Probabilistic assessment of fatigue failure data on ultra high molecular weight polyethylenes

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INTRODUCTION:
The current challenge of ultra high molecular weight polyethylene (UHMWPE) in total joint replacement continues being to reach a polyethylene with high wear resistance, oxidative stability and good mechanical performances. In this last aspect and related to fatigue behavior, most of the previous articles are focused on fatigue crack propagation, whereas few ones deal with long-term fatigue behavior, practically always under the S/N stress-based approach. In this work, a general regression model is applied for statistical analysis of stress-life fatigue data obtained under different failure criteria, which allows estimating the fatigue life of structural components of highly crosslinked UHMWPE’s in a more reliable way.

INPUT FATIGUE DATA:
Two set of data are considered from the literature. The first one [1], corresponds to the GUR 1050, electron beam irradiated at 50 and 150 kGy and post-thermal treatment at 150 C (remelting) and 120 C (annealing), here denoted NI, β50, β150, β50R, β150R, β50A, β150A, respectively. The data were performed at R = 0 with a strain failure criterion (12 %) as depicted in Figure 1.

The second group [2] corresponds to five UHMWPE formulations: conventional, gamma irradiated at 65 kGy and 100 kGy follows by remelting or annealing processes, denoted by C, γ50R, γ150R, γ65A and γ150A. The cylindrical samples presented a circular notch with an elastic concentration notch factor kC = 2.7. The failure criterion was the fracture.

MODEL:
The probabilistic S-N regression model proposed by Castillo et al. [3] arises from physical and statistical conditions, particularly, on the extreme value analysis and the necessary compatibility between the lifetime and stress range distributions. This leads to the establishment of a functional equation which solution provides the probabilistic definition of the S-N field as

\[ p = 1 - \exp \left[ -\frac{(\log N - B)(\log \Delta \sigma - C)}{\delta} \right]^\beta \]

where \( B \) is the threshold value of the lifetime, \( C \) the fatigue limit for \( N \to \infty \), and \( \beta, \delta \) and \( \lambda \), respectively, the shape, scale and location Weibull parameters. The percentiles curves are hyperbolas sharing the asymptotes \( \log N = B \) and \( \log \Delta \sigma = C \), whereas the zero percentile curve represents the minimum possible required number of cycles to achieve failure for different values of \( \log \Delta \sigma \). The probability of failure of an element subject to a stress range \( \Delta \sigma \) during \( N \) cycles, depends only on the product \( V = (\log N - B)(\log \Delta \sigma - C) \) that becomes a normalizing variable. The statistical normalization permits data pertaining to a Weibull distribution with the same shape parameter \( \beta \) to be pooled in a single distribution. Thus, the model parameters are estimated with higher reliability allowing the analytical expression of the whole S-N field to be known. This enables a probabilistic prediction of the fatigue failure under constant amplitude loading to be achieved. Since the model extends the Wöhler field up to an infinite number of cycles, an extrapolation of the lifetime outside the range of number of cycles tested is possible allowing an evaluation of data results in the very high cycle fracture region.

RESULTS AND DISCUSSION:
The application of the model to the former materials leads to a Weibull distribution for the normalizing parameter \( V \) and the percentile curves of fatigue failure. As an example, Fig. 2 plots the results of β50R material.

This type of probabilistic curves allows compare the fatigue resistance of the different material for the same probability value \( p \) and, therefore, to evaluate the influence of different parameters like irradiation doses, post-thermal treatments and stress concentration factors, which are involved in the studied materials. On the other hand, the parameter C points out also the fatigue limit for each material.

CONCLUSIONS:
This, being the first time that this probabilistic model applies to UHMWPE, allows us to define in a better way the failure probability and to make a comparison among the different materials involved in the study. The model proves to be superior to other current methods, as the up-and-down or the arcsin/p methods, concerning reliability and capability to reproduce the whole Wöhler field and to extrapolate to very high number of cycles.

REFERENCES: