LAMBDA Technologies Group

Diffraction Notes

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# THE CRITICAL ROLE OF ACCURATE FATIGUE DATA IN RESIDUAL STRESS DESIGN

High-cycle fatigue (HCF) poses a significant engineering challenge, where components may endure millions of load cycles during service. To achieve robust fatigue-resistant designs, accurate material fatigue behavior data is required for the specific component under consideration. Fatigue strength is not merely a material property; it is a critical input to advanced design frameworks. Among these, the Fatigue Design Diagram (FDD) methodology explicitly accounts for residual stress effects when predicting fatigue performance.

## FATIGUE DESIGN DIAGRAM KEY CONCEPTS

The FDD is a powerful design protocol that integrates residual stress effects into fatigue life prediction. Building on the classical Haigh diagram and predictive methods like Goodman, Gerber, and Soderberg, the FDD provides a more comprehensive means to model and optimize fatigue performance under service conditions. Unlike those traditional approaches, which often treat mean stress as purely externally applied, the FDD uniquely incorporates residual stress as an intrinsic mean stress component.

A key theoretical advantage of the FDD is its construction efficiency. With only a few key material properties it is possible to theoretically construct the FDD. One of these properties is the fully reversed bending (R=-1) fatigue strength value ($S_e$). This single material property allows derivation of critical prediction lines, including Goodman and modified Smith lines, creating a comprehensive framework for fatigue prediction.

## THE IMPORTANCE OF RESIDUAL STRESS-FREE DATA

While compressive residual stresses can significantly enhance fatigue life by retarding crack initiation and early growth, their presence in test specimens used to construct the FDD will compromise the FDD predictions.

To ensure the reliability of the FDD, it is imperative that the input fatigue strength is derived from specimens free from residual stress, or whose stress state is well characterized and theoretically accounted for in the analysis. Otherwise, the derived FDD will be fundamentally flawed, causing designers to underestimate the necessary design margins or incorrectly predict the effect of residual stress on fatigue.

## EXPERIMENTAL INSIGHT: EFFECT OF SPECIMEN MACHINING PARAMETERS

Lambda Research conducted in-house RR Moore-style rotating beam fatigue tests to investigate the impact of specimen machining parameters on residual stress and R=-1 fatigue performance. Figure 1 shows residual stress profiles of test specimens in three conditions: as-machined, machined + mechanically polished, and machined + etched. X-ray diffraction results show that as-machined specimens contain significant compressive residual stress near the surface, while mechanical polishing results in both reduced depth and magnitude. Etching is most effective at minimizing the stress, providing a truer baseline.

Figure 2 demonstrates that as-machined specimens possess the greatest fatigue strength, attributed to the presence of compressive residual stress. Specimens that have undergone mechanical polishing show a moderate relative decrease in fatigue strength, whereas etched specimens, which are mostly devoid of residual stress, best represent the material's baseline fatigue performance at R=−1.

## CONSTRUCTING THE FDD WITH ACCURATE INPUTS

The implications of these findings are visualized in the constructed FDD shown in Figure 3. The alternating stress limit determined from the R=-1 fatigue tests defines the vertical intercept of the $k_f$=1 line, which represents the idealized unnotched fatigue behavior and serves as the upper bound for fatigue performance at each mean stress. This baseline is crucial for all subsequent design decisions, especially when engineered residual stress is considered.

Fully reversed fatigue data from specimens with residual stress (e.g., as-machined) artificially inflate the baseline fatigue strength, leading to overestimated fatigue performance across the entire diagram. This results in unsafe design margins, double-counting of residual stress benefits, and misleading evaluations of surface treatments.

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## FINAL THOUGHTS

In residual stress design, the accuracy of the initial material property data, particularly the R=-1 fatigue strength, is paramount. These data form the cornerstone of the FDD. Because published fatigue data, when available, can vary significantly due to differences in material processing and testing conditions, it is best practice to a perform a fully reversed fatigue analysis on specimens carefully manufactured from the material of interest.

Moreover, accurate FDD-based design enables strategic residual stress engineering, empowering designers to mitigate failure modes like foreign object damage (FOD), erosion, and pitting. By intentionally leveraging compressive residual stress in design, components can be optimized for strength, weight, durability, and service life.

Precision in fatigue testing translates directly into precision in real-world performance, where the consequences of failure far exceed those encountered in the laboratory.

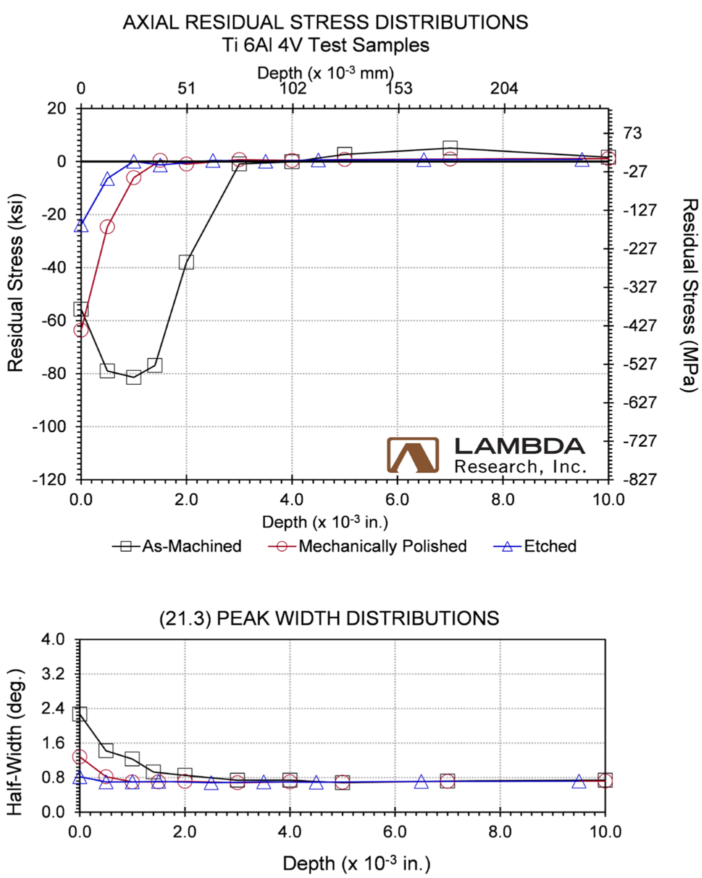


**Figure 1 – Residual Stress Profiles of Test Specimens**

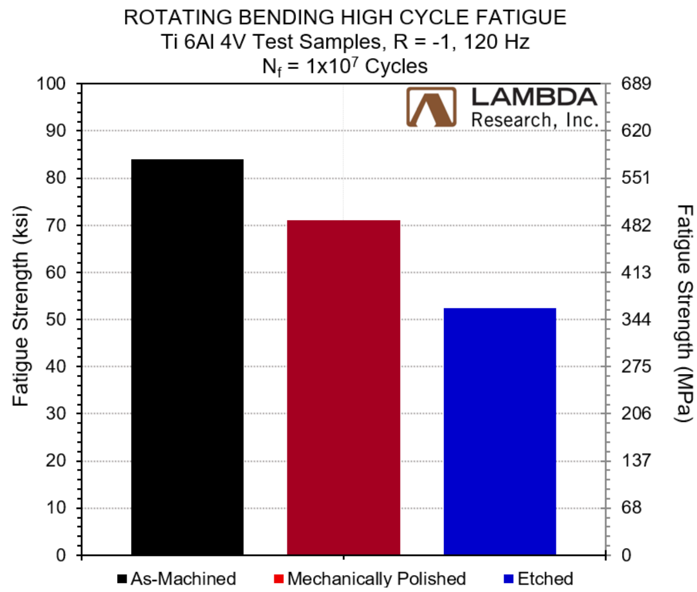


**Figure 2 – High Cycle Fatigue Results**

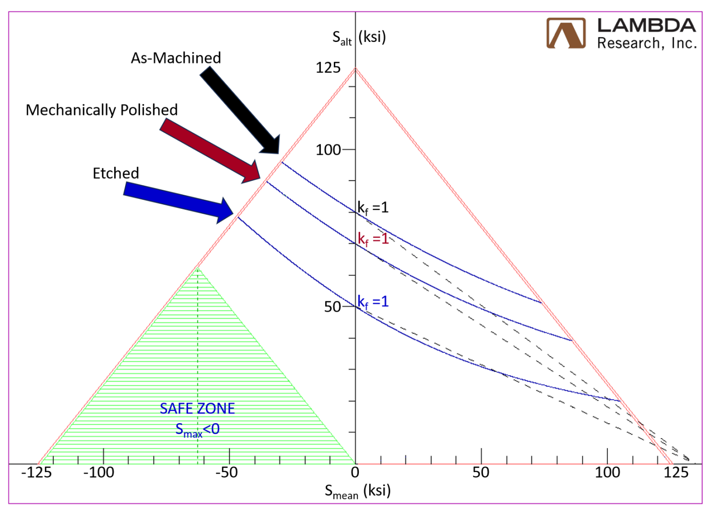


**Figure 3 – Constructed Fatigue Design Diagram**