2009 ME Graduate Student Conference
April 18, 2009

RAPID DETERMINATION OF FATIGUE FAILURE BASED ON TEMPERATURE EVOLUTION

Mehdi Amiri
Ph.D. Candidate

Faculty Advisor: Dr. Michael M. Khonsari

ABSTRACT

The evolution of surface temperature of Aluminum 6061 and Stainless Steel 304 specimens that experience hysteresis heating when subjected to cyclic torsion and bending tests is studied. It is proposed that the rate of temperature rise as a function of time can be utilized as an index for fast prediction of fatigue life. The proposed model uses an empirically derived relationship that was confirmed using analytical relationships and material properties. An empirical correlation of the form $N_f = c_1 R_\theta^{c_2}$ is derived that relates the rate of temperature rise, R_θ, to the number of cycles to failure, N_f. It is shown that c_1 is dependent on material properties and stress state whilst c_2 is a constant.

When exposed to cyclic loading, most of the energy dissipated due to hysteresis effect manifests itself as heat and causes an increase in the temperature of the specimen. Experiments show that particularly when metals are subjected to high-stress cyclic testing, their temperature rises significantly during the first few cycles. That is a characteristic of metals experiencing hysteresis heating. If the loading rate is rapid enough —a characteristic that is generally observed in low-cycle fatigue— the temperature rise can be surprisingly high. For fatigue tests at 1,000 Hz, for example, the temperature could increase 200ºC to 400ºC above the initial temperature, depending on the material tested and specimen geometry [1]. Thus, the relationship between temperature and fatigue characteristics has become a subject of considerable interest [2-4],

In the present work, a novel approach of nondestructive thermographic technique is used to characterize the fatigue behavior of metals. The results of a series of experiments reveal that the surface temperature of a specimen experiencing fatigue can be directly related to the number of cycles to failure. Further, it is shown that the fatigue test results of both Aluminum and Stainless Steel undergoing bending and torsion can be effectively represented by a single curve which gives the number of cycles to failure as a function of initial slope of the temperature evolution. A two-dimensional form of a thermal-mechanical coupling model for a low-cycle bending fatigue was formulated to ensure the validity of the experimental results and to provide insight into the complex fatigue behavior.

Our experimental study reveals that a metal undergoing ~~a~~ fatigue is subjected to an increase of the surface temperature, such that the higher the applied load the higher the hysteresis heating and the associated temperature rise. Figure 1 shows the results of bending tests for two displacement amplitudes of δ_1=44.45 and δ_1=49.53 mm for Aluminum specimen. In this figure, a larger displacement amplitude corresponds to a higher applied load. It is observed that the temperature evolution during low-cycle bending fatigue undergoes three distinct stages: an initial increase during the first phase of the test (Phase 1), followed by a fairly flat temperature profile representing a "quasi-steady" operation (Phase 2), and finally a rapid increase immediately prior to failure (Phase 3). These three distinct phases are illustrated in Figure 1. Starting from the ambient, initially, the temperature rises since the associated energy density increases with the hysteresis effect that is produced at greater level than the heat transferred out of the specimen. In Figure 1, the rate of temperature rise in first phase is identified by two slopes $R_{\theta 1}$ and $R_{\theta 2}$ corresponding to stress levels δ_1 and δ_2, respectively. During the second phase, the cyclic stress and strain responses become stable: There is balance between the hysteresis-energy generation and heat dissipation as the temperature tends to steady state. For loads greater than the fatigue limit, the rate of temperature increase in phase 1, and the steady state temperature in phase 2, increases as the load increases. In the third phase—the stage where failure occurs—the temperature increases rapidly for comparatively very few number of cycles. In the third stage, macrocracks are formed. It is generally accepted that when a macrocrack appears, there is large plastic deformation at the crack tip and the plastic work generated during this deformation is mostly converted to heat.

Consequently, temperature rises rapidly just before the fatigue failure occurs [5].

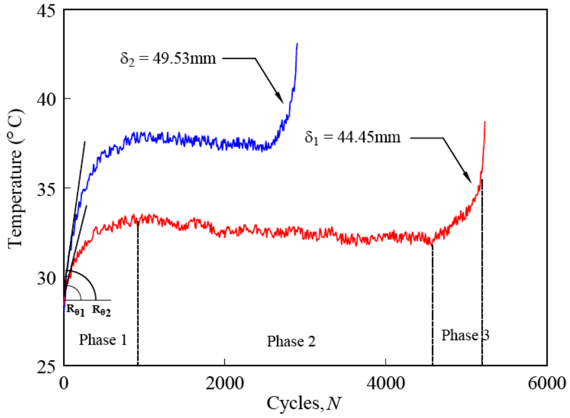

Figure 1. Temperature evolution of two tests for bending fatigue

A thermal analysis has been carried out to predict the temperature of the specimen under the fatigue bending load. A two-dimensional heat conduction model is developed to analyze the problem. It is analytically treated using the integral transform technique [5]. Figure 2 shows the temperature distribution for Aluminum sample at three different stress amplitudes. It can be seen that the analytical solution accurately captures both the initial rise and the steady state temperature.

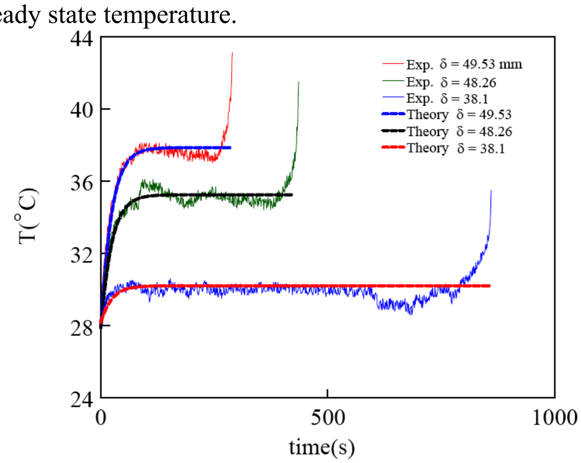

Figure 2. Comparison between experimental results and analytical solution

The present result of present work provides a novel technique to predict the fatigue life of specimens considering the initial slope R_θ of the temperature evolution in the first phase as shown in Figure 1. Test results show that the number of cycles for failure, N_f can be correlated to the slope of the temperature curve in the first phase, R_θ as follow:

$$N_f = c_1 R_\theta^{c_2} \qquad (1)$$

where c_1 and c_2 are constants. The empirical correlation given by Eq. (1) confirms that the constant c_2 is nearly identical for both Aluminum 6061 and Stainless Steel 304 subjected to either bending or torsion load. The value of c_2 is found to be c_2= -1.22 for the best curve fitting. The c_1 value is derived empirically by plotting the data points using Eq. (3) with constant c_2=-1.22, until the best curve fit is obtained. The value of c_1 for Aluminum 6061 in bending and torsion is 204 and 8120, respectively. The c_1 values determined for Stainless Steel 304 in bending and torsion are 14102 and 183830, respectively. Since constant c_2 is almost identical for both Aluminum and Steel, the results of N_f/c_1 versus R_θ consolidated in the form of a single, universal curve. Figure 3 shows the universal fatigue-life curve as a function of slope of the temperature rise during first phase. The results of both Aluminum 6061 and Stainless Steel 304 subjected to torsion and bending load are plotted in this figure. Having the surface temperature or particularly slope of the temperature rise at the very beginning of the fatigue test, the fatigue life of a specimen can be predicted, thereby preserving testing time. This technique is applicable to other types of loadings like axial tension/compression loading, rotating-bending of tubes [5].

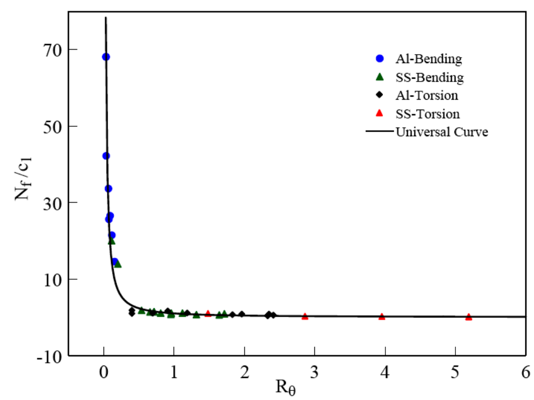

Figure 3. Universal curve for prediction of fatigue failure based on initial slope

ACKNOWLEDGMENTS

Continuation of this research is made possible in part by a support by Smith Services, primary manufacturer of drilling products and services. We would like to gratefully acknowledge this support. Also, the author would like to thank his advisor, Dr. Khonsari for his constant guidance and support. He also likes to thank all his colleagues in LSU Center for Rotating Machinery (CeRoM).

REFERENCES

1. H. Wang, L. Jiang, C.R. Brooks, P.K. Liaw , "Infrared temperature mapping of ULTIMET alloy during high-cycle fatigue tests", Metall. Mater. Trans. A, **31,** 1307 (2000)
2. N. Ranc, D. Wagner, P.C. Paris, "Study of thermal effects associated with crack propagation during very high cycle fatigue tests", Acta Mater. **56**, 4012 (2008)
3. G. Fargione, A. Geraci, G. La Rosa, A. Risitano, "Rapid determination of the fatigue curve by the thermographic method", Int. J. Fatigue, **24**, 11 (2002)
4. G. Meneghetti, "Analysis of the fatigue strength of a stainless steel based on the energy dissipation", Int. J. Fatigue, **29**, 81 (2006)
5. M. M. Khonsari, M. Amiri, "Rapid determination of fatigue failure based on temperature evolution" Patent application is published (2009) Application #12/221,103