

Sensitivity/Uncertainty Analysis of Material Thermal Degradation Models

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ABSTRACT

Time-temperature analysis methods are usually applied to predict the useful life of automotive components. Components life is affected by exposure to heat during vehicle service life. The extent of reduction in component life, which may be caused by material thermal degradation, depends on the component temperature and the time duration at that temperature. The rate of material thermal degradation of automotive components varies widely depending on material thermal stability, vehicle duty cycle, and the thermal environment that the component is exposed to. Thermodynamic properties such as the activation energy of each material are used to determine the rate of thermal degradation [1,2]. In this approach, material thermal degradation models are used to predict component life during the service life of a vehicle. As the rate of thermal degradation increases with increasing material temperature, the useful life of a component will be reduced as the material temperature increases. Therefore, it is desired to keep the rate of thermal degradation low enough so that a certain level of component performance can be maintained at the end of the vehicle life. The acceptable performance level may be component dependent and vehicle dependent. For example, a passenger car will require different performance than a heavy duty truck even if same material is used on both vehicles. To maintain the required component performance, the definitions of "long term temperature goal" and "short term temperature goal" are introduced. Therefore, the factors affecting the predicted component life can be summarized as follows: measured component temperatures, material long and short term temperature limits (goals), material activation energy, and vehicle duty cycle. All of these factors typically have an inherent uncertainty. These uncertainties will affect the overall confidence level in the predicted time-temperature calculations. Therefore, it is the main purpose of this paper to estimate the uncertainty in component life predictions and their sensitivity to each of the input factors. Given these uncertainties, it is statistically possible to determine the most influential parameters and the overall uncertainty in the predicted component life. Several examples are given where the sensitivity/uncertainty analysis for different vehicle components are presented.

CITATION: El-Sharkawy, A. and Kamrad, J., "Sensitivity/Uncertainty Analysis of Material Thermal Degradation Models," *SAE Int. J. Mater. Manf.* 5(2):2012, doi:10.4271/2012-01-0955.

INTRODUCTION

Mathematical models are normally used in engineering fields for analysis and design purposes. In general, one uses nominal or mean values for model input parameters. In reality, there are uncertainties associated with nominal values, which would cause uncertainties in predicted calculations. Thus, there is a need to evaluate the reliability of these analyses or design results; as well as, there is a need to determine what effect the inaccuracies in input data have on the model results and which parameters are of significant importance. In an uncertainty analysis concerning a heat exchanger design, Cho [3] reported that if a heat exchanger is

designed using the mean values of the design parameters then the probability that the exchanger will meet its thermal-hydraulic duty during actual operation is fifty percent. From this, an engineering or mathematical model result can be judged adequate for an intended purpose only if the uncertainty of that result is quantified. Therefore, it is only possible to reasonably estimate the actual (or true) measured quantity within a specified range or interval of possible errors (called uncertainty).

In this paper, the critical input parameters for time-temperature analysis model are determined and the sources of uncertainty are defined. Global and local sensitivity analysis

methods [4,5,6,7,8,9] are applied to determine the most influential parameters and overall model uncertainty. The major factors that affect time-temperature analysis include the following:

1. Measured component temperatures

The uncertainty in measured component temperatures is caused by inaccurate instrumentation. Component temperatures are usually measured using thermocouples. Therefore, the thermocouple readings should represent the true material temperature and should not be affected by other environmental or material interference factors. Thermocouples should also respond fairly quickly to changes in the surrounding thermal environment with minimum time lag. Examples of sources of errors during thermal testing include the following:

Thermocouple attachment methods

Improper attachment methods can reduce thermocouple reading. For example, if a thick layer of adhesive is used to attach thermocouples to rubber or plastic surfaces, the result will be a slower thermocouple response which may cause a significant time lag. This, in turn, will result in lower peak temperatures during transient conditions [10].

Thermocouple location within the measured component

Due to the thermal gradient within the measured component, a thermocouple reading may not represent the highest temperature location. This is more severe for non-metallic materials such as rubber or plastics due to the lower thermal conductivity. For metals, temperature gradients are much less due to their higher thermal conductivity. Thermocouple location within rubber or plastic material should be at the closest point to the heat source. For example, inserting a thermocouple at distances greater than 3 mm from the outer surface may lead to reduced temperature reading and slower thermocouple response [11].

Radiation errors

Thermocouple readings may also be affected by thermal radiation. If a thermocouple is not properly imbedded inside the material, the thermocouple bead may receive radiation from external heat sources. The thermocouple bead should absorb heat only from the material it is imbedded inside. Radiating errors have been reported in literature [12, 13] and are a strong function of the surrounding heat source temperature.

Conduction errors

A bare thermocouple lead will conduct heat away to the surrounding environment. Therefore, the measured component temperature will be lower than actual material temperature. More detailed analysis of thermocouple measurement errors are covered in several articles [14, 15].

2. Material temperature limits (goals)

Material temperature limits (goals) are defined so that an acceptable level of component performance should be maintained by end of life of the vehicle. The definition of material goals includes the “long term temperature goal” and the “short term temperature goal”. These goals are defined as follows:

Long term temperature goal is the maximum temperature that a component can be exposed to, for a maximum of 500 hours throughout the life of the vehicle, without losing its performance.

Short term temperature goal is the maximum temperature that a component can be exposed to, for a maximum of 50 hours throughout the life of the vehicle, without losing its performance.

Determination of the “long term” and “short term” temperature goals requires a series of experiments where the component is exposed to different temperatures for several hours. The material property which may be of interest to specific application is usually measured at different time durations. Based on these tests, the long and short term temperatures are determined. Therefore, uncertainties in material temperature goals may be due to measurement errors in material property, linear regressions, or statistical analysis. In addition, variations in material composition, formulation, or processing may vary from one supplier to another.

3. Material activation energy

Activation energy has been widely used [16, 17] in material science and engineering to determine the rate of thermal degradation and expected material life. Activation energy is determined from experimental data by measuring the rate of thermal degradation at different temperatures. Several variations in the measured activation energy have been reported in literature [18, 19]. The value of the determined activation energy can be affected by the testing procedure, data analysis, and variations in material composition.

4. Vehicle duty cycle

Vehicle duty cycle is a critical input to the time-temperature analysis (figure 1). During time-temperature analysis, component temperature data, which were previously collected from actual vehicle thermal testing, are used to determine if a component temperature has exceeded any of the temperature goals. Vehicle thermal tests are designed to cover most typical driving conditions for each vehicle type. Therefore, the selected thermal tests should represent a combination of the most typical driving conditions. These tests include city traffic, highway driving, driving on grades, as well as extended idle or soak conditions. A typical duty cycle is used for each vehicle type. The duty cycle information is based on surveys or data gathered from customer or fleet vehicles. Statistical analysis is used to process the data and determine the most representative cycle. Therefore, variations will always exist in the suggested

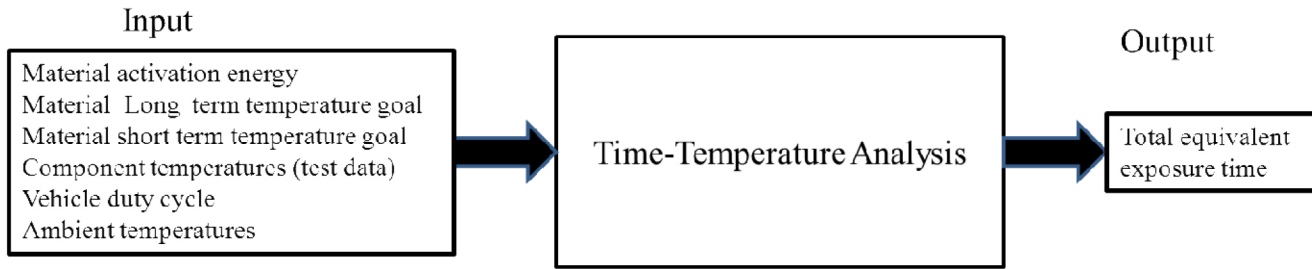


Figure 1. Input-output relationship

customer usage pattern. These variations will impact the accuracy of the predicted useful component life.

TIME-TEMPERATURE ANALYSIS

The purpose of the time-temperature analysis tool is to predict the material useful life throughout the life of the vehicle. Material thermal degradation is expected to affect material physical properties. If the analysis indicates a component will not meet this design life (150,000 miles for example) due to excessive exposure to high temperatures, additional protection to the component or a material upgrade should be considered. Since component temperatures are usually unique to each test condition, the material degradation rate will differ for each test, depending upon the actual component temperature. The rate of thermal degradation is directly related to component temperatures. It follows that the higher the component temperature, the higher the rate of thermal degradation, as explained by the Arrhenius equation (1).

$$k_{(T)} = Ae^{-\frac{E}{RT}} \quad (1)$$

Similar kinetic models have been adopted by Kamal [20] for kinetic of polymeric reactions where,

$k_{(T)}$: is a rate coefficient which is a strong function of temperature.

A : is the Arrhenius coefficient,

E : is the activation energy ($\frac{Kj}{mol}$)

R : is the universal gas constant ($\frac{Kj}{mol \cdot K}$)

The extent of material degradation depends also on the exposure time and frequency of exposure to high temperatures. The exposure frequency is related to the vehicle duty cycle and weather conditions at a given geographical location. Actual vehicle test data for selected test conditions are used to determine component temperature under different test scenarios. From the definition of material temperature goals, it is possible to determine the equivalent exposure time (EET) at any temperature using equation (2) as explained in literature [21].

$$EET = t_h \exp\left\{\frac{E}{R}\left(\frac{1}{T_l} - \frac{1}{T_h}\right)\right\} \quad (2)$$

In the above equation, the following terms are defined:

t_h : is the time duration above the material temperature goal

T_l : is the lower temperature (material temperature goal)

T_h : is the measured material temperature

In the time-temperature analysis, equation (2) is applied whenever a material exceeds its temperature goal during any test for any time duration. In these instances, equation (2) is used to determine the equivalent exposure time, which is the time required to achieve the same thermal degradation as if the material were kept the goal temperature. Figure 2 is an illustration of applying equation (2) for determining the EET for natural rubber. Each material has a specific value for the activation energy. Table 1 is an illustration of some typical materials. Applying standard methods for evaluating the Equivalent Exposure Time EET allows determination of the remaining time in a component life. Figure 2 is an illustration of the concept of EET . It provides the equivalent exposure time at different temperatures for natural rubber.

SENSITIVITY ANALYSIS

In time-temperature analysis, it is required to estimate the useful life of critical vehicle components. The effect of thermal environment, duty cycle, and material thermal properties are evaluated. These evaluations are conducted early in the development phase so that any additional design changes or thermal protection can be considered before a vehicle is built. Normally, calculations for component life are based on nominal values of input parameters (Figure 1). Therefore, it is important to determine the effect of variations in these parameters on the expected component life.

LOCAL SENSITIVITY ANALYSIS

Local sensitivity methods are based on the gradient approach and are used to determine sensitivity to relatively small variations of the input parameters. For a parameter, f , which is a function of several input components, p_i , can be written as