Modelling of thermal stresses in bearing steel structure generated by electrical current impulses

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Abstract. This work is the study of one particular candidate for white etching crack (WEC) initiation mechanism in wind turbine gearbox bearings: discharge current impulses flowing through bearing steel with associated thermal stresses and material fatigue. Using data/results from previously published works, the authors develop a series of models that are utilized to simulate these processes under various conditions/local microstructure configurations, as well as to verify the results of the previous numerical studies. Presented models show that the resulting stresses are several orders of magnitude below the fatigue limit/yield strength for the parameters used herein. Results and analysis of models provided by Scepanskis, M. et al. also indicate that certain effects predicted in their previous work resulted from a physically unfounded assumption about material thermodynamic properties and numerical model implementation issues.

1. Introduction

WEC formation is a common yet poorly understood fatigue failure mode in machinery components subject to cyclic and/or transient loads. WEC occurrence is widespread (automotive gearboxes, industrial gearboxes, mill drives, cranes, etc.), but it is especially frequent in wind turbine gearbox bearings. These undergo breakdowns much earlier than predicted by rolling contact fatigue (RCF) models, which implies that other factors are also responsible for shorter bearing lifetimes (6 – 24 months VS the desired 20 years). A solid, rigorous explanation of this phenomenally rapid bearing breakdown in wind turbines eludes the scientific community to this day. The resulting annual expenditures in the wind energy industry due to turbine standstills and maintenance are tremendous (especially in case of relatively distant offshore installations), which is why investigations in this field are of utmost importance. [1]

Most bearings unavoidably fail via spallation damage at the end or their operational lifetimes. One of the standard measures of these is the $L_{10}$ life: the RCF life of a bearing for a given operating condition at which statistically 90% of bearings survive. The failure type in question here, dubbed the white structure flaking (WSF), typically sets in at 5 – 20% of expected $L_{10}$ values [1]. WSF is due to microstructural alterations in bearing races at about 1 mm depth beneath the contact surface. The resulting altered structure areas are known as white etching areas (WEAs) and these are usually associated with cracks found in close proximity, WECs, which come in two varieties: surface (originate from contact surface) [2,3] and subsurface (the majority of WECs have no connection to contact surface) [4,5,6]. The reason for such peculiar nomenclature is that the appearance of WECs and WEAs becomes distinctly white colored...
after the containing steel structure is subjected to nital etching during the post failure structure analysis of cross sectioned bearings [1]. It has been shown that WEA consists of nano ferrite grains and is considerably harder than the surrounding steel matrix [1,7,8], which is in agreement with the Hall-Petch relationship.

Considering that pure RCF cannot be responsible for premature failure, several hypotheses and theories proposing different WEC formation assisting mechanisms have been developed and are clearly outlined in the recent review article by Evans [1]. These include steel corrosion (during standstill periods and due to maintenance contamination), lubricant water contamination [9-11], tribochemical processes (such as hydrogen generation within lubricant film) [12-15], bearing slip (during accelerations/decelerations, intentional or otherwise), vibrations [10,16], electrical currents (due to lightning strikes, lubricant self charging/discharging and other stray currents) [1,17-19], additional bending stresses and impact loads (for instance, due to bearing misalignment, wind gusts, irregularities in electrical grid power supply regime) [10,20,21]. The current objective is to identify the root WEC initiation cause(-s) among the above mentioned factors, but given that these may or may not influence the RCF process simultaneously (degrees of influence depend on operational conditions), it is not at all trivial. It is therefore vital to ascertain the severity of each of the potential WEC initiators and, if possible, eliminate the irrelevant ones from the rather long list of suspects.

A recent investigation by Smelova et al. [22] on an RCF test rig has demonstrated that premature cracks form well before and in absence of material transformation (including WEAs). It must be noted that cracks that precede WEAs were, although under different conditions, previously demonstrated by Gould and Greco [23] and others, but such cracks were preceded by dark etching area (DEA) formation. This is a milestone result, because a long standing topic for debate was whether WEAs are merely symptoms of WECs or the other way around: WECs are caused by stresses localized at WEA/steel matrix boundaries due to significant hardness differences and thus mechanical incompatibility [1]. With this controversy seemingly resolved, one of the avenues of research has been potentially eliminated, which is important because of the sheer number of theories and working hypotheses that are currently in play.

Hydrogen generation and subsequent uptake by steel results in a considerable decrease of material yield strength and, consequently, fatigue limit, as well as other effects [12-15]. Damage to steel surface facilitates hydrogen penetration through microcracks: an effect further enhanced by vibrations [24]. However, it has been reported repeatedly that industrial tests, including those by Schaeffler Technologies, have produced WSF in bearings lubricated with virtually hydrogen-free oils; some tests were conducted in vacuum and eliminated water/air contamination [25,26]. These results imply that hydrogen diffusion into steel in not a requisite for premature bearing failure, which raises a question of just how relevant this process actually is, if at all, under certain conditions [1]. Note that the above mentioned rig tests also eliminated additional transient loads usually present during wind turbine operation.

Even more importantly, tests have indicated that WEC formation could be accelerated by applying external voltage to bearings, between inner and outer rings, as seen in publications by Smelova et al. [22], Loos et al. [18] and other cases, with or without external voltage [25,27]. More recently, Scepanski et al. [28] have reported empirical evidence of voltage self-generation in a lubricated tribocontact. While the exact relationship between electrical currents and WEC formation is unknown, these experimental facts suggest that it could be a major influence and should be regarded seriously.

In contrast to extensive experimental research, very few theoretical or modelling works regarding WECs have been published to date, most of which deal with contact mechanics, material transformations, hydrogen diffusion, crack propagation (not initiation) or attempt to explain how WEAs are formed (for instance, see [16,20,29-39]; while [36] is not directly related to bearing steels, in author’s opinion, it demonstrates microstructure modelling capabilities
very well). This is especially true in case of electricity, in which, to the author’s knowledge, no modelling results were published that would showcase the influence of electrical current on fatigue acceleration, except for the article by Scepanskis et al. [17], wherein it has been proposed that electrothermally generated stress is concentrated at defect sites, such as carbides, due to discharge current generated Joule heat where current flows around defects.

That publication displays some very intriguing, but equally alarming results: predicted thermal stresses (on the order of $10^2$ MPa) are dangerously close to common bearing steel yields strengths (also on the order of $10^2$ MPa) and temperature increase is on the order of tens of kelvins. Significant carbide grain and surrounding matrix deformations are observed and the model in question predicts that they are severe enough to lead to the formation of nanovoids near carbide grains. Voids in vicinity of defects are, in fact, readily found in failed bearing steel microstructure and are obvious crack initiators: for instance, see [17, Fig. 8].

The major problem is that almost no estimates for the microstructure material physical properties are available, the exceptions being somewhat rough values, hence the relative infrequency of theoretical/modelling articles. The authors of the present work believe addressing this issue is one of the priorities, since microstructural process modelling has the potential to provide many new insights into premature crack initiation drivers and dynamics. There is also little to no data on characteristic electric current densities and discharge durations, so Scepanskis et al. [17] assume certain values, which may have been exaggerated.

Nevertheless, [17] showcases a very important result that opens up another avenue of research. The authors of present work believe that it certainly warrants further investigation and also, being the only result, validation, hence the present publication. Since the work of Scepanskis et al. [17] was published, more rig tests were conducted to investigate WEC promotion by electricity [18,22], notably the work of Loos et al. [18], wherein electrical discharges in bearings are studied: it is possible to derive a rough discharge duration estimate from the data presented therein.

With that in mind, the authors present the development of a model for thermal stress accumulation within the steel structure due to discharge currents known to flow through bearings during operation. The objectives of this study are to construct a more generalized model including a wider range of effects and to verify the previously obtained results. In case of a positive investigation outcome, electrothermal WEC initiation could be confirmed as a key bearing failure acceleration mechanism. This work would then serve as ground zero for further efforts to predict the extent of damage inflicted to bearing steel by stray electric currents.

2. General modelling framework
One must note that currently there is little to no information regarding the range of magnitudes of stray currents in operational gearboxes. There exist hypotheses as to the origins of these discharges, but none have been verified with certainty. However, rig tests where cyclic loads were combined with artificially applied voltages across bearings [18,22] provide grounds for initial attempts to ascertain the magnitude of current induced stresses without delving into the details of current generation/propagation.

Steel microstructure tends to be rather complex, so for generality purposes models presented herein assume a spherical carbide (grain) within the otherwise homogeneous martensite phase steel structure by default, with various model to model modifications (discussed below). A thin relatively heightened thermal/electric resistance interface layer between the grain and the surrounding structure commonly seen in alloys is accounted for. Discharge current is assumed to flow through a straight cylindrical channel containing the carbide grain.

In light of the work by Scepanskis et al. [17], presented models will match material parameters used therein for verification purposes. Discharge duration ($t_{dis}$)/delay ($t_{del}$) are $1 \mu s$ and $100 \mu s$ respectively loosely based on the data obtained by Loos et al. [18], which is
used as a reference due to lack of information about the actual discharge times in wind turbine bearings. All presented calculations are based on parameters in table 1.

### Table 1. Relevant material properties.

| Parameter, units | Martensite steel | Carbide grain | Material boundary |
|------------------|------------------|---------------|-------------------|
| $\sigma$, electric conductivity, $S/m$ | $100 \cdot 10^5$ | $10^5$ | $10^5$ |
| $k$, thermal conductivity, $W/(m \cdot K)$ | 50 | 1 | 0.01 |
| $c_p$, specific heat capacity, $J/(kg \cdot K)$ | 400 | 600 | 600 |
| $\alpha$, thermal expansion coefficient, $1/K$ | $15.0 \cdot 10^{-6}$ | $7.6 \cdot 10^{-6}$ | N/A |
| $\rho$, density, $kg/m^3$ | 7500 | 7500 | 7500 |
| $E$, Young’s modulus, $Pa$ | $2.1 \cdot 10^{11}$ | $1.9 \cdot 10^{11}$ | N/A |
| $\nu$, Poisson ratio, none | 0.30 | 0.32 | N/A |

Boundary layer thickness is assumed to be 0.01 $\mu$m. Note that only rough estimates of the boundary layer parameters are available. Since the model only deals with an isolated defect, the surrounding structure is assumed to be regular in the sense that grains are spaced by separating distances of 10 $\mu$m (some of the longest seen in micrographs, as evident from [1] and references therein) in an array of cells where a grain is surrounded by steel matrix, current channel being directed through the cell. Grain radius is set to $r_g = 0.5 \mu$m, current density is set to $10^8 \ A/m^2$ throughout the discharge period.

### 3. Proposed models

#### 3.1. Analytical model

Proposed model hierarchy schematic representation is found in figure 1.

![Figure 1. Model hierarchy schematic representation.](image)

First, a simplified analytical model is constructed. Its purpose is twofold: firstly, it provides order of magnitude estimation and approximation of temperature distribution profiles and accumulated thermal stresses (time evolution) within the domain of interest to later verify numerical model results; secondly, it assists in numerical model definition and establishment of validity bounds.
The assumption is that when current flows around a spherical defect, Joule heat is concentrated near the grain/steel boundary along grain equator. Current density magnitude at the equator is estimated from the discharge channel (radius $r_c$) base/grain restricted cross section areas ratio for $r_c/r_g$ close to 1. Due to rotational symmetry with respect to current channel axis, temperature profile time evolution is solved for using a one dimensional radial line (coplanar to heat source) approximation, wherein two domains are considered: grain and steel, where a point-like Joule heat source is placed at the interface. To further simplify the problem, it is solved separately for each domain on a semi-open interval, which is essentially equivalent to placing a layer with zero thermal conductivity between the materials (later compared to numerical results with resistive layer enabled). Stresses are obtained similarly, but from three dimensional equations wherein the temperature profile is used as input. Isotropic materials and small strains are assumed. This means that the model will overestimate temperature/stresses by some margin while maintaining orders of magnitude.

The initial conditions are $293.15 \text{K}$ uniform temperature field and stress-free material. The heat transfer problem is then solved to yield the following temperature function $T(r,t)$ and subsequently stress profiles $\sigma(r,t)$ via thermoelasticity equations

$$T(r,t) = \frac{g}{2a^2} \left( (2a^2t + r^2) \cdot \text{erfc} \left( \frac{|r|}{2a\sqrt{t}} \right) - 2a|r|\sqrt{\frac{T}{\pi}} \cdot \exp \left( \frac{r^2}{4a^2t} \right) \right)$$

$$\sigma_{rr}(r,t) = -\frac{2f}{r^3} \cdot F(r,t)$$

$$\sigma_{\theta\theta}(r,t) = \sigma_{\phi\phi}(r,t) = f \left( \frac{F(r,t)}{r^3} - T(r,t) \right)$$

$$F(r,t) = \int_0^r r^2 T(r,t) dr$$

Here $g, a(r), f(r)$ contain electric, thermal and mechanical parameters of materials and are assumed to be constant in time and space within respective domains. In this case, the above mentioned grain cell dimension is $5.5 \mu m$, where the heat source is at $r = 0 \mu m$, grain center is at $r = -0.5 \mu m$, cell boundary is half the grain separation distance away from origin, at $r = 5 \mu m$.

### 3.2. Numerical models

COMSOL Multiphysics 5.3 environment is used for finite element modelling throughout this work. Three modules are utilized: AC/DC (solves for electric potential), Heat Transfer (temperature) and Structural Mechanics (displacement field), all of which are coupled. These compute current distribution and Joule power output over the domain of interest, resulting temperature and stresses, as well as other derived physical quantities. Meshes are very fine (0.005 – 0.02 $\mu m$ element size) near the grain boundary and are coarsened further away (element growth rate is tailored for each model). Lines indicated by (x) in figure 2 designate mesh refinement areas that are adapted to channel width changes.

The first model is the toroid heat source along grain equator (Fig. 2.1). The source is artificial: here it is not calculated from current distribution, but rather its intensity matches that of the analytical model. Toroid diameter is set based on $r_c/r_g$ value from the analytical model. Computation results are then compared against analytic estimates to check for consistency.

The next step is the actual discharge model (Fig. 2.2). Here current influx is set at the upper end of the channel whereas the other one is grounded. This model comes in two variations with/without material boundary layer. This is used to investigate material boundary layer influence on stress accumulation. Again, to verify model validity, the one with no boundary
Figure 2. Numerical model geometric configurations: here (k) denotes k-th model geometry (described and referenced in text); hemispheres correspond to carbide grain domains; blue lines represent grain/matrix and martensite sheet boundaries; lines indicated by (x) designate extra mesh refinement areas; vertical lines in (2-4) represent discharge channel boundaries.

layer is parametrically studied to check whether or not and how strongly it is related to the above verification models. Specifically, current channel radius is varied to see if the discharge model converges to the toroid source model as channel radius tends to that of the grain. Afterwards, this model is further upgraded to three variations: two different configurations where a defect consisting of two adjacent grains is modelled (Fig 2.3 and its counterpart configuration, which is 3 dimensional; see Fig. 1) to investigate proximity effects (grain separation distance is varied); the other is an attempt at martensitic structure modelling (Fig 2.4) where martensite sheets [1] are placed in proximity to the grain and respective boundary layers are accounted for.

Model 1 is 2-dimensional, axially (left boundary) symmetric. The outer boundary is electrically/thermally insulated and set as freely mechanically displaceable. This also applies to models 2, 3, 4. In 1, the heat source is set as a circle of a very small radius. Models 2, 3, 4 include a discharge channel (a narrow rectangle of variable radius with grains inside) with an electrically insulated boundary. Model 3 contains two grains (separation distance variable). Model 4 represents an attempt to model the interaction of grains with martensitic steel sheet shaped domains; specifically, it models the effect of physical contact on stress accumulation near the carbide grain. For these reasons the problem is reduced to an axially symmetric 2-dimensional. The five long radiating lines in Fig 2.4 indicate sheet boundaries.

In addition, inclusion shape study is conducted using model 2. The assumed grain shape is elliptic and its semi axes are varied at constant grain volume for various channel widths to investigate how this affects stress accumulation. There is also the matter of various common defect types in bearing steels aside from the above mentioned carbides. Among these are cavities (voids), $Al_2O_3, MnS, TiCN$ and other types of inclusions [1]. Using model 2, material study is conducted to identify the most dangerous inclusion type. Material parameters for inclusions are taken from Juvonen, P., page 16 [40].

4. Results and analysis
First, the analytical model is used to estimate temperature/stress distributions within the grain and the surrounding steel (figure 3).

Note that the temperature difference (from here on simply temperature) and von Mises stress (from here on simply stress) maxima are just outside the grain boundary. The model clearly indicates that current induced overheating and stress levels are minuscule, about 80 $\mu K$ and
Figure 3. Analytical solution: temperature difference (left) and von Mises stress (right). Grain boundary is at 0 μm.

250 Pa respectively. Stress is predicted to be compressive with respect to the grain. Obviously, profile shapes farther away from the grain surface should be perceived as simple sketches as magnitudes thereof are expected to fall off more rapidly with distance.

Next, the model is used to determine the effective heat impulse propagation time to the adjacent cell boundary. This is important because it indicates whether or not adiabatic external boundary conditions are well suited for numerical models in terms of potentially introduced errors. This characteristic time scale was found to be $\tau = 1.5 \mu s$, which exceeds the discharge duration. Given the temperature overestimations introduced by the model, this value has a safety margin. Thus, numerical model dimensions will match those proposed in the above sections without risking considerable errors due to heat impulse rebound. This also justifies the use of mechanically free external boundary in numerical models. Nevertheless, all numerical models were also tested by doubling exterior dimensions: the results differed at most by 2%.

As a consistency check numerical model 1 is run, indicating that COMSOL simulations are in order of magnitude agreement with the analytical calculations (figure 4).

Figure 4. Numerical model 1 results. Grain boundary is at 0.5 μm. Temperature (left) and stress (right) are plotted along heat source coplanar grain radial line.

The rates of temperature/stress build-up are also consistent, given the differences. Temperature profile asymmetry is also quite similar to that predicted analytically, with the
expected difference in magnitude decrease over distance. Temperature build-up and stress are concentrated just outside the grain as predicted. Clearly, for such small temperature variations and stresses, the temperature dependence of $\sigma$ and thermoelastic damping can be neglected and the small strain approximation is valid. Nevertheless, all numerical models are tested and indicate that these effects are in fact irrelevant.

Model 2 is first run for a single grain with/without a boundary layer. Initial channel width is set to $d_c = 1.5 \, \mu m$ (the default value for subsequent models). Current is shown to concentrate near grain equator, as initially thought (also seen in [3]), forming a heat source similar in shape to a toroid, which hints at a relationship between this model and the two described above. Indeed, varying $d_c$ shows that as it tends to that of the grain the model converges to the toroid model in the sense that temperature and stress profiles become increasingly similar, almost to the point of matching in shape and magnitude.

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**Figure 5.** Model 2: temperature field (a,b,d,e) and radial line temperature (c, f). Boundary layer is present in (d,e,f).

It is found that even a very thin material boundary layer has a considerable impact on temperature field evolution for such time scales as evident from figure 5. In absence of the boundary layer the grain quickly overheats, but in the opposite case there is a very steep gradient about the boundary (figure 5c, 5f). It should be noted that figure 5f closely resembles the analytical model solution. This is no coincidence, since solving for two domains separately has the same effect as placing an infinitely resistive thin layer inside the two material interface and more heat is transported further away from the grain, reducing the rate of temperature
decrease over distance.

Figure 6 Displays the resulting stress field. Material boundary layer presence results in a \( \sim 10\% \) stress magnitude increase. Note the two regions above and below the grain that are in contrast with the high stress zone. These correspond to stagnation zones where very little current flows.

Simulations indicate that the grain is generally being stretched along channel axis and compressed in axis orthogonal plane containing the grain equator. As in the above models, stresses monotonously increase over time. Calculated volumetric strain and stored elastic energy values are negligible.

Varying \( d_c \) (1–2 \( \mu m \)) with fixed total current or fixed current density shows that in the former case narrower channels produce higher stresses, while in the latter the outcome is the opposite, with \( \sim 20\% \) changes in stress magnitude. All tests result in stress patterns similar to the default (figure 6) case. Boundary layer parameter variations indicate strong sensitivity to its thermal resistance. From here on, all models are implemented with material boundary layers enabled.

Next, model 3 is run. Current flow stagnation zone is observed between the grains, but otherwise the pattern around each grain is similar to the single grain case. Proximity effect manifests as additional stress accumulation (figure 7) due to heat entrapment between the two grains (maximum stress values are still just outside the grain boundary near grain equator).

Grain separation distance parametric study indicates that the maximum stress magnitude increases twofold as the distance decreases from the initial 0.5 \( \mu m \) to 0 \( \mu m \). Here the grains are stretched in opposite directions away from the proximity zone and compressed in every other direction.

The model where the two grains are placed in the channel cross section plane yield similar results, where extra stress is accumulated between the grains due to current density relative increase as well as proximity effect. Here stress values are \( \sim 15\% \) greater.

Finally, model 4 is run. It evident that sheet/sheet boundaries act to confine the current flow (figure 8a) to an increasingly narrow channel near the grain boundary. The current is forced through a very small volume close to grain/sheet boundaries (figure 8b). One must note that
Figure 7. Model 3: stress field resulting from grain proximity. Grain separation is 0.2 \( \mu m \); \( d_c = 1.5 \mu m \); current flows from top to bottom.

Figure 8. Model 4: current distribution (a, b), temperature field (c). Note: the radial lines within the grain are geometry drawing artefacts, not domain boundaries.

this is only true for material boundary layer \( \sigma \) values less than or close (in figure 8 equal) to that of the carbide grain, as indicated by parametric studies. This results in a number of intense heat generation zones near and beneath the grain surface, especially in the latter case, where, as a consequence, grain volume overheat relative to the exterior steel matrix is very pronounced: the temperature maximum is within the grain volume (figure 8c, 9a), as opposed to the previous cases.

Stress is still concentrated just outside of the grain surface (figure 9b), but magnitudes are up to \( \sim 40\% \) higher than in the case of homogeneous steel structure. Grain deformation character is the same as in model 2.

Discharge channel width parametric sweep reveals tendencies similar to those observed above,
but unlike the two previous models, this one is much less sensitive to current channel radius variations.

Since \( t_{del} = 100 \mu s \), stress relaxation occurs well before another discharge occurs, as indicated by the frequency-transient analysis of presented models. It is also clear that should the \( t_{dis}/t_{del} \) ratio be high enough, residual electrothermal stress accumulation could, though unlikely, eventually assist RCF induced material failure. This is something that needs to be investigated further however, different models must be constructed for larger time scales.

Upon request, Scepanskis, M. has provided the model used in [17] for examination (see figure 11).

![Figure 9](image9.png)

**Figure 9.** Model 4: radial line temperature (a) and stress field (b).

That model is of similar nature, but its radial dimension is 1 \( \mu m \) and \( t_{dis} = 100 \mu s \) by
assumption. In figure 11, (1) is the grain \( r_g = 0.5 \, \mu m \), (4) is bulk steel matrix: these have the properties given in Tab. 1; (3) represents martensite phase steel needle structure (actually a sheet cross section) [1] and (2) is a domain where orientation differs from (3) and has lower \( \sigma \) and \( k \). It is stated in [17] that \( C_p \) of (3), \( C_{p3} \), is expected to be much less than that of (1), (2), (4) and is set to 1 J/(kg · K) (see [17, Fig. 6]). This is not backed by any valid arguments and is dubious given that for temperature range of interest \( C_p \) and \( k \) of metals are proportional and thus also proportional to \( \sigma \) via the Wiedemann-Franz law (here \( \sigma_3 \) and \( k_3 \) are very high, but \( C_{p3} \) is very low) and the dimensions of (3) domains are not such that thermal/electrical conduction are restricted enough to affect \( C_p \) so drastically. \( C_p \) is varied from 1 J/(kg · K) to 100 J/(kg · K), but resulting stresses are not displayed [17].

Thorough testing indicates that certain effects reported in [17] are a product of artefacts introduced by a very coarse mesh. Moreover, the deformations, although claimed to be significant, are not. Volumetric strain calculations yield values of the order of \( 10^{-3} \), which is well within the small strain model. The deformations seen in [17, Fig. 5,6] are found to be a product of scaling by a factor of \( \sim 5800 \) (much greater in case of [17, Fig. 7]), which was not mentioned. The size of the reported nanovoid is three orders of magnitude below that of the smallest finite element. Tests with a high quality mesh indicate that for \( C_{p3} > 4 \) J/(kg · K) stresses decrease tenfold and for \( C_{p3} > 40 \) J/(kg · K) the model quantitatively reverts to model 2 presented herein: for \( C_{p3} > 300 \) J/(kg · K), the model breaks down, because its \( t_{dis} \gg \tau \). Interestingly, this is where the model quantitatively converges to analytical estimates at \( C_{p3} = 400 \) J/(kg · K) both predict stresses on the order of 0.01 to 0.1 MPa, the former yielding greater magnitudes due to heat impulse rebound at the model boundary.

![Stress Field](image)

**Figure 11.** A reproduction of the numerical model courtesy of Scepanskis et al. [17]: stress field for \( C_{p3} = 40 \) J/(kg · K). Note the similarities between this and figures 6, 9b.

As for the inclusion shape/types, it is abundantly clear that varying these does not result in stresses even close to the fatigue limit/yield strength either. It is, however, interesting and
important to study the underlying physical picture itself so as to predict inclusion behaviour under similar conditions in the future.

Carbide shape study shows that elongating the grain along the discharge channel axis (case 1) or in the channel cross section plane (case 2) is not equivalent to varying the channel width, as one might expect. For equal grain/channel wall spacing it is found that stresses are always higher in case 2, which is due to the smaller curvature radius of the inclusion boundary near the stress maximum area; there is also considerable inclusion internal stress, as opposed to a spherical grain. However, for a $1 \mu s$ discharge, stresses decrease over time in case 2, which can be explained by the fact that the current flow stagnation zones are much larger now and as heat flows away from sources and into these zones, thermal stress relaxation occurs as temperature gradient decreases. In case 1, the dynamics and stress magnitudes are in general similar to what is observed for a spherical grain.

Figure 12. Stress field around an elongated void defect.

Inclusion type study indicated that the most dangerous (in terms of thermal stresses) inclusion type is a void/cavity in steel structure, for which stresses were much higher compared to the carbide grain (figure 12). In fact, for a cavity shaped as in case 2 above, peak stress value is more than double that around the spherical carbide. Ranking the defect types, the carbide grain comes in second, then in, order of descending hazard, come $Al_2O_3$, $MnO$, $TiCN$.

5. Conclusions

• It is demonstrated that for discharges of magnitudes/durations modelled herein the resulting stresses are several orders of magnitude below the fatigue limit/yield strength. It is clear then that premature bearing failure observed by Loos et al. and in other similar tests are not due to the mechanisms proposed in present work, especially given that current densities were, most likely, greatly exaggerated.

• Several noteworthy effects are observed: carbide grain/steel material boundary layer noticeably facilitates stress accumulation at inclusions; grains proximity within the discharge channel greatly increases stress levels at said defects; martensitic structure simulations reveal subsurface heat generation within carbide grains in cases where
grain/steel boundary electrical conductivity is close to or lower than that of the grain interior.

- Results obtained by Scepanskis, M. et al. are shown to have been a product of an unfounded assumption about material thermodynamic properties and numerical model definition and implementation issues.

- It is found that the most dangerous kind of inclusion, by a large margin, is a void in steel structure. Then, in order of descent, come carbide, $\text{Al}_2\text{O}_3$, $\text{MnO}$ and $\text{TiCN}$ inclusions. Inclusion shape studies have hinted that elongated defects, when oriented normally to the current flow, tend to be much better stress concentrators than spherical grains, especially in case of structural voids.

- This work is to be perceived as a semi-quantitative study as well, due to many of the parameter values being unknown or known only to a certain degree of approximation (current density, discharge duration/delay, boundary layer parameters, discharge channel geometry).

- New models must be developed in order to investigate transient response of many-defect bearing steel structure for higher $t_{dis}/t_{del}$ values; energy dissipation at material boundaries and electromagnetic forces are to be accounted for all this cannot be accurately done within the framework assumed herein.

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