

AN ULTRASONIC STUDY ON ANELASTICITY IN METALS

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INTRODUCTION

Ultrasonic waves are highly sensitive to microstructural variations in materials and have been used extensively to investigate anharmonic effects in various metals and alloys[1-3]. A major focus of these studies is on the higher order elastic constants and their relation to the microstructure of the material. Ultrasonic techniques have also proven quite useful for characterizing the stress state of a material [4-6]. Recently, while using the magnetoacoustic (MAC) method to investigate the residual stress in various steel samples, a time dependent change in the results was observed. It became apparent that the measurements were exhibiting anelastic effects due to some intrinsic properties of the samples.

Anelasticity is a phenomena that can occur whenever there is a rapid change in the external stress applied to a crystalline solid. The change in stress will cause the induced strain to adopt a new equilibrium position. If the changes in the resulting strain does not take place instantaneously, the material is said to exhibit anelastic behavior. Investigations into anelastic relaxation in crystalline solids have been carried out for many years and provide important information relating to the microstructure of the material [7-13].

The time dependence of our MAC test results led us to propose a new approach for studying the causes of anelasticity in metals. Typical studies on anelasticity use strain gauges to monitor the recovery process. We propose tracking the ultrasonic natural velocity, as a function of time, to identify and characterize the mechanisms responsible for anelastic behavior. The time dependence of the ultrasonic natural velocity immediately following sudden changes in the applied stress states in both ferrous and nonferrous alloys was studied using the pulsed-phase-locked-loop (P2L2) method [2]. One problem is the sensitivity of the natural velocity to changes in temperature. To isolate the thermal effects from other variations the temperature change was monitored to estimate and account for this separately. The focus of this paper is on the experimental setup and results of tests performed on aluminum 2024 T-4, yellow brass and 1020 steel. In a companion paper [14] we provide a more

detailed analysis of the theory and causes associated with our results.

THEORETICAL CONSIDERATIONS

In what follows, a brief description of the essential features of anelasticity, anharmonicity and the ultrasonic natural velocity considered in this paper is presented. Anelastic behavior arises if a material undergoes a sudden change in loading and requires time to attain a new equilibrium configuration (See Fig. 1). To varying degrees, all metals exhibit anelastic behavior. The phenomenon is usually studied by monitoring the strain, ϵ , as a function of both time and load, however, it is also possible to fix the strain and measure the relaxation rate of the resulting stress. In terms of the strain the relevant anelastic relation is given by,

$$\epsilon(\sigma, \xi, t) = J_U \sigma + \sum_i \chi_i \xi_i(t). \quad (1)$$

Here σ is the applied stress, J_U is the unrelaxed compliance (a measure of the deformation that occurs when no time is allowed for relaxation to take place), ξ_i are internal variables responsible for the anelastic behavior and χ_i are the coupling constants [7]. The key to studying anelastic phenomena is identifying and characterizing the internal variables, ξ_i . Most experiments use strain gauges to monitor the strain after a load change. An analysis is then performed on the resulting strain data to estimate the number of internal variables along with their relaxation rates. From these results one can investigate the internal properties of the material.

A large part of anelastic relaxation can be attributed to the sudden change in the internal temperature of the material when the loading configuration is modified. In addition, other effects such as the motion of dislocations, which do not move instantaneously after the load is changed, have also been found to have a profound impact on the relaxation time in metals [12]. A variety of linear and nonlinear models have been proposed to account for this behavior and have proven to be useful analytical tools [7, 11].

Anharmonicity, on the other hand, is concerned with the dependence of the elastic constants on strain. It is best understood in terms of the third-order elastic constants defined by the potential energy per unit volume, U , of a strained crystal which can be expressed as,

$$U = U_0 + \frac{1}{2} \sum_{i,j=1}^6 C_{ij} \epsilon_i \epsilon_j + \frac{1}{6} \sum_{i,j,k=1}^6 C_{ijk} \epsilon_i \epsilon_j \epsilon_k + \dots \quad (2)$$

Here U_0 is the potential energy in the absence of strains, the C_{ij} are the ordinary (second-order) elastic constants, the C_{ijk} are known as the third-order elastic constants, and ϵ_i , ϵ_j and ϵ_k are strains [7]. The presence of the third-order elastic constants causes a nonlinear stress-strain relation. These third-order elastic constants can be measured by monitoring changes

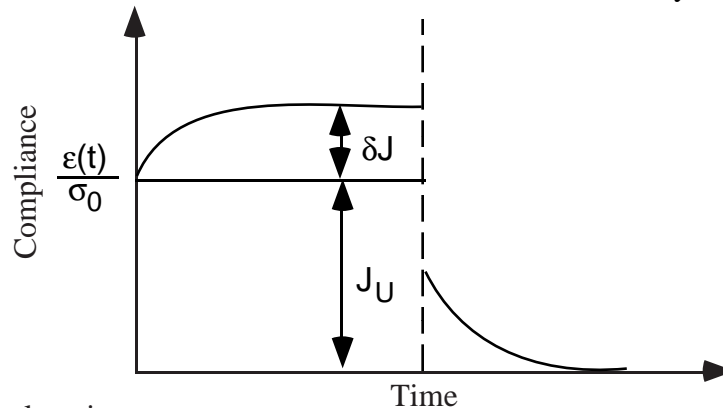


Fig.1 Anelastic relaxation

in the ultrasonic natural velocity as a function of static stress [3].

The term natural ultrasonic wave velocity was first introduced by Thurston and Brugger [1]. Since that time it has been used extensively throughout the ultrasonic community [2-6]. This velocity is defined as a natural consequence of results readily obtainable from experiments. The natural velocity, W , is proportional to the measured frequency and is given as $W = 2L_0F$. Here F is the repetition frequency (the inverse of the time required for a round trip between opposite faces) and L_0 is the initial length the wave travels before the sample is stressed. The true wave velocity, on the other hand, involves the actual path length of the wave which changes as the sample is stressed. Furthermore, the direction of the actual velocity may change with an applied static stress. The propagation direction of the natural velocity, on the other hand, remains constant. Thus, the natural velocity provides a more convenient means of monitoring changes in the sample. To monitor the natural velocity we use the P2L2 technique [2]. The technique measures relative changes in the natural velocity which is given by the relation,

$$\frac{\Delta W}{W} = \frac{\Delta F}{F} = \frac{\Delta V}{V} - \frac{\Delta L}{L}. \quad (3)$$

Where F is the frequency, V is the phase velocity and L is the sample length. Further details on this method can be found elsewhere [2].

EXPERIMENTAL SETUP

Samples of 1020 steel, aluminum 2024-T4 and yellow brass were prepared from 30mm diameter cylindrical rods that were 35 cm long. The centers of the rods were machined down to a 16x25x100 mm³ solid rectangular region. The samples were then placed in a load frame operating with a constant stress. A damped 10 MHz compressional wave ultrasonic transducer was attached to the surface of the sample. The wave was directed across the 16 mm length of the sample. The transducer was connected to a Pulse Phase Locked Loop System (P2L2). The P2L2 system uses a phase feedback system with a voltage controlled oscillator (VCO). The VCO output produces a tone burst input to the transducer. The return echo is amplified and phase detected with the VCO as the reference. With a sample and hold circuit, the frequency of the VCO is changed until quadrature is achieved. Once the VCO is locked, the system maintains quadrature. We then monitor the normalized change in frequency that is given in equation (3) above.

The tests were adiabatic so, in addition to the natural velocity we also monitored the change in the sample temperature. This was accomplished by attaching a platinum resistance temperature sensor, also called a resistive temperature device (RTD), to the surface of the sample. The sensors are capable of monitoring temperature changes of 0.01 °C. A computer was used to automate the entire experiment by controlling the load frame and recording the data from the P2L2 and the temperature sensor. The load on the sample was cycled from zero to a peak tensile load by using a short duration ramping function. After a half hour the load was change to a peak compressive load and held fixed for another half hour. This cycle was repeated two more times with the final load being brought to zero instead of compression. A series of progressively larger loads were used as the peak load for each run up to a maximum of 30 ksi. To monitor the effect of temperature on the natural velocity, independent of loading, a small thermal chamber was constructed. We slowly raised and lowered the temperature of the sample while monitoring the temperature and the change in the ultrasonic natural velocity of a 10 MHz compressional wave. The results of these tests are given below.

RESULTS AND DISCUSSION

Fig. 2 shows a comparison of the natural velocity change for the brass, steel and aluminum samples stressed in tension and compression with a peak load of 30ksi and -30ksi respectively. The results for both steel and aluminum are antisymmetric with respect to tension and compression. The brass, however, has a much smaller change in the natural velocity in tension than in compression at the 30ksi load. At lower loads, however, the brass behaves in a more antisymmetric manner. Due to thermoelasticity a temperature change is also induced in the samples as they are stressed and is shown in Fig.3. An interesting observation is that the temperature change is always in opposition to the natural velocity change. This is further highlighted in Fig. 4 where the natural velocity change in regions directly preceding a load change is plotted. As the load changes from compression to tension, the brass behaves in a completely different way than aluminum and steel. The change in the nat-

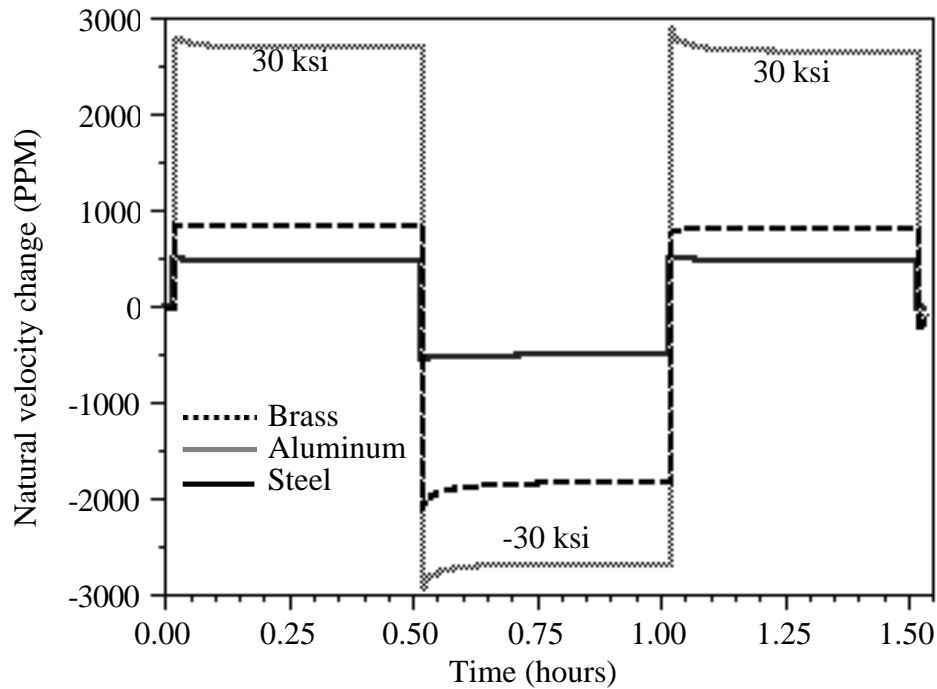


Fig. 2. Change in the ultrasonic natural velocity over loading cycle.

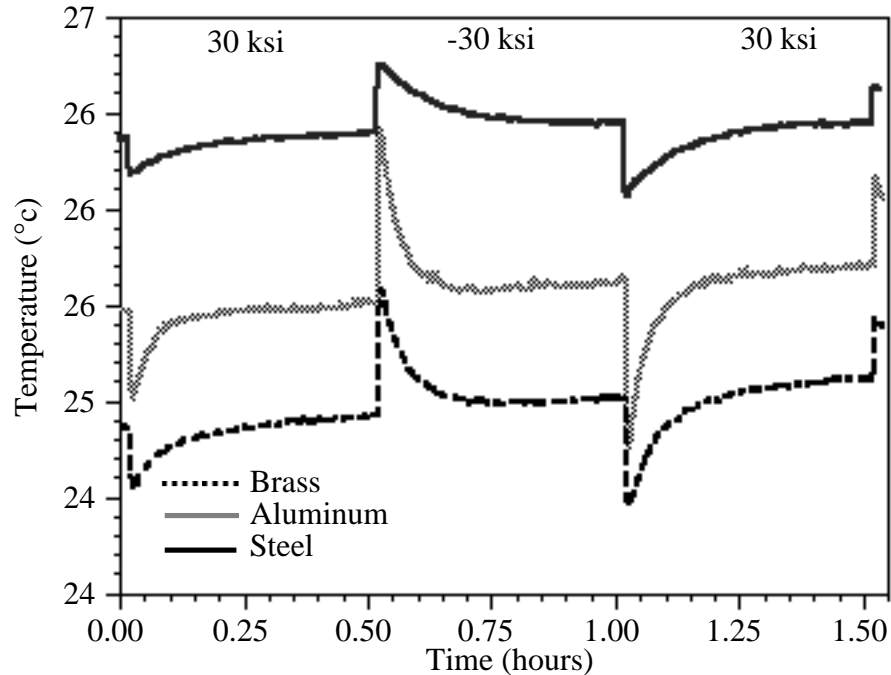


Fig. 3. Temperature dependence of samples undergoing loading.

ural velocity of brass does not rise as sharply as it does for the other samples. This phenomena also exits at lower loads, although it is not as pronounced. Another interesting observation is that aluminum is perfectly antisymmetric. Even the scaling for the natural

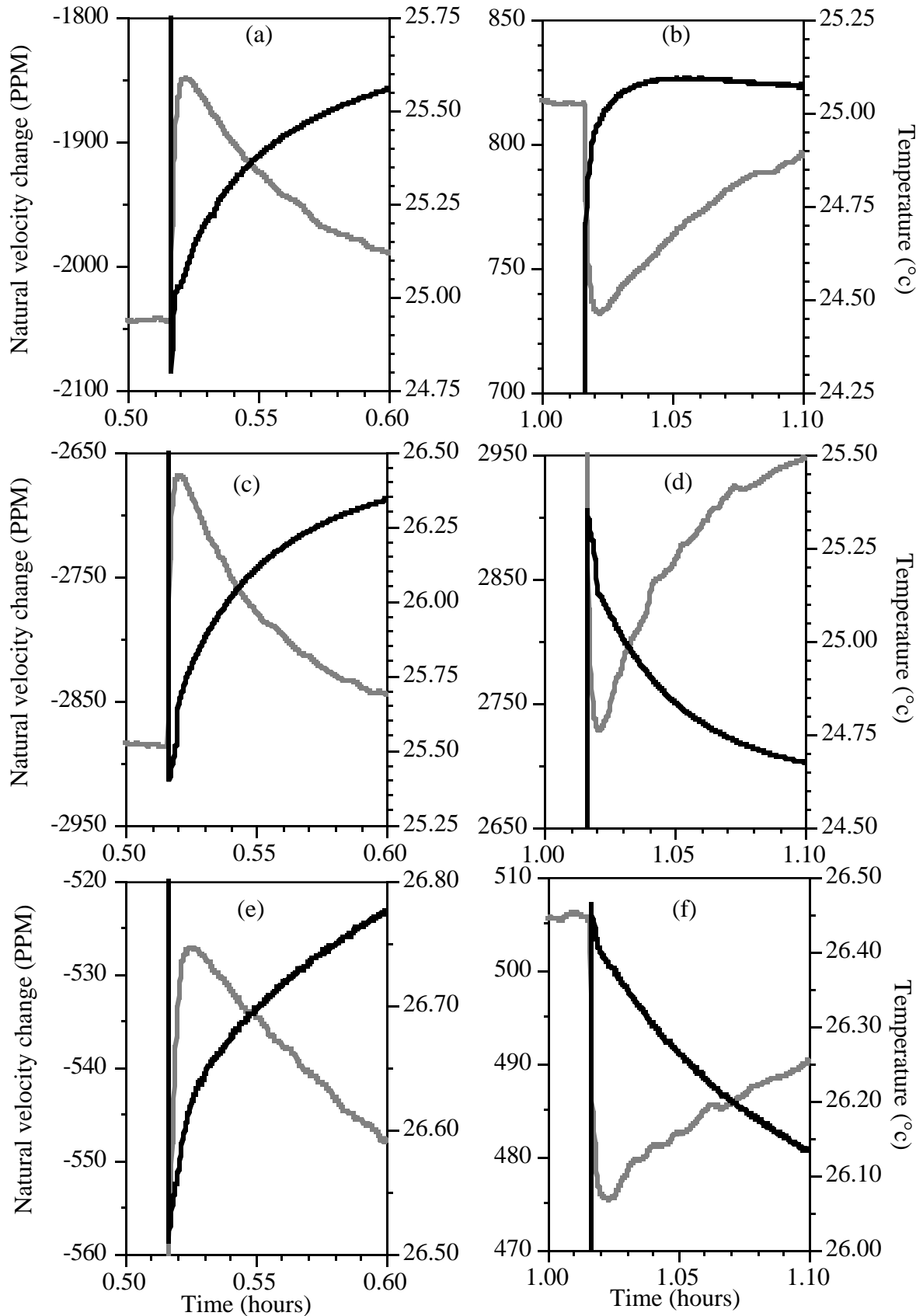


Fig. 4. Magnified natural velocity change and temperature profiles for (a) brass after a load change from 30 ksi to -30 ksi, (b) brass after -30 ksi to 30 ksi, (c) aluminum after 30 ksi to -30 ksi, (d) aluminum after -30 ksi to 30 ksi, (e) steel after 30 ksi to -30 ksi, (f) strrl after -30 ksi to 30 ksi. — Temperature — Natural velocity change

velocity graph is reversed. To a somewhat lesser extent this is also true of the steel sample.

It is apparent that what we are observing is a combination of anelastic effects along with a temperature dependence of the natural velocity. To account for this, the temperature was varied and the velocity change monitored. The resulting relationship is linear and fairly repeatable. A typical curve for brass with its best linear fit is given in Fig. 5 along with the best fits for both aluminum and steel. An increase in temperature causes a decrease in the velocity as was evident from the previous load curves. Furthermore, this effect is more pronounced in aluminum than either brass or steel. The theory behind the temperature dependence of the elastic constants has been considered in detail by Born [15].

It is assumed that the temperature dependence of the velocity can be separated from any underlying anelastic effects. This requires that the temperature affect on the natural velocity is simply superimposed on the other effects. Thus, there is no coupling with anelasticity or loading. We should emphasize that we are not talking about anelastic effects which are due to temperature changes in the material. We are only considering the temperature dependence of the natural velocity. If the assumption is true, then we can simply subtract the ultrasonic temperature dependence and be left with only anelastic effects. This was done and the results are shown in Fig. 6 below. The curves now resemble typically observed anelastic graphs (Fig.1). There are, however, large spikes in the curves where the initial temperature gradient is large. This is due to the inability to measure the internal temperature of the sample. It takes time for the temperature change to diffuse to the surface of the sample where the temperature is measured. Thus, the temperature change used in the processing is slightly shifted in time, causing a spike when subtracted.

Another interesting observation concerns the brass sample. When the load changes from a compressive load of -30 ksi to a tensile load of 30 ksi, the response of the brass sample appears to be viscoelastic. The resulting curve does not approach an equilibrium configuration. Instead, it continues to exhibit linear creep (Fig. 6(b)). However, when the load change is not as large the curve does not continue to creep, but instead approaches a constant value. Another interesting result is seen when the load changes from tensile to compressive (Fig. 6(a)). The transformed results are still qualitatively similar to the preprocessed results and do not exhibit the expected anelastic effects.

Overall, the magnitude of the velocity change due to anelastic effects is comparable in both steel and aluminum over a wide range of stress change, i.e., ± 30 ksi. The fact that the anelasticity exists in the alloys that do not contain solid solutions, such as carbon, clearly indicates that there is little or no effect due to the stress-induced directional alignment of elastic dipoles. Rather, the most dominant effect is due to the motion of dislocations which

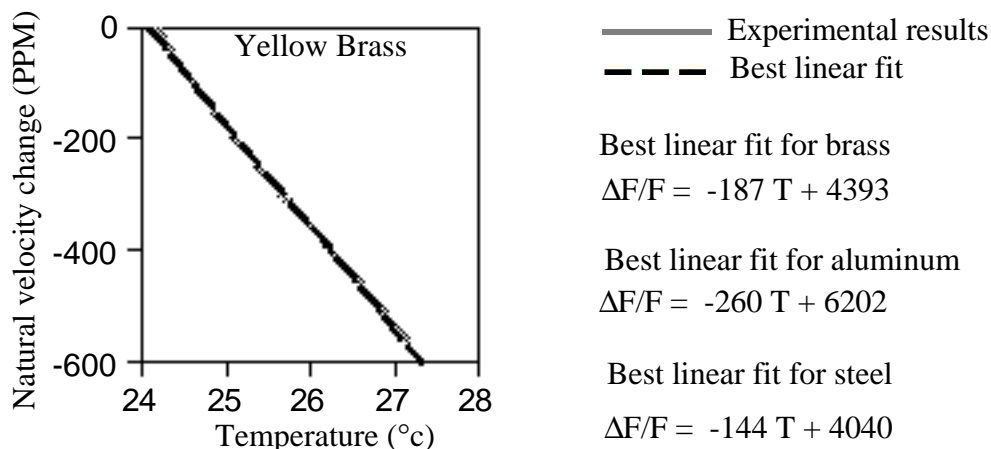


Fig. 5. Material and temperature dependence of the natural velocity.

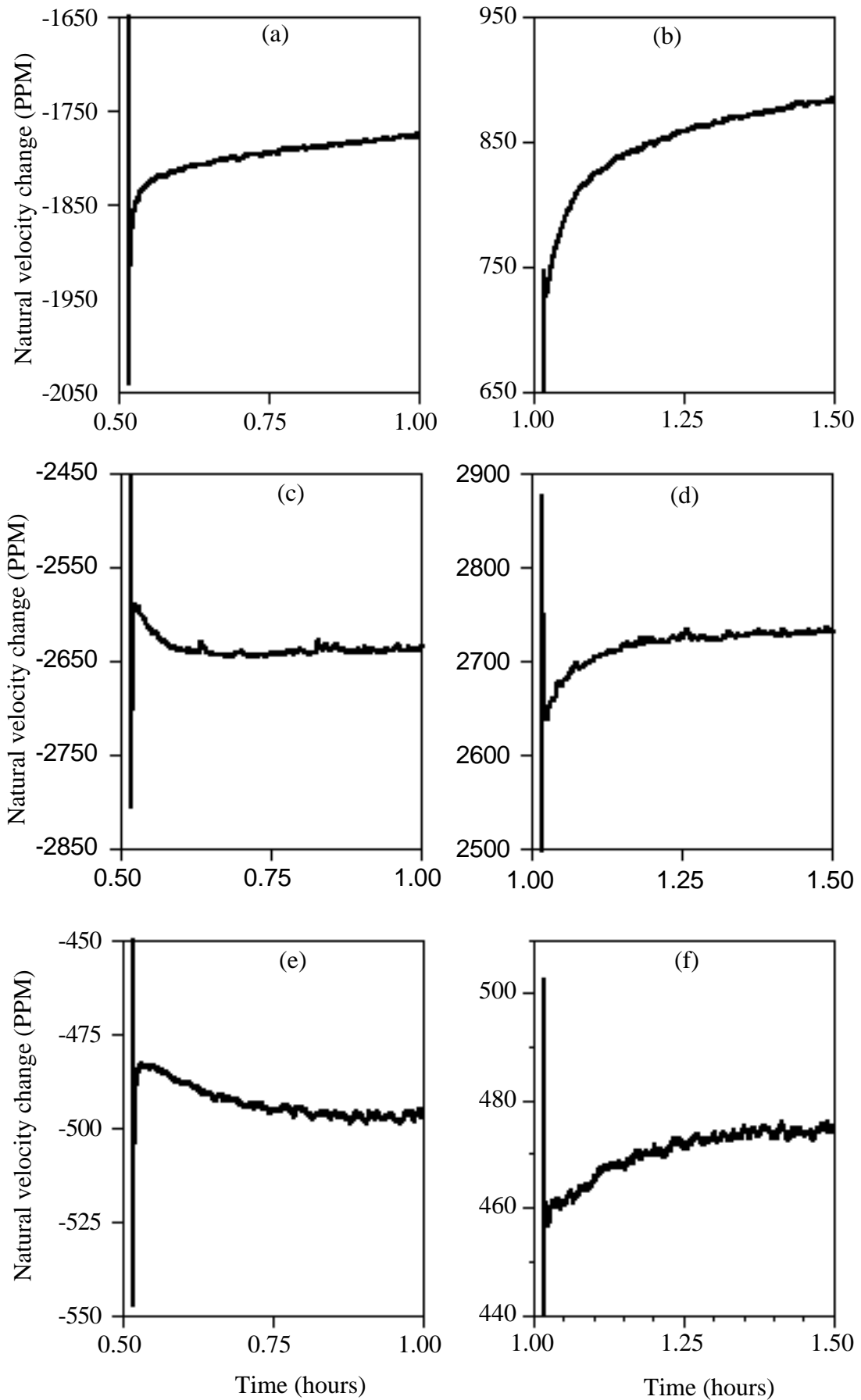


Fig.6. Magnified natural velocity change with temperature effects subtracted off (a) brass after a load change from 30 ksi to -30 ksi, (b) brass after -30 ksi to 30 ksi, (c) aluminum after 30 ksi to -30 ksi, (d) aluminum after -30 ksi to 30 ksi, (e) steel after 30 ksi to -30 ksi, (f) steel after -30 ksi to 30 ksi.

is not necessarily opposite under opposite signs of stress. The anelastic effect of the brass, on the other hand, was much higher than for the steel or the aluminum suggesting a much higher density of dislocations which is consistent with other work concerning copper alloys [6].

SUMMARY AND FUTURE DIRECTIONS

A new ultrasonic approach for monitoring the anelastic behavior of metals and alloys was presented. The approach poses some problems related to separating the temperature dependence of the anelastic phenomena from the natural wave velocity's susceptibility to temperature changes. However, these effects can be distinguished and separated without much difficulty. Due to its high sensitivity to microstructural changes, the new technique will be quite valuable when used in conjunction with strain gauges for studying anelastic behavior. The two techniques should complement each other quite well.

In the future, tests using both the P2L2 and strain gauges to more thoroughly monitor the samples will be conducted. Further work will be done to fully characterize the temperature sensitivity of the velocity and provide a more solid foundation for separating its effects.

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