Critique of the ISO 15144-1 Method to Predict the Risk of Micropitting

This is About Micropitting — Not Nitpicking

From the Editors

Great minds think alike — but not always at the same time.

Indeed, arriving at a consensus of "great minds" can be tricky — like the shepherding cats thing.

Witness proposed ISO/TR/TR Standard 15144-1 — Method to Predict Risk of Micropitting — as a perfect example.

As far as international standards go, this one on balance is not particularly controversial; it does not seek to reinvent the wheel — it's about micropitting, after all.

Not, on the other hand, to minimize what has been a very serious gearing issue — especially in such vital sectors as the wind industry — on and offshore.

The following Voices submission is a Robert Errichello opinion piece (and a virtual micropitting tutorial) regarding a portion of the mentioned work-in-progress micropitting standard — 15144-1. (*Full disclosure: Errichello is a both a longtime Gear Technology Technical Editor and contributor*.)

It will be followed by a joint ISO/TR-AGMA statement addressing this issue.

Some brief backstory for perspective: Errichello is of the opinion — along with 20 fellow peer reviewers — that the proposed micropitting standard is "flawed." And his submission on the issue that you are about to read explains in great detail his opinion why this is so.

By going public, is it possible Errichello runs the risk of perhaps being perceived by his colleagues as "gearing's gadfly?"

Regardless, *Gear Technology* is certainly not here to judge — nor even to referee. We simply thought gear folk might find some behind-the-scenes back-and-forth on how standards are drafted to be of some interest. Again, Errichello's statement is followed by a brief ISO/TR/AGMA joint statement.

Robert Errichello, PE heads his own gear consulting firm, GEARTECH; is the designer of GEARTECH Software, Inc.; is a longtime AGMA member and contributor and winner of its TDEC award; its E.P. Connell award; its Lifetime Achievement award; a winner of the STLE Wilbur Deutch Memorial award; STLE Edmond E. Bisson award; AWEA Technical Achievement award; and for many years an invaluable Gear Technology and Power Transmission Engineering magazine technical editor.

Robert Errichello

Introduction

There exists an ongoing, urgent need for a rating method to assess ***micropitting risk***, as AGMA considers it a "a very significant failure mode for rolling element bearings and gear teeth — especially in gearbox applications such as wind turbines."

In response, ISO Technical Report ISO/TR 15144-1 has been proposed as an International Standard for rating *gear micropitting risk*. Currently, it is a Technical Report that is being tested by several members of ISO and AGMA technical committees. Because micropitting is a very complex failure mode that is influenced by a vast array of parameters, the AGMA decided to conduct a peer review of ISO/TR 15144-1 by recognized tribologists specializing in elastohydrodynamic lubrication (EHL). Reviewers were selected for their expertise in EHL and micropitting. All reviewers had published technical papers in peer reviewed journals and many of the reviewers are tribologists who have conducted research at technical universities or industrial laboratories. Their affiliations are located in the US, UK, and France. The invitation was sent to 39 potential reviewers and 22 accepted the invitation. Ultimately, as of the date of this report, 20 reviews were completed and submitted.

Critique of ISO 15144-1 Method to Predict Risk of Micropitting

ISO 15144-1 (Ref. 1) is technically flawed. Its postulate that Blok's flash temperature reduces the elastohydrodynamic lubrication (EHL) film thickness is fundamentally wrong. A peer review of the document concluded that the postulate flies in the face of established science. Therefore, I recommend that ISO 15144-1 be withdrawn.

AGMA Peer Review Process

The peer review (Ref. 2) was performed by world-renowned tribologists; they were encouraged to review the entirety of ISO 15144-1, but were asked to focus their review on the novel feature of ISO 15144-1 — i.e., the sliding parameter $S_{GF,Y}$. The results of the review showed that ISO 15144-1 is technically flawed.

What is the problem? The heat generated within the EHL film by shearing of the lubricant and rubbing of asperities does not affect the inlet temperature once the bulk temperature reaches equilibrium. Consequently, the temperature rise due to frictional heating within the Hertzian zone only affects film thickness indirectly by influencing the gear tooth bulk temperature, and it does not change the EHL film thickness, which is determined by the gear tooth bulk temperatures in the inlet zone to the EHL contact. Therefore, the ISO 15144-1 postulate that Blok's flash temperature reduces the local film thickness is fundamentally wrong.

What, in fact, is the proper way to account for sliding? Tribologists have found that it is not the sliding within the Hertzian zone that influences EHL film thickness, but rather it is the sliding in the inlet zone to the contact that controls EHL film thickness. In the inlet zone, the lubricant that is adsorbed on the surfaces of the contacting bodies is

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entrained into the EHL contact by the rolling motion of the bodies. Entrainment of the lubricant is greatly facilitated by its viscosity increase because the high viscosity resists flow, makes it more difficult to squeeze the lubricant out, and viscous drag forces cause it to move with the surfaces into the Hertzian zone. As a result, the inlet pumps the film up to a thickness sufficient to separate the opposing bodies.

EHL film thickness is determined by the viscosity and pressure-viscosity coefficient of the lubricant in the inlet zone. For gears, the lubricant that is entrained into the inlet is molecularly bonded to the surfaces of the pinion and wheel teeth and consists of thin boundary layers that immediately take on the bulk surface temperatures of the pinion and wheel teeth. Consequently, EHL film thickness is determined by the equilibrium bulk surface temperatures of the pinion and wheel teeth in the inlet zone before the lubricant reaches the Hertzian zone.

Why is inlet shear heating important? In a fully flooded EHL contact, only a fraction of the lubricant can pass through the contact. Therefore, some of the lubricant is rejected and reverse flow occurs in the inlet. Furthermore, if there is sliding in addition to rolling, heat is generated by shearing of the lubricant. Churning and shearing generate heat that increases the lubricant temperature above the average bulk surface temperatures. Therefore the temperature that controls lubricant viscosity and EHL film thickness is the temperature of the lubricant in the inlet. Although it is well known that inlet shear heating reduces EHL film thickness, and there are published thermal correction factors for accounting for inlet shear heating, ISO 15144-1 neglects inlet shear heating.

What about sliding within the Hertzian zone? Sliding friction within the EHL film increases the bulk temperature of the gear teeth from a cold start by accumulating heat from each tooth engagement. The bulk temperature of the gear teeth increases until the heat input is equal to the heat loss to the surroundings. Once the bulk temperature reaches equilibrium there is no further change in gear tooth bulk surface temperature unless the operating conditions change. The heat input is confined to the immediate area of the Hertzian zone and its duration is only a fraction of a millisecond long. Consequently, the heat produced by frictional heating within the EHL film is removed by conduction through the film into the tooth surfaces and by convection as the hot oil exits the outlet zone. Due to the short contact time, the heat penetrates only a shallow distance into the gear teeth and is rapidly dissipated. And so as the contact point moves on, the heat input disappears immediately and the surface temperature of the gear teeth returns promptly to the equilibrium bulk temperature. After one revolution of the gear, a particular point on the gear flank comes into engagement with essentially the same bulk temperature as the previous engagement. Although frictional heating does not directly alter the film thickness within the Hertzian zone, any increase of the bulk surface temperatures due to frictional heating indirectly reduces film thickness by decreasing the viscosity of the lubricant in the inlet zone.

The sliding is significant because it generates traction forces that result in energy losses. If the lubricant behaved like a Newtonian fluid, the high viscosity would lead to extremely high traction force. Fortunately, however, when subjected to

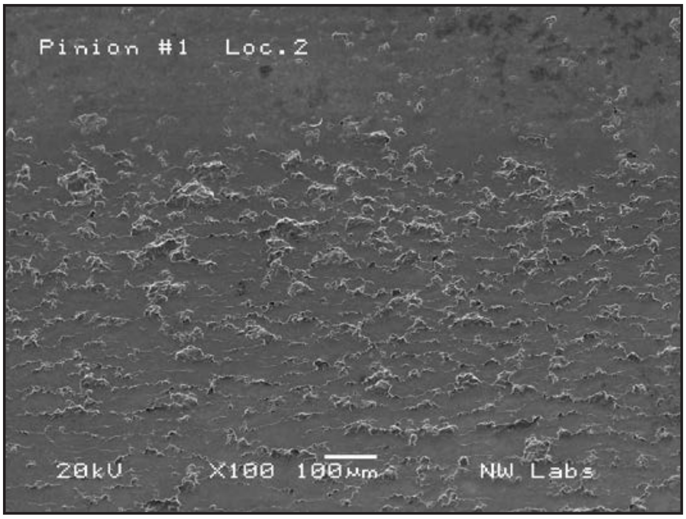

Figure 1 SEM image of micropitting on wind turbine pinion at 100X magnification.

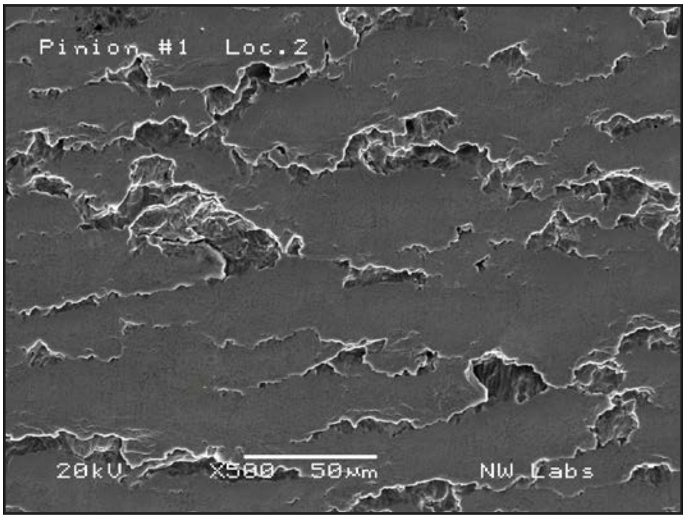

Figure 2 Same as Fig. 1—but at 500X magnification.

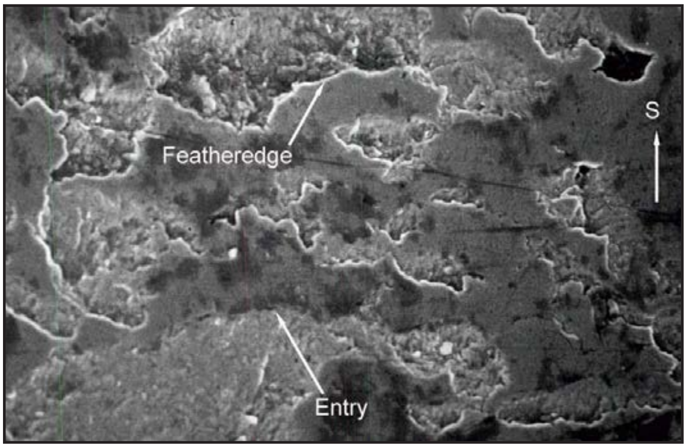

Figure 3 Detail of micropitting on wind turbine pinion at 1000X magnification (Courtesy of AGMA Standard ANSI/AGMA 1010-F14; Figure 56).

high shear stresses the lubricant behaves like a plastic pseudo-solid with limited shear strength that is characterized by its traction coefficient. The bulk surface temperatures are controlled by heat generated in the Hertzian zone, and the temperatures can vary significantly, depending on the molecular structure of the lubricant base stock — which influences a lubricant's solidification pressure, shear strength, and traction coefficient. Furthermore, depending on antiwear and antiscuff additives that may be in the lubricant, the sliding and heat generates boundary tribofilms that help to prevent adhesive wear.

What about Blok's flash temperature? Blok defined the contact temperature as the sum of the bulk surface temperatures of the gear teeth and the flash temperature rise associated with frictional heating in zones of asperity contact. Blok's theory of scuffing proposes that scuffing occurs when the maximum value of the contact temperature reaches a critical temperature; he predicted the surface temperature based on the following assumptions:

1. The surfaces are in intimate contact or perfectly insulated
2. All the heat is removed by one-dimensional conduction, straight down into the surfaces
3. The two bulk temperatures are identical

Assumption 1 is violated if an EHL film is present; assumption 2 is violated if the speed of either surface is too slow; and assumption 3 is violated for a high gear ratio because the pinion typically runs hotter than the wheel. Therefore Blok's flash temperature theory applies only to the boundary lubrication regime where the EHL film is non-existent, and the only protection against scuffing is any tribofilm deposited by lubricant additives. Once the tribofilms fail the only remaining protection is the natural oxide layer on the gear teeth. As a result, Blok's flash temperature is not applicable to the mixed-film or full EHL regime that is considered in ISO 15144-1.

Quoting (anonymously) one of the AGMA peer reviewers:

"The use of the flash temperatures for the calculation of the properties for the sliding parameter $S_{GF,Y,}$ presume that mixed or boundary lubrication occur; in which case, what is the point of calculating a film thickness reduction?"

Thus, ISO/TR 15144-1 incorrectly uses Blok's flash temperature to reduce the EHL film and contradicts Blok's assumption that the surfaces are in intimate contact without an EHL film.

The heat generated within the EHL film by shearing of the lubricant and rubbing of asperities does not affect the inlet temperature once the bulk temperature reaches equilibrium. So the temperature rise due to frictional heating within the Hertzian zone only affects film thickness indirectly by influencing the gear tooth bulk temperature; it does not change the EHL film thickness, which is determined by the gear tooth bulk temperatures in the inlet zone to the EHL contact. Which means that the ISO 15144-1 postulate that Blok's flash temperature reduces the local film thickness is fundamentally wrong.

What film thickness is relevant to micropitting? ISO 15144-1 calculates the minimum EHL film thickness at the exit to the EHL contact. In contrast, AGMA 925-A03 (Ref. 3) calculates the central film thickness in the center of the EHL contact. The minimum film thickness is not relevant to micropitting because there is little interaction between surface asperities because the width of the exit zone is narrow, and the film pressure is very low in the exit zone. Conversely, there are more stress cycles on asperities and much greater film pressure in the central zone of the EHL contact. Result: the central film thickness is relevant to micropitting. And: ISO 15144-1 uses the wrong film thickness equation and AGMA 925-A03 uses the correct one.

ISO 15144-1 uses a linear sum to combine the surface roughness of the pinion and wheel. However, AGMA 925-A03 — and all current tribology literature — use a root-mean-square sum to combine the roughness of the pinion and wheel. Therefore ISO 15144-1 is not consistent with the science of tribology.

What's wrong with ISO 15144-1? The peer review disclosed not only the fundamental flaw in ISO 15144-1 that assumes Blok's flash temperature reduces film thickness, but also disclosed many other shortcomings of ISO 15144-1:

- Postulate that Blok's flash temperature reduces EHL film thickness is incorrect
- Blok's flash temperature applies only to boundary regime, but not mixed-film or full EHL regimes
- The mathematical derivation of sliding factor $(S_{GF,Y})^{0.22}$ technically flawed
- Sliding factor $(S_{GF,Y})^{0.22}$ is without mathematical basis
- Exponent derived by regression analysis, but details not given
- Shear heating in the Hertzian zone contributes to bulk temperature — but does not reduce EHL film thickness
- Derivation doesn't include analysis of flow rate to ensure mass conservation
- Derivation uses form of Reynolds' equation that is unsuitable for thermal analysis because it excludes temperature variations throughout thickness of EHL film
- Coefficient of friction highly dependent on film thickness, temperature, traction coefficient, and tribofilms; therefore a thermally coupled analysis required to determine consistent estimates of friction, temperature, and film thickness
- Minimum film thickness calculated rather than the more relevant central film thickness
- Composite surface roughness is incorrectly defined
- Derivation assumes Newtonian fluid, but in high-speed gears fluid is non-Newtonian
- P-V coefficient applies only to low-pressure inlet zone and not high-pressure Hertzian zone
- ISO adopts engineering approach that is excessively convoluted
- ISO definition of micropitting failure is ambiguous
- Micropitting depends on many factors other than EHL film thickness
- Running-in neglected
- Inlet shear heating neglected
- Shear thinning neglected
- Non-Newtonian behavior neglected
- The bulk temp assumed to be same for both pinion and wheel, but actually different for gearsets with high gear ratio
- Single value of thermal conductivity is used, but actually varies with gear steel

Can ISO 15144-1 regain credibility? ISO 15144-1 cites the Elstorpff dissertation (Ref. 4) as the source for the sliding factor. However, several mathematically inclined peer reviewers (Ref. 2) analyzed Equations 7.18–7.24 of the Elstorpff dissertation and they unanimously agreed that the derivation of the sliding factor $S_{GF,Y}$ is mathematically flawed and has no basis in Reynolds' equation. As such, it is clear that the analytical basis for the sliding factor is unsound. Without an ana-

lytical foundation for the sliding factor, it might be justified via regression analysis that empirically derives the sliding factor by comparing isothermal and thermal EHL analyses for a large range of gear examples. Furthermore, the Elstoropff dissertation mentions that the exponent for the sliding factor was derived from a regression analysis, but no details of the analysis are given. Therefore a minimum revision of ISO 15144-1 would include adequate documentation of the regression analysis. Furthermore, the software used for the regression analysis should be made available to AGMA members so that they can validate the software and replicate the calculations. The scientific method requires that empirical results be replicated by independent researchers. ISO 15144-1 cannot be considered creditable without such replication.

Is there a path forward? *Quoting from recent research on micropitting* (Ref. 5): "The use of a 'specific lubricant film thickness' (similar in definition to the λ ratio) as the basis of a numerical aid to avoid micropitting is embodied in a current ISO standard (Ref. 1). The document recognizes that other specific factors, including lubricant chemistry, have an influence, but it is appreciated that the science has not developed sufficiently to allow such factors to be included directly in a calculation method. Thus the specific lubricant film thickness is recommended 'as an evaluation criterion when applied as part of a suitable comparative procedure based on known gear performance.' It is therefore clear that gear practitioners recognize the need for a better understanding of the phenomenon of micropitting before it will be possible to provide a truly comprehensive design method to prevent it."

Hence, because micropitting is such a complex phenomenon, any analytical method cannot be based solely on specific film thickness if it is expected to reliably predict the risk of micropitting.

A subcommittee of the AGMA Helical Gear Rating Committee is currently updating AGMA 925-A03 (Ref. 3). The subcommittee includes tribologists, chemical engineers, gear engineers, gear consultants, lubrication engineers, lubricant formulators, and end users of gears. One of the goals of the subcommittee is to develop a method to predict the risk of micropitting. AGMA 925-A03 is consistent with the state-of-the-art in gear tribology, whereas ISO 15144-1 has many shortcomings. I therefore believe the shortest path to a reliable method to predict the risk of micropitting is to withdraw ISO 15144-1 and develop the update of AGMA 925-A03 through collaboration between AGMA and ISO members.

The updated AGMA 925-A03 could then become an international standard — upon approval by all ISO delegates.

References

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3. AGMA 925-A03. "Effect of Lubrication on Gear Surface Distress," 2003.
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Joint Statement on Current State and Future Activities on ISO 15144-1 & AGMA 925

Prepared by, Robin Olson, Chairperson, AGMA Sub-Committee Revising AGMA 925 and **Dr. Ing Thomas Tobie,** Head of Department, Machine Elements, FZG-TUM.

AGMA and ISO Working Group 15 applaud the efforts of *Gear Technology* magazine to educate the gear community on ISO 15144-1 (Calculation of micropitting load capacity of cylindrical spur and helical gears — Part 1: Introduction and basic principles). The document is a technical report — not an international standard — which means that it is an informative document. It has been available since 2010 and was recently updated with a second revision at the end of 2014.

ISO/TR 15144-1 predicts the risk of micropitting through the use of a safety factor that is the ratio of the *minimum* specific lubricant film thickness to the *permissible* lubricant film thickness (Ed. italics added). The minimum specific lubricant film thickness is calculated in the contact zone of the gear mesh — taking into account tooth surface roughness and geometry; lubricant; load; and relative sliding between the pinion and gear. The permissible value can be determined by running similar gears — or an adequate test — until micropitting just occurs. This method has been used with various FZG test gears, with gears in wind turbine applications and some other industrial applications. ISO Working Group 15 is working to make the method applicable to a broader set of gear applications in preparation for the re-designation of ISO 15144-1 as an international standard.

AGMA 925-A03 (Effect of Lubrication on Gear Surface Distress) is an information sheet that describes micropitting, but does not contain a method to predict risk. A subcommittee of the AGMA Helical Gear Rating Committee has been formed to review the document and develop a method to calculate a percent of risk, rather than a safety factor. This is consistent with the existing methods that evaluate scuffing and wear in the same document.

Each of these documents is a collaborative effort between members of the ISO Working Group and the AGMA Helical Gear Rating Committee, with a focus on developing a method that can be used to predict micropitting for a broad range of gear applications.

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