NONDESTRUCTIVE METHODS FOR THE DETERMINATION OF MECHANICAL PROPERTIES OF MATERIALS

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INTRODUCTION

The nondestructive determination of mechanical properties of materials is desirable because of the rising cost of both materials and labor as well as safety concerns. In most alloys, changes in thermal and/or mechanical history results in microstructural changes and consequently different mechanical properties. Thermal or mechanical cycles may result from processing or occur in service. Therefore nondestructive detection of microstructure and mechanical properties would prove useful in all phases of metallurgical use. This paper reports on efforts to determine selected mechanical properties of structural materials by nondestructive means such as electrical, acoustic and magnetic techniques as well as hardness. Various thermal and mechanical conditions have been imposed on aluminum, titanium and ferrous alloys to arrive at a wide range of mechanical properties. It is concluded that the intimate knowledge of the microstructure and environmental effects are essential to select the nondestructive method that is most sensitive to property changes.

EXPERIMENTAL PROCEDURES

The alloys and heat treatment used in this investigation are listed in Table I.

Aluminum Alloys

As reported earlier (2-6) flat specimens were prepared from the Al-Li binary and the Al 2090 and used for determination of eddy current response at 5 kHz, dc conductivity, Vickers (DPH) and Meyer hardness, sound velocity and the acoustic attenuation. Mechanical properties were obtained using standard tensile specimens and an Inston screw driven tensile machine at a strain rate of approximately 1.6 x 10^{-4} s^{-1}. The 0.2% offset yield stress, σ_y, the ultimate tensile stress, σ_{UTS}, the strain hardening exponent,n, and the strain to failure, ϵ_F, were determined.

Al 2024 is a widely used commercial alloy based on the Al-Cu-Mg ternary system. Six cubes 25 mm x 25 mm x 25 mm were cut from a plate of Al 2024-T351. The cubes were returned to the T4 condition by a solution treatment at 495°C for 2 h followed by a water quench. Five of the cubes were then placed in a 530°C furnace for 5, 10, 15, 30, or 60 min. followed by a water quench. NDE measurements will be used to find a technique sensitive to the undesirable effects of eutectic melting.

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 200C for 3 to 33 h
Al 2090 (1)	540 C for 1 h	AC, WC	150, 164, 175 or 200 C for 3 to 33 h
Al 2024-T4	530 C for 5, 10, 15, 30 or 60 min.	WC	
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
	844 C for 1 h	AC, WC	540 or 450 C for 4 h

Titanium alloys

Sample blocks of 13 mm x 25 mm x 25 mm were cut from 13 mm Ti-6Al-4V plate in the mill annealed condition. Tensile coupons were also taken from this plate along the rolling direction. The blocks and tensile coupons were wrapped in titanium foil and sealed in quartz tubing under a vacuum of 4 x 10^{-5} torr or better. The encapsulated samples were solution treated to the temperatures listed in Table I for 1 h followed by either air or water cooling. Samples were then aged for 4 h at either 540 or 450°C followed by air cooling. Selected samples from the 958°C treatment were also aged at 785, 650 or 350°C to provide additional microstructural features, i.e., Ti_3Al and omega phases. NDE and mechanical measurements are planned for the near future.

Ferrous Alloys

Measurements were made on four steel specimens taken from a railroad bridge. The material was machined into standard S/N geometries and fatigued at strain amplitudes ranging from 0.002 to 0.005. As fatigue progressed measurements of several magnetic properties, including initial permeability, remanence, coercivity and hystersis loss, were made at intervals corresponding to typically 10% increments in expended fatigue life.

The experimental system used to make the measurements was a portable magnetic inspection device with a contoured magnetic inspection head made from soft Armco Iron. The device was capable of measuring the magnetic properties of the material without the need for an encircling flux coil. Therefore measurements were made simply by placing the inspection head in contact with the specimen. Changes in the magnetic properties were observed as the material was fatigued.

RESULTS AND DISCUSSION

Aluminum Alloys

This project began as an effort to predict the mechanical properties of Al-Li alloys nondestructively. As expected changes in mechanical properties go hand in hand with microstructural changes. In the course of the work, we found that some NDE techniques are more sensitive to

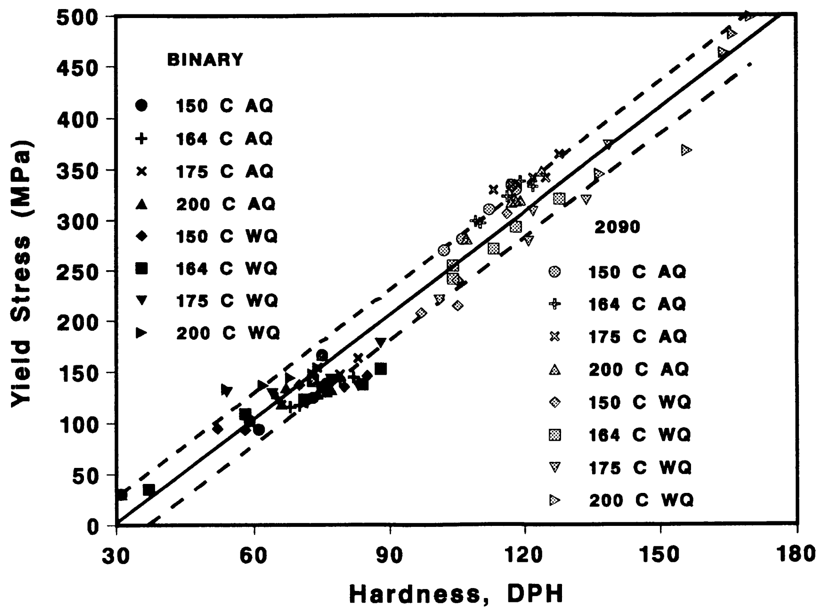

Fig. 1. Yield stress vs. Vickers hardness (DPH) for Al 2090 and Al-2.2 Li Binary, air and water cooled.

these changes than others. Hardness measurements provide an excellent method for prediction of the yield stress in other aluminum alloys (7,8) as well as in Al-Li alloys (4,5). A linear correlation was found between DPH and σ_y for both the binary and Al 2090 with a correlation coefficient of R=0.97. The results are shown in Fig. 1. However not all results were this conclusive. Fig. 2 shows the correlation between uniform strain and DPH. Qualitatively ln ϵ is proportional to DPH but the scatter was too great to provide quantitative correlations. The scatter results from difficulties in determining the uniform strain.

Acoustic measurements revealed no systematic trends with aging treatment for either alloy. However differences were found between the two alloys. Table II lists the physical properties determined for these alloys. Note the elastic modulus is in the range reported for aluminum lithium alloys (9). It is possible that nonlinear acoustic measurements may be more sensitive to microstructural changes as is the case in other aluminum alloys (10). These measurements are planned.

A linear relationship was found between eddy current response and dc conductivity for both the binary and Al 2090 indicating that conductivity can be estimated from simpler eddy current measurements. A linear correlation was also found between either eddy current or conductivity and DPH with the exception of samples containing the T_1 phase. The occurrence of the T_1 phase was verified using TEM (6). Therefore, T_1 which is detrimental to fatigue properties (11) can be detected using a combination of eddy current or conductivity and hardness measurements.

Al 2024 is a widely used structural alloy composed of 4.4 Cu, 1.5 Mg, and 0.6 Mn. As with many aluminum alloys, Al 2024 is heat treated to increase strength by precipitate formation with the usual procedure being solution treatment followed by aging. The mechanical properties are greatly affected by the solution heat treatment temperature. If the solution temperature is too low, the hardening phases are not completely dissolved prior to quenching, lowering the precipitate density and therefore the yield stress. If the solution temperature is too high, melting of some of the phases will occur, resulting in a decrease in

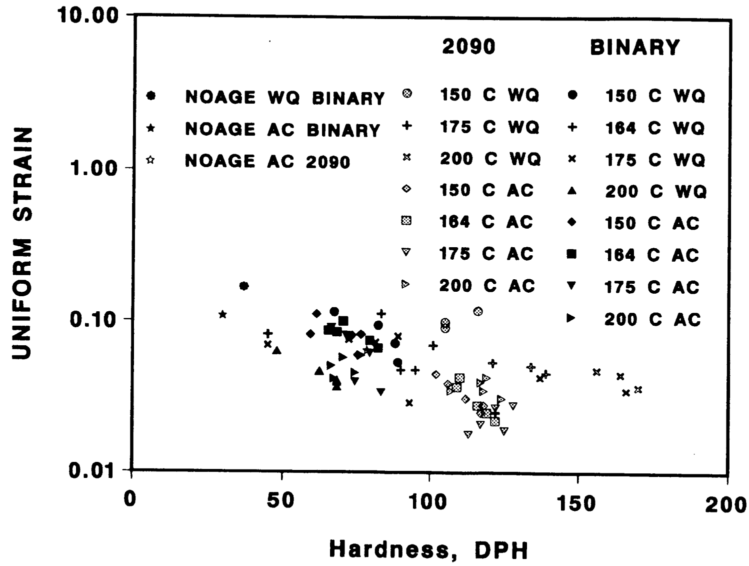

Fig. 2. Uniform Strain vs. Vickers hardness (DPH) for Al 2090 and Al 2.2 Li Binary.

Table II. Physical Properties of Al-Li alloys. (x: measurements performed; S_{yx} = standard deviation)

Material Al 2090 WQ	AQ	Binary WQ	AQ	Physical Property	S_{yx}
x	x			ρ = 2.59	
		x	x	ρ = 2.56	
x				η = 0.31	
		x	x	η = 0.32	
x				c_L'' = 6471.2	12.0
		x	x	c_L'' = 6557.8	8.0
x				c_S = 3470	
		x	x	c_S = 3460	
x				c_L' = 6590	
		x	x	c_L' = 6710	
x				E = 78.7	0.3
		x	x	E = 77.2	0.2
x				μ = 1.26	0.65
		x	x	μ = 3.46	1.33
x	x			Grain size = 15 μm	
		x	x	Grain size = 150 μm	

Definitions:

ρ = density (g/cm^3)

η = Poisson's ratio

c_L'' = longitudinal velocity determined in immersion at 10 MHz

c_L' = longitudinal velocity determined in contact at 5 MHz

c_S = shear velocity determined in contact at 2.25 MHz

E = Young's modulus (GPa)

μ = attenuation (dB/cm)

strength and ductility rendering the material useless. To avoid this condition referred to as overheating or eutectic melting (14), the general practice is to solution heat treat about 5°C lower than the lowest melting eutectic. Because of the close control required to insure eutectic melting does not occur in this alloy, we hope to develop a NDE technique to detect its presence. Presently we have an Al 2024-T4 control sample and five samples that were heated to 530°C for various times as listed in Table I. These samples will be examined optically followed by various NDE measurements.

Titanium Alloys

In preparation of the Ti-6Al-4V samples, heat treatment temperatures and times were chosen that are used by industry to produce a wide range of strength-ductility combinations. In addition to the usual commercial heat treatments, samples were produced to contain either the omega or the Ti_3Al phase, both of which are detrimental to mechanical properties. The omega phase is a nonequilibrium phase that can occur in the transition from beta to alpha during aging at low temperatures (< 400°C). Omega can lead to severe embrittlement (12). Ti_3Al, an ordered phase, causes increased fatigue crack propagation rates and enhanced susceptibility to stress corrosion cracking (13). It forms on slow cooling at elevated temperatures (650-800°C). One objective of this effort is to develop an NDE technique to detect the presence of omega and Ti_3Al. In addition relationships between mechanical properties, microstructure and NDE measurements will be sought.

Ferrous Alloys

Changes in remanence are shown for the four railroad bridge specimens in Fig. 3. In all cases there was a monotonic increase in remanence with fatigue life up to at least 80% and in some cases to more than 90% of expended fatigue life. The increase in remanence over this range of fatigue life was 10% for specimen 1, 18% for specimen 2, 23% for specimen 3 and 12% for specimen 4. In the final stages of fatigue a

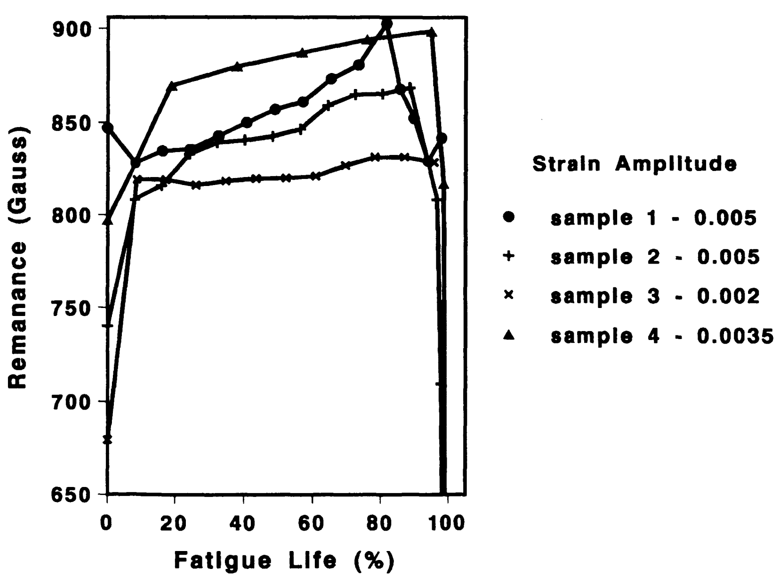

Fig. 3. Remanance vs. fatigue life for steel samples at strain amplitudes listed.

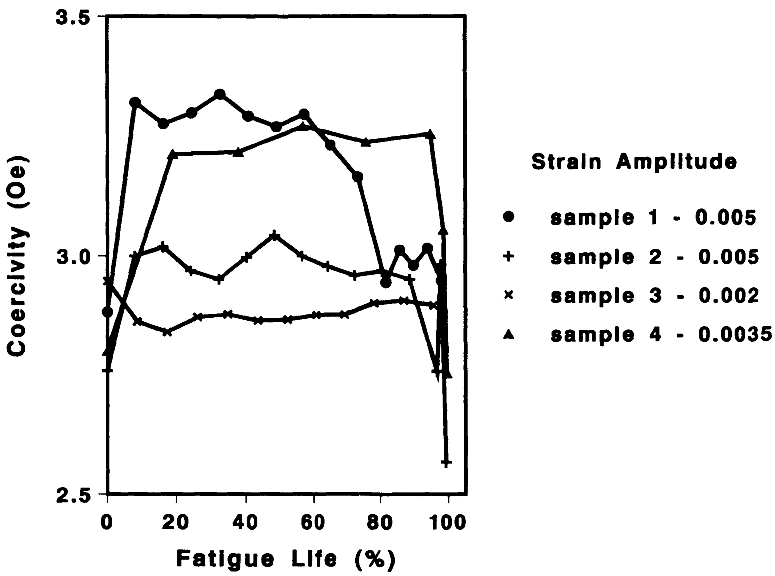

Fig. 4. Coercivity vs. fatigue life for steel samples at strain amplitudes listed.

sudden decrease in remanence was observed as shown in Fig. 3. This decrease converts to 9% in sample 1, 20% in sample 2, 1% in sample 3 and 42% in sample 4. Therefore in three of the four cases the remanence declined rapidly as the end of fatigue life was approached. Coercivity measurements also revealed progressive changes with expended fatigue life in the three specimens fatigued at higher strain amplitudes as shown in Fig. 4. In each of these cases the coercivity showed a rapid initial increase, followed by a "plateau" region in which the coercivity remained fairly constant and finally a rapid decline in the last 10-20% of fatigue life.

Without further study the interpretation of these results can be only tentative. It is known that stress cycling as in the case of fatigue causes a build up of dislocations which eventually form bundles or cell walls and finally cracks which lead to failure. It is also known that dislocations and regions of inhomogeneous microstrains impede Bloch wall motion and thereby lead to change in coercivity, remanence and hysteresis loss. Therefore, our present interpretation of the results is that the build up of dislocations leads directly to the rapid increase of coercivity, which was also observed in earlier fatigue investigations (15), and to the progressive increase in remanence. The reasons for the critical behavior of the remanence and coercivity in the final stages of fatigue are as yet not certain. Measurements are planned on a polycrystalline iron specimen. In addition to magnetic measurements, other NDE quantities will be measured as a function of fatigue to explore possible correlations.

CONCLUSIONS

As the cost of materials continues to rise the need for NDE techniques to insure their integrity becomes more pressing. The objective of this work is to explore ways to determine heat treatment or mechanical condition of various alloys nondestructively. To accomplish this, samples were heat treated using various times and temperatures followed by mechanical testing and nondestructive examination. Correlations between mechanical properties and NDE measurements were then explored. In addition, microstructural changes were examined. Reliable

NDE methods have been presented to predict the strength of Al-Li alloys. The T_1 phase in Al 2090 which is detrimental to fatigue properties was detected using NDE measurements. An effort is also being made to detect eutectic melting or overheating in Al 2024. Samples were prepared from a Ti-6Al-4V plate to allow extension of this work to other alloy systems. It appears from the present results on railroad bridge steels that the bulk magnetic properties such as coercivity and remanence provide a useful tool for monitoring the progress of fatigue in ferromagnetic materials such as steels.

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