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# RELIABILITY ANALYSIS FOR GEARS USING ACCELERATED TESTING THROUGH MONTE CARLO SIMULATION

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**ABSTRACT**

*This paper presents a study about indicators of reliability (reliability function, non-reliability function, failure rate, probability density function, mean life) of gears using Monte Carlo simulation based on the time of failure. The technical systems´ increase of their automation and complexity degree and ask for in-depth research of their precision and reliability, as a warranty for increasing the level of quality and the competitiveness of those industrial products. The main advantages of the accelerated life tests reside in the decrease of the testing duration and of the allocated costs. As a result, the use of accelerated life tests represents a main and permanent concern of practitioners from the areas of mechanical products´ reliability.*

**Keywords:** reliability, accelerated life test, mean life, Monte Carlo simulation, gears

## 1. INTRODUCTION

The gears are machine elements made of rotational bodies, which have external or internal teeth provided. These are used to transmit the rotational movement and torque, through direct contact of the teeth, achieving in this way a transmission ratio (the ratio between the rotational speed of the leading gear and that of the led gear), constant or variable. The *elements of a* gear [1] are described in Fig. 1.

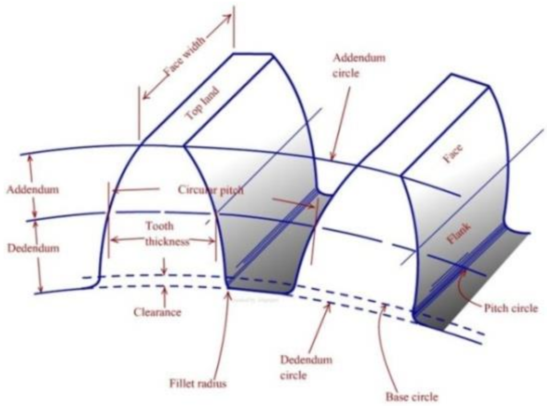



Fig. 1. The elements of a gear [2]

The gears are the most used machine elements with applications in various industries like: aero-spatial, automobile, medical, renewable energy, petrochemical. The main advantages and disadvantages of gears are shown in Fig. 2. The gears are essential components for a geared transmission and these can wear out because of the complex stresses that are subjected to, so, for this reason, their specific failing modes are multiple and comprise of complex phenomena. As a result of the complex stresses in the service of the gear teeth, these may get deteriorated by breaking or contact fatigue on the active surfaces of the teeth.

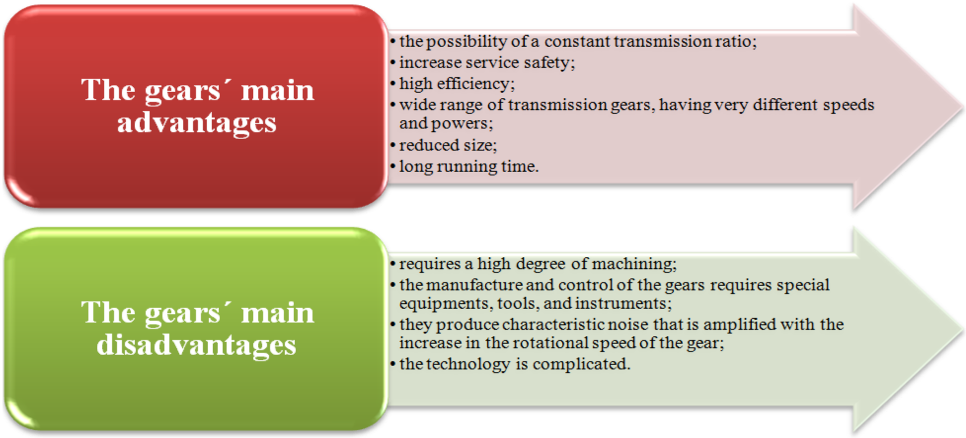



Fig. 2. The advantages and disadvantages of the gears

The breaking of the teeth can occur because overload in static regime or fatigue in dynamic regime. The breaking of the teeth in static regime occurs because of overloads or of high shocks the moment the gear system stops suddenly. This breaking can be fragile or through plastic deformation in the case of low strength teeth materials and usually shows up at the bottom of the tooth, sometimes manifests through breaking of the tooth corner (at reclined teeth) or under uneven load distribution on the width of the teeth. The fatigue breaking of the teeth (dynamic regime) occurs because jerking work cycle, when the load is handled directly by the gear, in the case of intermediary gears, respectively, when the rotation and loading is carried out on both ways (alternating cycles) [3].

The main types of deterioration for the active surfaces of the gear teeth are as follows: wear, plastic deformation, jamming, contact fatigue, cracking, breaking at the root of the teeth through bending fatigue. In this paper for a Monte Carlo simulation, shall be used the root breaking of the tooth by bending fatigue. Root breaking of the tooth by bending fatigue is a way of deterioration of the tooth having progressive characteristic following the particular stages of the fatigue: initiation, propagation and breaking. The most part of the lifespan for the teeth of the gears subjected to fatigue takes place within the first two stages. This type of deterioration can manifest itself as low cyclic fatigue when the loadings generate plastic deteriorations, the lifespan does not go beyond 10000 cycles or at a higher number of cycles when the alternating stresses are below the material yield limit [4].

During the research it, was identified a modern device that is used to test the stress bending for the teeth of an entire gear, at which the blocking of the gear is made using a support which sits under a tooth that has not been subjected to the tests, as it can be seen in Fig. 3 [5].

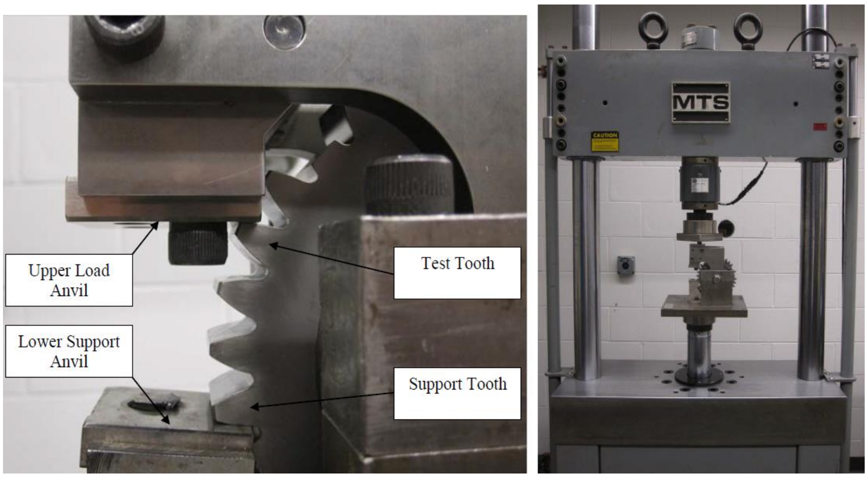



Fig. 3. The device used to test the fatigue bending of the teeth

## 2. THE RELIABILITY TESTS OF THE MECHANICAL SYSTEMS

The reliability of mechanical systems is a complex problem considering the probabilistic-statistic character of the proprieties that define it and the fact that their evaluation, with a certain precision, asks for prolonged costly tests, a good organization, collection, transmission and data processing about the behavior of the technical system in service. Because of the random character of the factors that influence the reliability of mechanical systems (the quality of the technical documentation, of the raw materials and materials, the correctness and stability of the manufacturing process, the wearing degree of the tooling machines, the fatigue of the workers, maintenance, management etc.), the mathematical base for the reliability theory is represented by statistics and probability theory. The reliability of a mechanical system is defined as the capacity of the system to work according to its technical book and without malfunctions, for a certain time span. The time span from commissioning to the first failure is called the product lifespan. A product lifespan, in most cases, is determined by the least reliable components that are included in the system or by the failure of the most stressed component [6].

The obtaining information regarding the reliability of mechanical products is usually done either by following the behavior of the products during operation, or during the reliability tests. In the real time operation we carefully record all the phenomena that occur during the use of the product. A study based on this information represents only a "historical" study, its value being only that of collecting experimental data or screening factors that can lead to a low reliability of products. The information gathered from the operation usually refers to products or equipments suffering from the wear process, so that, at the moment of the conclusions, they might not be that important for the improvement of some aspects concerning the design and manufacturing of the products, as a requirement of reliability. Considering the main requirement of reliability - the increase of performance of the industrial products, in direct connection with the scope of the study -, it is necessary to extend a more significant importance to reliability tests. A reliability test is represented by an experiment performed to determine the parameters of reliability for a well-defined product. The main reliability parameters during reliability tests is the mean time to failure (MTTF), knowing that, based on the existing relations between reliability parameters, they can be easily deduced from one to the other.

The growing global competition determined the manufacturers to develop products having multiple characteristics and high reliability, at reduced costs, as fast as possible. The challenges raised by these requests motivate the manufacturers to develop and to use efficient reliability methods that include the accelerated life tests.

The reliability accelerated tests can be classified as follows [7]:

- qualitative accelerated tests: the practitioner is interested to identify the technical system´s faults without assessing the lifespan in normal testing conditions. The following analysis and the corrective actions will lead to improve the analyzed systems´ reliability.

- quantitative accelerated tests: the practitioner is interested in determining the systems´ lifespan in normal testing conditions and also the reliability indicators (the reliability function, the non-reliability function, the probability density, the malfunctioning rate, B10).

Accelerating the tests is a way of speeding the attainment of information concerning the system behavior, in terms of economic efficiency. The acceleration of the testing conditions in the way of a “compression of the testing time” can be also studiedaccording to the number of cycles till failure. As a result, determining the reliability indicators shall be done according to the number of working cycles [8].

Accelerated life testing is used in electronics (resistors, lasers, liquid crystal displays, electronic bounds, switches, relays, cells and batteries), in the study of metals and composite materials, but also for certain components and mechanical assemblies (hydraulic components, tools, bearings). The degree of interdisciplinary of research in the field of accelerated life tests is complex and can include the following industries: manufacturing engineering, aerospace industry, nuclear industry, electronic industry, dental industry, t pharmaceutical industry and industry of renewable energy resources [9, 10].

## 3. THE SIMULATION OF THE FAILURE TIMES USING THE MONTE CARLO METHOD

Simulation for technical system reliability analysis is dependent on the Monte Carlo simulation that generates random failure times from failure distribution of each element. The overall technical system reliability is, then, obtained by simulating the system operation and empirically calculating the reliability values for a series of time values. Through the use of computers, simulation has become a very popular analysis tool. Simulation is simple to apply and it can produce results that may be rather difficult to solve analytically. On the other hand, simulation methods also have certain drawbacks, not the least of which is that the results depend on the number of simulations, which results in a lack of repeatability. Other drawbacks are those that systems with static components cannot be simulated, and that most of the reliability optimization and allocation techniques cannot be applied [11, 12 ].

In this paper, the times to failure are simulated using the Monte Carlo method, for a gear subjected to accelerated tests at bending the teeth till fatigue. The normal testing regime for fatigue teeth bending in the structure of the gear is of 20 kN. Using the Monte Carlo method we simulated has N stages of a gears, with the help of an acceleration model (Inverse Power Law) and statistical distribution (Weibull), which are suited to the analyzed case study. Using the previously determined parameters ($\beta$=6; k=1.55E-13; n=5.34) and the two accelerated levels (25 KN and 30 KN), we simulated, with the help of ALTA7 software, the values for the number of cycles to failure in accelerated conditions (Fig. 4).

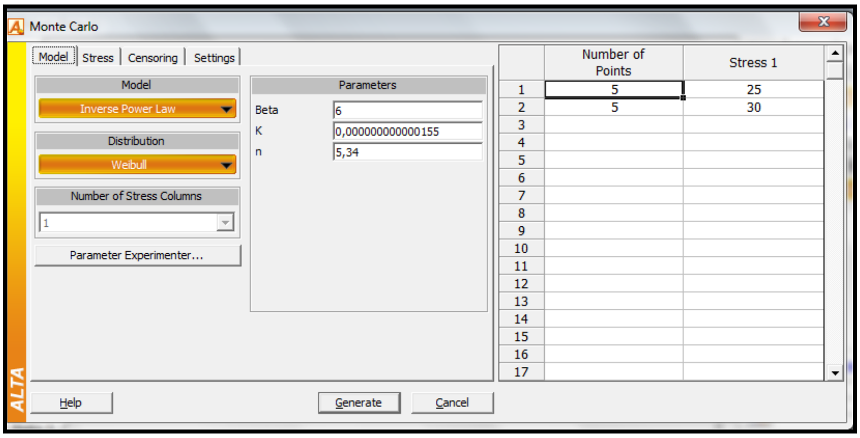



Fig. 4. The simulation using the Monte Carlo method of the data in accelerated conditions for the gears

Figure 5 shows the determination of failure times for the two accelerated regimes (25 KN and 30 KN), as obtained from the Monte Carlo simulation in ALTA 7 software. For the determination of the mean life and of the reliability indicators under normal testing conditions (20 KN) for the gears, the experimental data, resulted from accelerated conditions, have been processed using the ALTA7 software.

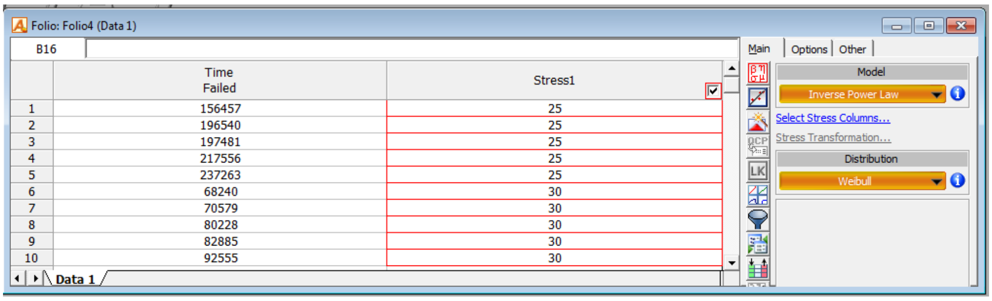



Fig. 5. The accelerated test data from Monte Carlo analyzed in ALTA

## 4. RESULTS AND DISCUSSION

For the statistical-mathematical models for data processing to be valid, the data must satisfy the following terms:

- to be authentic;
- to be representative for the studied phenomena;
- to be statistically homogenous;
- to belong to a distribution rule, according to the nature of the studied process.

To determine the reliability indicators a statistical processing of the experimental data is necessary. For the Inverse Power Law relationship the acceleration factor is given by:

$$F_a = \frac{L_u(V)}{L_a(V)} = \frac{\dfrac{1}{kV_u^n}}{\dfrac{1}{kV_a^n}} = \left(\frac{V_a}{V_u}\right)^n \qquad (1)$$

where $L_{Use}$ is the life at use stress level; $L_{Accelerated}$ is the life at the accelerated stress level; $V_u$ is the use stress level; $V_A$ is the accelerated stress level.

It was determined the acceleration factor corresponding to the IPL model using the relation (1). This is determined for every level of acceleration of the bending force. The accelerated levels are: La1=25 KN, La2=30 KN and the normal testing level is Lu=20 KN. By calculating the product of the calculated values of the acceleration factors and the number of cycles to failure in accelerated conditions, we determined the number of cycles to failure in normal testing conditions (Fig. 6).

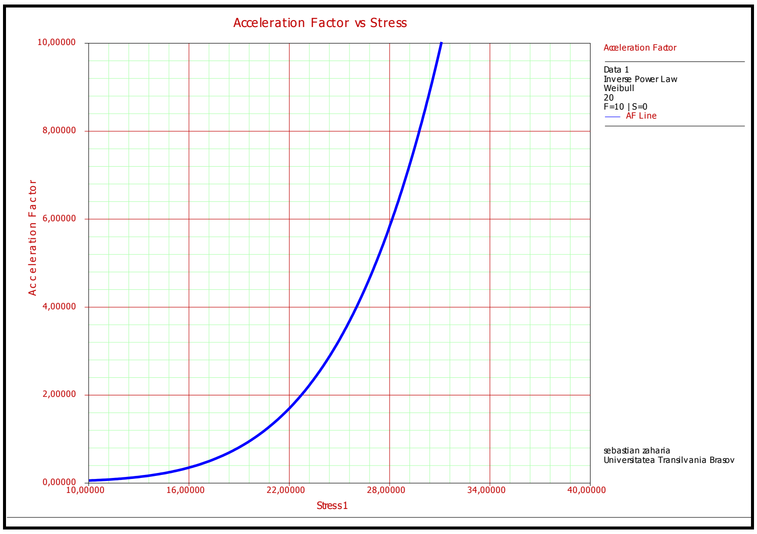
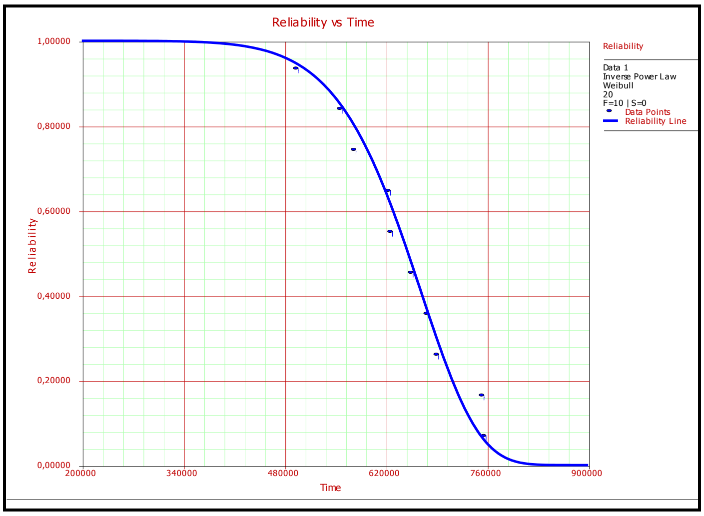



Fig. 6. Acceleration factor

Using the calculated values (the number of cycles in normal testing conditions), the reliability function 2D and 3D (Fig. 7) were plotted. In the graphical 3D representation of the reliability are determined and shown the reliability values for: different stress levels (20-30 KN) using a range domain of the number of cycles to failure of 100,000-700,000 cycles.

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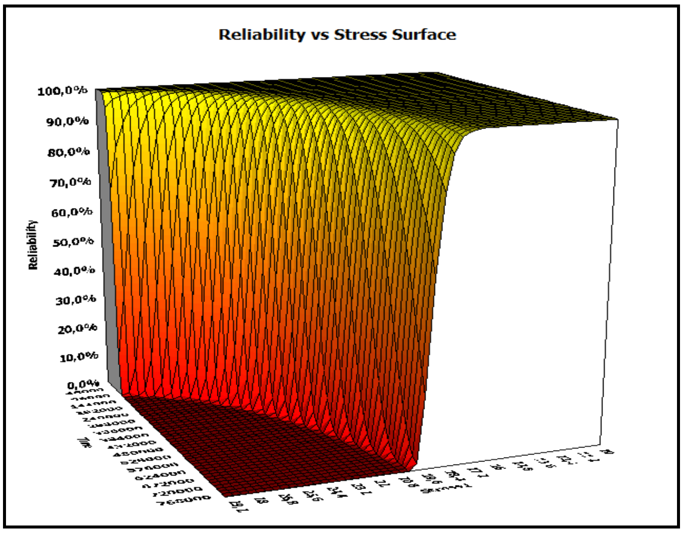
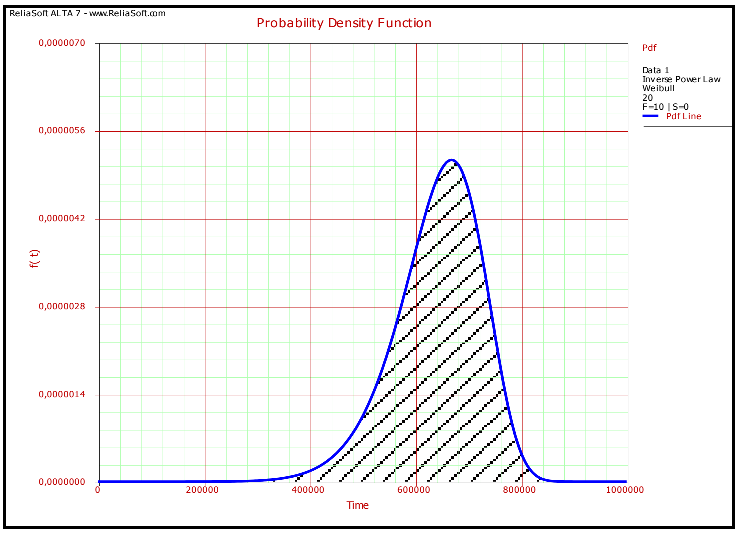



b)

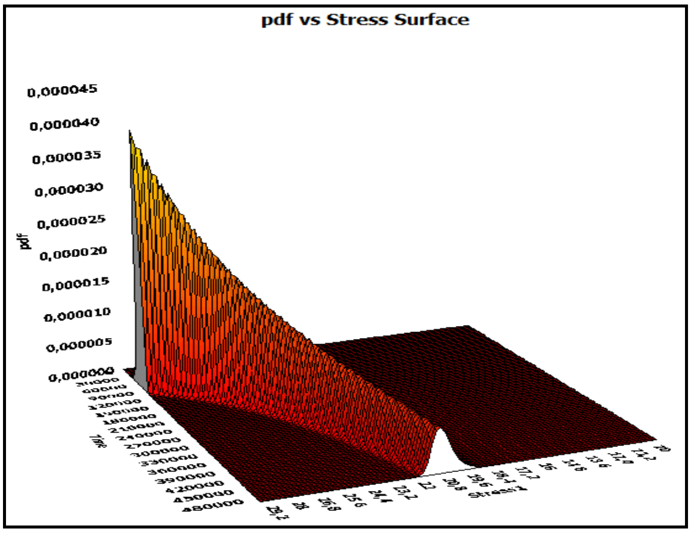
Fig. 7. Reliability function 2D/3D

The probability density for the number of cycles until failure (Pdf or f(t)) describes the relative rates of failure as a function of the number of cycles until failure and stress (Fig. 8). To determine the reliability density for the number of cycles until failure the IPL-Weibull model´s relation is used.

Another important indicator in the accelerated life testing area is the rate of failure. To determine a rate of failure according to the normal loading of the gears (20 kN) the IPL-Weibull model´s relationship is being used (Fig. 9).




a)




b)

Fig. 8. Probability density function 2D/3D

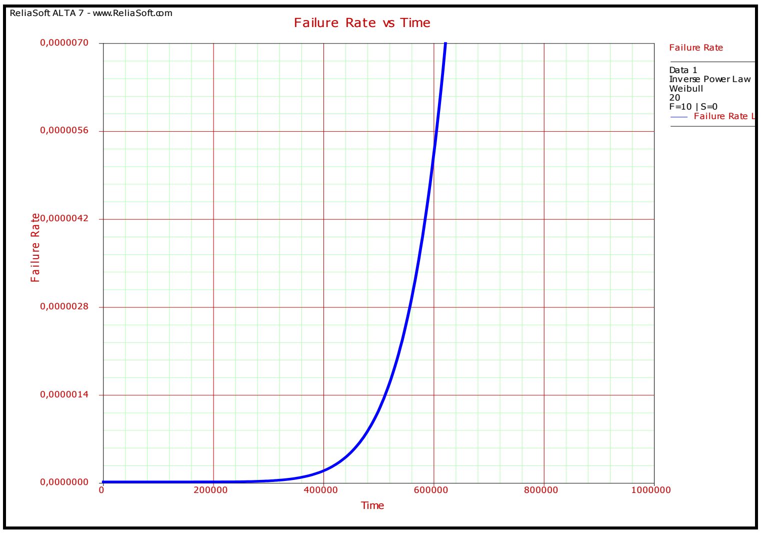



Fig. 9. Failure rate

The main scope of accelerated life tests is to determine the life time in normal testing conditions. Using the data resulted from accelerated life tests, we can determine the mean number of cycles to failure for the gears in normal testing conditions. Life versus stress plots are widely used for estimating the parameters of life-stress relationships. Any life measure can be plotted versus stress in the life vs. stress plots available in ALTA 7. In figure 10, by drawing a line through the mean number of cycles to failure for the 2 levels of acceleration (25 KN and 30 KN) and marking the point of intersection of this line with the vertical line, at the normal level under stress of 20 KN, we found out the mean number of cycles to failure in normal testing conditions.

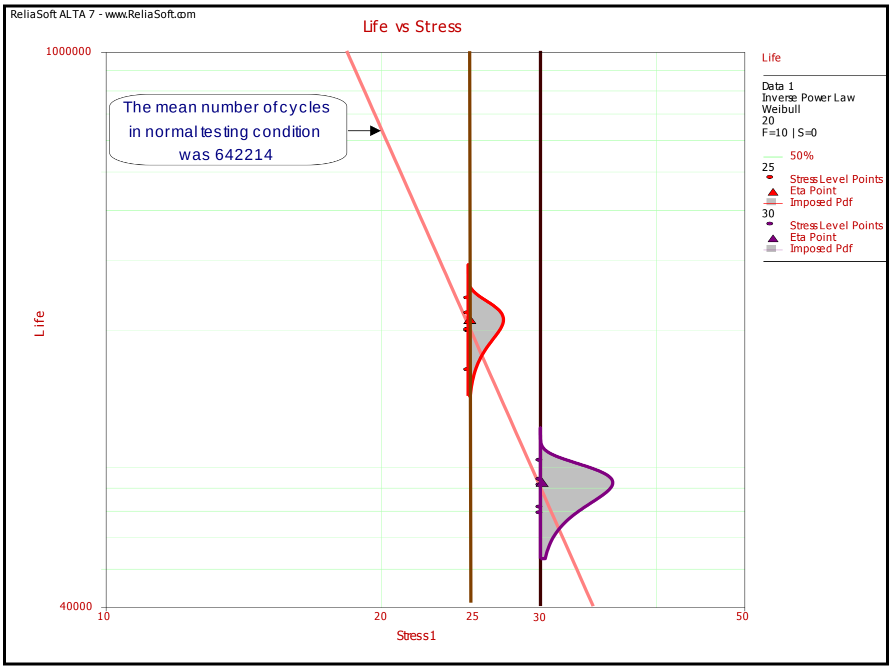



Fig. 10. The determination of the number of cycles to failure of the gears in normal testing conditions

## 5. CONCLUSION

Accelerated life testing is a methodology comprising a series of test methods, which can shorten the service life of products or significantly increase the rate at which their properties degrade. If a mechanical product requires $10^8$ cycles to cause a failure from fatigue in normal use condition, by using an accelerated life test, we can obtain the same result in $10^5$-$10^6$ cycles. The design of the accelerated life test and the interpretation of data require the understanding of the relation, in the course of the considered destructive process, between the level of stress and the failure rate. The implementation of accelerated life tests on the products, from manufacturing field has produced a significant reduction of the testing time. By adding the number of cycles to failure resulted from the accelerated life tests, this is of 1399784. The total number of cycles to failure in normal testing conditions is 7706568. For the case study under analysis, Fig. 10 shows the mean number of cycles to failure in the normal testing conditions, from the simulation with the Monte Carlo method. We may notice that, by using the accelerated life tests, the testing time has been reduced by 5.5 times.

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