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# MATHEMATICAL MODELING OF FATIGUE DAMAGE IN 4140 STEEL USING FINITE ELEMENT METHOD[1]

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**Abstract**
The fatigue life of AISI 4140 steel under certain conditions using alternating stress in specimen standard in the fatigue test of flexion rotation type was studied. The finite element method (FEM) was applied by commercial software ANSYS quantification of fatigue damage in this material. The effect of roughness, machining, polishing and annealing was evaluated in the generation of fatigue damage. The results obtained by experimental, analytical and numerical method was compared. The rule linear Palmgren-Miner applied was adequate in predicting the fatigue failure when applied to the experimental results. This Palmgren-Miner model can be applied for control tools process production mechanical components metallic used and improvement industry metal mechanical using in CAD simulation.
**Key words:** Mechanical fatigue; Damage fatigue; Damage accumulation; Finite element method.

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## 1 INTRODUCTION

All engineering materials used in the metal mechanics industry can use the finite element numerical simulation to predict the fatigue life of mechanical components. You can enable this prediction of life through the quantification of plastic deformation suffered, the evaluations of mechanical degradation of the material, and especially the accumulate that can cause fatigue damage in structural support. The research on fatigue indicates trends in the application of constitutive models based on the theory of harm. Thus comparisons between results predicted by these models, producing successive refinements between the values of numerical simulations and the experimental values to generate correction factors are one of the technological importances of this study. The objective of this research project was to compare life in fatigue and damage in the specimen standard by the analytical method, numerical and experimental an AISI 4140 steel. It was possible to apply the theoretical model for calculating the damage as the Palmgren-Miner rule, the results obtained experimentally. For this purpose, we used the analytical method, using equations, numerical simulation and the experimental method in body-of-proof standard. The damage caused by changes in the material surface under cyclic loading was measured alternately. Thus, studying the effect of surface roughness due to different manufacturing processes of the specimens: machined and polished measuring the damage produced in each case separately, and find the range of the thermal treatment of stress relief on the surface of the specimen in the generation of damage in fatigue was working objects in conducting this experiment.

## 2 STATE OF THE ART

The state of the art of fatigue damage in components and structures of materials engineering involves issues of quantification, accuracy, damage and specific conditions of loading. The topic has been investigated for over a century and continues to be researched by Jono,[(1)] whose understanding of the concept of cumulative fatigue damage and crack growth under variable load was the object of research for over thirty years and a summary of the estimation of fatigue life is shown in Figure 1. When life is estimated based on SN curves, several factors can affect the fatigue life and damage accumulated value changes depending on the material and loading conditions. There may be effects on the complex relationship between stress-strain due to strain rate and loading history. There is also the method of estimating crack growth for experimental work under load variable amplitude. The history of the load in this case only affects the behavior of crack closure and the increment of crack growth can be well estimated by linear integration. The results led to the conclusion that the law accumulated damage was confirmed to be a good approximation to predict the life under variable-amplitude loading scheme for low-cycle, and that the effect of load variations appears on the stress-deformation, making estimate of life based on SN curves. Besides that there are other complex factors that affect the fundamental conception of the fatigue damage accumulation, such as: the environment, the transition mechanism of cracking due to load variations and the effect of unsteady loads that require more studies and research.
According Puchi-Cabrera et al.[(2)] the mechanical properties of materials are changed due to fatigue damage, and developed a model to predict fatigue life when subjected to variable amplitude voltage. The objective was to evaluate the effect of fatigue damage in the change of properties such as modulus, strain resistance, flow and

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ductility, and concluded that the damage induced in notched sample flow caused an increase in voltage, while the other properties remained constant, and also observed that the number of fatigue cycles can be predicted by the linear cumulative damage (Palmgren-Miner rule).
The effect of the machining parameters on the surface of the test piece was studied by Novovic et al.(3) order fatigue performance and found that in the absence of residual stress value of the roughness has a strong influence on the fatigue life, and that the presence inclusions nullifies the effect of surface topography. Thus for surface roughness ($R_a$) from 2.5 to 5.0 microns the residual stress is not a significant factor in fatigue life and surface treatment is beneficial to the specimen, but depends on the properties of materials.

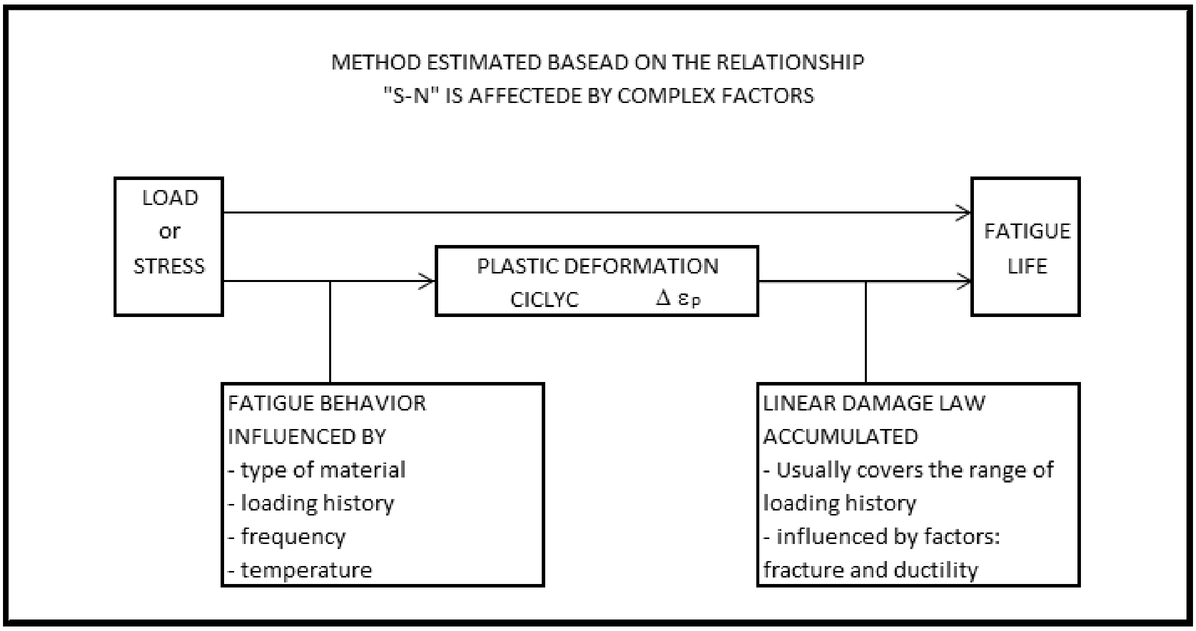

**Figure 1.** Summary of the estimation of fatigue life.

The definition of a variable representing the state of deterioration of a part, in order to characterize the fatigue damage is a complex problem according Mansur.(4)
According Warhadpande et al.(5) fatigue damage in the test piece of steel AISI 4140 under various loading conditions and deformation can be obtained by varying the modulus of elasticity (E) where the experimental curve of damage (D) versus number cycle (N) can be used to property determine the resistance ($\sigma_R$ ).
Zhang et al.,(6) the parameters of materials can be obtained by the test results of fatigue in the specimen standard, where the numerical simulation in a commercial software platform can be used to predict the onset of fatigue crack.
Finally the accumulated damage was confirmed to be a good approximation to predict the life history as the load causes a state of increasing damage. The Palmgren-Miner rule is shown as a good approximation for calculating the damage.
The variation of mechanical properties can be a way to assess the damage caused by fatigue in the material. Therefore in this experiment it was decided to test this hypothesis, the design of work anchored in the analytical model proposed which is based on variation of elasticity modulus of the material. And determining the maximum possible strength of the material from the graph of experimental damage number of cycles.

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## 3 EXPERIMENTS AND RESULTS

The experimental approach adopted in the development of this study was to compare the methods used to predict the fatigue damage (Figure 2), and the method is divided into two stages, namely.

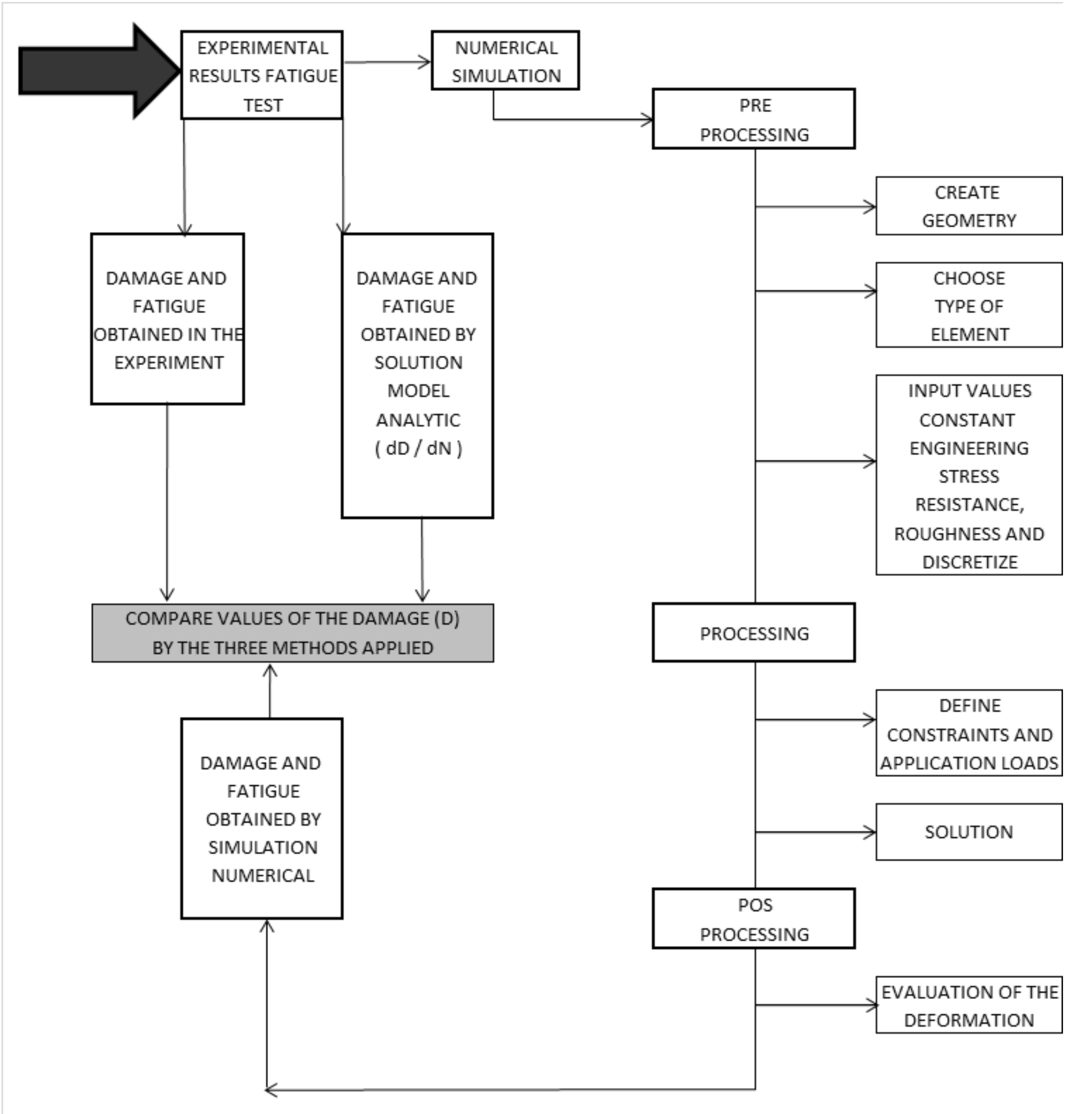


**Figure 2.** Methodology used in the experiment.

- Step 1 – the first step was to estimate the accumulated damage (D) the fatigue life (N) and a numerical solution was to evaluate the analytical model developed. The equation proposed by the analytical method was calculated by input parameters and boundary conditions used in the experimental stage;[7]
- Step 2 – in the second stage was performed in the simulation plane stress specimen standardized achievement tests for rotating bending fatigue through the platform commercial software ANSYS. Thus, simulating the conditions laid down in shallow Lopes[7] experimental work, such as the difference in surface roughness due to the process used to manufacture the specimen, and adopting the technique of refining the mesh in the regions most susceptible to fatigue failure, can to obtain the value of the damage caused on the proof-of-the approximate solution of the equations of charge.

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### 3.1 Analytical Method

The equation proposed by Warhadpande et al.,[5] expresses the variation of damage (D) fatigue to the number of cycles (N).

$$\frac{dD}{dN} = \left( \frac{\Delta\sigma}{\sigma_R(1-D)} \right)^m \quad (1)$$

$$\sigma_R = \sigma_{RO}\left( 1 - b\frac{\sigma_{média}}{\sigma_u} \right) \quad (2)$$

$$\overline{E}_c = E(1-hD)$$

$$\overline{E}_t = E(1-D) \quad (3)$$

$$\overline{\nu} = \nu \quad (4)$$

Where:

- m - exponent for 4140 steel: (value of the "m" = 3.97);
- $\sigma_R$ - limit final strength;
- $\Delta\sigma$ - stress range;
- $\sigma_{RO}$ - reverse loading stress (value of $\sigma_{RO}$ = 6486,5 MPa);
- $\sigma_u$ - stress rupture;
- b - coefficient modification for 4140 steel: (value of the "b" = 0.41);
- $E_c$ - elasticity modulus in compression;
- $E_t$ - elasticity modulus in traction;
- $\nu$ - rate Poisson;
- $\underline{\nu}$ - rate Poisson of the damage.

Solving the equations 1-4, the boundary conditions to obtain the equation 5:

$$D = \left\{ 1 - \left[ 1 - (m+1)\left( \frac{\Delta\sigma}{\sigma_R} \right)^m N \right]^{\frac{1}{m+1}} \right\} \quad (5)$$

Where:
D - variable damage

- N - number of cycles
- m, $\sigma_{RO}$ and b are empirical constants introduced in the evolution law of damage. It is assumed the stress range ($\Delta\sigma$) is constant.

### 3.2 Numerical Method

It is intended by simulation study the effect of the roughness in the specimen machined and polished under cyclic loading alternate generation of fatigue damage during a given time. The voltage values ($\sigma$) and the number of cycles (N) to be fed to the numerical come from study conducted by Lopes.[7] The mechanical properties of AISI 4140 steel as the modulus of elasticity, the limit of fatigue strength, the yield strength and tensile strength at break values are needed to feed the simulation software. In this case the values used are those measured in studies by Lopes.[7] In this simulation by ANSYS, the specimen standard dimensions in Figure 3, the test shall be subjected to fatigue loadings. The finite element adopted in this study will be

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the platform Ansys tetrahedral 4 node. For comparison in this study will be used 244 nodes, 1245 nodes (standard software) and 1719 nodal points of the tetrahedral element to check the accuracy of results generated by numerical simulation (Figure 4).

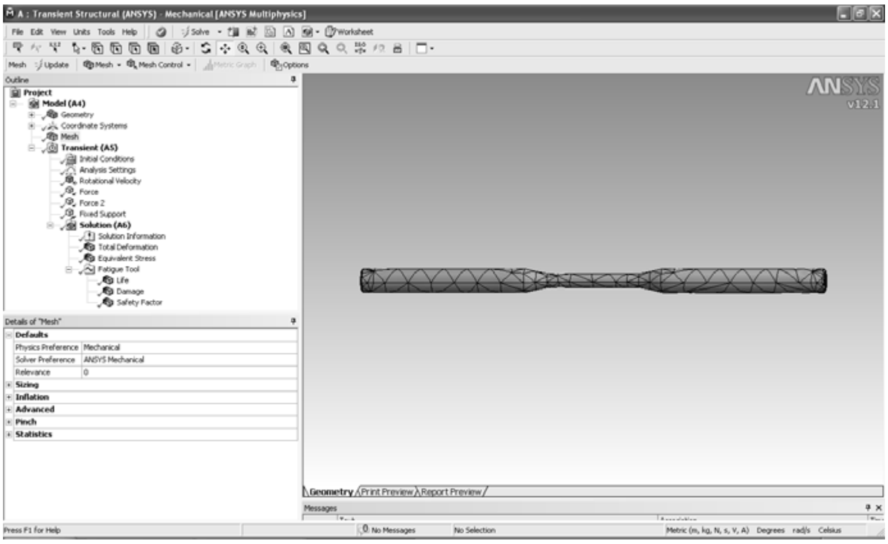


**Figure 3.** Specimen standard.

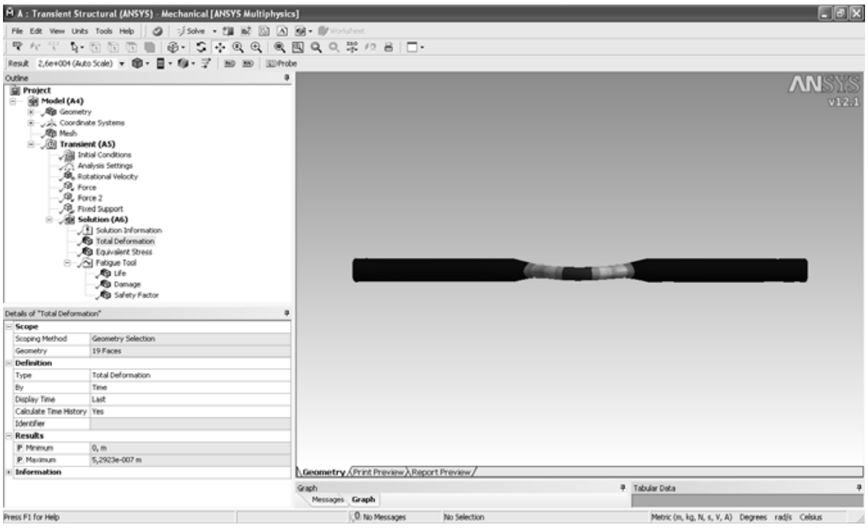


**Figure 4.** Simulation numerical in ANSYS.

### 3.3 Analytical Model Application

Was added to experimental data Lopes(7) damage results obtained by assuming a linear rule fatigue life than 1,000,000 cycles to 10%, 50% and 90% failure, as presented in the table 1 for a proof-of-body machined. The specimen fatigue test were machined, polished and subjected to annealing treatment. Puchi-Cabrera *et al.*(2) observed that the number of fatigue cycles can be predicted by the linear cumulative damage (Palmgren-Miner rule). They developed a model to predict fatigue life when the specimen is subjected to variable amplitude voltage. The evaluation of the mathematical model with the experimental results of the fatigue test was performed using the coefficients of the empirical material AISI 4140 proposed by Warhadpande *et al.*(5) and the values of mechanical properties used in the experiment.

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From the solution of the equation, obtaining the value of damage (D) from the number of cycles (N). The graph in Figure 5 shows a relationship between the damage (D) and number of cycles (N) generated by applying the model to experimental condition specimen machined as provided by Warhadpande et al.[(5)] The experimental results of the condition specimen polished are illustrated by the graph in Figure 6.

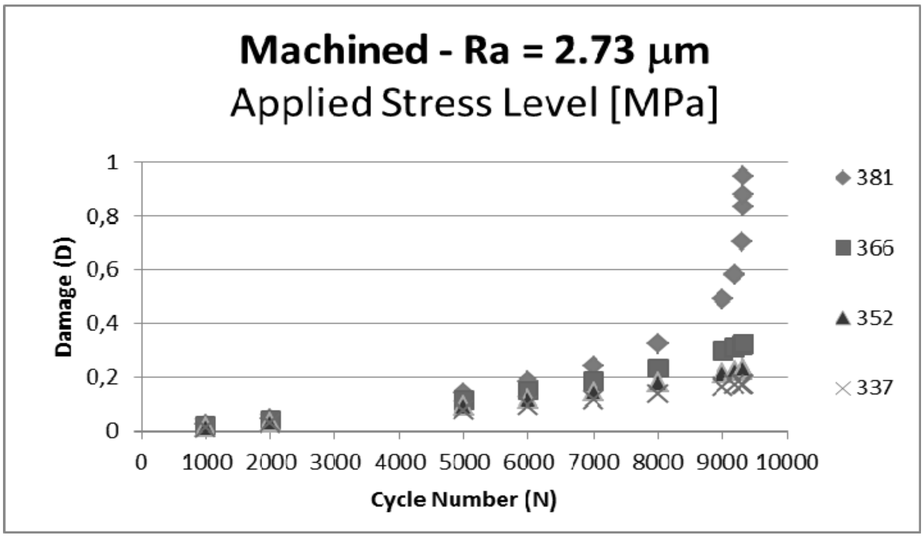

**Figure 5.** Graphic Damage versus Cycle Number: Machined Condition.

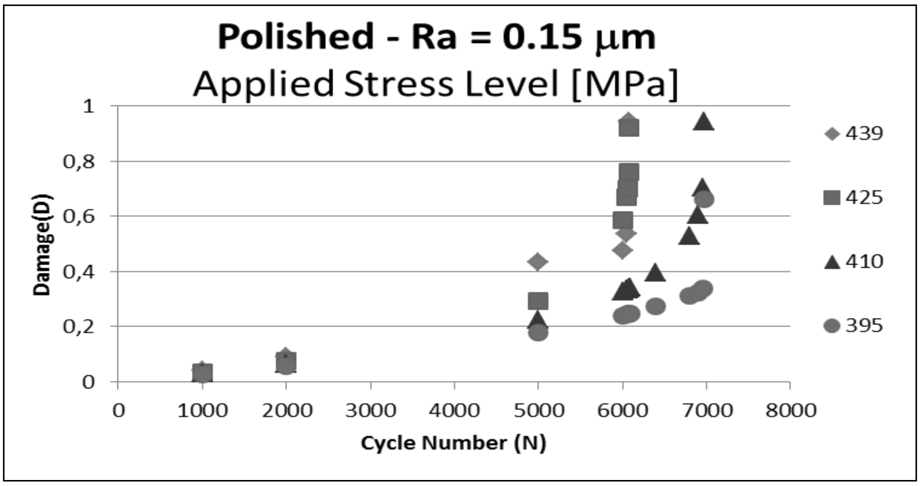

**Figure 6.** Graphic Damage versus Cycle Number: Polished Condition.

Comparison Methods Applied: Linear Rule, and Numerical Simulation Model Analytic by Ansys.
The Tables 2 and 3 illustrate the results obtained for the fatigue damage in applying the three methods provided by the methodology: the linear rule (experimental), the analytical model and numerical simulation by ANSYS program under the conditions presented by the roughness of specimen of the experimental results.

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**Table 1.** Results for specimen machined

| Roughness Average ($R_a$) = (2.73 ± 0.36) µm | | | | | | |
|---|---|---|---|---|---|---|
| Specimen | Experimental | | | Rule Linear | | |
| | Stress (Mpa) | Cycle Aplied | Fracture? | Damage with failure 10% | 50% | 90% |
| 1 | 439.0 | 1,108298 | YES | 0.090 | 0.451 | 0.812 |
| 2 | 424.5 | 2,541757 | NO | 0.039 | 0.197 | 0.354 |
| 3 | 439.0 | 1,720474 | YES | 0.058 | 0.291 | 0.523 |
| 4 | 424.5 | 3,029888 | NO | 0.033 | 0.165 | 0.297 |
| 5 | 439.0 | 831162 | YES | 0.120 | 0.602 | 1.083 |
| 6 | 424.5 | 2,042000 | NO | 0.049 | 0.245 | 0.441 |
| 7 | 439.0 | 2,000381 | NO | 0.050 | 0.250 | 0.450 |
| 8 | 453.5 | 1,186892 | YES | 0.084 | 0,421 | 0,758 |
| 9 | 439.0 | 1,165466 | YES | 0.086 | 0.429 | 0.772 |
| 10 | 424.5 | 1,244599 | YES | 0.080 | 0,402 | 0,723 |
| 11 | 410.1 | 1,637713 | YES | 0.061 | 0.305 | 0.550 |
| 12 | 395.6 | 2,014828 | NO | 0.050 | 0.248 | 0.447 |
| 13 | 410.1 | 2,007513 | NO | 0.050 | 0.249 | 0.448 |
| 14 | 424.5 | 1,501524 | YES | 0.067 | 0.333 | 0.599 |
| 15 | 410.1 | 2,006053 | NO | 0.050 | 0.249 | 0.449 |

**Table 2.** Machined and Annealed Condition: $R_a$ = (4.79 ± 0.13) µ m

| Specimen | Experimental | Numerical | Analytic |
|---|---|---|---|
| 1 | 0.0027 | 0.0100 | 0.0060 |
| 2 | 0.0025 | 0.0115 | 0.0071 |
| 3 | 0.0028 | 0.0100 | 0.0060 |
| 4 | 0.0023 | 0.0115 | 0.0071 |
| 5 | 0.0027 | 0.0100 | 0.0060 |
| 6 | 0.0025 | 0.0115 | 0.0071 |
| 7 | 0.0022 | 0.0100 | 0.0060 |
| 8 | 0.0034 | 0.0089 | 0.0051 |
| 9 | 0.0020 | 0.0100 | 0.0060 |
| 10 | 0.0030 | 0.0089 | 0.0051 |
| 11 | 0.0044 | 0.0100 | 0.0060 |
| 12 | 0.0060 | 0.0115 | 0.0071 |

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**Table 3.** Polished Condition: $R_a$ = (0.15 ± 0.01) μ m

| Specimen | Experimental | Numerical | Analytic |
|---|---|---|---|
| 1 | 0.0035 | 0.0064 | 0.0033 |
| 2 | 0.0025 | 0.0071 | 0.0038 |
| 3 | 0.0040 | 0.0064 | 0.0033 |
| 4 | 0.0025 | 0.0071 | 0.0038 |
| 5 | 0.0024 | 0.0064 | 0.0033 |
| 6 | 0.0065 | 0.0064 | 0.0029 |
| 7 | 0.0073 | 0.0064 | 0.0033 |
| 8 | 0.0017 | 0.0071 | 0.0038 |
| 9 | 0.0036 | 0.0064 | 0.0033 |
| 10 | 0.0014 | 0.0071 | 0.0038 |
| 11 | 0.0031 | 0.0064 | 0.0033 |
| 12 | 0.0025 | 0.0071 | 0.0038 |
| 13 | 0.0026 | 0.0064 | 0.0033 |
| 14 | 0.0090 | 0.0071 | 0.0038 |
| 15 | 0.0047 | 0.0079 | 0.0045 |

The graphs of Figures 7 and 8 show the distribution of fatigue damage to the three methods used according to the sequential number of the specimen.
The damage produced by the experimental method was obtained by dividing the fatigue life by 10,000 in order to normalize the values of damage for comparison with other methods adopted. It was found that the damage in this case generated was the same for all three situations compared in this study: machined, polished and annealed. Therefore this comparison it can be said that there is no difference in the level of damage generated in the body of the test piece machined or polished annealed, the values obtained were around 0.003.

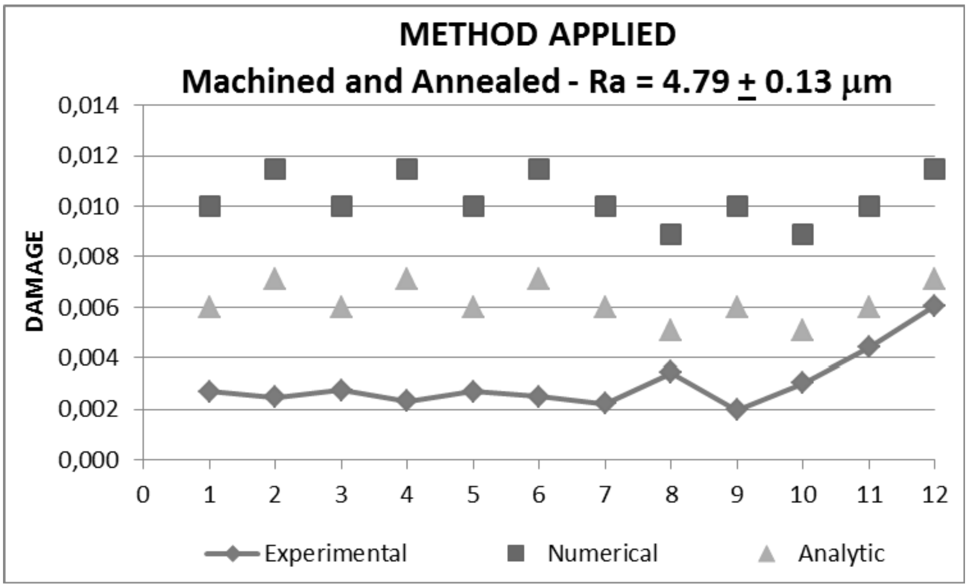

**Figure 7.** Annealed condition: comparison of damage between the methods applied.

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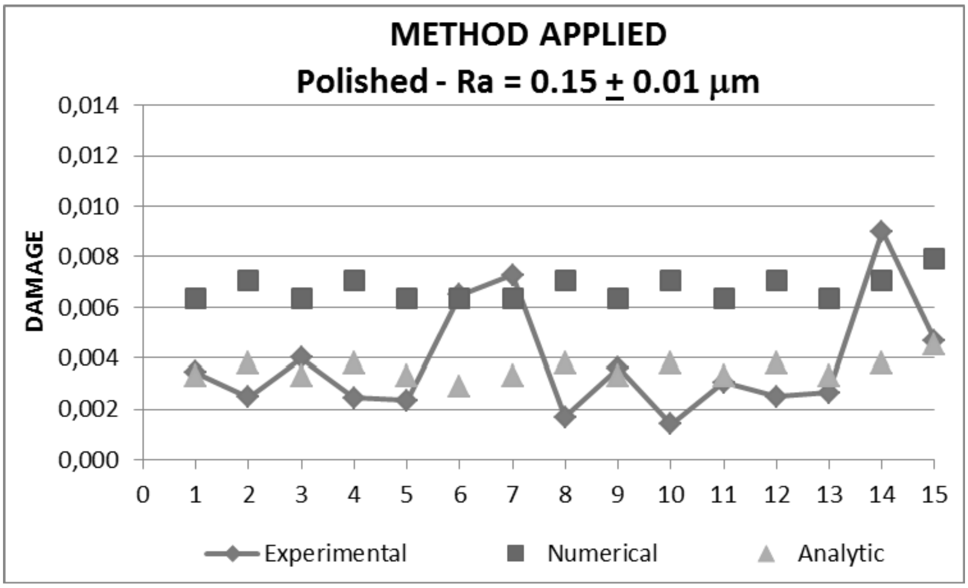


**Figure 8.** Polished Condition: comparison of damage between the methods applied.

It was observed the same mathematical behavior of the damage done to the analytical method and numerical situations in the three comparison object: machined, polished and annealed. It is further understood that the values of the numerical method damage were consistently higher than the analytical method. In the situation polished can be said that there is no difference between the analytical and experimental method, ie, there is a good approximation between the experimental and analytical methods. In studies carried out by Novovic et al.[(3)] of the machining parameters on the body surface of the test piece in fatigue, it is concluded that the value of the roughness has a strong influence on the fatigue life.

In this study, this evidence can't be verified perhaps due to the presence of residual stress for the range of roughness ($R_a$) from 2.5 microns to 5.0 microns, as Novovic *et al*.[(3)] is not a significant factor in fatigue life. As predicted by Masahiro Jono,[(1)] fatigue life is influenced by factors such as surface roughness, the residual stress and strain hardening. For the roughness range studied in this experiment the effect of roughness on the generation of the damage was not observed. Therefore, an increased roughness can lead to an increase of stress concentration due to the level of surface irregularities.

A specimen has a higher endurance limit fatigue perhaps due to the presence of compressive residual stress generated on the surface during polishing. Thus, the fatigue life increases in specimen after polishing.

## 4 CONCLUSIONS

The rule linear Palmgren-Miner was adequate in predicting the fatigue failure when applied to experimental results obtained by Lopes.[(7)] The analytical model proposed was a good correlation in the prediction of life (N) and damage (D) in fatigue with numerical results provided by the commercial program Ansys Workbench 12.1, for all the proposed conditions: machined, polished and annealed. In this study the surface roughness had little influence on the generation of damage in fatigue. After comparing the results obtained by the methods adopted in the proposed methodology was found that there was no significant difference in the damage produced by the specimen machined, polished and annealed.
The simulation using ANSYS platform proved to be good approximation for the finite

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element discretization adopted as tetrahedral 4 knots. The mesh refinement results in the improvement of the strain and stress within each element domain studied was quite significant. In all test conditions of fatigue by increasing the number of nodal points and numbers of elements beyond the standard set by the software there was no effect on the generation of damage to these preconditions. The fatigue test results obtained by simulation (FEM) using Ansys were representative for model validation Palmgren-Miner for direct application in the metal mechanical fatigue.

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