# NONDESTRUCTIVE METHODS FOR DETERMINATION OF MECHANICAL PROPERTIES OF ALUMINUM AND TITANIUM ALLOYS

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## INTRODUCTION

In general, the mechanical properties of an alloy are determined by the microstructure that results from the alloy's thermo-mechanical history. The thermo-mechanical path in alloy processing is chosen to take advantage of a least one of several strengthening mechanisms such as grain size, dispersion strengthening or dual phase structures. Optimization of an alloy's strength is accomplished by control of the microstructure which determines the operative strengthening mechanism. Therefore NDE techniques sensitive to microstructural changes should prove useful in detecting mechanical property differences. In this work, various thermo-mechanical treatments have been used on aluminum and titanium alloys to provide a wide range of mechanical properties. From the results obtained it is concluded that selection of an NDE detection plan depends on the alloy's thermo-mechanical history and will vary with alloy system.

Another concern of alloy selection is detection of detrimental mechanical conditions or phases that may result from incorrect processing, heat treatment, or in service. The $T_1$ phase that occurs in Al-Li-Cu alloys that are heat treated at temperatures greater than 175°C has been found to decrease fatigue life. A useful detection plan using NDE techniques resulted from this effort. In titanium alloys, hard alpha case and hard alpha inclusions can result in cracking and ultimate failure of the component. Development of a detection plan for these defects is underway.

## EXPERIMENTAL PROCEDURES

Alloys used in this investigation include aluminum-lithium and titanium which are heat treated to optimize mechanical properties. The aluminum-lithium alloys are strengthened by precipitation while heat treatment of the titanium alloys takes advantage of variations in the morphology of the alpha and beta phases. Both tensile coupons and flat specimens of 25 mm x 25 mm x 13 mm were machined from as-received plate of Al 2090, Al-2.2 Li, and Ti-6Al-4V. The heat treatments included solution and aging treatments as listed in Table I with full details reported previously (1-3). Mechanical properties were determined using an Instron screw driven tensile machine to determine the 0.2% yield stress, $\sigma_y$, the ultimate tensile stress, $\sigma_{UTS}$, the strain hardening exponent, n, and the strain to failure, $\epsilon_F$. The flat specimens were prepared for determination of eddy current response, conductivity,

Table I. Alloys and heat treatment parameters used.

| Material | Solution Treatment | Quench | Aging Treatment |
|---|---|---|---|
| Al-2.2 Li | 430 C for 1 h | AC, WC | 150, 164, 175 or 200 C for 3 to 33h |
| Al 2090 | 540 C for 1 h | AC, WC | 150, 164, 175 or 200 C for 3 to 33h |
| Ti-6Al-4V | 1062 C for 1 h | AC, WC | 540 or 450 C for 4h |
| | 958 C for 1 h | AC, WC | 350, 450, 540, 650 or 785 for 4 h |
| | 902 C for 1 h | AC, WC | 540 or 450 C for 4 h |
| | 855 C for 1 h | AC, WC | 540 or 450 C for 4 h |

Vickers hardness (DPH) and/or Rockwell hardness, sound velocity and acoustic attenuation. All measurements are complete for the Al-Li alloys and are in progress in the titanium samples.

## RESULTS AND DISCUSSION

### Aluminum Alloys

Initial work revealed the sensitivity of NDE techniques such as eddy current response, conductivity and hardness to changes in the microstructure and mechanical properties of aluminum alloys. The success of these techniques is attributed to the sensitivity of the sensor, which in the case of eddy current response and conductivity is electrons, to the strengthening mechanism which for Al-Li alloys is precipitation of the $\delta'$($Al_3Li$) phase. As aging progresses, lithium precipitates out to form $\delta'$, thereby decreasing the number of electron scatterers in the matrix and consequently causing the conductivity to increase. Because precipitation of $\delta'$ also increases the strength of the material, electrical property changes in turn are sensitive to increases in strength.

The increase in yield strength depends primarily on the density of precipitates which act as obstacles to dislocations. The precipitates give rise to local distortions and strain fields which restrict dislocation motion. Hardness, which measures a material's resistance to plastic deformation, was found to correlate linearly with $\sigma_y$. As the density of precipitates increased, the number of pinning sites for dislocations increased with the expected increase in $\sigma_y$ and hardness. Therefore for aluminum alloys which are strengthened by precipitation hardening, NDE techniques sensitive to precipitate formation namely hardness and electrical property measurements, will be sensitive to mechanical properties.

A second aspect of the effort with aluminum lithium alloys was detection of the $T_1$ phase which has the composition, $Al_2CuLi$. While the $T_1$ phase does increase strength, it also has detrimental effects on crack propagation in fatigue (4) and should be avoided. As reported previously (3), a combination of eddy current and hardness measurements reveal the presence of the $T_1$ phase. A linear correlation was found between eddy current and hardness for the samples that did not contain $T_1$, while samples aged at 200°C showed a decrease in eddy current response with increasing aging times. This anomaly was attributed to $T_1$ precipitation as verified using TEM techniques (3). This is a clear case of NDE techniques being useful in detection of a deleterious mechanical condition, i.e., increase in fatigue crack propagation caused by $T_1$ precipitates in Al 2090.

Titanium Alloys

The successes in prediction of mechanical properties and in detection of detrimental phases using NDE techniques on Al-Li alloys, lead these authors to a similar approach with the titanium alloy, Ti-6Al-4V. Ti-6Al-4V is the most widely used titanium alloy particularly in aerospace applications. It is strengthened primarily through a solution treatment in the alpha-beta range followed by aging at intermediate temperatures to produce a microstructure of alpha, beta and martensite phases. The strength of the alloys is determined by the morphology and ratios of the alpha and beta phases. The series of heat treatments listed in Table 1 was used to produce a variety of alpha/beta morphologies and the corresponding changes in mechanical properties. The objective of this work is to determine which NDE techniques are sensitive to these changes in mechanical properties.

Heat treatment of the samples as well as optical microscopy and mechanical property measurements are complete. In general, the water quenched samples which have an acicular microstructure were found to have higher strengths than the air cooled samples which have a microstructure comprised of primary alpha platelets and alpha-beta Widmanstatten platelets. In addition, Vickers hardness or DPH measurements are complete and a correlation with $\sigma_y$ attempted as shown in figure 1. The correlation revealed considerable scatter resulting from the large error bars on the DPH measurements. The scatter resulted because the Vickers indentor is on the same order of size as the grains in this material. Therefore the hardness measurements are for a particular phase instead of for the bulk material. To alleviate this problem, Rockwell hardness which has a larger indentor, was also measured. The scatter was reduced but trends to distinguish between heat treatments were not apparent. Thus even though hardness is a useful technique for aluminum alloys, it is not reliable for titanium alloys primarily because the strengthening mechanisms for the two alloys are different. Therefore a single answer to nondestructive determination of mechanical properties does not exist for all alloys, but must be evaluated for each alloy of interest.

The most promising NDE techniques for distinguishing heat treatment variations in titanium alloys are ultrasonic velocity and attenuation measurements (5). The beta phase has been found to be more attenuative than the alpha phase (6) and correlations between alpha and beta morphologies and mechanical properties have been found for other titanium alloys (7). Ultrasonic measurements are underway and correlations with mechanical properties will be reported next year.

The second aspect of our work with titanium relates to detection of hard alpha defects. Hard alpha defects can be divided into two classes, hard alpha case and hard alpha inclusions. Both result from high concentrations of the interstitials oxygen, nitrogen and/or carbon. Alpha case is surface contamination that results when titanium alloys are heated in the presence of air. If the alpha case is not machined away prior to service, the brittle layer can result in surface cracking and ultimately failure of the component. Detection of alpha case is possible using an etching technique (8) and this procedure is routinely used.

Hard alpha inclusions are more dangerous because they are located in the interior of the material making detection more difficult. These inclusions also known as high interstitial defects, are regions of interstitially stabilized alpha of substantially higher hardness than the surrounding material. It is the result of very high localized oxygen or nitrogen concentrations which increase the beta transus and produces a brittle alpha region. Hard alpha inclusions result from use of starting

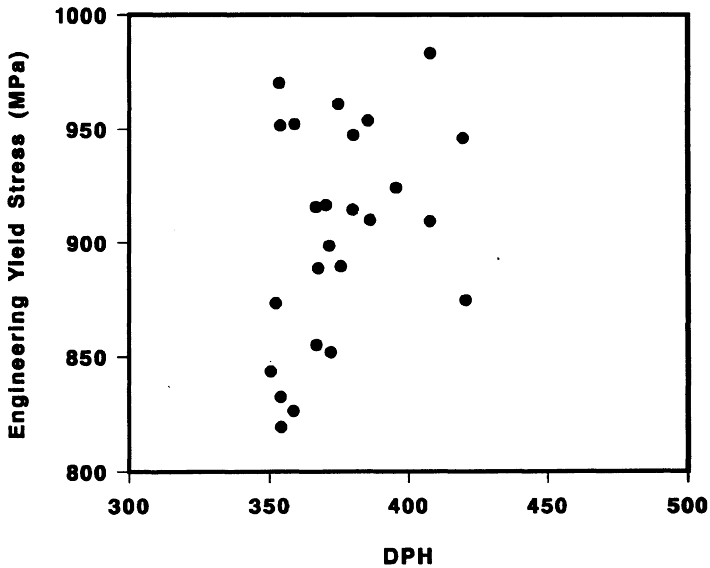


Fig. 1. Engineering yield stress vs. Vickers Hardness (DPH). The average standard deviation for DPH was ±27.

material that contains nitrogen or oxygen contaminated regions, insufficient time at temperature to break up alpha stabilized regions, or direct contamination during the melt process (9-11). Presently titanium material is ultrasonically inspected at the mill in an attempt to remove material with hard alpha inclusions. In general, hard alpha inclusions that are detected have been found in the presence of cracking or voids. The implication is that the ultrasonic indication is from the void or cracks and if hard alpha occurs without their presence it goes undetected. Our present effort is two fold: 1) to produce samples of pure hard alpha case to allow basic material properties to be measured, and 2) to produce samples that contain hard alpha inclusions without cracking or voids and determine if the inclusion is detectable using NDE techniques.

Three techniques were used to produce alpha case samples, one that is an oxygen rich case and two nitrogen rich case samples. Ti-6Al-4V in the mill annealed condition was heated at 955°C for 3 days in air to produce an oxygen case of 130μ thickness. Additional material was heated at 900°C for 2 days in a pure nitrogen environment to produce a nitrogen case of 50μ. Because the 50μ layer causes difficulties in making accurate measurements, another Ti-6Al-4V sample was placed in a hot isostatic press for 2 days at 900°C and 4500 psi to increase the case depth. The depth of this case layer is being determined presently. Once the case depth layer is determined using optical microscopy, the layer is removed. The layers are then used to determine ultrasonic velocity, attenuation, hardness, density and conductivity. These measurements are in progress.

In addition to preparation of alpha case, we are attempting to produce Ti-6Al-4V material seeded with hard alpha inclusions (12). The procedure involves drop casting of molten Ti-6Al-4V. The hard alpha defect is then dropped into the mold followed by additional molten material. This approach is underway and if successful, the seeded samples will then be used to determine the feasibility of various detection plans now proposed. In addition we also have samples provided to us by industry that will be used in the feasibility study.

## CONCLUSIONS

As the types of materials used are expanded and their useful lifetime is extended, the need for reliable nondestructive techniques to determine their mechanical condition becomes more important. The present effort concentrates on nondestructive determination of mechanical properties and detection of detrimental conditions that may occur in selected alloys.

Initial work successfully determined linear correlations between yield stress and hardness for aluminum lithium alloys. In addition a technique using nondestructive measurements was found to detect the detrimental $T_1$ phase in Al 2090. The major conclusion of this work was that nondestructive sensors sensitive to precipitation, the operative strengthening mechanism for aluminum alloys, would also be sensitive to microstructural changes and mechanical property variations. In the case of aluminum lithium alloys, the optimal sensors are electrons and dislocations, with the most sensitive techniques being eddy current, conductivity and hardness. While these techniques work well with aluminum, efforts with the titanium alloy, Ti-6Al-4V, were less successful.

Hardness measurements for the titanium alloy were not indicative of the bulk properties of the material but rather measured the hardness of individual phases within the alloy. The failure of this technique indicates that the sensor, in this case dislocations, is not sensitive to the strengthening mechanism operative in Ti-6Al-4V. Unlike the aluminum alloys, Ti-6Al-4V is not strengthened by precipitates, but by the presence of the two phase structure, alpha and beta. Therefore a successful nondestructive detection plan will need to distinguish changes in the alpha and beta phases. It is proposed that ultrasonic measurements will be successful because the beta phase is more attenuative than the alpha phase and changes in attenuation should indicate changes in the alpha and beta morphologies. This work is in progress. In conclusion, note that a single nondestructive technique will not provide an indication of the mechanical condition of all alloys, but that each system must be evaluated based on the microstructural features that determine its mechanical properties. In a related effort, these authors are developing a system to measure the nonlinear acoustic properties of materials.

Microstructural features that are of interest in titanium alloys are hard alpha case and hard alpha inclusions. This work now concentrates on measuring the basic material properties of hard alpha case and determining the most feasible detection plan for hard alpha inclusions.

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