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Fatigue damage characterization using surface acoustic wave nonlinearity in aluminum alloy AA7175-T7351

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Nonlinear ultrasonic (NLU) harmonic generation system was used to characterize the fatigue damage in a flat hour-glass, high strength Al–Cu–Zn–Mg alloy, AA7175-T7351 specimens. Experiments were carried out to introduce controlled levels of fatigue damage under constant amplitude loading to determine the NLU response using surface acoustic wave (or Rayleigh mode) at regular intervals of fatigue life. The NLU parameter (A_2/A_1^2) plotted as a function of percentage of fatigue life shows two peaks for all the samples tested, independent of the amplitude of fatigue loading. The first peak appeared between 40%–50% of fatigue life and the second peak between 80%–90% of fatigue life. Among the two flat surfaces of the specimen, a higher nonlinearity response was observed on the surface which had the first crack initiation. The appearance of two peaks in the nonlinear response during fatigue damage progression is explained based on the dislocation dynamics and dislocation-crack interaction present in the specimens during the fatigue process. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2956396]

I. INTRODUCTION

Fatigue is an important consideration in the design of high performance, safety critical structures and components, as fatigue failure constitutes nearly 70% of failures in dynamically loaded components. Traditionally, damage in materials is characterized by using one or more of the nondestructive evaluation (NDE) techniques, but these are effective in detecting the defects that are of the order of 0.1–1.0 mm, but if one were to characterize the defects which are of the order of 1–100 μm, only a few techniques are available such as acoustic microscopy,[1] acoustic emission,[2] linear ultrasonics based on attenuation[3–5] and Rayleigh wave reflection,[6] positron annihilation,[7,8] nonlinear ultrasonic (NLU) technique,[9–25] etc.. For detecting cracks and other flaws which are of considerable size (∼0.1 mm), many conventional techniques can serve the purpose, whereas for early detection of damage even before the crack initiates, NLU harmonic generation technique is considered to be an emerging method compared to linear conventional NDE methods.

NLUs generally entails the study of both the acoustoelastic effect and finite amplitude ultrasonics. The acoustoelastic effect technique[9] requires application of stress and measurement of small changes in the sound velocity in the material. In most cases, this technique is not considered to be very practical as very subtle changes in velocity has to be measured. In NLU technique, a finite amplitude ultrasonic wave is introduced into the material, the wave gets distorted as it propagates through the material due to the nonlinearity present in the material. This distortion on the wave gives rise to the second and higher harmonics besides the fundamental frequency in the frequency spectrum of the received signal. Measurement of these harmonics offers a unique method for the study of anharmonicity of the solids.[26] In characterizing a material using NLU technique, the nonlinearity parameter or the nonlinearity coefficient (β) is a key parameter that represents the nonlinear elastic characteristics of material. The nonlinearity parameter is the intrinsic property of the material and is a function of the higher order elastic constants, which are very sensitive to interatomic changes and the presence of microlevel defects in the material.

Hikata *et at*.[27] first proposed during their NLUs studies on aluminum that the NLU response of a material can also arise from the interaction of ultrasonic wave with dislocations in the material and plastic deformation process can be monitored using this technique. Later on, many researchers applied this technique for detecting early damage during fatigue processes in materials during which change in dislocation dynamics occurs. Grosskruetz[10] suggested that long dislocation loops produced during the fatigue after deformation led to subsequent increase in the second harmonic. Second harmonic generation under cyclic loading has been reported by Yermilin *et al.*[11] and observed an increase in second harmonic in titanium and steel samples subjected to fatigue loading. Buck *et al.*[12] showed that as the number of fatigue cycles increase, the surface cracks appear on the component and act as the additional sources for the nonlinearity. The harmonic generation was studied for a wide range of fatigue loading conditions, fundamental amplitudes, and also external load has been reported. Further, it was also observed experimentally that long dislocation loops developed during fatigue after deformation can lead to subsequent increase in the second harmonic.[13]

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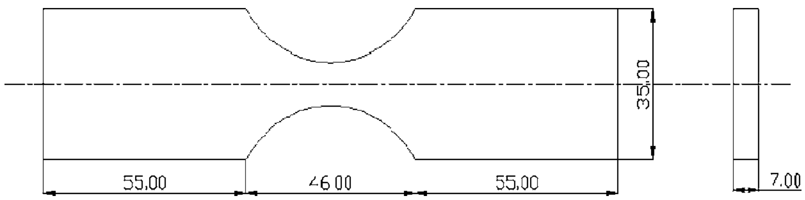

FIG. 1. One dimension of hourglass specimen used for fatigue studies.

Yost and Cantrell[14–17] presented the experimental evidence as well as an analytical model, which suggests a strong nonlinear interaction of acoustic waves with dislocation dipoles in fatigued metals. The model presented by them predicts generation of a substantial acoustic second harmonic that depends on the distance between the glide planes of the dipole pair, the dipole density, and on the particular arrangement and volume fraction of dipoles in a given substructure of the fatigued solid.

Subsequent to Cantrell's work Frouin *et al.*[18] and Jhang and Kim[19] followed suit to show that fatigue life can be monitored using NLUs. Recently, Oruganti *et al.*[20] have studied systematically variation of nonlinear parameter with dislocation density based on a theoretical model developed by them substantiated by microstructural characterization studies using transmission electron microscope (TEM).

Most of the research in the area of NLUs study of fatigue induced damage discussed above has been concerned with one-dimensional, bulk longitudinal waves. Since surfaces are more prone to effects of fatigue, one could expect that the NLU response will be much more sensitive; however, there are a few attempts to use surface waves to monitor the fatigue process in materials. Morris *et al.*[21] were the first one to carry out surface wave NLU measurements by applying 5 MHz surface acoustic waves (SAWs) on fatigue damaged Al 7075-T6 samples and the harmonic components were received using a 10 MHz transducer. The nonlinearity of the SAWs obtained from the fatigue samples is attributed to the opening and closing of the microcracks under the influence of an acoustic stress wave. Based on this work, recently, Ogi *et al.*[22] for the first time reported two distinct peaks in the variation of the nonlinear parameter with fatigue life in carbon steel using a noncontact surface wave generation and detection using electromagnetic acoustic transducer (EMAT). The first peak in nonlinear response (at ~60% of the fatigue life) was attributed to crack nucleation and growth, whereas the second nonlinearity peak (at ~85%)was attributed to the presence of crack and associated discontinuity interaction between the crack faces. However, there are experimental studies on SAW nonlinearity versus fatigue life do not show this two peak feature. For example, Blackshire *et al.*[23] studied the NLU response of Rayleigh wave using a nonlinear laser system and characterized the fatigue state of fractured Ti–6Al–4V sample. An assessment of the local fatigue damage of the material was made where the local amplitudes of the fundamental and second harmonic displacement fields are monitored simultaneously. However, for a large increase in β observed between the nonfatigued area (near the grip section) and the heavily fatigued area (gauge section) for a fractured dog-bone specimen, the authors have not reported two peak behavior. However, it should be noted that they have not measured the nonlinearity versus fatigue life. On the other hand, another experimental report by Barnard *et al.*[24] from the low cycle fatigue (LCF) tests conducted on Ni alloy samples using Rayleigh wave harmonic generation measurements suggested two consistent features, an initial decrease in the harmonic generation that is followed by a gradual increase toward a peak after which the harmonic generation drops off rather quickly. Similar observation has been reported by Hermann[25] on nickel based superalloys from the Rayleigh wave NLU measurements. Therefore, though the SAW is a very sensitive tool to monitor the fatigue induced damage accumulation, whether the two peak behavior is a common feature of SAW nonlinearity measurements in nonlinearity as observed by Ogi *et al.*[22] remains to be an open question.

The present work has been carried out in the spirit of resolving this issue of two peak behavior as discussed above. Results of SAW NLU measurements carried out to characterize early damage in the hour glass specimens of a structural alloy AA7175-T7351 are discussed.

II. EXPERIMENTAL DETAILS

A. Sample preparation

Flat hour-glass specimens, as shown in Fig. 1, having a nominal thickness of 7 mm and a gauge section length of 25 mm were fabricated for fatigue studies. The specimen surface was mirror finished on the flat sides and stress relieved. Fatigue loading under constant amplitude loading was performed using a 100 kN MTS® servohydraulic test system

Totally six specimens were prepared. The first batch of three specimens were tested between a maximum load of 30 kN and a minimum load of 3 kN (which corresponds ~95% and ~10% of material yield strength), under tension-tension cycling at a test frequency of 1–2 Hz. The second batch of three specimens was tested between a maximum load of 27 kN and a minimum load of 2.7 kN (which corresponds ~88% and ~8% of material yield strength) of the yield strength. The loading parameters were essentially in the elastic limit of the material, which permits load control testing of the specimens on a servohydraulic test system; however, the load levels were chosen to be close to low-cycle fatigue regime to ensure that failure initiation over a finite life. Similar loading conditions were chosen by Barnard *et al.*[24] and Oruganti *et al.*[20] in their experimental studies. The specimens were unloaded at regular intervals of 1000 cycles (approximately 5% of fatigue life) from the test system and tested for NLU response using SAW mode; this procedure was continued until the specimen failed. Table I presents the specimen and loading conditions.

TABLE I. Fatigue loading details.

First set	Second set
Maximum load—95% of yield strength	Maximum load—88% of yield strength
Maximum load—30 kN	Maximum load—27 kN
Minimum load—3 kN	Minimum load—2.7 kN
Frequency of loading—1–2 Hz	Frequency of loading—1–2 Hz
No. of cycles per step—1000	No. of cycles per step—1000
Observed fatigue life—~18 000 cycles	Observed fatigue life—~23 000 cycles
Instance at which a visible crack appeared ~15 000 cycles	Instance at which a visible crack appeared ~18 000 cycles
Number of specimens—3	Number of specimens—3

B. Description of surface wave nonlinear harmonic generation experimental system

Figure 2 shows the block diagram of the nonlinear measurement system and sequence of the operation involved in the measurement. The purpose of this experimental setup was to transmit a radio frequency (rf) tone burst of surface/Rayleigh wave of a certain frequency and pulse width into the material under study through an ultrasonic transducer system and for receiving the distorted signal through another broadband ultrasonic transducer. Rayleigh wave was generated on the sample surface using a longitudinal wave transducer mounted on an acrylic angled wedge. A similar probe was also used for the detection of the Rayleigh (surface acoustic) wave. The distance between the angle blocks was kept as a constant at 46 mm, which was the same as the gauge length of the sample. This was accomplished by keeping the point of entry of the ultrasonic wave in the wedge along the lines that describe the gauge length. The central frequency of the receiving transducer was chosen in such a way that its value is twice or thrice the frequency of the transmitting transducer. No couplant was used between the wedge and the specimen surface, while a very small thin film of couplant was used between the transducer and the wedge. The surface of the wedge and the sample were both polished surfaces and the ultrasonic waves were coupled from the wedge onto the sample using the same constant pressure during every experiment. The influence of the surface asperities and roughness that arise during the fatigue was determined to have negligible effect on the NLU data here due to the fact that the wedges were kept away from the gauge length, i.e., in the low stress regions near the grip where the surface conditions were expected to remain uniform. The longitudinal (L) wave, while passing through the acrylic wedge, loses energy as acrylic is a highly attenuative material, and only a small fraction of the energy can be converted as surface wave in the specimen. A 2.25 MHz transmitter (Olympus NDT Panametrics, V115) and 5 MHz receiver (Olympus NDT Panametrics, V110) were used. The frequency of excitation was selected as 2.0 MHz as the output peak-to-peak voltage of the response signal showed a maximum at this particular frequency. The number of cycles or the pulse width of the tone burst was chosen in such a way that there is no overlap between first received signal and the back wall echoes. In the present study, 20 cycles of tone burst was chosen. Since measurement of fundamental and second harmonics is not in terms of displacement, the nonlinear response is expressed in terms of A_2/A_1^2. If a linear relationship exists between the second harmonic and the square of the fundamental, it can be confirmed that the data obtained from the experiments is appropriate.

A computer-controlled transmitter receiver (RITEC® Advanced Measurement system RAM-5000) that can generate high amplitude sinusoidal tone-burst inputs with an adjustable number of cycles at a single frequency was used for driving the ultrasonic transducer. The RITEC® gated rf amplifier module is designed to derive the very high power rf bursts needed for modern transducers. A RITEC® broadband receiver BR-640A receives the signal. The output from the broadband receiver was digitized using the Agilent 54631A 8 bit digital storage oscilloscope, which operates at a sampling

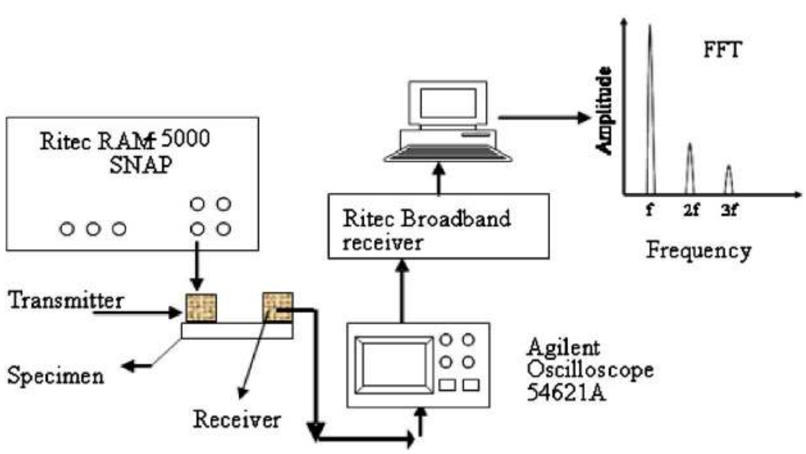

FIG. 2. (Color online) Experimental setup using RITEC-RAM-5000.

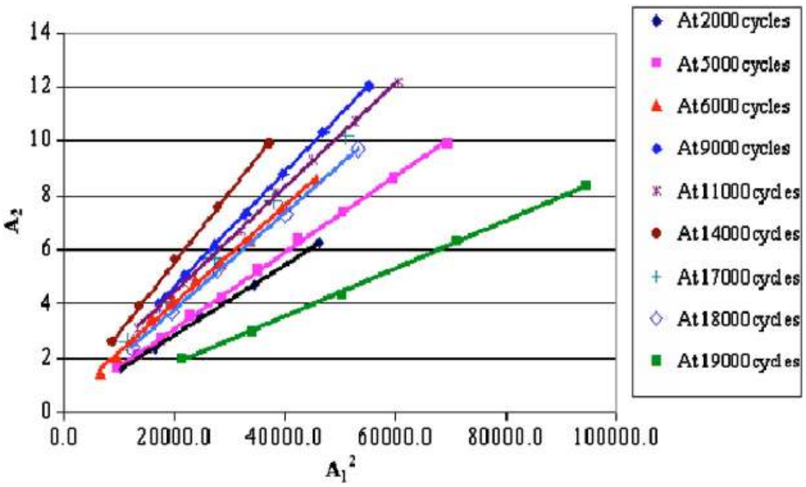

FIG. 3. (Color online) Variation of A_2 with A_1^2 in fatigue specimen 3 at different number of fatigue cycles showing linearity relationship.

rate of 400 MHz, for storing the data in ASCII format. For further analysis of the data, the digitized data from the oscilloscope was transferred to a computer through an Agilent General Purpose Interface Bus 83357A interface cable with 2000 data points per window. A MATLAB® code is used to convert the time domain data into frequency domain spectra. The amplitudes of the fundamental (A_1) and the second harmonics (A_2) are evaluated from the frequency domain spectra

C. Measurement of nonlinear parameter

The expression given below for nonlinear parameter β indicates that there exists a linear relationship between the second harmonic amplitude (A_2) and the square of the fundamental amplitude (A_1^2) as there exists a unique value of β for a given measurement condition,[27]

$$\beta = \frac{8\upsilon^2 A_2}{\omega^2 z A_1^2} \Rightarrow A_2 \alpha A_1^2.$$

Since measurement of fundamental and second harmonics is not in terms of displacement, the nonlinear response is expressed in terms of A_2/A_1^2 measured in volts. The linear relationship between the second harmonic and the square of the fundamental frequency response was used to confirm that the ultrasonic data obtained from the experiments is appropriate.

III. RESULTS

NLU harmonic generation measurements were conducted on the aluminum alloy AA7175-T7351 specimens fatigue cycled at the loading conditions described earlier in Table I. Six hour-glass fatigue specimens were prepared for the fatigue damage studies, of which a batch of three specimens was fatigue cycled between 88% and 8% of yield strength and the other batch was fatigue cycled between 95% and 10% of yield strength.

A. Results on fatigue specimens loaded to 95% of the yield strength

A visible macrocrack could be observed in all specimens at about 15 000 cycles and the specimens ultimately failed at a failure life of ~19 500 cycles with a deviation of about 500 cycles. After every thousand cycles of fatigue cycling (approximately 5% of life), the fundamental and the second harmonic amplitudes were measured at different power levels. To confirm the repeatability of readings, three repeat measurements of NLU response were made and the readings were linear averaged. Figure 3 presents the plot of A_2 versus A_1^2 for different input power levels.

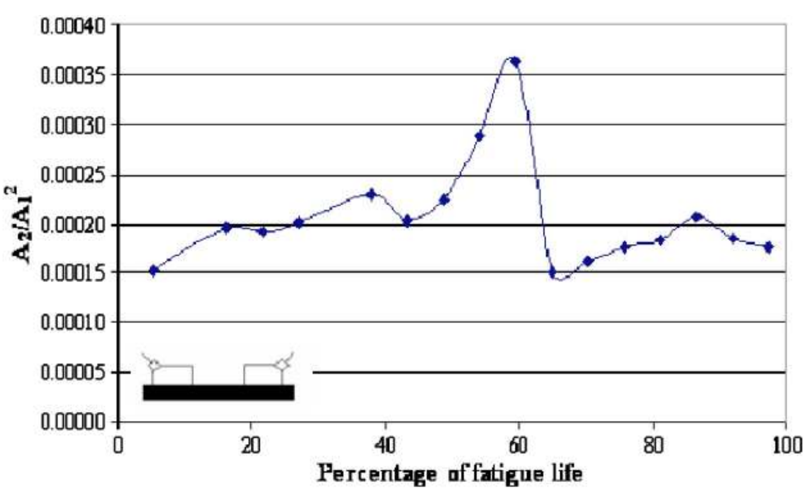

FIG. 4. (Color online) Variation of nonlinear parameter (A_2/A_1^2) with percentage of fatigue life in specimen 1.

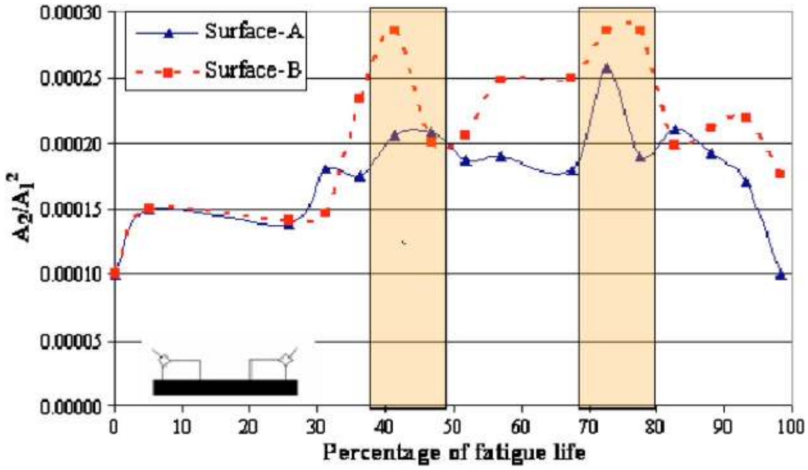

FIG. 5. (Color online) Variation of nonlinear parameter (A_2/A_1^2) with percentage of fatigue life in specimen 2.

It can be seen from the Fig. 3 that the variation of A_2 with A_1^2 at various stages of the fatigue life is linear, hence the data obtained is appropriate. The slope of the straight lines in A_2 versus A_1^2 plot was taken as the measure of the nonlinear parameter and, in the present work, wherever the variation in the magnitude of A_2/A_1^2 is shown, it implies that the slope of the A_2 versus A_1^2 is taken. Each measurement was done thrice and the slope (A_2/A_1^2) value taken for consideration is the average of the three values. The variation between repeat NLU measurements was found to be within $\pm 4\%$.

As fatigue is a surface phenomenon and cracks tend to initiate on either of the two surfaces of the specimen, it was considered appropriate to measure the NLU response on both the top and the bottom surface of the flat hour glass specimens which were marked as surfaces A and B at the start of the experimentation; and the same was implemented from specimen 2 onwards. Figures 4–6 show the variation of the nonlinear parameter (A_2/A_1^2) as a percentage of fatigue life for both the surfaces of the sample. The magnitude of the nonlinear parameter was observed to vary with cycles of fatigue loading in an independent manner for both the top surface and the bottom surface of the specimens. Table II provides the details of number of cycles to failure for each specimen and the surface where the fatigue crack was visually noticed first. Based on the above statements, one could correlate that the fatigue crack initiates first on the surface that has the highest nonlinear response.

It can be observed that the NLU response for the two surfaces show two distinct peaks for all the samples examined, though the percentage of life at which they occur varies marginally. This variation was observed to be within 1000 cycles (5% of fatigue life) and could be due to various factors such as specimen-to-specimen variation in size, surface quality, and local microstructural effects. It was observed that the surface that showed a higher value of nonlinear parameter had the first crack initiation. From the results presented in the Figs. 4–6, it can be observed that the first peak appears at about 40%–55% of fatigue life and the second peak at about 75%–90%. The occurrence of the second peak can be linked to the appearance of a visible crack at one of the edges on the hour-glass specimen. The NLU response thereafter drops sharply within the next 500 cycles of fatigue loading coinciding with specimen failure. The results also suggest that the absolute value of A_2/A_1^2 varies from specimen to specimen from the start of experiment until specimen failure, though all specimens were prepared in an identical manner. It is therefore important to characterize the NLU response from the virgin specimen to track onset of fatigue cracking.

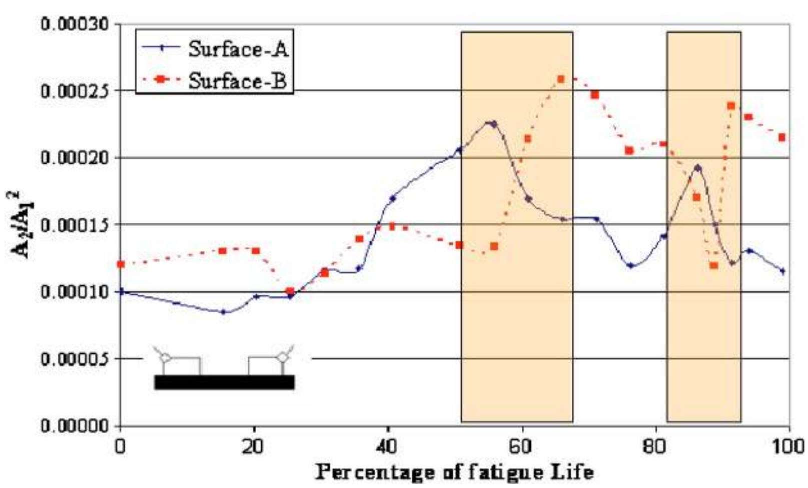

FIG. 6. (Color online) Variation of nonlinear parameter (A_2/A_1^2) with percentage of fatigue life in specimen 3.

TABLE II. Details of number of cycles taken for failure in each specimen and surface on which the crack has initiated.

Specimen ID	Crack initiated surface	Total fatigue life (cycles) for each specimen	
1		~20 000	Specimens cycled between 95% and 10% of yield strength
2	B	~19 000	
3	B	~19 500	
4	B	~25 200	
5	A	~24 500	Specimens cycled between 88% and 8% of yield strength
6	B	~23 800	

B. Results on specimens loaded to 88% of the yield strength

NLU measurements on fatigue specimens that were loaded to 88% of yield strength suggest similar two peak responses (Figs. 7–9). The second peak occurs prior to the appearance of visible crack on one of the edges and the magnitude of nonlinear parameter drops sharply within the next ~500 cycles of fatigue loading. It can be observed that there is an increase of about 200% in the nonlinear parameter in fatigue cycled samples when compared to the virgin samples.

In summary, it was found that the first peak appears over a range of 40%–55% fatigue life and the second peak appears over a range of 75%–90% fatigue life. The percentage of life and the magnitude of the nonlinear parameter at first and second peaks of the NLU response with percentage of fatigue life are as shown in Table III.

IV. DISCUSSION

The observation of two peaks in the variation of nonlinearity with percentage of life expended from our results is similar to what has been reported by Ogi *et al.*[22] in carbon steel rather than the single nonlinearity peak behavior reported by Barnard *et al.*[24] and Herman[25] in nickel based superalloys at the later stages of fatigue life. The absence of first peak in the initial stages of fatigue life in nonlinearity observed from the measurements of Barnard *et al.*[24] and Herman[25] could be due to fact that their NLU measurements were carried out at large intervals of fatigue cycles. On the contrary, as discussed earlier, our measurements were carried out at the intervals of 1000 cycles. Therefore, our results suggest that if measurements are made at smaller intervals of fatigue cycles, the two peaks in the variation of nonlinearity with fatigue life can be observed in agreement with the results of Ogi *et al.*[22]

These two nonlinearity peaks suggested by Ogi *et al.*[22] are based on the fact that the first peak could be due to the nonlinearity arising from fatigue cracks by Richardson's mechanism[28] that was verified by experimental observation of surface wave nonlinearity by Buck *et al.*[12] and Morris *et al.*[21] arising from the cracks. Further, they attribute the second nonlinearity peak seen at the later stages of fatigue life to arise from the nonlinearity due to the dislocation dynamics. However, the present authors differ with Ogi *et al.* at least on the origin of the first nonlinearity peak that is observed around 40%–50% of the fatigue life. The authors believe that there will also be contribution from persistent slip band (PSB) formation of dislocations to the nonlinearity at this stage of fatigue life and cannot expect contribution only to come from cracks.

In a recent paper, Cantrell[16] has argued out how fatigue cracks at the initial stages of fatigue cannot contribute to the nonlinearity in bulk samples based on the expression derived by Nazarov and Sutin.[29] They have derived an expression for the nonlinearity parameter associated with noninteracting cracks in bulk material. Based on this work,[29] Cantrell presents an expression β^{crk} arising from cracks,

$$\beta^{crk} \approx 5 \times 10^6 N_0 R_{crk}^4,$$

where N_0 is the concentration of cracks (number of cracks per unit volume) in the interior of the material and R_{crk} is the radius of the crack. As an example, based on the crack density and the linear dimensions of cracks polycrystalline nickel, he has evaluated the nonlinear parameter to have an insignificantly small value of $\beta^{crk} = 1.3 \times 10^{-17}$ arising from such microcracks with linear dimensions of 45 nm.

At the same time, Cantrell[16] points out, that when the crack size grows to value of $R_{crk} = 500\ \mu$m, one would expect a measurable value $\beta^{crk} = 3.1$ and the appearance of macrocracks of this size occurs late in the fatigue life of a material, generally after more than 80%–90% total fatigue

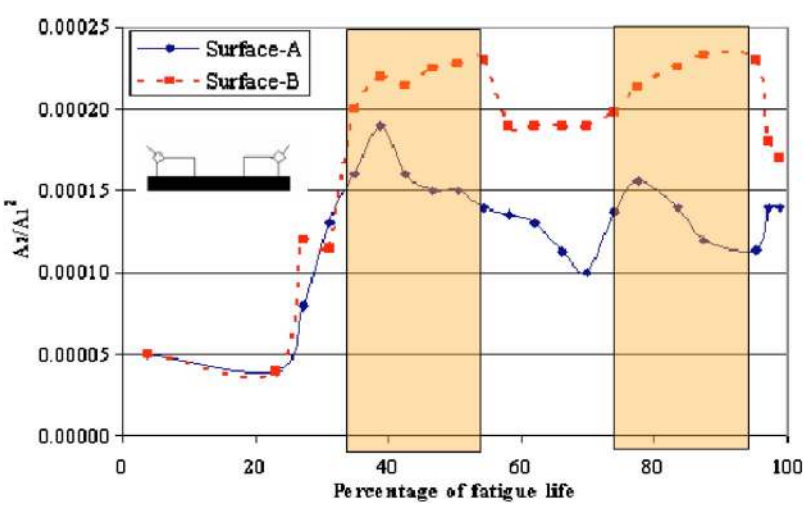

FIG. 7. (Color online) Variation of nonlinear parameter (A_2/A_1^2) with percentage of fatigue life in specimen 4.

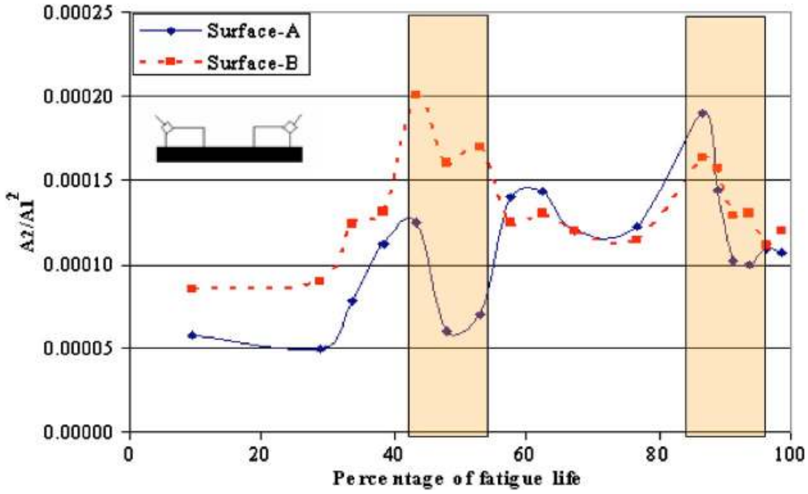

FIG. 8. (Color online) Variation of (A_2/A_1^2) with percentage of fatigue life in specimen 5.

life. It is the fourth-power dependence on crack radius produces a dramatic increase in β_{crk} as the macrocracks rapidly grow to several millimeters in radius before fracture. Based on his above argument, Cantrell[16] further suggests that it is important to note that macrocrack-induced changes in β generally arise during the last 10%–20% of full fatigue life and occur in addition to that of the microstructural contributions arising from dislocation dynamics.

It should also be noted that a similar LCF measurement using surface wave by Barnard *et al.*[24] on the Ni alloy samples (Inconel 718) did not show the two nonlinearity peaks, but only one at the later stage of fatigue of life. In their normalized harmonic ratio (A_2/A_1^2) of fatigued with respect to that of an unfatigued sample variation with expended life showed a gradual increase toward a peak 80%–90% of life depending on the load. Thereafter, the harmonic ratio was found to decrease rapidly. Barnard *et al.*[24] suggested that the gradual increase toward a peak in harmonic ratio is thought to be the result of dislocation networks formed as a result of fatigue. The rapid decrease in the harmonic ratio was thought to be the result of the surface crack growth. In the case of the second harmonic, its penetration depth is less than the fundamental, and so will experience greater loss due to reflections from the crack faces. Similarly, a fatigue test with a low-cycle fatigue test by Hermann[25] shows a consistent increase in the harmonic ratio, β' (the β value was corrected for a surface wave), as a function of fatigue life until β' drops before the failure of the specimen. Both the works of Barnard *et al.*[24] and Hermann[25] show that they observe a peak in the nonlinearity parameter peak near 90% of the failure and it should be noted that the absence of first peak in their results in the initial stages of fatigue could be due the long intervals of fatigue cycles used for nonlinear measurements, as discussed earlier. This is in agreement with Cantrell's[16] argument of the contribution of fatigue cracks to the nonlinearity only at the later stages of fatigue.

Morris *et al.*,[21] though their main emphasis was that the nonlinearity arises only from fatigue induced cracks, also have not observed any two nonlinearity peaks behavior. Instead, their harmonic ratio observed to be increasing monotonically in the early stage of fatigue with increase in the percentage of life expended and showed a steep increase in nonlinearity only near 10%–20% of the remaining fatigue life, showing that the cracks could effectively contribute only at the later stage of fatigue life.

Recently, Kawashima *et al.*[30] reported nonlinear acoustic response through minute surface cracks based on simulation studies and experimentation. The results suggest that the nonlinearity parameter increases as the crack length increases and saturates for a crack length of around

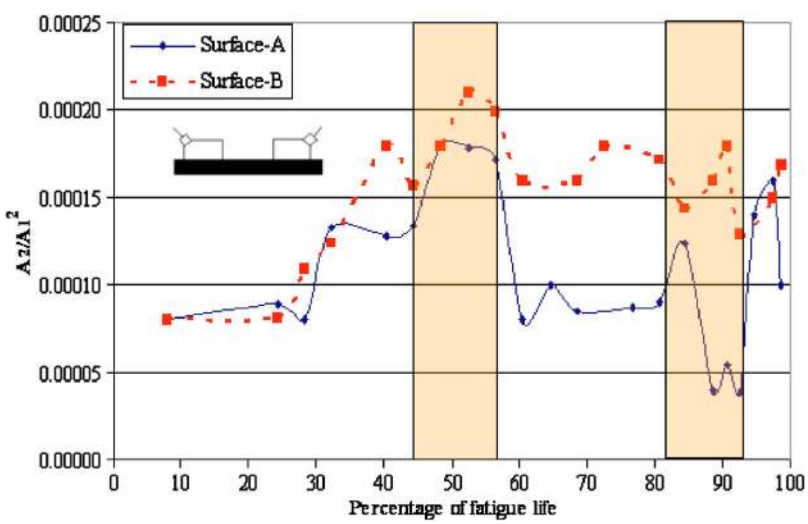

FIG. 9. (Color online) Variation of (A_2/A_1^2) with percentage of fatigue life in specimen 6.

TABLE III. Variation of A_2/A_1^2 for the first and second peaks as a function of fatigue life.

Specimen ID	Details of First peak		Details of second peak		
	% fatigue life	$A_2/A_1^2 \times 10^{-4}$	% fatigue life	$A_2/A_1^2 \times 10^{-4}$	
1	55	2.39	86	1.50	Specimens loaded to 95% of yield load
2	46	2.1	82	1.90	
3	55	2.5	86	1.92	
4	40	2.2	77	2.14	
5	48	2.28	90	2.25	Specimens loaded to 88% of yield load
6	44	2.15	88	1.95	

150–200 μm for a crack opening of about 1 nm. Therefore, for nonlinearity to arise from cracks, their opening should be smaller than the wavelength of the second harmonic frequency. Ogi *et al.*[22] has also suggested that the opening and closing of the crack tip could cause the nonlinearity. However, one cannot come to such a conclusion unless the size of crack tip or crack opening is known. Ogi *et al.* have reported to have measured an average crack length of 50 μm and crack density of 200 mm^{-1} near the fatigue life of first nonlinearity peak. According to Cantrell,[16] the contribution from cracks to the first nonlinearity peak will be very small for these values of average crack length and density reported by Ogi *et al.*[22]

Moreover, in general, such a crack initiation will not happen until PSBs are formed.[31] It is well known that fatigue crack initiation processes are often related to the formation of PSBs.[31–34] It is normally observed that during LCF, even prior to macroscale plasticity, dislocations are generated during cyclic loading, which cluster and form channel-vein structures and later on form ladderlike structures. Ladderlike structures are found inside PSBs which carry most of the plastic deformation and lead to surface roughness, in the form of so-called extrusions, intrusion, and protrusions. These slip bands, which have a typical width of several micrometers, lead to extrusions at the sample surface and stress concentrations, or to strain localization. The development and broadening of the PSB is often accompanied by the initiation of small fatigue cracks. A widely accepted model of PSB and fatigue crack initiation is the Essman–Gosele–Mughrabi extrusion theory.[32]

Cantrell and Yost,[14–17] in a series of theoretical and experimental work, have shown the contribution of nonlinearity from veinlike dislocation structure and its subsequent development to PSB will be more than 100% at every stage of this dislocation structure development.

Considering these aspects of dislocation dynamics and surface crack initiation and the contribution of magnitude of nonlinearity from various stages of dislocation dynamics, one cannot rule out the contribution of nonlinearity (in the present study also) from dislocation dynamics and still preserving the contribution of nonlinearity from fatigue cracks to a latter stage. Therefore, one may suggest that the increasing nonlinearity and its subsequent development into a peak value may arise from the formation of PSB, discussed above. After the peak, the decreasing trend in nonlinear parameter could be due to the microcrack initiation and crack-PSB interaction. Since the nonlinearity is decreasing, it is believed that the effective interaction of the wave with PSB is reduced after sufficient density of minute cracks were formed. In effect, it will reduce the distortion in the wave and thus the nonlinearity parameter. Therefore, instead of expecting a contribution only from cracks, for the first peak to appear, one could suggest that it could be due to PSB-crack interaction.

The second peak arising at the later stage might arise partly due to the possible dislocation-crack interaction mechanism suggested by Ogi *et al.*[22] In a subsequent work, Ogi *et al.*[5] have observed a PSB-cell structure transition occurring in their system at the late stages of fatigue life (70%–85%) from their TEM and ultrasonic attenuation studies using EMAT. This type of transition is seen to occur only at the late stages of fatigue[35] and has been observed experimentally in many materials.[36] This transition, observed by Ogi *et al.*[5] in their later work, might cause the increase in the nonlinearity and subsequently cell structure–crack interaction would reduce the nonlinearity after a peak, observed in their nonlinear measurements reported in[22] on the same material. Therefore, as observed by Ogi *et al.*,[5] the second peak in the present study also could be due to such PSB-cell transition and subsequent crack dislocation interaction.

V. CONCLUSION

NLU harmonic generation measurements were conducted on the aluminum alloy AA7175-T7351 specimens fatigue cycled at two loading conditions and the observations are as follows.

(1) Along both the surfaces of the specimen, two distinct peaks in the nonlinear parameter A_2/A_1^2 were observed for all the samples.
(2) The first one appears at ~40%–55% of fatigue life and the latter at ~75%–90%. The second peak appears just before a visible crack appears at one of the edges on the hourglass specimen. The magnitude of nonlinear parameter drops thereafter—within about 500 cycles (2% of fatigue life) of fatigue loading and prior to specimen failure.
(3) Similar results were obtained in case of fatigue specimens that were loaded to 95% of yield strength. Results showed that there is an increase of ~200% in the nonlinear parameter A_2/A_1^2 at the first peak in the fatigue sample when compared to the virgin sample.
(4) Surface with a fatigue crack showed a larger change in nonlinearity when compared with the other surface. It

was also observed the crack appeared on the surface of the specimen where the magnitude of the nonlinear parameter is higher when compared to the other.

(5) It is suggested that the two peaks occurring in the variation of nonlinearity parameter with increase in the percentage of fatigue life in the present study could be due to both dislocation dynamics as well as crack mechanism (a) In the case of first peak, the formation of PSBs and crack initiation and interaction of PSB with cracks. (b) In the case of second peak, the transition from PSB-cell structure of dislocations and their interaction with cracks. However, it is felt that a much more systematic study with the help experimental observation of microstructural variation at every stage of fatigue is required to prove this mechanism.

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