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A FINITE ELEMENT STUDY OF THE INFLUENCE OF GRAPHITE NODULES SIZE ON SUBSURFACE CONTACT STRESSES OF AUSTEMPERED DUCTILE IRON GEAR

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Abstract. *Economic advantages and desirable mechanical properties have motivated academic research involving ADI (Austempered Ductile Iron) to replace traditional alloy steels, like AISI 8620 and AISI 4140, in the manufacture of gears. As known, there are graphite nodules inside the ADI matrix which work as stress concentrators in the evolving matrix during the contact between teeth. Each type of ADI has different nodule count and size, which influence on the properties of these materials. Hence, the aim of this work is to study, through finite element modeling, the influence of size and distance between nodules in order to understand previous experimental wear results with ADI. A finite element model of the gears in contact (called global model) is built and analyzed, followed by two local analyses using the submodeling technique. Two types of ADI with different nodule sizes are considered. The results show that the variation of the nodule size, positioned in the highest shear stress region does not substantially affect the stress concentration factor, reaching approximately 2.363 for all tested diameters. On the other hand, the study reveals that the presence of a second nodule can relieve stress in the nodule neighborhood. It was observed that when the nodule is positioned in the parallel direction to the stress flow lines, distant 0.5 to one diameter from another nodule, the second nodule works reducing the stress of the first nodule. This effect is more intense in ADI with smaller nodule size, which is a possible reason for higher contact fatigue strength of ADI with higher nodule count (and consequently with smaller nodule size), as observed in previous experimental studies performed with spur gears on a FZG equipment.*

Keywords: *austempered ductile iron, finite element analysis, graphite nodule, contact fatigue, spur gear;*

1. INTRODUCTION

Austempered Ductile Iron (ADI) is a material with high mechanical strength and ductility, which has been observed as a possible replacer for alloy steels to manufacture gears. Some authors have been studying the influence of the nodules' characteristics on ADI's properties. Dommarco *et al*. (2006) investigated the performance of materials with smaller nodules showing that it affects positively the fatigue life by interfering in crack ramification (propagation). Furthermore, they showed that a higher nodule count improves the rolling contact fatigue life of the materials with similar structure.

Previous experimental studies performed with gears using a FZG equipment at the Universidade Tecnológica Federal do Paraná (UTFPR) also investigated the fatigue life of ADI gears (Koda, 2009; Martinez, 2011). Figure 1 shows the pinion teeth photomicrograph for two types of ADI: ADI1 and ADI2, with different graphite nodule sizes and distribution, before and after the fatigue tests.

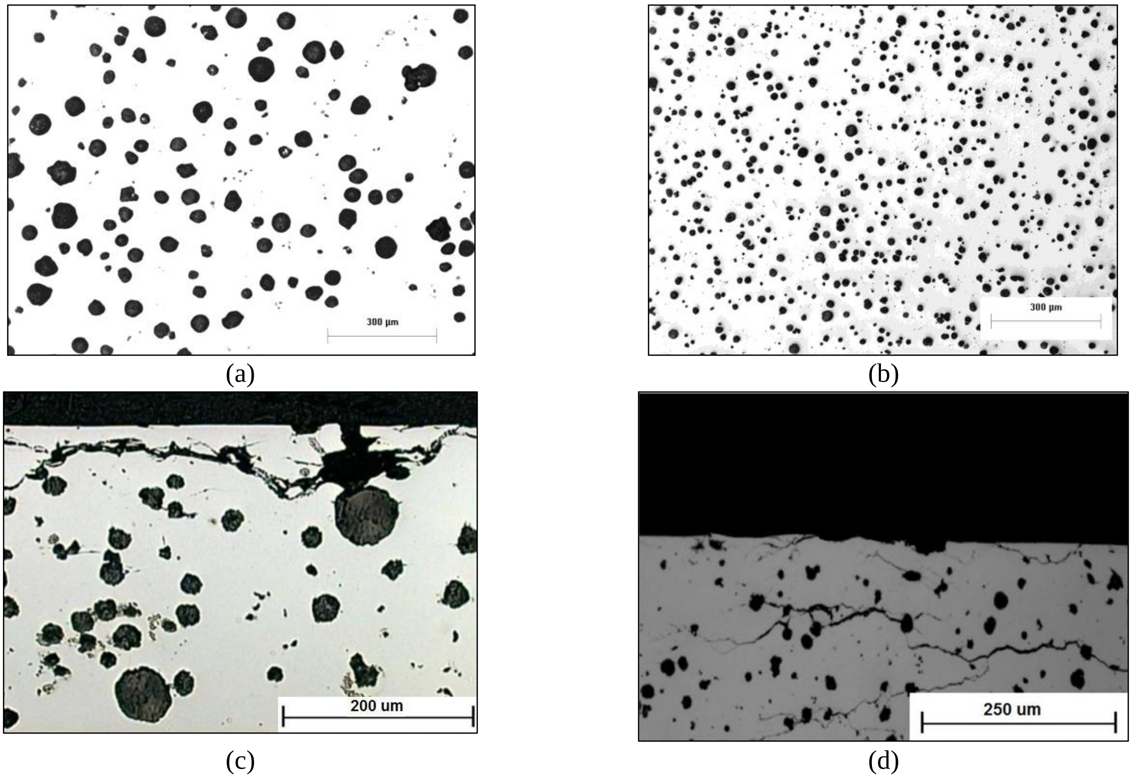


Figure 1. Light microscopy, unetched. Size, shape, and distribution of graphite nodules in region of pitch line of: (a) ADI 1 - 196 (nodules/mm^2); (b) ADI 2 – 532 (nodules/mm^2); transversal section of teeth (c) of ADI 1 after FZG gear tests and (d) of ADI2 after FZG gear tests. (Guesser *et al.*, 2012).

Note that in the ADI 2 there are more cracks, with branches and also cracks connected between the nodules, both spreading toward the surface and into the tooth. Analyzing ADI 1, the cracks present less branching ability and tend to grow toward the tooth surface. This fact can provoke a higher material release (spalls) and speed up the wear process.

Figure 2 presents the failure probability in relation of load cycles (Weibull chart) for both ADIs. It is possible to observe that, besides the fact that ADI 1 and ADI 2 have very similar compositions, the ADI 2 is more suitable for gear application than the ADI 1, and the main difference between them is related to the size of graphite nodules. The hypothesis is that the smaller size nodules (ADI 2) lead to a higher local stress concentration factor and to a formation of cracks from the nodules in shorter times. However, for the formation of pitting craters, beyond the period of cracks nucleation, the propagation stage is also very important.

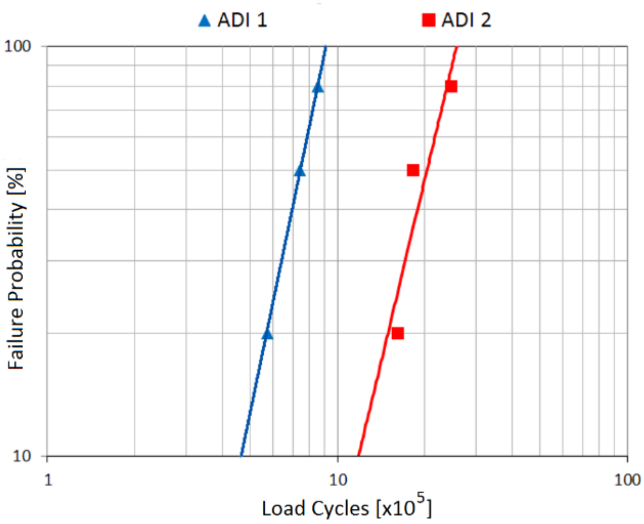


Figure 2: Failure probability versus load cycles for: (▲) ADI 1 and (■) ADI 2 (adapted from Guesser, 2012).

The presence of graphite nodules provides antagonist effects over the crack nucleation and growth stages. The graphite induces a stress concentration in the evolving matrix (Gans *et al.*, 2015), which makes it easier to nucleate cracks. However, when a crack grows, it may reach a graphite nodule, that increases the tip radius substantially, and this reduces its growth rate. The pitting generation in gears seems to be controlled by the crack propagation, so that the ADI with a higher amount of graphite presents a lower pitting generation rate.

Greno et al. (1999) explain that in ADIs with higher amount of nodules, the higher is the occurrence of crack branching mechanisms, which lead to a greater resistance to pitting formation, as observed in ADI 2 compared to ADI 1. As analytical solutions are unavailable to analyze the influence of nodules, the Finite Element Analysis (FEA) was chosen here to perform some comparisons. FEA is widely used in many applications, including porous and composite materials, as observed by Kohout (2001).

Therefore, the aims of the present study were:

1. To understand the effect of the graphite nodules dimensions on the state of subsurface contact stresses of gear teeth;
2. To understand the effect of the distance between graphite nodules on the subsurface shear stresses.

2. ANALYTICAL AND NUMERICAL PROCEDURES

Considering that the aim of this study is to understand the characteristics of the stress field near to the tooth contact of Austempered Ductil Iron gears, the procedures were divided into three stages:

1. Definition of mechanical properties and characteristics of graphite nodules, in order to provide either input parameter to the numerical model and analyses of final results;
2. Detail of the numerical model used and additional information about the analysis techniques used;
3. Parameter definition, similar to a stress concentration factor, which enables the understanding of how graphite nodules affect the stress field in the analyzed region.

2.1 Graphite nodules

As already mentioned, the experimental results obtained for ADI 1 and ADI 2 were chosen as references, in order to compare with the numerical results obtained in the present work. Some characteristics of the two kinds of ADI are shown in Table 1 and 2 (Guesser, 2012). This data is important to implement the numerical model properly and to analyze the results.

Table 1: ADIs nodules characteristics (Guesser, 2012).

	Form type	Nodularity (%)	Graphite fraction area (%)	Nodule count (nodules/mm^2)	Average nodule diameter (µm)
ADI 1	VI	99	13	196	29.1
ADI 2	VI	98	13	532	17.6

Table 2. ADIs mechanical properties (Guesser, 2012).

	Ultimate tensile strength (MPa)	Elongation (%)	Young's modulus (GPa)	Hardness (HRc)	Poisson's ratio
ADI 1	1546	2.1	186.9	56	0.25
ADI 2	1273	3.5		54	

2.2 Finite element modeling

Knowing the characteristics of the materials acquired experimentally, the software ANSYS Workbench was used to perform the numerical analysis by finite elements. The necessary steps to generate the results were a global analysis followed by two local analyses using a tool called submodeling. This tool was chosen in order to provide a way to refine the mesh around the nodules by cutting the model in the region where it is located. This different modeling approach allows the model to be solved either with the significant magnitude order difference between the gear and the nodules, by creating an initial evaluation of a coarser global model, followed by an analysis of the interested region, where the nodules are located. The procedure used to perform the analyses is shown schematically in Fig. 3.

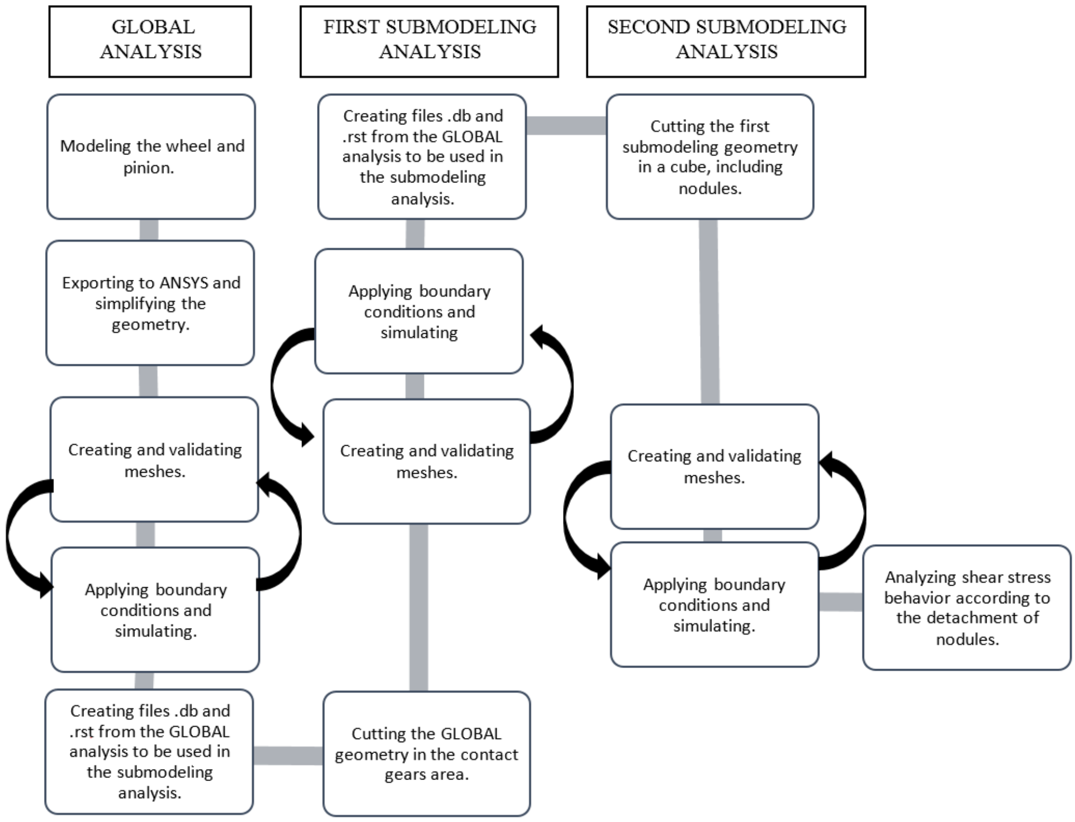


Figure 3. Schematic sequence of global and submodeling analysis.

2.2.1 Global Analysis

The geometry of the wheel and pinion were modeled using the software SolidWorks and $GearTeq$ ® to generate the profile of the gears. Subsequently, the model was exported to ANSYS® to perform the analyses. The dimensions and the characteristics of the gears were based on the previous experimental studies at UTFPR using the FZG machine (Koda, 2009). The characteristics of the gears used and the torque applied can be observed in Table 3 and 4.

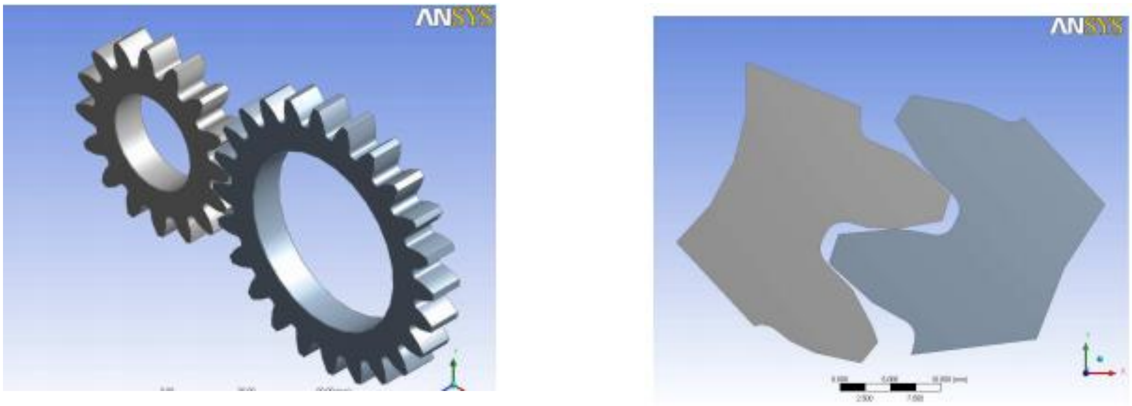
Table 3: Gear type C parameters (Koda, 2009).

Parameter	Unit.	Pinion	Wheel
Number of teeth – Z	–	16	24
Module – m	mm	4.5	
Center distance	mm	91.5	
Pressure angle – α	°	20	
Face width – b	mm	14	
Addendum modification – x	–	+ 0.182	+ 0.171

Table 4: Loading stages and speed used in contact fatigue tests (Koda, 2009).

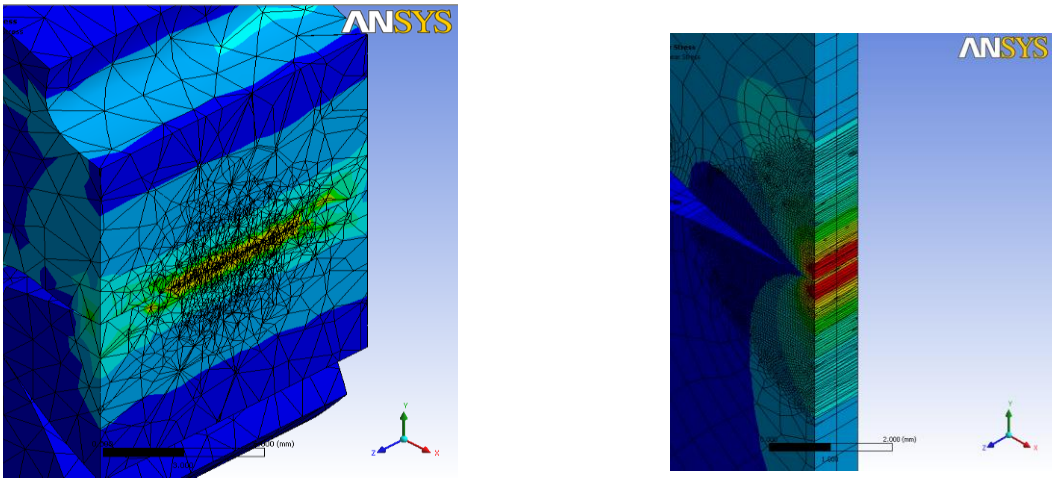
Stage of test	Wheel speed (rpm)	Torque (N.m)	Normal load (N)	Oil temperature (°C)
Running-in (k6)	1450	135.3	3990.7	60
Pitting (k9)		302.0	8927.2	90

Some simplifications were applied in the model. The first procedure was the cutting of the gears in the area where the contact occurs, to reduce the time to generate the results (Fig.4). In addition, the thickness of the gears were reduced from 14mm to 1mm to avoid the shear and von Mises stresses heterogeneity in the Z direction (Fig. 5). At this point, after this simplification, to guarantee the same contact pressure of the original problem, the torque applied was reduced 14 times. The model was validated by using an iterative procedure, in order to reach the ideal mesh the model.



(a) (b)

Figures 4. Geometry generated by the CAD software and the first simplification created in the softwareANSYS®, (a) Isometric view of gears assembled (b) cross section showing the contact between teeth.



(a) (b)

Figure 5. Shear stress field in the region where the contact occurs: (a) using tooth thickness of 14 mm; (b) after the reduction of the gears' thickness to 1 mm.

The following boundary conditions were imposed to the model:

- A torsion moment was applied clockwise in the pinion with a modulus of 21.571 N.mm (the torque 302.000 N.m applied in the experimental test was reduced 14 times, because of the thickness reduction).
- The pinion was fixed in the Z and Y direction. The only free movement is the tangential.
- The movement of the wheel was restricted in all directions in order to generate the reaction forces in the pinion.
- Restriction of the movement in the Z direction in order to create a homogeneous behavior in the Z direction.

2.2.2 Local analysis

The very different order of magnitude of gears and nodule dimensions leads to the use of a tool called submodeling. It is a very useful tool to achieve an accurate model, which enables a much more refined mesh around the nodules. The analysis using this tool is called a local analysis, which is detailed in the following.

2.2.2.1 First local analysis

The geometry of the local analysis consists in a cut of the original model (Global), where it is intended to apply the refinement. The first Local analysis consisted of a square of 2.5mm side and 1mm thick where the gear contact occurs (Fig. 6). The mesh in this model was reduced to its general elements reached 0.045mm and the elements in the contact area reached 0.02mm, using the command “contact size”. Meanwhile, the magnitude of the mesh was not the same of the nodules, and it was necessary to redefine the geometry again in order to reach smaller meshes.

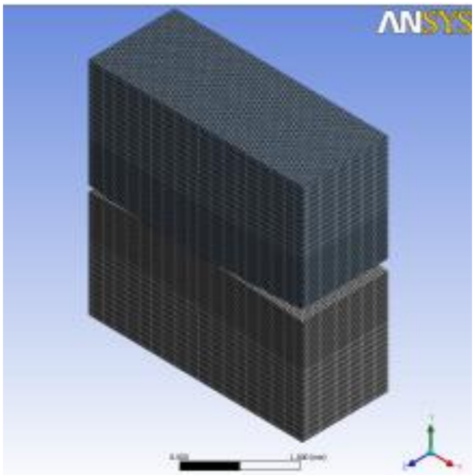


Figure 6. Geometry of the first local analysis. A square of 2.5mm side and 1mm thick located on the contact of the gears.

2.1.4.3 Second local analysis

The submodeling command was applied in a smaller geometry to reach the order of magnitude of the nodules (29.1 µm to ADI 1 and 17.6 µm to ADI 2). After some analyses, it was observed that an advantageous geometry would be a cube with 0.3 mm side.

The cube centroid in the second local analysis was positioned approximately 200 µm from the contact surface of the two gears, where, according to Hertz contact theory, the maximum shear stress occurs (Johnson, 1987). The 0.3 mm side cube mesh was also validated, reaching elements with 0.006 mm, a suitable scenario to start the analyses with nodules.

2.3 Nodules and the stress concentration factor- K_{ntns}

In order to analyze and compare the results, firstly, the shear and von Mises stresses were collected at some chosen points in the 0,3 mm side cube without nodules (1); after, a nodule was positioned in the maximum shear stress point at 200 µm from the contact surface (2) and finally, a second nodule was included in two different directions from the first nodule: parallel and perpendicular to the stress flow generated by the contact between gears (Figure 7 – 3 (a) and (b) respectively). The scheme of Figure 7 illustrates the procedure.

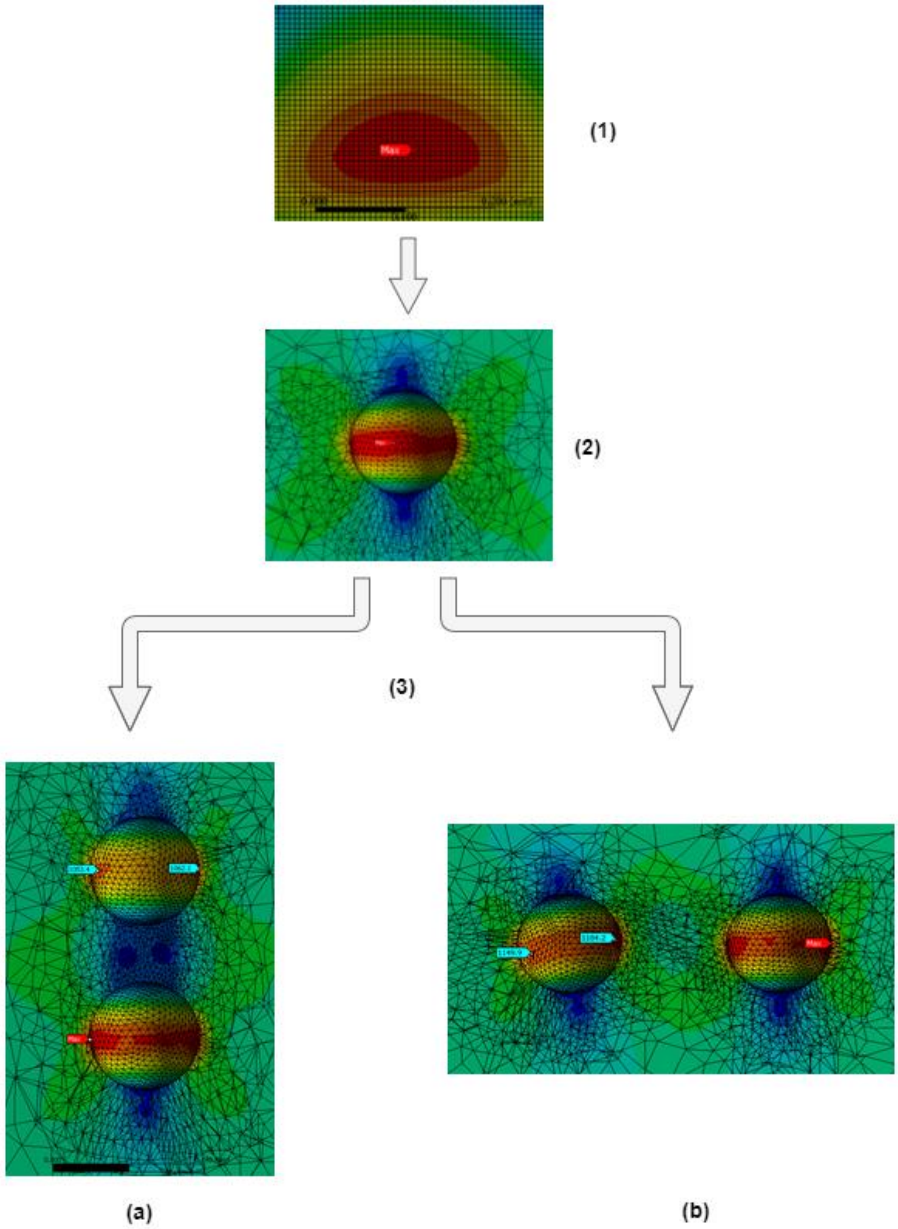
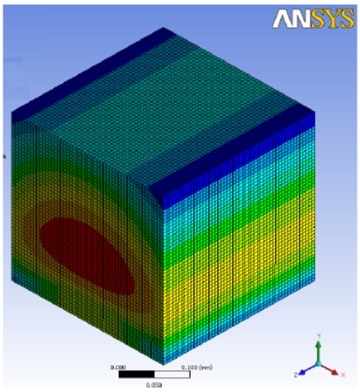
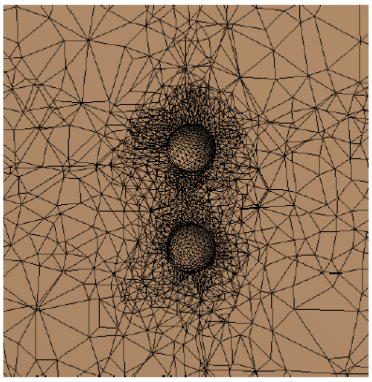


Figure 7. Sequence of analysis performed: Shear stress generated by (1) contact of two gears without nodules; (2) one nodule with different diameters and (3) two nodules in two different directions, parallel and perpendicular to the stress flow respectively (a) and (b).

The models with nodules were also submitted to a mesh validation. Meanwhile, it was observed that because of the non-uniformity of the geometry, the mesh cannot be homogeneous, and a command to refine the mesh around the nodules was used, as it is possible to observe in Fig. 8.



(a)



(b)

Figure 8. (a) Uniform distribution of shear stress in a cubic model without nodules; (b) Inclusion of nodules with refined mesh around them.

The geometry of the graphite nodules was simplified as an empty sphere. This simplification is possible because of the nodularity of both materials ADI 1 and ADI 2 that is approximately 100%, which means that the nodules are almost spherical (Table 1). The nodules can be also simplified as empty spheres. The reason for that is explained by the difference between the Young's Modulus of graphite module and the ADI matrix (Table 5) (Yan et al., 2011).

Table 5. Elastic properties of ADI (Yan et al., 2011).

Material	**Young's Modulus (GPa)**	**Poisson's ratio**
Graphite nodule	35	0.126
ADI matrix	210	0.290

3. RESULTS AND DISCUSSION

The value of K_{ntns} was determinated for four different nodule diameters. The isolated nodule was positioned where the maximum shear stress occurs (0.200 µm from the contact surface between gears). Figure 9 shows that K_{ntns} is quite similar for all analyses, approximately 2.363. This result shows that K_{ntns} is not dependent on the nodule size in the region of maximum shear stress.

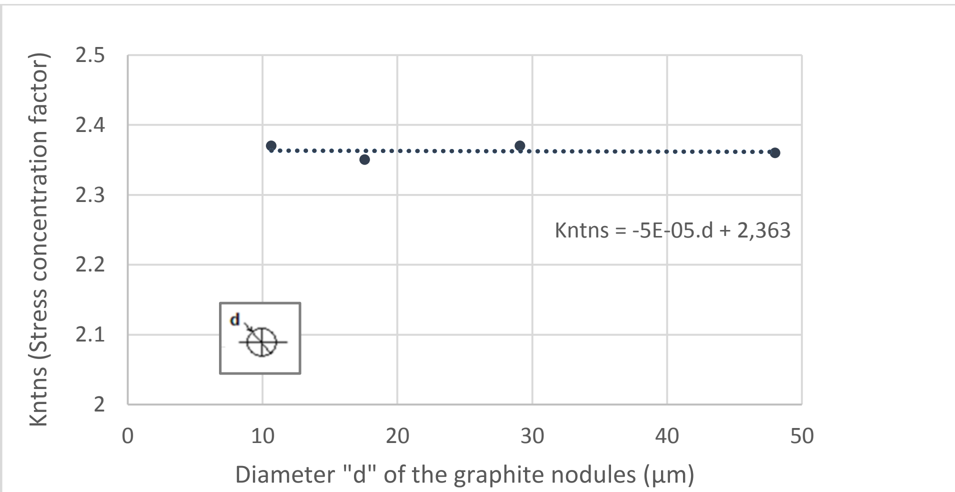


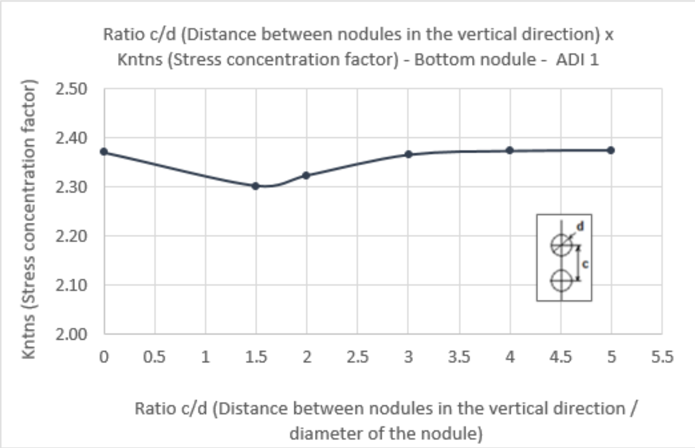
Figure 9: K_{ntns} for four different nodule sizes.

After the analysis using one nodule, a second nodule was included in two different directions to understand the influence of one nodule on another:

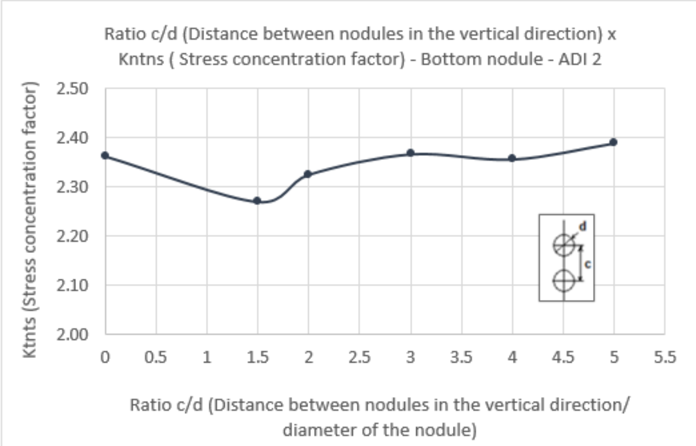
- Horizontally, or in the perpendicular direction to the to the stress flow, a second nodule was located with 1, 2 and 3 diameters distance from the reference nodule;

- Vertically, or in the parallel direction to the to the stress flow, a second nodule located with 0.5, 1, 2, 3 and 4 diameters from the reference nodule.

Figures 10 (a and b) and 11 (a and b) show the results, where the x-axis is the ratio between the distance “c”, between nodules, and the nodule diameter “d”, and the y-axis represents K_{ntns} .

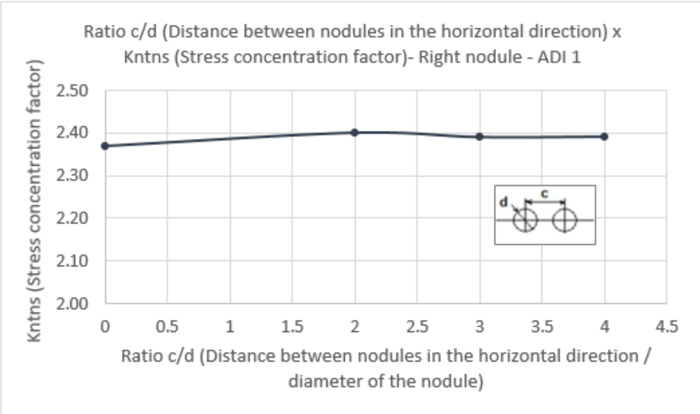


(a)

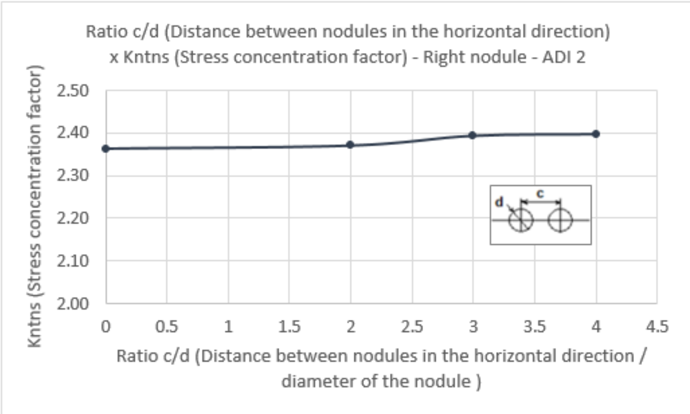


(b)

Figures 10. Graphs of K_{ntns} in vertical analysis: (a) ADI 1 and (b) ADI 2



(a)



(b)

Figures 11. Graphs of K_{ntns} in horizontal analysis: (a) ADI 1 and (b) ADI 2.

Observing the results, it is possible to conclude that when two nodules are positioned with a distance of 0.5 and 1 diameter, parallel to the stress flow (vertical), either to ADI 1 or to ADI 2, the second nodule provides stress relief in the first nodule. This behavior is observed by the reduction of 3% and 4% in the shear stress for ADI 1 and ADI 2 respectively, when the distance between nodules is 0.5 nodules of graphite and 2% for both materials when the distance between nodules is 1 diameter. Figure 12 shows a similar phenomenon that happens to metal sheets with holes, when they are aligned to the stress flow lines. It is possible to observe that when they are close to each other the curves are smoother, reducing the effect of stress concentration, if compared with the isolated hole.

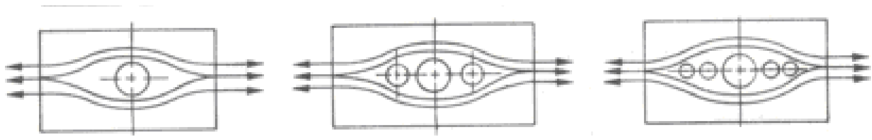


Figure 12. Stress flow for metal sheet with holes (Deutchman (1975) *apud* Franquetto, 2007).

Observing Figures 10 (a and b) and Figure 11 (a and b), it is possible to observe that when the distance between nodules is bigger than 2 diameters, the values of K_{ntns} tend to a constant value, which means that the second nodule does not affect significantly the first nodule anymore.

On the other hand, in the case where the two nodules are positioned perpendicularly to the direction of the stress flow (horizontal), it was observed that the values of K_{ntns} have less than 1% of variation when the distance between nodules changes. In this case, it is possible to conclude that the second nodule does not exert significant influence on the second nodule, regardless of the distance.

The results show a possible reason for the best properties of the material ADI 2 compared to ADI 1. Besides the fact that the percentage of graphite in both materials is almost the same, the nodules count of ADI 2 is much bigger than for ADI 1, which means that the nodules of ADI 2 are closer than in the ADI 1. The mean distance between the nodules in the ADI 2 is 35.6±9 μm. This distance is approximately the distance from one nodule to the surface of another, as was observed in this study, and it can be the reason for the reduction of K_{ntns} in this material.

4. CONCLUSION

In the present study, a finite element model using ANSYS Workbench was created. The submodeling technique was employed to analyze the stress generated by two gears in the order of magnitude of ADI nodules.

Analyses with one nodule show that the variation of the diameter does not significantly affect the stress concentrator factor K_{ntns}, reaching approximately 2.363 for all tested diameters. Further analyses using two nodules positioned in the perpendicular direction to the stress flow lines showed that the influence of the second nodule on the first one is really small. Nevertheless, when the nodules are positioned in the parallel direction of the stress flow, distances 0.5 and 1 diameter between nodules, the second nodule works to reduce the stress, which is more intense to ADI 2.

This study contributed to show the antagonist effects of the nodules in the Austempered Ductile Iron. As known, the graphite nodules induce stress concentrations in the evolving matrix, which contributes to the crack nucleation. On the other hand, materials with a high amount of nodules lead to a higher resistance to pitting formation, characteristic that is observed in the ADI 2 when compared with ADI 1.

This phenomenon can be explained by the fact that the nodules act as obstacles to cracks development inside the matrix, but also, according to the present study, can be a consequence of the fact that the nodules inside ADI 2 are closer to each other, which can lead to a stress relief and may reduce the negative effect of the nodules in the crack nucleation.

REFERENCES

Dommarco, R. C., Jaureguiberry, A. J. and Sikora, J A., 2006. Rolling contact fatigue resistance of ductile iron with different nodule counts and matrix microstructures. Wear, 261, p. 172-179.

Gans, L.H.A., 2013. “Numerical Analysis for Wear Study for Cast Iron Used in Gears”, Research Report of the Scientific Initiation Program - UTFPR. Curitiba, Brazil.

Greno, G.L., Otegui, J.L. and Boeri, R.E., 1999. Mechanisms of fatigue crack growth in ADI. Int. J. Fatigue.

Guesser, W., Koda, F., Martinez, J. and Da Silva, C. 2012. Austempered Ductile Iron For Gears. Congresso SAE Internacional: 2012-36-0305. Brazil.

Johnson, K.L., 1987. Contact Mechanics, Cambridge University Press, Cambridge.

Koda, F., 2009. “Study of contact fatigue in cylindrical spur gears”. Master's Dissertation (Mechanical Engineering) – UTFPR. Curitiba, Brazil.

Kohout, J., 2001. A simple relation for deviation of grey and nodular cast irons from Hooke’s Law.Materials Science and Engineering: A, Volume 313, Issues 1–2, 3, p 16-35.

Martinez, J. A. B., 2011. “A Comparison of wear resistance due to contact fatigue of gears made of AISI 4140 steel and austempered nodular cast iron”. Master's Dissertation (Mechanical Engineering)- UTFPR. Curitiba, Brazil.

Yan, W., Pun, C. L., Wua, Z., 2011. Some issues on nanoindentation method to measure the elastic modulus of particles in composites. Composites: Part B 42: 2093–2097.

Franquetto, P. R., 2007. “Parametric optimization of classical stress concentrators”. Final Paper (Mechanical Engineering) – UTFPR. Curitiba, Brazil.

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