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Application of NDE Techniques for Damage Measurements in IMI-834 Titanium Alloy Under Monotonic Loading Conditions

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Abstract

The characterization of microstructures, mechanical properties, deformation, damage initiation and growth by Non Destructive Evaluation (NDE) is assuming a vital role in various industries for assessing the performance of a range of components. In the recent past, a variety of NDE techniques have been developed for the assessment of various kinds of damages such as ductile, creep and fatigue damage. Hence, a study was undertaken to assess the damage in a near-ά IMI-834 titanium alloy, currently being used in the compressor module of aeroengine, under monotonic loading conditions using ACPD, AE, and IRT techniques.

Keywords: *Damage, Monotonic loading, IMI-834Ti alloy, Alternating current Potential Drop, Acoustic mmission, Infrared thermography*

1. Introduction

Most of the aeroengine components have to operate under complex loading conditions at elevated temperatures in extremely hostile environments. Under such an environment, several-damaging mechanisms (such as plastic, fatigue and creep damages) become operative, thus deteriorating total life span of the aeroengine components. Under such conditions, the components are designed based on conventional Safe Life and more recently Damage Tolerance based lifing philosophies. These approaches fail to predict the life of the components where there is a continuous degradation of material under hostile service conditions. To ward off these deficiencies, new life prediction methodologies, based on Continuum Damage Mechanics (CDM) approach, are being developed worldwide. In this approach, a damage function is required in terms of service conditions such as cycles, time, stress/ strain or temperature as input to the CDM based life prediction analysis. Here, the damage process is regarded as the generation and growth of micro-defects within an initially perfect material. The material remains the same but its physical as well as mechanical properties may change with its microscopic degradation. The damage variable, 'D' is a macroscopic measure of the microscopic geometrical deterioration of the material [1]. The direct measurement of damage by means of microscopic observations of the surface of defects is very difficult to perform, practically. A relatively easier indirect way is to deduce damage from its influence on measurable properties such as stiffness loss, electrical resistance, ultrasonic velocity, ultrasonic attenuation and micro-hardness change etc [2]. Thus, the parameters for the damage function are experimentally calibrated by NDE based damage measurement techniques. In the recent past, different NDE techniques have been developed for the assessment of various kinds of damages such as ductile, creep and fatigue damages. NDE techniques like Acoustic Emission (AE), Infrared Thermography (IRT), Ultrasonic Attenuation and Velocity Measurements, Acoustic Harmonic measurements, Laser Interferometery, Positron Annihilation, Eddy Current and Alternating Current Potential Drop (ACPD) Techniques etc., are used for measurement of damage [3]. In-service assessment of the damage state is important for ensuring safe operation, predicting the remaining life and promoting a life-extension program. In the present work, a preliminary study was undertaken to explore the possibility of damage assessment in a near-á IMI-834 Titanium alloy, currently being used in the compressor module of aero-engine under monotonic loading conditions using three techniques namely, ACPD, AE, and IRT techniques.

2. Alternating Current Potential Drop (ACPD) Technique

The potential drop technique is an indirect method of measurement of damage [4]. The principle behind the technique is "for a constant current flow, the electric potential/voltage drop across the gauge length will increase with increase in damage due to the modification of the electrical field and associated perturbation of the current stream lines". The potential drop technique can use either AC or DC systems [5, 6, 7]. This technique allows the use of low AC currents to produce sufficient potential difference for accurate measurement while inducing negligible thermal effects.

2.1 Experimental Study

Flat tensile samples of 25 mm gauge length and 3 mm thickness were used in this study. Platinum wires of 0.5 mm were found to be the most spot-weld-compatible with Ti-alloys for both the current as well as the potential leads. The current leads were spot-welded at two end portions near grip location and potential leads across the gauge length of the specimen. During the tensile loading, an alternating current of 0.5 Amps was passed through the specimen using an ACPD system as shown in Fig.1 and the voltage drop across the gauge length was monitored insitu using data recorder. The output voltage is considered to be proportional to the damage induced in the material

$$D = \frac{V_i - V_0}{V_f - V_0} \tag{1}$$

where V_i is the instantaneous voltage, V_0 the initial voltage at starting of the test and V_f the voltage at onset of fracture. The damage thus measured in smooth specimen during tensile test, was plotted with respect to plastic strain**.** The damage evolution curve appears to have three distinct stages. To illustrate the physical significance of the three stages of damage, true stress true strain curve of the material is superimposed on the damage curve as shown in Fig. 2. During the stage I, damage is observed to remain nearly negligible upto a certain level. During stage II, damage progresses linearly upto a critical level of $D_c \approx 0.769$. Beyond this point during stage III, damage progresses unstably as indicated by a rapid increase in slope. From the Fig.2, it is clear that the threshold strain, ε_0 corresponds to the plastic strain around the *yield point* in the smooth specimen, whereas the critical strain, ε_c corresponds to the onset of drop in load after crossing *ultimate tensile strength* level.

3. Acoustic Emission (AE) Technique

Acoustic Emission signals are transient lastic stress waves generated by the sudden release of stored elastic strain energy by dynamic processes such as plastic deformation, crack initiation and propagation and martensitic phase transformation, from the material under stress [8]. Detection of an AE signal is usually accomplished with a piezoelectric crystal sensor mounted on the surface of the structure to be monitored. The sensor output is amplified through a high gain low noise preamplifier, filtered in order to remove any extraneous low frequency hardware and high frequency electromagnetic noise. The AE signals are analysed in a time domain and or frequency domain depending on the type and characteristics of the AE signals. In some cases, the time domain parameters would be able to distinguish different AE sources. Frequency domain analysis can be adopted for both burst type and continuous AE signals. The dynamic nature of AE makes it a useful technique for monitoring the structural integrity of components in various industries with respect of identifying micro-and macro-yielding and propagating cracks. A unique advantage of the AE technique is its ability to detect defect at remote location and on-line monitoring of growing defects even in complex geometries. The technique allows the whole volume of the structure to be inspected non-intrusively in a single loading operation.

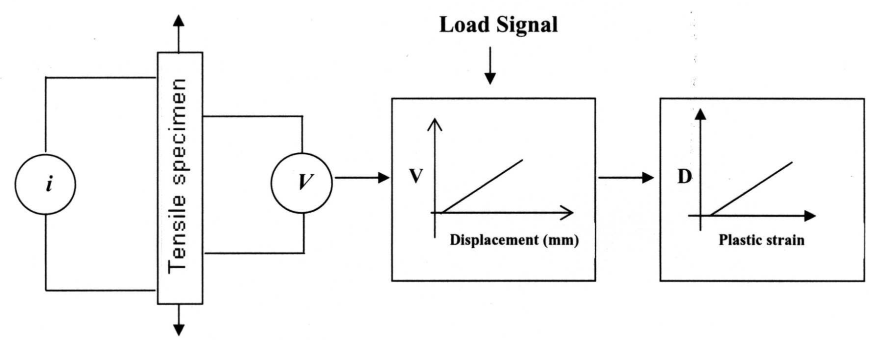


Fig. 1: Schematic diagram of ACPD Technique for damage measurement

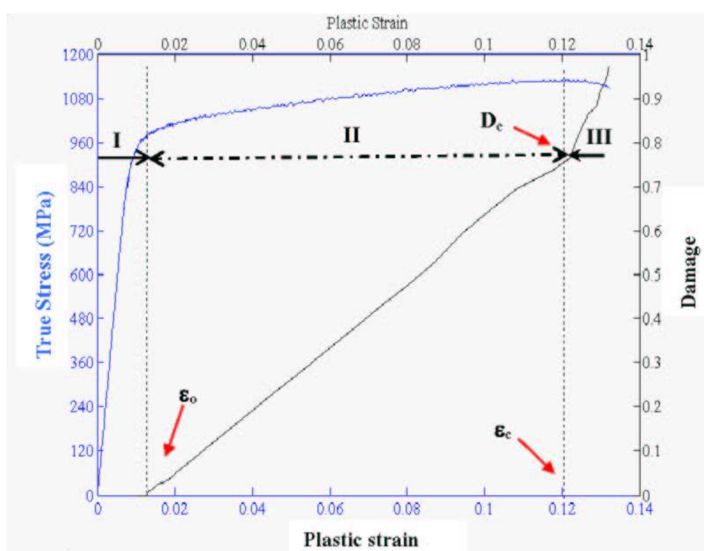
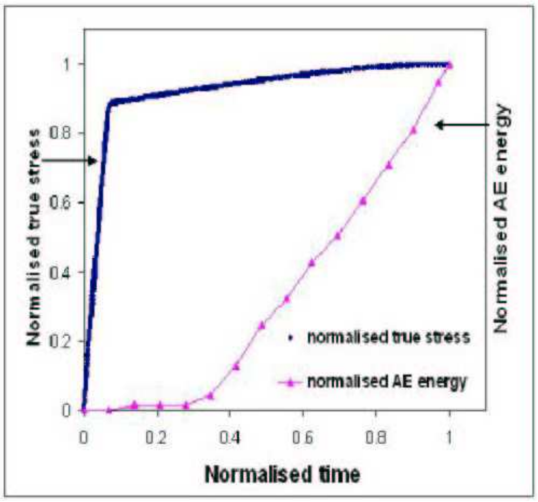
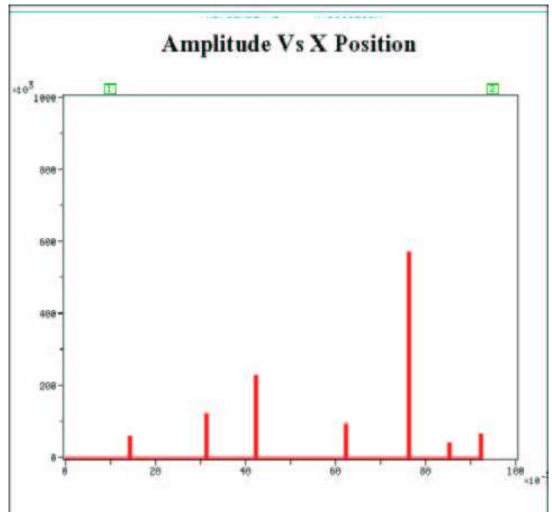


Fig. 2: Damage-plastic strain-true stress curve

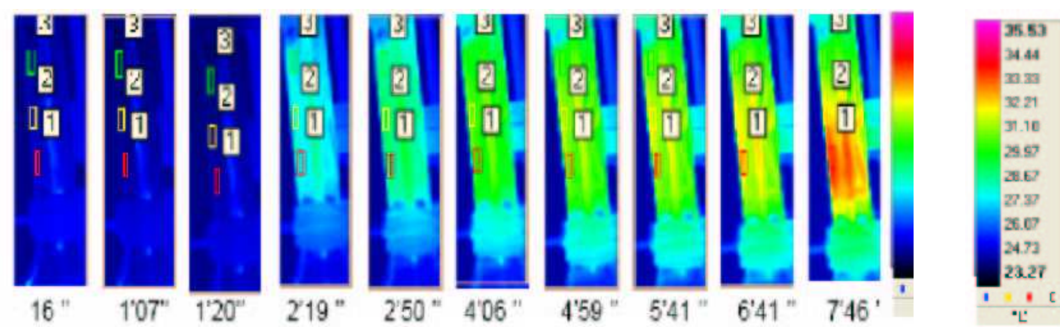


(a)

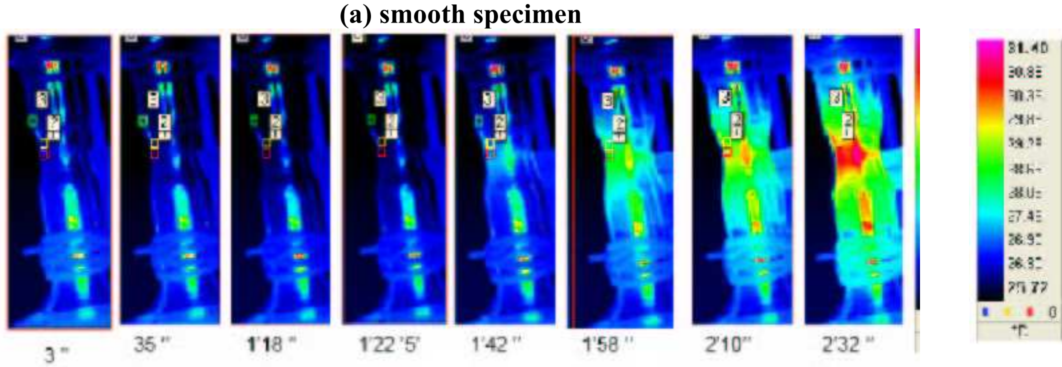


(b)

Fig. 3: Typical AE signals for near-ά IMI-834 Ti alloy under monotonic loading conditions



(a) smooth specimen



(b) notched specimen

Fig. 4: Thermograms at different time intervals for the IMI-834 Ti alloy

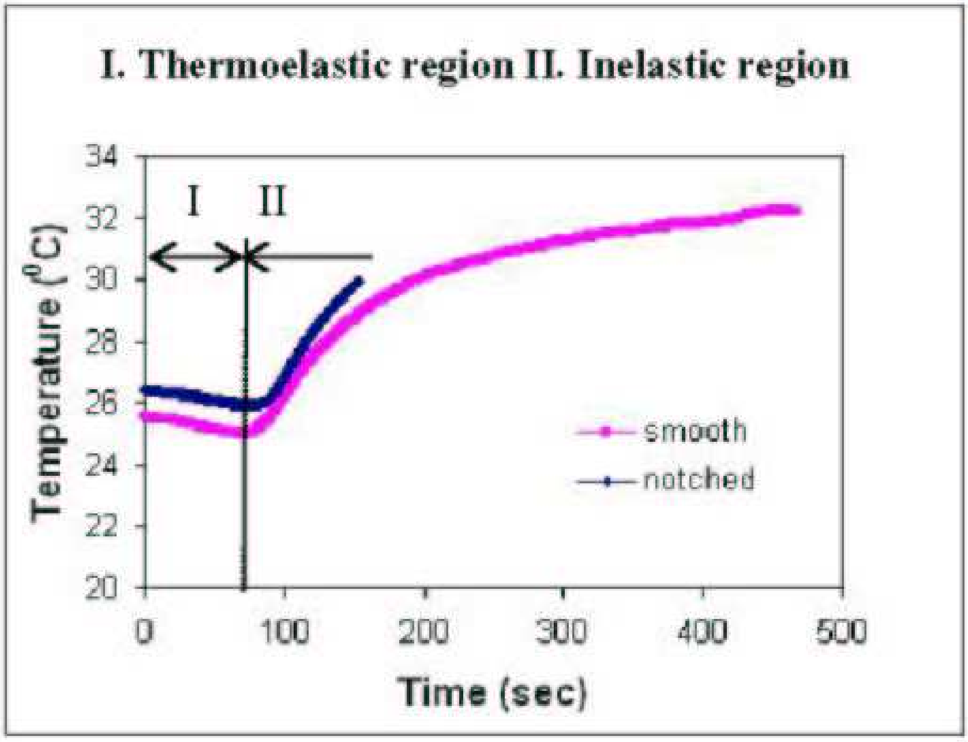
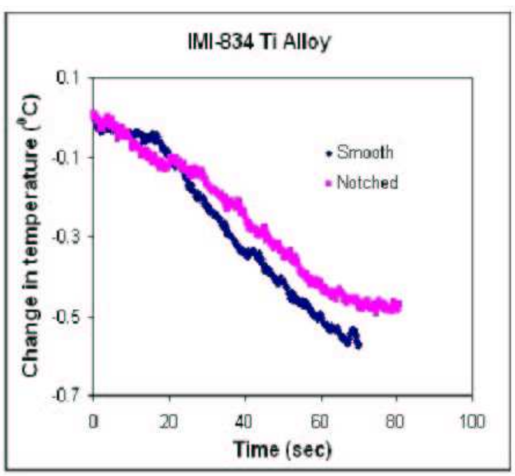
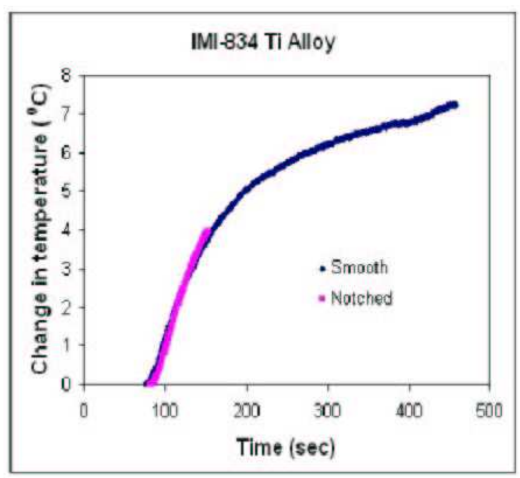


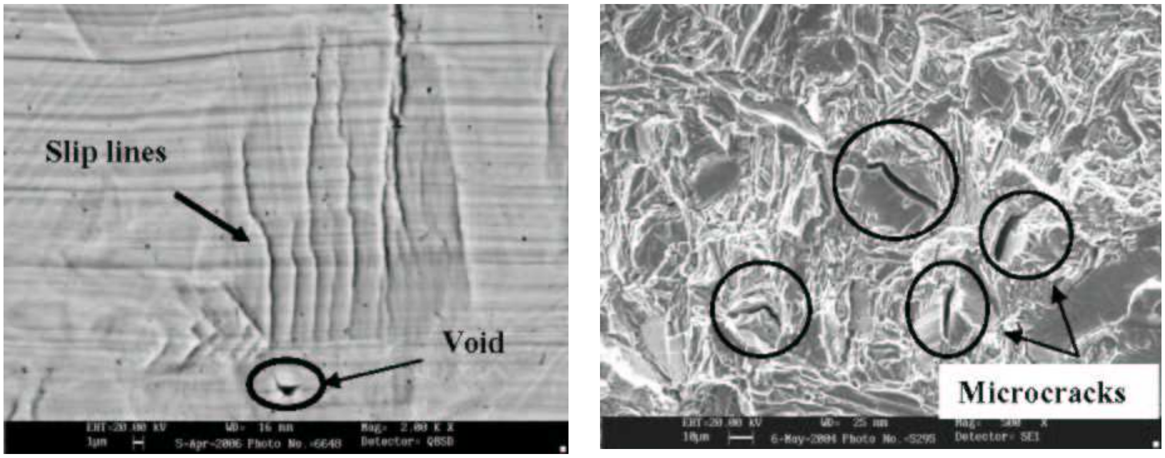
Fig. 5: Temperature-time curve for IMI-834 Ti alloy





(a) elastic region **(b) inelastic region**

Fig. 6: Change in temperature-time curves for smooth and notched tensile specimen



(a) Interrupted specimen **(b) Fractured specimen**

Fig. 7: Damage micromechanism in IMI-834 Ti alloy

3.1 Experimental Study

Flat tensile samples of 25 mm gauge length with 8 mm width and 3 mm thickness were used. The 8 channel AE system (M/s. PAC) with digital processing, data acquisition and analytical software along with a piezoelectric transducer of 5x4 mm with a frequency of 200-750 KHz was used. Various AE parameters such as events, counts, energy, peak amplitude, average frequency etc have been identified from the AE signals.

AE signals have been used for qualitative interpretations of damage evolution in the alloy. In the Energy Vs Time graph (Fig.3a), the beginning portion of the curve is very quite which could be associated with the incubation stage of damage as it was with ACPD signals (Fig.2). The released cumulative energy increases with straining during loading and can be possibly related to accumulated damage in the material. The Amplitude Vs X-Position graph (Fig.3b) shows the damage accumulation in the specimen at various locations. The location of damage accumulation could be used to validate the prediction made by CDM based damage models.

4. Infrared Thermography (IRT) Technique

Thermography is an advanced NDE method based on detection of infrared radiations emitted by the object. Thermography technique is a sophisticated method of measuring the amount of damage in a material under test using an IR camera [9, 10]. The mechanical energy given while loading under adiabatic conditions or high strain rates is almost converted into heat energy which propagates in the form of medium wave infrared radiations. The efficiency of the camera depends upon its ability to capture these radiations (thermal gradients on the surfaces). A thin graphite coating was applied on the specimen gauge length section to minimise the surface reflectivity problems. The severity and distribution of damage in a specimen can be known from the severity and distribution of the heat patterns. As the damage progresses the heat dissipated increases, which is shown in the thermogram as an increase in temperature. This increase in temperature is shown as contrasting optical images by the electronics of the camera. The advantage of the thermal imaging is that it is a non-contact method, non-intrusive in nature, provides a full field image, on-line monitoring and hence fast inspection rates are possible. The main limitations of thermography lie in the difficulty of quantitative estimation of temperature which is prone to errors due to emmisivity and other thermal losses and its incapability to detect deep surface defects.

4.1 Experimental Study

Round smooth tensile specimens of 6 mm diameter and 25 mm gauge length were used. The effect of triaxiality was investigated on axi-symmetrically notched round bar tensile specimens. In this study a high resolution IR camera with a fast frame rate has been used. A fully automated software system was employed to acquire the data of temperature distributions on the test sample. A thin coating was applied on the specimen gauge length to minimise reflectivity problems. The variation of temperature during monotonic loading with time at three different locations marked as '1, 2, 3' on the round smooth and notched tensile specimens of IMI-834 Ti alloy under monotonic loading conditions has been recorded. The corresponding thermograms obtained at different time intervals are shown in Fig. 4(a) and Fig. 4(b) respectively. Temperature-time curve obtained at the moderately heated site (gauge length) for IMI-834 Ti alloy round smooth and notched specimens are shown in Fig. 5.

4.1.1 Thermal evolution under monotonic loading

Two different regions namely thermoelastic and inelastic region are distinctly observed in the specimens (Fig.5). Thermoelastic region is confined to the elastic portion of load displacement curve. Inelastic region starts from the yield point till fracture.

Region I: Thermo-Elastic Effect

The initial decrease in temperature is attributed to thermo-elastic effect [11] as shown in Fig. 6(a). During tension test in elastic region volume dilatation (volume change) takes place i.e., atoms get pulled apart slightly and hence, there is a slight increase in bond lengths. If the loading is done under adiabatic conditions then there is no time for thermal equilibrium to take place between material and surroundings and hence, there is a gross decrease in temperature in this case of elastic tension by a tensile stress. Thermodynamic equation of state and first law of thermodynamics govern these heat effects. In IMI-834 alloy, there does not appear to be significant effect of notch on rate of change of temperature under constant strain rate.

Region II: Inelastic & Heat Conduction Effect

In the second stage of the curve, there is a steady increase in temperature, which can be attributed to inelastic effect [12, 13] as shown in Fig.6(b). In this stage, the temperature steadily increases, which is due to the inelastic or thermoplastic effect during which damage initiates to evolve. Once the elastic limit is exceeded, slip systems come into picture and mark the onset of plastic deformation and consequent damage events. Plastic deformation can be visualised as a process in which adjacent plane of atoms slide past each other and bring about a permanent change in shape by maintaining the volume constant. During this sliding operation, the work done on the material is almost converted to heat energy. But unlike elastic deformation, there is bodily sliding of atoms that amounts for a large part of heat energy released. IMI-834 Ti alloy, exhibits a sharp increase in temperature with deformation. The notched specimen shows marginally higher temperature change than smooth specimen. This behaviour requires more indepth understanding of thermo-plastic properties of two alloys.

5. Metallographic Investigation

To identify the damage micro-mechanisms, operative in the studied alloy, smooth tensile specimens were interrupted at different point of loading and were subjected for metallurgical investigations using Optical and Scanning Electron Microscope (SEM). Typical SEM pictures of specimens at maximum load and at fracture points are shown in Fig.7. It can be inferred from these pictures that the damage evolves through formation of slip lines (marked as arrow in Fig.7a) in the primary as well as in matrix phase and gradually develops into micro cracks and voids (circled in Fig.7a) at interface boundaries and then lead to final fracture (circled in Fig.7b).However, more in-depth understanding of damage micromechanisms is required by investigating several interrupted tensile specimens.

6. Conclusion

Damage measurements have been performed successfully by using ACPD, AE and IRT Techniques. The potential of different NDE techniques for the assessment of damages are different. In case of ACPD, the damage increases linearly with plastic deformation**.** AET was used to study the kinetics of damage evolution. The data clearly showed that the released cumulative energy increases with straining during loading and can be possibly related to accumulated damage in the material. In case of IRT technique, the change in the surface temperature is related to damage in the material. ACPD technique gives accurate results but the procedure is quite cumbersome, besides this it cannot be used at the component level. IRT on the other hand has problems in accuracy but can be successfully employed for in-surveillance applications. With ACPD it is easier to quantify damage in the alloys and the damage parameters thus found could be used for FEM based damage modeling of components. On the other hand, IRT, being a non-contact damage measurement technique could well be used for qualitative damage mapping of components under service conditions. So, if judiciously applied both techniques could complement each other for damage characterization of engineering alloys.

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