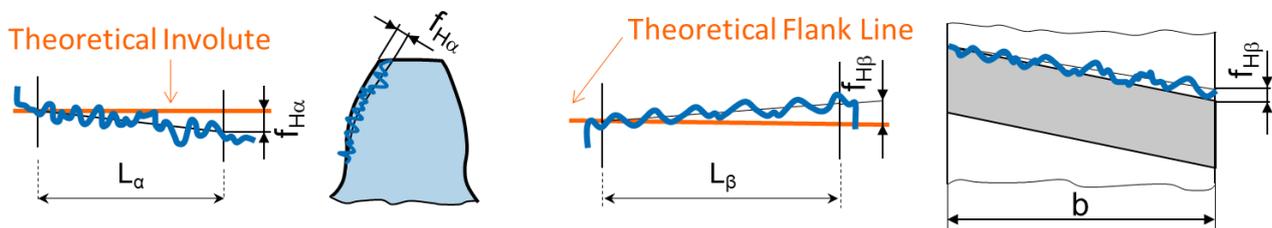


Figure 2. Definition of the profile slope (f_{Ha}) and helix slope manufacturing deviations ($f_{H\beta}$) in gears (Klocke and Brecher, 2017)

Helix deviations correspond to the amount by which an actual helix deviates from the designed helix, assessed along with the helix evaluation range (L_β). This range is determined by the length of the trace (face width of the gear, excluding the tooth end chamfers or roundings) shortened at each end by the smaller of two values: 5% of the face width (b) or the length equal to one module (ISO, 1995). A mean helix of a measured flank, also obtained by the least-squares method, is used to evaluate the distortions in the helix (ISO, 1995). As shown in Fig. 1, the helix slope deviation ($f_{H\beta}$) represents the actual and designed helix angle difference. It is evaluated as the distance between the mean helix and the theoretical flank line within L_β .

The tolerance limits defined by the AGMA (2014b) standard for $f_{H\alpha}$ and $f_{H\beta}$ according to the flank class are calculated, in micrometers, by Equation (1) and Equation (2) as follows.

$$f_{H\alpha} = (0.4m_n + 0.001d + 4)(\sqrt{2})^{A-5} \quad (1)$$

$$f_{H\beta} = (0.05\sqrt{d} + 0.35\sqrt{b} + 4)(\sqrt{2})^{A-5} \quad (2)$$

In the above expressions, m_n represents the normal module of the gear in millimeters, d is the reference diameter in millimeters, b is the gear face width in millimeters, and A is the flank tolerance class number. Rounded rules for these parameters defined by AGMA (2014b) state that:

- If the value is greater than 10 μm , the round must be to the nearest integer micrometer;
- If the value is 5.0 μm or greater but less than or equal to 10 μm , the round must be to the nearest 0.5 μm ;
- If the value is less than 5.0 μm , the round must be to the nearest 0.1 μm .

Besides comparing the $f_{H\alpha}$ and $f_{H\beta}$ class alteration impacts in the contact between teeth, additional analysis of the flank contact stress patterns was done by adding assembly deviations of the geared pair. Both in-plane deviations ($f_{\Sigma\delta}$) and out-of-plane deviations ($f_{\Sigma\beta}$), schematized in Fig. 3, were considered to identify possible combined effects with the flank deviations on the actuating stress heterogeneities along the gear flank.

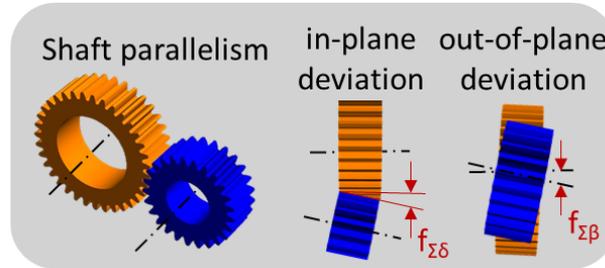


Figure 3. Types of assembling deviations of a geared pair.

2.3 Tooth contact analysis

The assessment of the impacts of varying the flank class number for the selected manufacturing deviation types was performed by evaluating the *Hertzian* pressures and the flank contact patterns resulting from each condition. For this, tooth contact analysis of the *ITA Geometry* pair was done on the *KISSsoft* software. This software gathers several standards in a unique interface and allows the execution of numerous computational simulations involving various factors combinations, being commonly used for machine elements design.

The simulations were done for the *ITA Geometry* pinion and gear contact without the presence of the microgeometry to account for the isolated effects of the $f_{H\alpha}$ and $f_{H\beta}$ class variation. Thereafter, additional simulations of flank contact patterns were done by adding in-plane deviations ($f_{\Sigma\delta}$) and out-of-plane deviations ($f_{\Sigma\beta}$). In all simulations, the torque level considered was *ITA Geometry*'s nominal value of 240 N.m at a rotational speed of 15,000 rpm.

3. RESULTS AND DISCUSSIONS

Through Eq. (1) and Eq. (2), the tolerance ranges for $f_{H\alpha}$ and $f_{H\beta}$ for classes 7 and 5 were calculated for each gear. For class 7, the determined ranges were, respectively, $\pm 10 \mu\text{m}$ and $\pm 12 \mu\text{m}$ for the pinion's $f_{H\alpha}$ and $f_{H\beta}$, and, $\pm 10 \mu\text{m}$ and $\pm 13 \mu\text{m}$ for the gear's $f_{H\alpha}$ and $f_{H\beta}$. In turn, the class 5 range for $f_{H\alpha}$ and $f_{H\beta}$ were calculated, respectively, as $\pm 5 \mu\text{m}$ and $\pm 6 \mu\text{m}$ for the pinion, and as $\pm 5 \mu\text{m}$ and $\pm 6.5 \mu\text{m}$ for the gear.

Figure 4 shows the results obtained by the tooth contact computational simulations varying the flank tolerance class of the manufacturing deviations, where index 1 is related to the pinion and index 2 to the gear. The map evidences the impact of a combination of values of $f_{H\alpha}$ and $f_{H\beta}$ in the maximum *Hertzian* contact pressure of the gears. The global axes are related to the pinion deviations, while the 25 internal squares constituting the global map are related to the gear deviations. By analyzing the profile and helix slope class variation effects, it can be seen that, for both *ITA Geometry*'s pinion and gear, the latter deviation parameter has higher effects on the contact pressure than the further. It is concluded that a flank tolerance class variation from 7 to 5 in $f_{H\beta}$ produces more significative effects in the *ITA Geometry* operating contact stresses than the same variation in $f_{H\alpha}$.

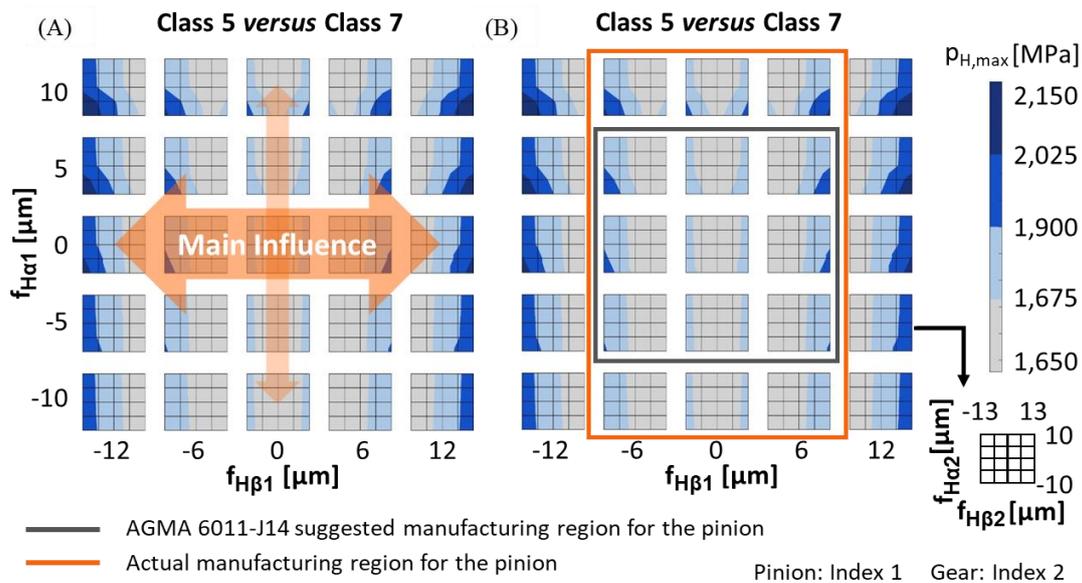


Figure 4. Effects of class variation of profile and helix slope deviations in the maximum *Hertzian* contact pressure of the *ITA Geometry*. (A) Main influence due to $f_{H\beta}$. (B) Actual and AGMA (2014a) suggested manufacturing working regions for deviations of the pinion.

The region delimited in grey in Fig. 4b indicates the AGMA (2014a) flank tolerance class 5 recommendation for the pinion at a rotational speed of 15,000 rpm. However, a close look at the map allows the constataion that there are other combinations of parameters outside the class 5 limits that has similar maximum *Hertzian* pressures. Once $f_{H\alpha}$ and $f_{H\beta}$ do not have the same effect on the gear contact pressures, the manufacturer's working region can be expanded to the area delimited in orange, less tight than suggested by AGMA (2014a). So, the results evidence that manufacturing might not necessarily need to meet the flank tolerance class recommendation for all factors to meet an adequate operating region.

These findings regarding the inequality effects of the deviation parameters are similar to that observed in the literature. The results of Hjelm *et al.* (2021a) and Hjelm *et al.* (2021b), summarized in Fig. 1, evidenced that a gear flank class variation of profile slope error and pitch error do not have the same impacts. Although this constataion was not presented in their studies, an analysis of their results in Fig. 1 allows the conclusion that, for the FZG C spur gear geometry, a class variation of pitch error has a higher influence in the maximum gear contact pressure and PPTE than profile slope. As contact pressure and peak-to-peak transmission error are related, respectively, to power density and NVH generation, two of the electromobility concerns for gears, knowing the flank deviations that mainly influence them is an important step in a design for e-mobility.

Although the analysis of tolerance class variation impacts on the intensity of the tooth contact pressures allowed important conclusions, it has to be complemented by an assessment of how these actuating stress are distributed along the entire tooth flank. Stress heterogeneities along the flank may indicate susceptible regions to failure initiation. To evaluate how profile and helix slope deviations influence the stress distribution in the flank, three combinations of deviation values were chosen among those presented in Fig. 4. For all of them, $f_{H\alpha 1}$ and $f_{H\beta 1}$ were fixed, respectively, in 10 μm and -12 μm . Then, three cases were selected as different combinations of $f_{H\alpha 2}$ and $f_{H\beta 2}$, as shown in Fig. 5. The chosen values for the pinion aimed to get a region of the map on Fig. 4 with elevated stress variations to highlight the influence of profile and helix slope deviations.

By analyzing the contact pattern distribution in the gear flank for the three selected cases, the greater influence of $f_{H\beta}$ variation is again observed. When assembly deviations are considered in the tooth contact analysis, the inequality effects of the gear deviations are highlighted. It is expected that the deviations in terms of shaft parallelism and/or deflection naturally lead to a heterogeneous distribution of the contact stress along the flank width direction. In these cases, as evidenced in Fig. 4, the loads are highly concentrated in one of the flank extremities. As $f_{H\beta}$ also actuates in the flank line direction, this explains its higher impact on the stress distribution compared to $f_{H\alpha}$. Since the points along the teeth height profile are successively brought into contact during gearing action, an alteration in $f_{H\alpha}$ should not significantly alter the pattern of flank and stress concentration generated by assembly deviations.

All the results lead to the constataion that there are manufacturing deviation types more influential in the gear tooth contact loads. By understanding its individual effects it is possible to rethink the gear tooth tolerance design and the manufacturing process to, together, solve the trade-offs brought by the electric mobility application in terms of the necessity of gears with higher qualities.

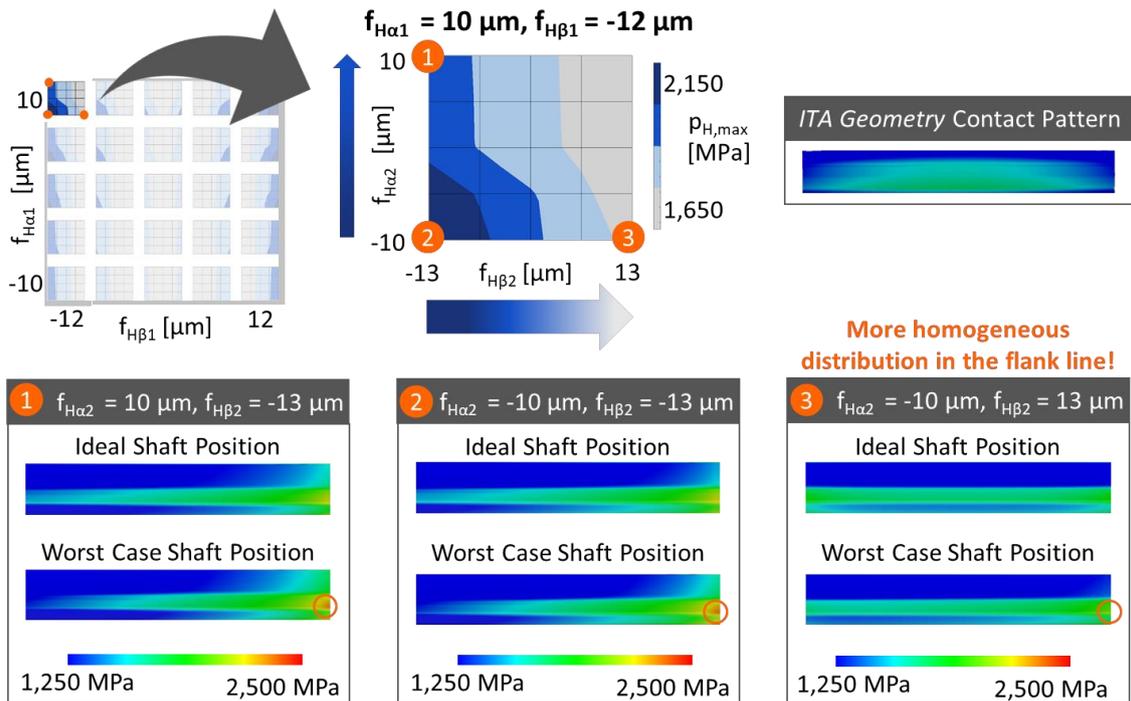


Figure 5. Influence of profile and helix slope deviations in the contact pattern of the *ITA Geometry* gear pair considering the existence of assembly deviations.

4. CONCLUSIONS

The study evidenced that the distinct gear tooth manufacturing deviation types have distinct impacts in terms of the maximum contact stresses and their distribution along the gear flank. Specifically, an alteration of gear flank tolerance class for the helix slope deviation was demonstrated to have a higher impact on the stress intensity and distribution than the same class alteration in profile slope deviation for the *ITA Geometry*. Although the results were generated for the profile slope and helix slope parameters, which are related, respectively, to distortions in the involute tooth profile and gear flank width directions, it is possible to qualitatively extrapolate them to other parameters that also correspond to these directions. In that sense, it is concluded that the manufacturing errors in the flank width direction are more harmful than the ones in the tooth profile direction. When assembly deviations were added to the tooth contact analysis, the distinct behavior of the manufacturing errors was highlighted.

The conclusions of this work are of great interest to the gear manufacturing chain, especially for the ones engaged with the electromobility demands in terms of high accuracy and precision gears. Once the manufacturing distortions have distinct impacts on the gearing contact, a design for tighter tolerances on the most impacting parameters and a manufacturing chain oriented to make it possible need to be discussed. If the attention is directed to reducing the manufacturing errors highly impacting the gear operation behavior, the cost increases in the manufacturing due to tighter tolerances will be lower than the ones in case all deviation limits were reduced as recommended by the AGMA specification for high-speed gears. If designers and manufacturers act together, the powertrain challenges of mobility electrification can be better faced by a design-for-manufacturing approach.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

- AGMA, 2014a. *ANSI/AGMA 6011-J14: Specification for High Speed Helical Gear Units*. Alexandria: AGMA.
- AGMA, 2014b. *ANSI/AGMA ISO 1328-1-B14: Cylindrical Gears – ISO System of Flank Tolerance Classification – Part 1: Definitions and Allowable Values of Deviations Relevant to Flanks of Gear Teeth*. Alexandria: AGMA.
- AGMA, 2021. *AGMA White Paper: A Gearing-Centric Snapshot of the EV Space*. Alexandria: AGMA.
- Carvalho, A. A., 2020. *Surface integrity evolution of Nb-Ti microalloyed steels along the gear manufacturing chain*. 113f. Dissertation of Master of Science in Materials, Manufacturing and Automation – Instituto Tecnológico de Aeronáutica, São José dos Campos.

- DIN, 1978. *DIN 3962-1: Accuracy of cylindrical gears: tolerances for individual errors*. Berlin.
- Dizdar, S. *et al.*, 2003. Process, quality and properties of high-density P/M gears. *ADVANCES IN POWDER METALLURGY AND PARTICULATE MATERIALS*, n. 9, p. 9-36.
- FENABRAVE, 2019. *Informativos – Emplacamentos*. São Paulo. 46p.
- Hjelm, R. *et al.*, 2021a. Influence of manufacturing error tolerances on contact pressure in gears. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, v. 235, n. 20, p. 5173-5185.
- Hjelm, R. *et al.*, 2021b. Gear tolerancing for simultaneous optimization of transmission error and contact pressure. *Results in Engineering*, v. 9, p. 100195.
- ISO, 1995. *ISO 1328-1: 1995: Cylindrical gears - ISO system of accuracy – Part 1: Definitions and allowable values of deviations relevant to corresponding flanks of gear teeth*. Geneva: ISO.
- ISS ESG, 2020. *The Future of Mobility: Potential and ESG Challenges of Alternative Drives*.
- Mileti, M. *et al.*, 2018. Design of a Hyper-High-Speed Powertrain for EV to achieve Maximum Ranges. In: *Proceedings of the CTI Symposium*, Berlin.
- Klocke, F; Brecher, C., 2017. *Zahnrad- und Getriebetechnik*. München: Hanser, 684p.
- PWC, 2017. *Five trends transforming the Automotive Industry*.
- Reichert, U. *et al.*, 2016. High speed electric drive with a three-speed gear box. In: CAR TRAINING INSTITUTE. *CTI Mag: The Automotive TM, HEV and EV Drives*, Dusseldorf: CTI, 25-27.
- Stadtfeld, H. J., 2020. Introduction to electric vehicle transmissions. *Gear Technology*, v. 37, n. 7, p. 42-50.

7. RESPONSIBILITY NOTICE

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