THERMO-ELECTRIC DETECTION OF EARLY FATIGUE DAMAGE IN METALS

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INTRODUCTION

There are numerous nondestructive inspection methods which can be used to detect and quantitatively characterize advanced fatigue damage following crack initiation. However, crack nucleation occurs at a much smaller microstructural scale following a more or less extended period of gradual material degradation which remains beyond the reach of known eddy current, ultrasonic, and other inspection methods. Before crack initiation, fatigue degradation remains an elusive process leading to distributed crystal defects on the scale of individual grains and grain boundary imperfections. This gradual evolution of early fatigue damage first results in increasing dislocation density, formation of slip bands, microplasticity, cold work, etc., then leads to crack nucleation at multiple sites. Following crack nucleation the growing microcracks ultimately coalesce into larger detectable fatigue cracks, but current NDE methods cannot detect the often quite serious preexisting fatigue damage in the material before this point.

Ordinary thermocouples use the well-known Seebeck effect to measure the temperature at the junction of two different conductors. The electromotive force generated by the heat depends on the difference between the respective thermopowers of the contacting metals and the interface temperature. Figure 1 shows the schematic diagram of the thermoelectric measurement. The thermoelectric voltage is given by

$$V = \int_{T_c}^{T_h} [S_A(T) - S_B(T)]\, dT \approx (T_h - T_c) S_{AB}, \qquad (1)$$

where S_A and S_B denote the so-called thermopower of materials A and B, respectively, and T is the temperature. As an approximation, the voltage often can be written as the difference between the temperatures of the hot T_h and cool T_c junctions multiplied by the relative thermopower of the two materials $S_{AB} = S_A - S_B$. Of course, regardless of the temperature difference between the junctions, only thermocouples made of different materials, i.e., materials of different thermopower, will generate thermoelectric signal. The

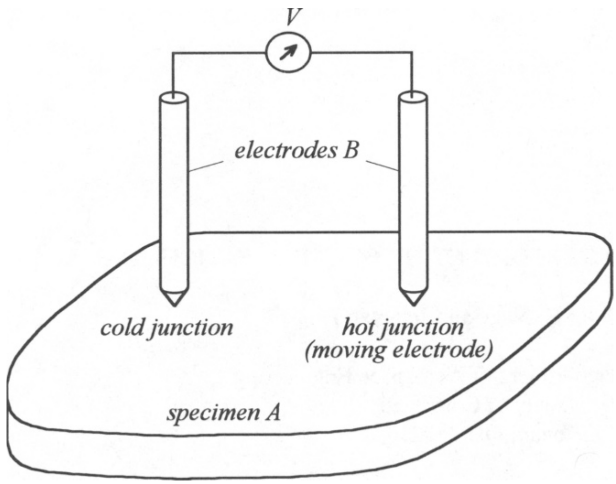

Figure 1. Schematic diagram of the thermoelectric measurement. In triboelectric measurements the heat is produced by friction between the specimen and the moving electrode.

fundamental question we have to answer is the following: What constitutes a sufficient difference in material properties to produce a measurable thermoelectric voltage? Clearly, chemical composition exerts the main effect on the thermoelectric properties and accordingly the basic application of thermoelectric materials characterization is metal sorting [1]. However, it is known that under special conditions materials of identical chemical composition can also produce an efficient thermocouple which can be further exploited for nondestructive testing of materials [2-6]. A circuit composed of a single homogeneous conductor cannot produce a thermoelectric voltage. It is important to emphasize that, in this context, homogeneous means perfectly uniform throughout. Even a chemically perfectly homogeneous sample made of an isotropic material can be inhomogeneous because of strain. For example, annealed and cold-worked copper were shown to form a rather sensitive thermocouple [7]. An additional effect can occur in a noncubic material like titanium. All physical properties characterized by second-order tensors, such as thermal conductivity, electrical conductivity, thermoelectricity, dia- and paramagnetism, and dielectricity, are represented be a symmetric ellipsoid [8, 9]. In the cubic system, the ellipsoid degenerates into a sphere and these properties become fully isotropic. However, in noncubic materials individual grains exhibit anisotropic thermoelectric properties. Actually, materials of hexagonal symmetry can form rather efficient thermocouples with themselves at different orientations [10]. As a result, coarse grain structure translates into apparent inhomogeneity and preferred orientation called texture can cause apparent macroscopic anisotropy.

In this study we investigated whether the thermopower in metals is sensitive to fatigue damage because of the accompanying cold work, plastic deformation, residual strain, or other physical effects. If so, then metals of identical alloying composition and metallurgical structure can produce perceivable thermoelectric signals if one of them is degraded by fatigue and the phenomenon could be exploited to detect and quantitatively assess fatigue damage before crack initiation.

EXPERIMENTAL TECHNIQUE AND RESULTS

Two types of heating techniques can be used to provide the required temperature rise at the junction. Commercially available thermoelectric metal testers usually apply external electric heating through the reference electrode [see, e.g., Ref. 11]. In this case, special care must be taken to clean the surface of the specimen in order to avoid false readings caused by contamination, oxidation, or corrosion. Alternatively, mechanical friction heating can be used to produce the thermoelectric voltage. The electromotive force generated by friction heat between sliding surfaces is called the triboelectric voltage. Even when the overall temperature of the specimen is not significantly raised by the friction heat, the local temperature at the contacting asperities of the surfaces can rise close to the melting point of the material therefore the triboelectric voltage is sufficiently high to be measured by simple electronic means. One of the main advantages of the triboelectric technique over external heating is that it is essentially self-cleaning therefore capable of detecting very slight material differences. Actually, the triboelectric voltage can be so high that the resulting current through the sliding interface can play an important role in the corrosion and wear behavior of metals [12]. Although the frictional heat is less reproducible therefore the triboelectric technique is less accurate as a quantitative tool, it is a very simple and efficient material discriminator. The experimental results presented in this section were obtained by the triboelectric method using slight manual rubbing of a reference electrode against the specimen to be inspected.

The triboelectric voltage is mainly determined by the chemical composition of the electrodes. As an example, Figure 2 shows the triboelectric signals generated by rubbing a 2024 aluminum electrode against different materials. The aluminum electrode becomes positive against titanium and nickel and negative against copper and steel. Most importantly, it does not produce a significant triboelectric signal when rubbed against an identical piece of aluminum. The fact that "identical" metals do not generate thermoelectric voltage regardless of the junction temperature makes this phenomenon uniquely suitable for differentiating purposes. We have recently discovered that, well before crack initiation, fatigued 2024 aluminum specimens exhibit readily detectable levels of thermoelectricity with respect to unfatigued specimens, which could be exploited to develop a novel NDE

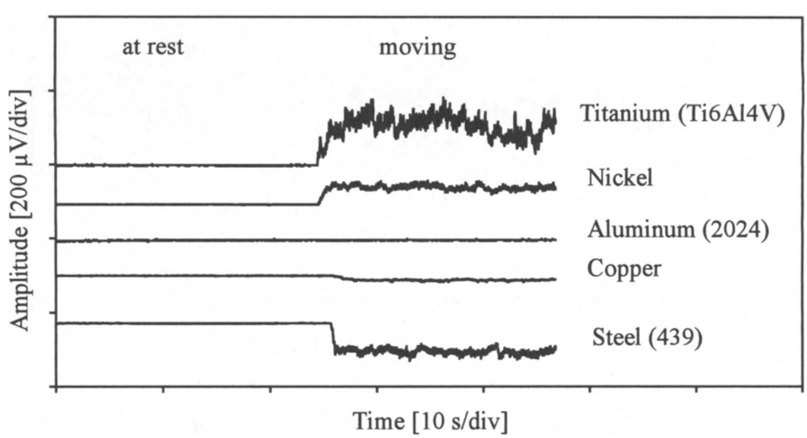

Figure 2. Triboelectric signals generated by rubbing a 2024 aluminum electrode against different materials.

technique to detect early fatigue damage in aircraft components. Figure 3 shows the triboelectric signals generated by rubbing a 2024 aluminum electrode against fatigued and unfatigued 2024 aluminum specimens. The electrode was continuously moving, but significant triboelectric signal was generated only in the vicinity of the plastic zone in front of the fatigue cracks on specimens #10 and #11. These 2024 Al specimens from a previous study were fatigued in a three-point bending mode for 169,000 and 173,000 cycles, respectively, at 29 Hz at max load 28.6 ksi and 0.9 load ratio [13]. The unfatigued ends of these specimens were used as reference materials. In order to verify that the method is not sensitive to cracks but rather to the cold worked plastic zone surrounding their tips, we produced a surface scratch on the unfatigued part of specimen #10 and found no detectable triboelectric signal.

In order to study the feasibility of thermoelectric assessment of pre-crack damage and crack precursors in titanium alloys, we first experienced with the above described simple triboelectric method. However, because of certain unfavorable physical properties of Ti-6Al-4V, the technique turned out to be much less effective. The Rockwell C hardness of Ti-6Al-4V is normally 30-36 HRC in the annealed condition and may increase to 39 HRC on age hardening and it is about 36 HRC in the solution-treated and over-aged condition [14]. Titanium is an extremely reactive metal and has a reputation for poor tribological properties [15-18]. Titanium does not gall against most metal counterfaces, but it does adhesively transfer and wears at a high rate. Both the pure and alloy grade of titanium have poor abrasion resistance (poorer than soft 300 series stainless) and generally their use should be avoided in systems involving low stress abrasion. Titanium is quite prone to fretting damage when coupled to itself.

Our experiments on Ti-6Al-4V specimens showed that two identical halves cut from the same plate can produce significant triboelectric voltage after 10-100 cycles depending on whether the rubbing is concentrated in a small area or distributed over a larger one. When a small spot on the moving electrode is rubbed over a larger area of the specimen the moving electrode hardens more and it produces a positive triboelectric voltage of approximately 30-40 μV. When a new moving electrode is used, initially the triboelectric signal becomes negative indicating that the specimen itself is also hardened, though to a

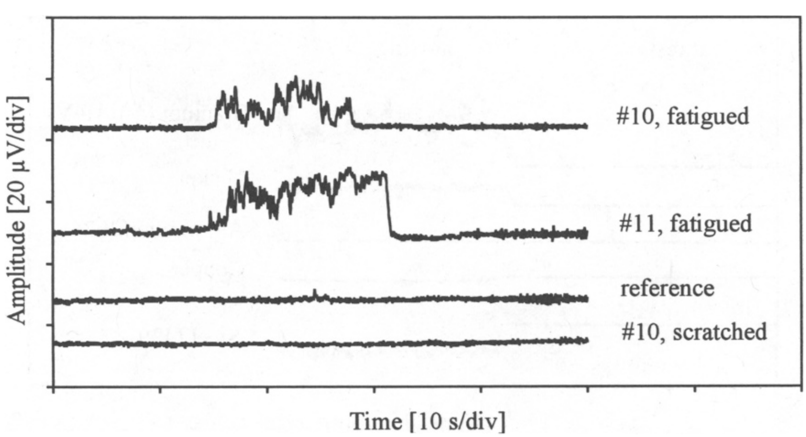

Figure 3. Triboelectric signals generated by rubbing a 2024 aluminum electrode against fatigued and unfatigued 2024 aluminum specimens.

smaller degree than the moving electrode since the rubbing is distributed over a large area. In a couple of cycles, the hardening in the new moving electrode overtakes that of the specimen and the triboelectric voltage becomes positive again. Although the hardened surface layer is extremely thin and can be easily removed by a few strokes with a fine sandpaper, it is clear that the triboelectric form of the thermoelectric method will not be feasible on Ti-6Al-4V alloy because of its poor tribological features. This adverse effect by itself does not render the thermoelectric method useless on titanium alloys, but rather it requires other types of heating or cooling techniques to be used to avoid surface damage. For the time being we continued our experimental investigation with the triboelectric technique, but took extreme care to polish the surfaces before inspection and use only a few strokes to do the measurement.

In the next step, we mapped the triboelectric voltage on the freshly polished surface of both fatigued and not fatigued Ti-6Al-4V tensile specimens. As an example, Figure 4 shows the measured signals at nine different locations on a fatigued (#38) and an unfatigued (#33) specimen. The moving electrode, which was a thin Ti-6Al-4V plate, was rubbed against the side of the specimens for 2-3 s at roughly the same force and speed. Because of the inherent uncertainties in the temperature rise at the sliding interface, the magnitude of the triboelectric signal might vary considerably, but its sign is more reproducible. On the fatigued specimen (#38), the potentially damaged necking region gave 24-32 μV more positive triboelectric signal than on the shank. In comparison, on the unfatigued specimen (#33), the necking region gave only 20-24 μV more positive triboelectric signal than on the shank. The separation between fatigued and unfatigued parts is obviously much worse than in the case of the previously shown Aluminum 2024 specimens. Of course, the main problem is the surprising fact that the unfatigued specimen also shows significant differences between its necking and its shank, which all but overshadows the additional effect of weak fatigue damage in the necking of the fatigued specimen. We have mentioned in the introduction that the thermoelectric properties of hexagonally symmetric materials like titanium are highly anisotropic. Thermoelectric anisotropy causes similar macroscopic effects as the mechanical anisotropy of individual grains in polycrystalline materials affects ultrasonic measurements. For example, coarse grain structure causes apparent inhomogeneity and preferred grain orientation called texture causes apparent macroscopic anisotropy. The only difference is that most structural metals (aluminum, copper, nickel, iron, etc.) crystallize in cubic symmetry which produces mechanical anisotropy but not thermoelectric one. Unfortunately, titanium happens to be one of the few structural metals of significant practical importance that crystallizes in non-cubic, namely hexagonal, symmetry and thereby is affected by thermoelectric anisotropy. Just like the mechanical anisotropy of grains can be exploited for ultrasonic materials characterization (e. g., grain size measurement, texture assessment, etc.), the thermoelectric anisotropy of titanium alloys can be also exploited. However, as for fatigue damage detection, the effect is clearly adverse and we will have to better understand how thermoelectric anisotropy might affect our measurements via texture if we were to adapt this method successfully.

Ultrasonic birefringence measurements readily revealed the strong axial texture present in the Ti-6Al-4V specimens used in our study. The effect is caused by the original forging and rolling rather then the low-stress grinding process used to form the necking and the subsequent rubbing and polishing during the triboelectric measurement itself. Our investigation into the mechanisms by which texture affects our measurements revealed that the primary effect is geometrical. The easiest way to demonstrate this geometrical effect of texture is by measuring the thermoelectric voltage between the ends of a tensile specimen when a commercially available FreezIt® cooling spray is used to produce a localized drop in

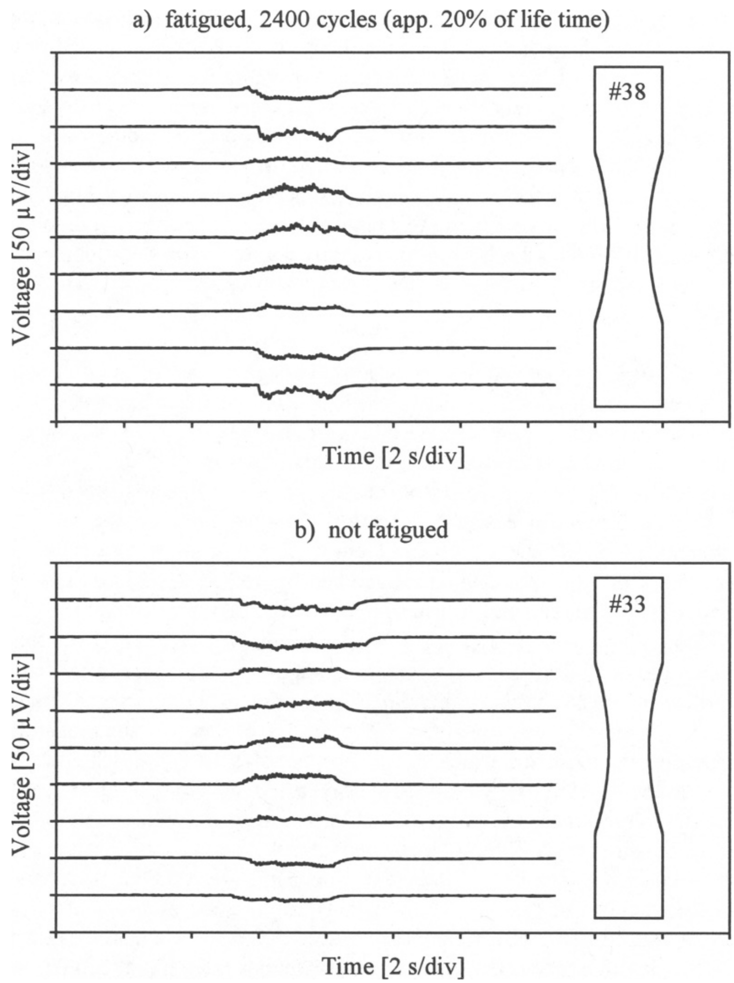

Figure 4. Measured triboelectric signals at nine different locations on a fatigued (a) and an unfatigued (b) Ti-6Al-4V specimen.

the temperature at different locations along the axis of the specimen. According to our previous measurements, app. 100 W cooling power can be delivered in this way to a small spot of app. 1/10" in diameter [13]. Regardless of the dynamic thermal gradient produced by localized cooling, a homogeneous, isotropic specimen will not produce a resultant thermoelectric voltage between the two ends since the temperature at the ends is not affected. More precisely, it is not affected immediately, i.e., within 1-2 s. After about a minute, the temperature equalizes over the whole specimen so that the temperature drops at both ends by the same very small amount, which does not produce a thermoelectric signal either. During the transition between these short- and long-term cases, there will be a very small thermoelectric signal as the end which is farther away from the point of cooling is temporarily warmer than the other end. Figure 5 shows the measured thermoelectric signals between the ends of a 6"x1/2"x1/2" unfatigued Ti-6Al-4V tensile specimen for seven different cooling locations. The cooling spray was applied for approximately 1 s at each location. At the beginning and the end of the necking part, where the heat is conducted at an angle relative to the axial direction, significant thermoelectric signals were recorded. As expected, the signal produced by cooling the transition region between the shank and the necking is opposite in sign with respect to the one produced by cooling the transition region between the necking and the shank (see Figure 5a). These signals are clearly not produced by the minute temperature changes at the ends of the bar where the measuring electrodes are connected since the signal diminishes on both sides as the point of cooling gets further away from the necking. We also measured the thermoelectric signal produced by cooling on the same specimen after the shanks were machined down to eliminate the necking (see Figure 5b). The previously described effect essentially disappeared, which indicates that the measured thermoelectric signal is primarily due to the interaction between the texture-induced macroscopic anisotropy of the specimen and the changing orientation of the surface. Theoretically, the effect could be also caused by the low-stress grinding used to

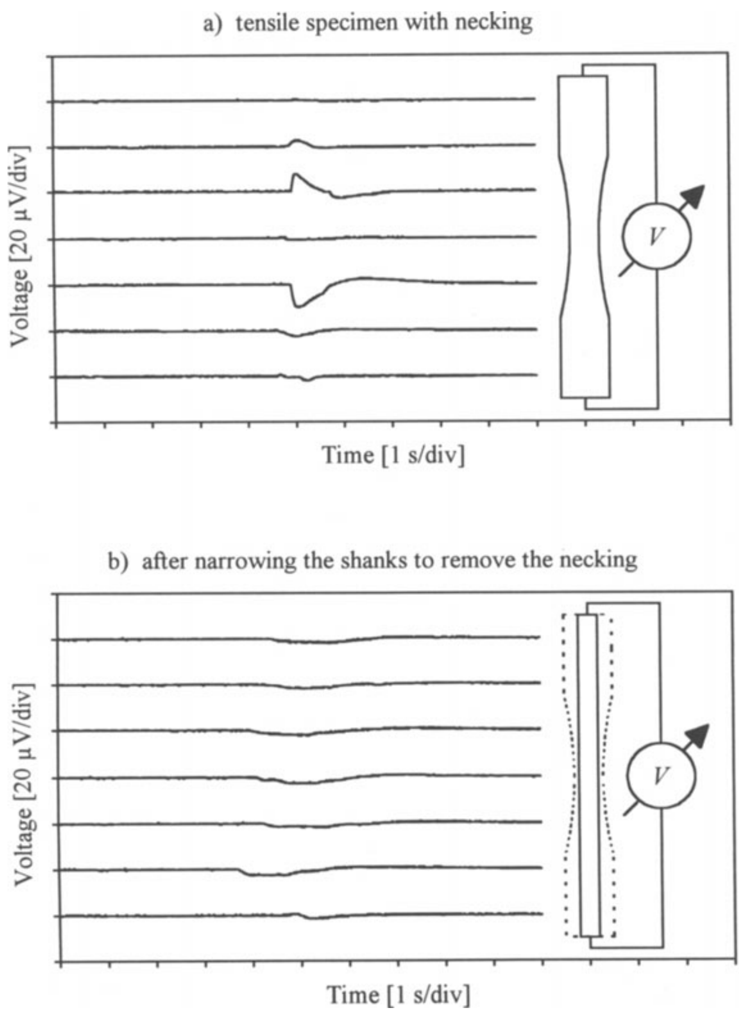

Figure 5. Measured thermoelectric signals between the ends of a 6"x1/2"x1/2" unfatigued Ti-6Al-4V tensile specimen for seven different cooling locations.

form the necking. However, the observed signal is a volumetric effect and we verified that even harsh grinding or polishing of the surface could not produce a sufficiently dissimilar surface layer that could give rise to such strong signals.

DISCUSSION AND CONCLUSIONS

Generally, thermoelectric measurements are most sensitive to variations in alloying content, which can be taken advantage in alloy sorting. It is known that this method cannot be applied to distinguish different aluminum alloys and heat treatments since essentially all compositions and tempers exhibit the same thermoelectric properties. From the point of view of fatigue damage detection, this insensitivity combined with the lack of anisotropy in cubic materials allows us to detect small variations in thermoelectric properties due to fatigue. In other cubic materials inherent variations in chemical composition and microhardness might adversely affect the detection sensitivity for fatigue. In titanium, which crystallizes in hexagonal symmetry, the possible effect of fatigue is further over-shadowed by thermoelectric anisotropy via inhomogeneity due to coarse grain structure and macroscopic anisotropy due to texture. Further efforts are necessary to establish the potentials and limitations of thermoelectric fatigue damage assessment, especially in titanium alloys, for which numerous difficulties have been identified by our research.

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