

HEAT GENERATION IN THE RAILROAD BEARING THERMOPLASTIC ELASTOMER SUSPENSION ELEMENT

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ABSTRACT

The main purpose of this ongoing study is to investigate the effect of heat generation within a railroad thermoplastic elastomer suspension element on the thermal behavior of the railroad bearing assembly. Specifically, the purpose of this project is to quantify the heat generated by cyclic loading of the elastomer suspension element as a function of load amplitude, loading frequency, and operating temperature. The contribution of the elastomer pad to the system energy balance is modeled using data from dynamic mechanical analysis (DMA) of the specific materials in use for that part. DMA is a technique that is commonly used to characterize material properties as a function of temperature, time, frequency, stress, atmosphere or a combination of these parameters. DMA tests were run on samples of pad material prepared by three different processes: injection molded coupons, transfer molded coupons, and parts machined from an actual pad. The results provided a full characterization of the elastic deformation (Energy Storage) and viscous dissipation (Energy Dissipation) behavior of the material as a function of loading frequency, and temperature. These results show that the commonly used thermoplastic elastomer does generate heat under cyclic loading, though the frequency which produces peak heat output is outside the range of common loading frequency in rail service. These results can be combined with a stress analysis and service load measurements to estimate internally generated heat and, thus, enable a refined model for the evolution of bearing temperature during operation.

INTRODUCTION

Thermoplastic elastomers are seeing increasing use in rail service in load damping and compliant component applications. Thermoplastic polyurethane (TPU) material offer a number of favorable characteristics in comparison to other elastomeric materials including ease of manufacture and superior abrasion and wear resistance. The use of elastomer elements reduces noise emissions and wear of metal components in the railcar suspension. The elastomer steering pad which is implemented in the wheel-axle-bearing assembly of a freight car, as seen in Figure 1, has proved to be extremely beneficial. The purpose of the elastomer pad is to prevent metal to metal contact between the bearing adapter and the side frame of the truck. The main benefits of implementing the elastomer steering pad on top of the bearing adapter include: improvement of axle-to-rail alignment which allows a controlled motion of the wheelset with reduced lateral force in curves, a wheelset life increase of 25%, and an 8% decrease in fuel consumption, among other benefits [1]. However, viscoelastic materials, such as the thermoplastic elastomer pad, are known to develop self-heating (hysteresis) under cyclic loading [2] which may lead to undesirable consequences in the structural integrity of the steering pad and the thermal management of the bearings.

In general, for viscoelastic materials subjected to a varying load, part of the deformation energy is stored and part is dissipated through internal molecular mechanisms as heat [3, 4]. This hysteretic heating in thermoplastic elastomer materials becomes particularly significant during cyclic loading and is a

potential problem when there is limited opportunity for heat dissipation. When the heat that is produced does not dissipate out of the system, the active temperature of the material increases. In general, the hysteretic dissipation of polymers increases with temperature so a thermal runaway is possible. Moreover, as the temperature increases, there is usually a significant decrease in the strength and stiffness of the material, or softening, which may lead to mechanical failure [1, 2]. The behavior of viscoelastic materials during cyclic load induced failure depends on the material system, stress state, and thermal environment. Individual polymers may have dramatically different responses to similar conditions. For example, previous work on polycarbonate (PC) and polymethylmethacrylate (PMMA) found that PC specimens show a rapid increase in temperature which levels off as the polymer fails while PMMA shows little significant increase in temperature before reaching failure [5].

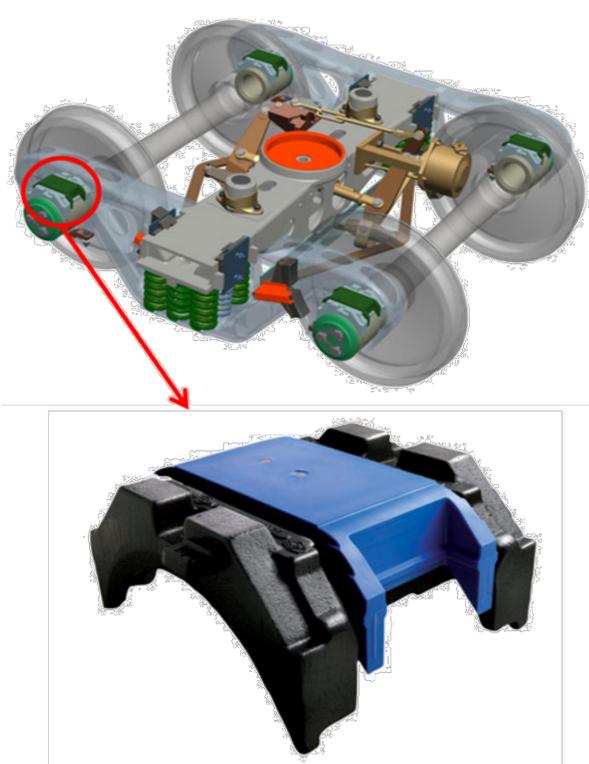


Figure 1. Configuration and location of thermoplastic elastomer steering pad (Blue) within wheel-axle-bearing assembly. [1]

The ongoing study presented in this paper is focused on the heat generation in the railroad bearing thermoplastic elastomer suspension element. The study was motivated by preliminary findings by the authors in the laboratory which included experiments on 6.3 cm diameter pucks of pad material which produced temperature increases as high as 25°C under loadings ranging between 2.2 kN (500lb_f) and 24 kN (5500 lb_f) in compression oscillating at a frequency of 10 Hertz at room temperature. Furthermore, this study is part of a larger project funded by The University Transportation Center for Railway

Safety (UTCRS) to study the effect of heat generation in the elastomer suspension element on the thermal behavior of the bearing assembly. Researchers associated with the UTCRS are conducting thorough research on, among other things, ways to better understand the dynamic behavior and the thermal response of railroad bearings when subjected to normal and extreme service operation conditions.

This paper focuses on the heat generation that occurs in elastomers used in the compliant suspension element. Effects of specimen fabrication are evaluated as the role of load intensity, load frequency, and temperature on hysteretic dissipation are studied. These results will help to determine the effect of this heat generation on the thermal behavior of railroad bearing assemblies under different operating conditions.

DMA SAMPLE PREPARATION

The contribution of the elastomer pad to the system energy balance will be modeled using data from dynamic mechanical analysis (DMA) of elastomer steering pad materials. Specimens were prepared by several methods to identify any process effects on the TPU response. The goal was to determine the simplest method of preparation which produced specimens representative of manufactured pads. The three types of specimen preparations, shown in Figure 2, are (a) transfer molded coupons, (b) injection molded coupons, and (c) coupons machined from an actual pad.

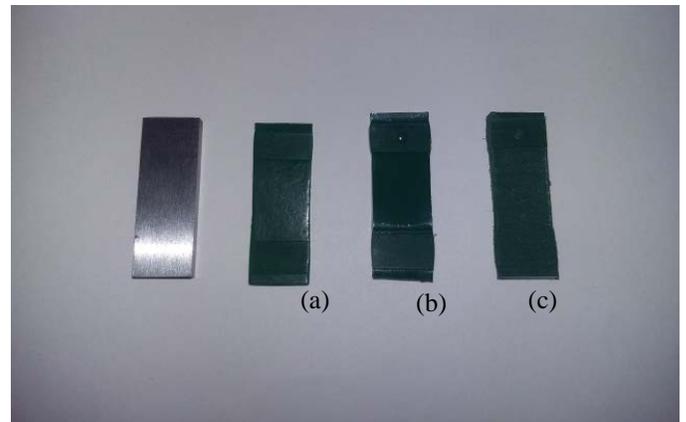


Figure 2. Specimens from left to right: calibration reference (steel), (a) transfer molded, (b) injection molded, and (c) machined from actual pad.

The transfer molded specimens were fabricated by shredding an elastomer pad and then transfer molding them in a heated platen press. The resulting thin disks were allowed to equilibrate for 36 hours and then cut into the appropriate size for DMA testing.

The second type of specimen was obtained by using the injection molding process. New pellets of material were molded into standard flex or tensile bars using a BOY injection molding machine. These specimens were then cut to length for use in the DMA.

Finally, the third type of specimen was milled out from an actual steering pad like the one shown in Figure 1.

EXPERIMENTAL SETUP AND PROCEDURES

The contribution of the elastomer pad to the system energy balance will be modeled using data from dynamic mechanical analysis (DMA). DMA is a technique used to study the viscoelastic behavior of polymers and provides a broad characterization of the elastic (energy storage) and viscous (energy dissipation) behavior of the material over a large range of temperatures and frequencies. The technique subjects a specimen to a steady-state oscillatory load or displacement while the specimen response is measured. The relatively low thermal mass of the specimen and capabilities of the instrument permit rapid measurement of properties over a wide range of temperature and frequency. In a viscoelastic material, the response will have an in-phase and a lagging response. Steady-state oscillation permits separation of these two responses and calculation of the material storage and loss moduli.

Time-Temperature Superposition (TTS) makes it possible to characterize the viscoelastic properties of materials at various temperatures over an experimentally convenient frequency range. The curve shifting procedure creates a master curve that represents the response of a material over a wide range of frequencies at a particular reference temperature. A TTS master curve takes advantage of the inverse relationship between temperature and time in their effect on polymer behavior. Runs at higher temperatures generate an equivalent response to that which would be obtained at a reference temperature but at much lower frequency. Similarly, higher frequencies have the same effect at lower temperatures. The use of TTS permits the extension of polymer modeling to temperature and time domains that cannot be directly tested economically. The theoretical assumptions behind the technique require that even if curves can be empirically shifted, the resulting shift factors must have certain characteristics. These include the requirements that shift factors for the storage modulus and loss modulus curves be nearly the same at a given temperature; that the plot of shift factors vs. temperature be linear; and that the coefficients of a curve fit to the shift factor plot be “reasonable”.

The curve shifting procedure creates a master curve that represents the response of a material over a wide range of frequencies at a particular reference temperature. The amount of shift of a frequency scan that is related to a certain temperature will be different from that of a frequency scan related with any other temperature. Therefore, for every temperature, there is a certain characteristic shift-factor.

Phase 1 Characterization

Analysis was performed using a TA Instruments Model Q800 DMA (see Figure 3) running the TA Rheology Advantage software. The instrument allows the specimens to be characterized in different deformation modes (e.g. shear, tension/compression, dual cantilever beam, 3-point bending,

and single cantilever). The single cantilever configuration was chosen for this study due to the smaller specimen size required.

Phase 1 testing procedure consisted of equilibrating the specimen at 35°C for 10 minutes. After that, the first frequency sweep was run. The frequency sweep subjects the sample to an oscillating load at frequencies varying from 0.1 to 100 Hertz; however, data analysis was only accounted for from 0.1 to 50 Hz. After each frequency sweep is completed, the temperature was incremented 10°C, held for 10 minutes and then another sweep was run. The final sweep was performed at 165°C, which is well above the maximum temperature an adapter is likely to see in service. These procedures were conducted for each of the different specimen preparation samples: injection molded, transfer molded, and actual pad. Two runs were conducted for each process type to check for consistency and repeatability.

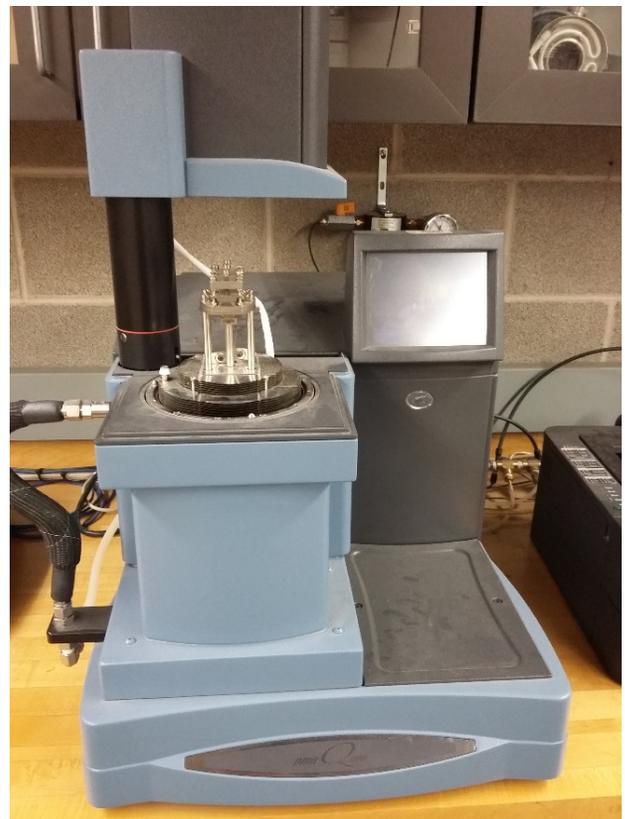


Figure 3. A photograph of the TA Instruments Q800 DMA

Phase 2 Characterization

Phase 2 characterization testing consisted of equilibrating the specimen at 30°C for 10 minutes. After that, the first frequency sweep was run. The frequency sweep subjects the sample to an oscillating load at frequencies varying from 0.1 to 50 Hertz. After each frequency sweep is completed, the temperature was incremented 10°C, held for 10 minutes and then another sweep was run. The final sweep was performed at 160°C, which is well above the maximum temperature an adapter is likely to see in service.

These procedures were conducted only for the injection molded specimen preparation samples since results consistently displayed to be representative of manufactured pads. Four different samples were run each one at a different strain percent: 0.05%, 0.50%, 2.5%, and 12.5%, however, for the specimen that was ran at 12.5% strain, the frequency range was reduced to 2 Hz due to load and displacement limitations of the software used to run DMA experiments.

RESULTS AND DISCUSSION

Phase 1

The storage modulus results for all three specimen preparations as a function of testing frequency are shown in Figure 4, Figure 5, and Figure 6. Storage modulus is analogous to elastic modulus though not necessarily equal to it. At higher frequencies, the storage modulus usually increases and all three specimens show this behavior. The top curve in each plot is for 35°C with each lower curve representing a 10°C higher temperature. Results are plotted only up to frequencies of 50 Hz since application of meaningful loads at frequencies higher than this in rail service are highly unlikely.

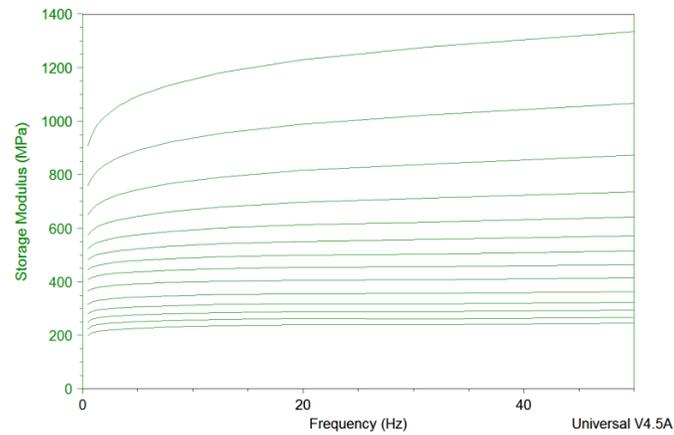


Figure 4. Storage modulus of specimen machined from actual steering pad.

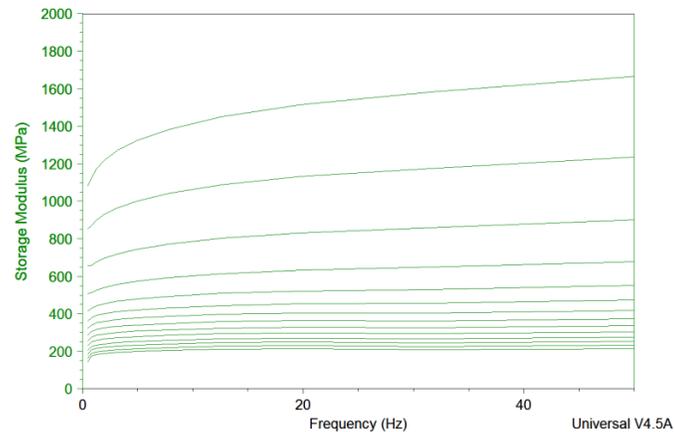


Figure 5. Storage modulus of injection molded specimen.

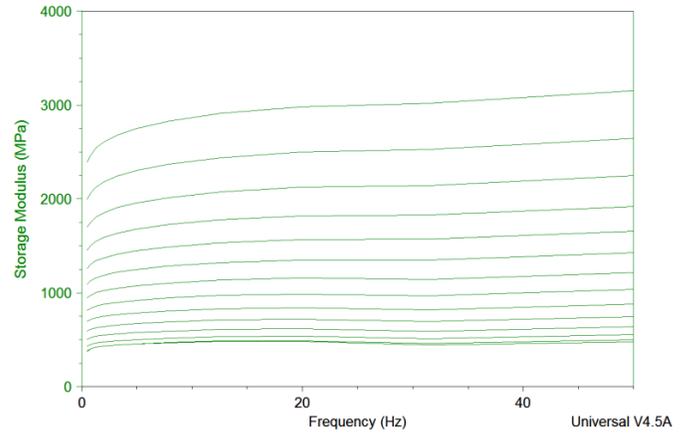


Figure 6. Storage modulus of transfer molded specimen.

The loss modulus of the injection molded and machined specimens are shown in Figure 7 and Figure 8, respectively, which represents the energy dissipated during deformation. The highest loss is for the low temperature sweeps and the loss declines with increasing temperature. Again, each curve represents the sweep at a different temperature starting at 35°C with each lower curve representing a 10°C higher temperature. These results indicate that the loss modulus is significantly smaller than the storage modulus over a wide range of frequencies and temperatures. It never reaches 20% of the storage modulus in magnitude which means that less than 20% of the mechanical work put into a pad will be turned into heat. At most temperatures and frequencies the loss will be closer to 5%. It is also significant that the highest losses are at the upper end of the frequency range.

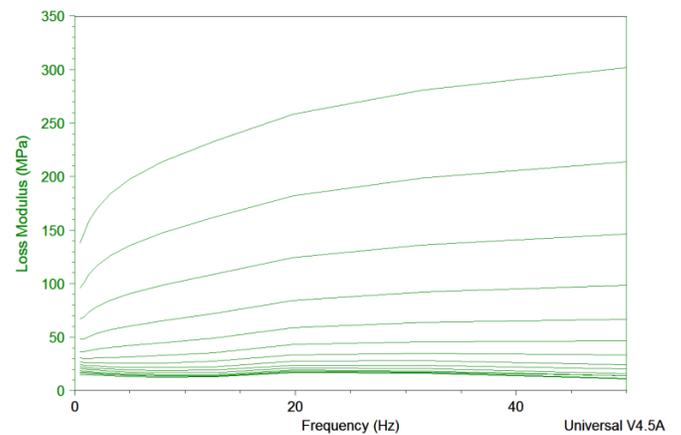


Figure 7. Loss modulus of injection molded specimen.

All three materials show similar frequency and temperature dependence, however, the transfer molded samples (Figure 6) start with, and maintain, a substantially higher storage modulus at all temperatures and frequencies. Thus, the material has apparently been stiffened by the grinding and remolding operation. This would be consistent with thermal oxidation of the material caused by the extra thermal cycle. The

forementioned suggests that grinding pads to provide raw material for molding specimens changes the material and the technique is not appropriate for producing test coupons. After the selection of the most appropriate method of sample preparation, experimental procedures were extended to phase 2 characterization.

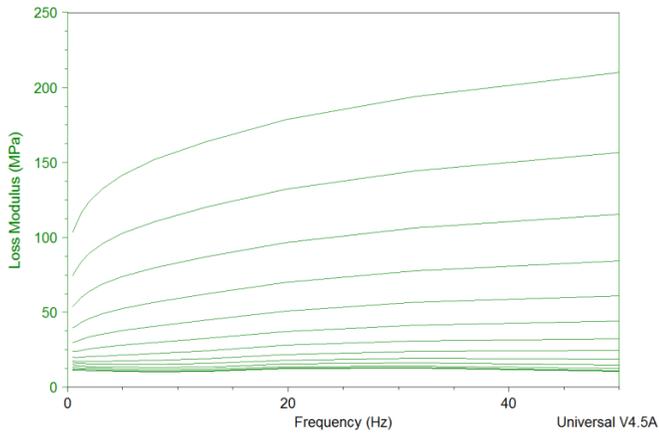


Figure 8. Loss modulus of specimen machined from actual steering pad.

Phase 2

Figure 9 and Figure 10 display the master curves of the storage modulus and the loss modulus vs. the loading frequency respectively for all four strain levels. The 40°C temperature curve of the 0.05% strain rate specimen is selected as the reference curve. The master curves display a linear trend of the storage modulus and the loss modulus as the temperature decreases and the loading frequency increases. The loss modulus curves only utilized data from 30°C to 70°C due to increasing experimental noise at higher temperatures which resulted in poor fit.

It is significant that the curves from all strain levels could be shifted to a common curve. Of particular significance is the generally good agreement between the results over the range of frequencies from 0.1 to 100 Hz as this is the range encompassing the majority of the high energy load events in rail service. The good agreement indicates that a simple linear fit of the loss curve over that range will be adequate for use in modeling the energy dissipation. This will significantly simplify the modeling task.

The shift factors can be seen in Figure 11 and Figure 12 for the storage and loss modulus, respectively, which display a linear increase in magnitude as the temperature increases. Also, for both moduli, comparing the shift factor at a specific temperature, the shift factor is greater for the specimens that were subjected to higher strain percentage rates. In accord with requirements for application of TTS, the factors fit a single line at a given strain level. However, the shift factors depend on the actual strain level used in the test which indicates that there is a strain dependence in the loss modulus.

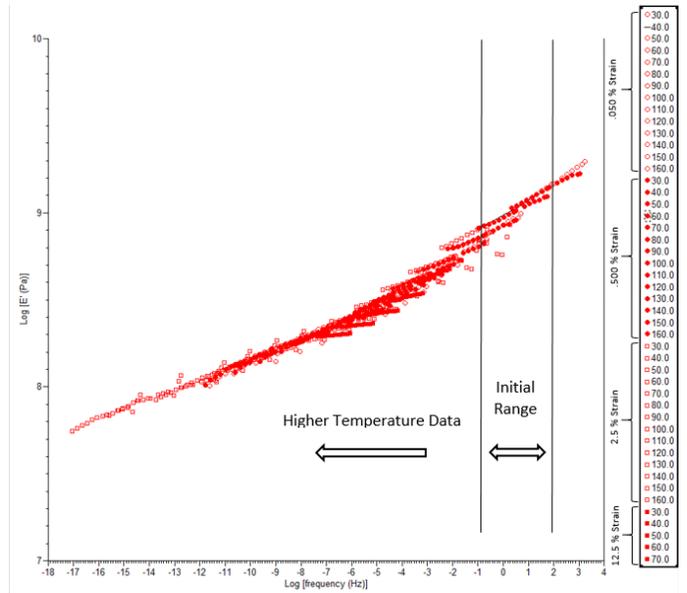


Figure 9. Log-scale master curve of storage modulus vs frequency.

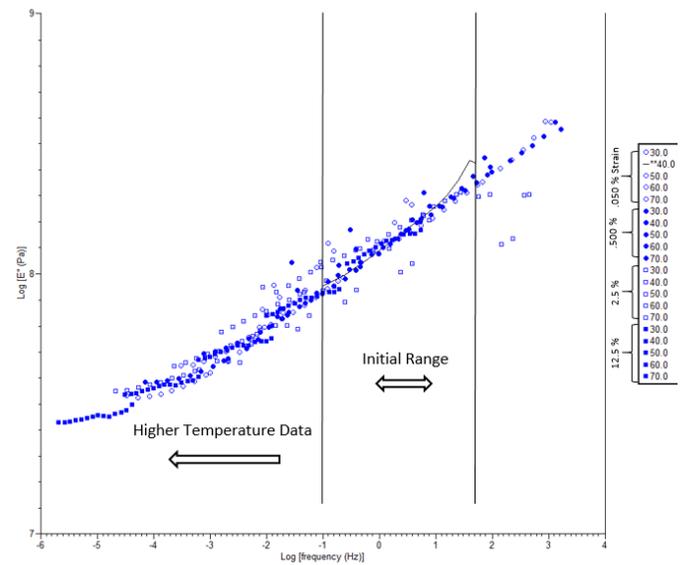


Figure 10. Log-scale master curve of loss modulus vs frequency.

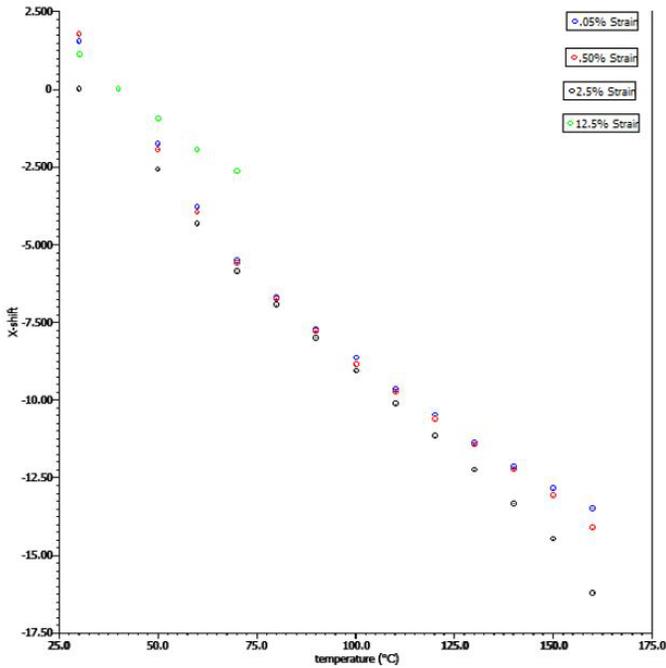


Figure 11. Shift factor vs temperature of storage modulus master curve.

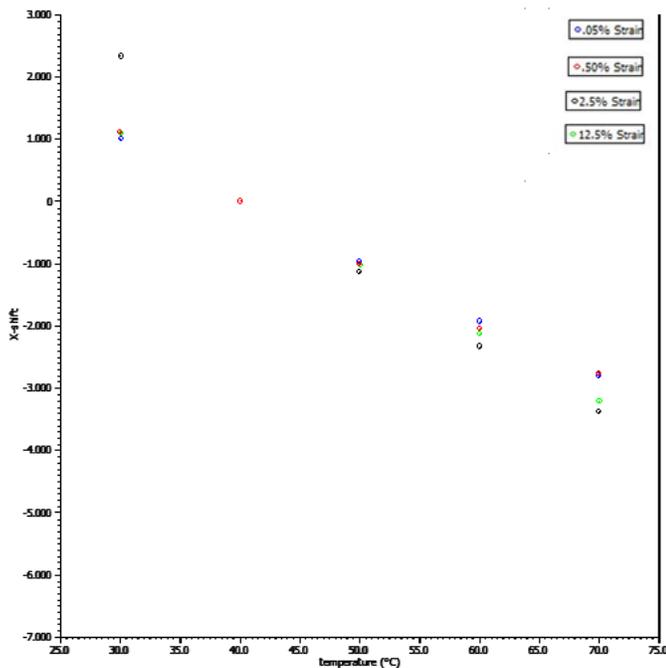


Figure 12. Shift factor vs temperature of loss modulus master curve.

CONCLUSIONS

These results show that:

- Specimens may be fabricated by injection molding standard bars without substantially altering the

viscoelastic behavior of the material when compared to the molded pad. The aforementioned will facilitate future work as convenient specimen types can safely be used to model pad behavior.

- The commonly used TPU elastomer does generate heat under cyclic loading. The peak frequencies for heat generation are at the high end of those commonly seen in rail service and the dissipation efficiency is not particularly high.
- The commonly used thermoplastic elastomer presents an elastically dominant behavior (i.e. elastic modulus is greater than loss modulus).
- The loss modulus or energy dissipating behavior can be treated as independent of strain level and DMA measurement of effects of temperature and frequency are adequate for purposes of system modeling.

FUTURE WORK

The results of this study will be used to investigate the heat generation in the elastomeric pad for use in an experimentally informed and validated finite element thermal model which can be used to obtain temperature distribution maps of railroad bearing assemblies under a variety of normal and abnormal service conditions. Among other things, these maps will be useful for sensor data interpretation and identifying ideal locations for sensor placement for continuous temperature tracking of railroad bearings.

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REFERENCES

- [1] "Adapter Plus Steering Pad System | Amsted Rail." *Adapter Plus Steering Pad System | Amsted Rail*. Web. <http://www.amstedrail.com/adapter-plus-steering-pad-system>
- [2] Rittel, D. "An Investigation of the Heat Generated during Cyclic Loading of Two Glassy Polymers. Part I: Experimental." *Mechanics of Materials* 32 (2000): 131-47. Print.
- [3] Rittel, D., N. Eliash, and J.I. Halary. "Hysteretic Heating of Modified Poly (methylmethacrylate)." *Polymer* 44 (2003): 2817-822. Print.
- [4] Ramkumar, A., K. Kannan, and R. Gnanamoorthy. "Experimental and Theoretical Investigation of a Polymer Subjected to Cyclic Loading Conditions."

- International Journal of Engineering Science* 48 (2010): 101-10. Print.
- [5] Rittel, D., and Y. Rabin. "An Investigation of the Heat Generated during Cyclic Loading of Two Glassy Polymers. Part II: Thermal Analysis." *Mechanics of Materials* 32 (2000): 149-59. Print.
- [6] "Energy Storage and Dissipation in Viscoelastic Material." *TA Instruments*. Web. 23 Oct. 2015. http://www.tainstruments.com/library_download.aspx?file=RH065.PDF
- [7] Tschoegl, Nicholas W. "The Phenomenological Theory of Linear Viscoelastic Behavior." Print.