PROJECT:

Failure Prevention for Sensitized Structural Alloys Used in Coastal Transportation

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1 Results obtained

The work was separated in two directions based on the information obtained from preliminary measurements of sensitization in 5000-series aluminum alloys, (AA5456): **(i)** optimize the pulse-echo measurements to reduce errors and make the measurements automatic and **(ii)** model the longitudinal velocity, shear velocity, and longitudinal attenuation coefficient in order to build a predictive algorithm of failure prevention for these materials.

1.1 Pulse-echo measurements optimization

Previous measurements showed error bars of 4% in the attenuation coefficient, α. Given the importance of precision in the value of α when failure predictions are formulated based on it, it was decided that lowering the errors was an initial scope for the project. The task was accomplished by employing signal processing techniques as follows. Instead of a broad-band pulse (including a wide range of frequencies), a narrow-band excitation signal was used. Even though the material is not expected to be dispersive, a narrow-frequency signal is cleaner to work with and data can be obtained for various frequencies individually. This was done using various windows to cut the sine-wave signal (10-cycles width): Hamming, Hanning, and Blackman–Harris. The spectra of the pulses resulting from each windowing were compared with the spectrum of a standard rectangular window cut. The Hanning and Blackman-Harris windows produced spectra with the lowest side-bands (above or below the main frequency of the signal) and the lowest errors. From each time-trace, that included nine reflections, velocity and attenuation were calculated. A set of ten time traces was used to find an average and an error. The error was calculated from the standard-deviation for the ten measurements. To find the time and the amplitude for each returning pulse, correlation was used in both the time domain and the frequency domain. Have a narrow-band pulse to work with, both correlations were not significantly affected by noise, and errors under 2% were obtained (half the original values). In addition, all the analysis was automated and performed in Matlab. It is a much faster process than using the fitting routine in LabView, previously used for the time traces. An example of a comparison of several sets (10-time traces) is given In the table below. A 5 MHz longitudinal-wave transducer (Ultran Inc.) was used to acquire the data. The frequency-domain correlation produces the lowest errors.

Index	% err. v_L (t-domain)	% err. v_L (f-domain)	% err. α_L (t-domain)	% err. α_L (f-domain)
1	0.12	0.009	3.2	2.2
2	0.10	0.007	2.7	1.2
3	0.11	0.005	3.0	0.8
4	0.10	0.007	3.0	1.3
5	0.10	0.007	3.2	2.2

Table 1: Errors (statistical) for sets (10-time traces are used for one data point). The Blackman–Harris window was used. The correlation between the first reflection and the subsequent ones was performed in both time- and frequency-domain; the frequency-domain analysis proved to produce slightly less errors, on average.

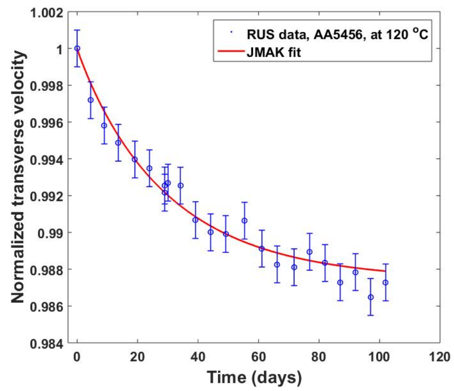

Figure 1: JMAK fit for transverse velocity data at 120^{0}C in AA5456 alloy (data taken with RUS, fit parameters given in Table 4).

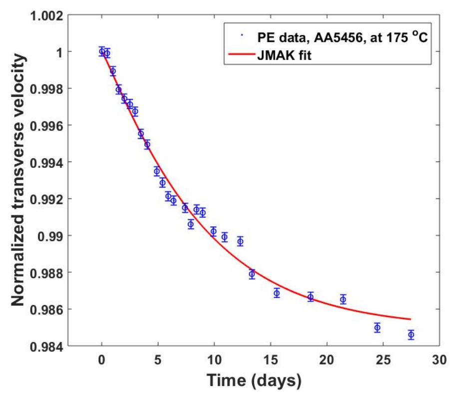

Figure 2: JMAK fit for transverse velocity data at 175^{0}C in AA5456 alloy (data taken with PE, fit parameters given in Table 4).

1.2 Modeling of velocity and attenuation with JMAK

We have presented these results at the 174th Acoustical Society of America Meeting in December 2017 and will soon submit a paper for peer-review.

To be able to build a predictive algorithm, the mechanism of kinetics of crystallization during the phase transformation should be modeled. In 2015, Matthew Steiner and Agnew Sean proposed the use of the Johnson-Mehl-Avrami-Kolmogorov (JMAK) model for understanding sensitization in 5xxx aluminum alloys and fitted NAMLT data to a mathematical model. Further works were aimed at understanding the kinetics of crystallization in the alloys by analyzing the specific heat changes with sensitization. Through this project, we performed a comparative study of kinetics of the β phase using the phase transformation rate, k, and the JMAK exponent, n, has been performed using the JMAK model to describe the observed evolution in three acoustic quantities: longitudinal velocity, transverse velocity, and longitudinal attenuation coefficient. The JMAK equation gives the time-dependence of volume fraction of transformed phase in a sample. We used this variation to find how the velocity and attenuation will change due to the new phase (β-phase) being present in the sensitized material. For the velocity, we obtained the following expected change in the measured velocity as a function of the time of heat treatment the sample is subjected to.

$$C(t) = \frac{C_A C_B}{C_B - \Delta C[1 - e^{-(kt)^n}]}, \quad (1)$$

where $\Delta C = C_B - C_A$.

In Equation 1, C_A and C_B represent velocities in the two phases, A-untransformed and B-transformed (β-phase). The parameters k (phase transformation rate constant) and n (Avrami exponent) are important parameters that describe the type of growth. The k parameter includes thermal effects and the n parameter describes the anisotropy of the growth.

For the attenuation coefficient (α), we obtained the following expected change in the measured α value as a function of the time of heat treatment the sample is subjected to.

$$\frac{\alpha(t)}{\alpha_A} = \left[1 - (\frac{\alpha_A - \alpha_B}{\alpha_A})(1 - e^{-(kt)^n})G\right]. \tag{2}$$

The numerical value of G is evaluated from the equilibrium phase diagram of Al-Mg. The phase diagram of each particular 500-series alloy shows the expected phases present while cooling from elevated temperature to room temperature at all compositions and therefore the ratio of their volumes.

Data for both velocity and attenuation were fitted with the JMAK model and parameters k and n were obtained for the type of material, temperature of heat treatment, type of quantity measured. Several example graphs are included here.

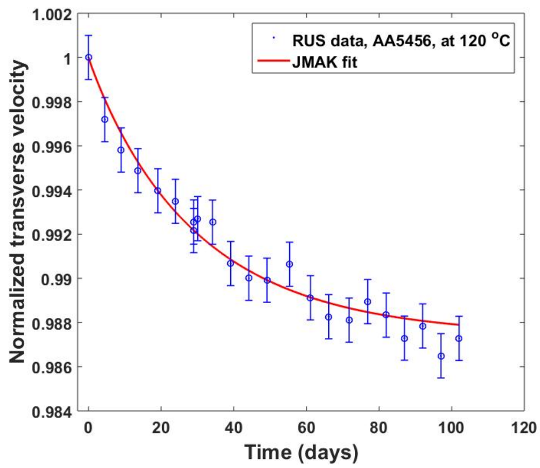

Figure 3: JMAK fit for transverse velocity data at 120^0C in AA5456 alloy (data taken with RUS, fit parameters given in Table 4).

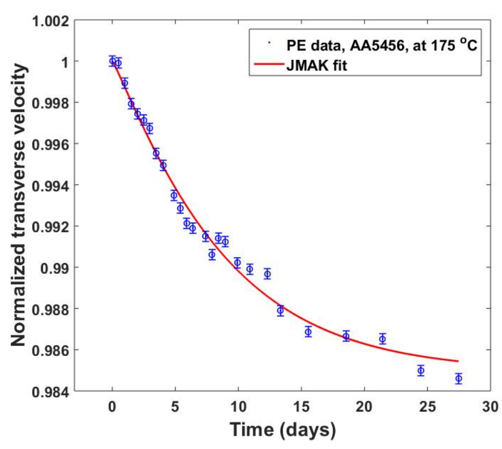

Figure 4: JMAK fit for transverse velocity data at 175^0C in AA5456 alloy (data taken with PE, fit parameters given in Table 4).

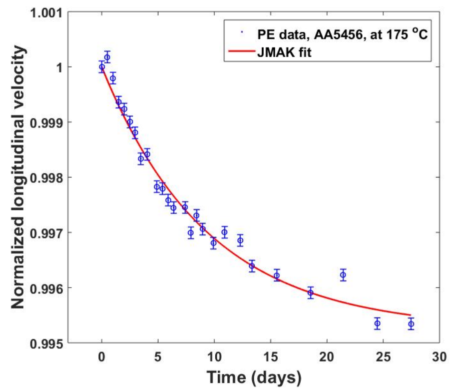

Figure 5: JMAK fit for longitudinal velocity data at 175^0C in AA5456 alloy (data taken with PE, fit parameters given in Table 4).

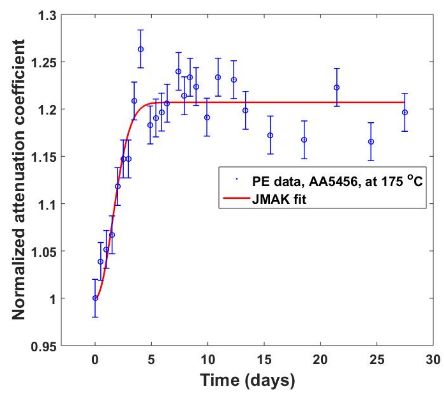

Figure 6: JMAK fit for attenuation coefficient (longitudinal waves) data at 175^0C in AA5456 alloy (data taken with PE, fit parameters given in Table 4).

AA5083, RUS measurements				
T(^oC)	**Quantity**	**Rate constant(k)**	**Avrami exponent(n)**	R^2
120	transverse velocity	0.032 ± 0.003	1.244 ± 0.237	0.97
183	transverse velocity	0.087 ± 0.008	0.932 ± 0.128	0.97
230	transverse velocity	0.384 ± 0.068	1.661 ± 0.718	0.93

Table 2: Values for k and n in AA5083 at different heat-treatment temperature (errors in k and n resulted from fits).

AA5456, RUS measurements				
T(^oC)	**Quantity**	**Rate constant(k)**	**Avrami exponent(n)**	R^2
120	transverse velocity	0.033 ± 0.003	0.956 ± 0.145	0.97
183	transverse velocity	0.146 ± 0.017	0.888 ± 0.143	0.97
230	transverse velocity	0.550 ± 0.090	1.077 ± 0.299	0.96

Table 3: Values for k and n in AA5456 at different heat-treatment temperature (errors in k and n resulted from fits).

AA5456, PE measurements				
T(^oC)	**Quantity**	**Rate constant(k)**	**Avrami exponent(n)**	R^2
175	transverse velocity	0.110 ± 0.006	1.104 ± 0.098	0.99
175	longitudinal velocity	0.105 ± 0.007	0.996 ± 0.110	0.98
175	attenuation coeff. (L)	0.460 ± 0.090	1.997 ± 1.070	0.86

Table 4: Values for k and n in AA5456 at same heat-treatment temperature for different physical quantities (errors in k and n resulted from fits).

2 Future Plans

The oven acquired through the grant will be used to produce controlled sensitization on AA5083 and AA5456 at any desired temperature (the samples have been acquired). The data analysis is now streamlined and the results have less error. We expect to run through multiple sets at a fast rate, being able to run parallel tracks.
(i) Higher frequencies will be tested.
(ii) Shear and longitudinal waves will be tested at multiple frequencies (1, 2, 5, 10 MHz - 10 for L-waves only).
(iii) Samples with a known Mass-Loss value will be measured ultrasonically to establish a correlation between ultrasonic parameters and Mass-Loss. Samples at four Mass-Loss values (i.e. four sensitization levels) have been acquired this fall for each alloy (AA5456 and AA5083).