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Acoustic emission analysis of fatigue crack growth in steel structures

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The Acoustic Emission (AE) characteristics and source mechanism during fatigue crack growth in steel structures and weld connections are investigated experimentally by three point bending testing of specimens under low cycle constant amplitude fatigue loading using the Hilbert Huang Transform (HHT). The characteristic frequencies corresponding to crack growth sequence, that is, initiation, crack propagation and fracture is studied using Hilbert's Spectral analysis. AE sources at the three stages during fatigue cracking were investigated using the AE counts and the constitutive ratios of the Intrinsic Mode functions of HHT. The effect of peak load on AE during fatigue crack propagation was discussed. A comparison of results with Linear Elastic Fracture Mechanics (LEFM) analysis indicated that HHT is an effective technique superior to the traditional envelope spectrum method for signal feature extraction during fatigue crack growth in steel structures.

Key words: Acoustic emission technology, Linear Elastic Fracture mechanics, Hilbert Huang Transform, Intrinsic Mode Function.

INTRODUCTION

The problem of cracks in structural steel and welds is a major issue in several industries, more especially civil engineering. Crack in welds can be formed mainly during the welding process itself or later as results of residual stress and the martensite formed during cooling (Fang et al., 1997). Characterization fatigue crack growth in steel and weld has been thoroughly researched over the accumulated decades with a combination of mechanical and non-destructive techniques (Robert and Talebzadeh, 2003; Kulkarni et al., 2006; Mathieu et al., 2012). Determination of the period of crack propagation between the initial and critical crack sizes requires knowledge of crack propagation rates. Acoustic emission has emerged as the most appropriate (NDT) method for studying fatigue crack growth in civil engineering steel structure because it can monitor their health in real time (Singh et al., 2007). Per the (ASTM E610, 1982) definition; Acoustic emission is a class of phenomena whereby transient elastic waves are generated by the rapid release of energy from a localized source within a material or the transient elastic waves so generated. A relationship between the AE parameters and fatigue crack propagation similar to the Pairs law were reported by (Bruzelius and Mba, 2004; Robert and Talebzadeh, 2003). Based on these deductions, several other models have been proposed for predicting the remaining life of steel structures (Yu et al., 2011).

Even though unprecedented results have been achieved using AE parameters for fatigue crack characterization in steel and welds, the AE sources at various crack growth stages still require investigations. It has been reported that, ductile crack growth is a weak source of AE (Moorthy et al., 1994). Some other studies (Moorthy et al., 1996) indicated that for a ductile material, the major source of AE was the plastic deformation at the tip of the crack, whereas for brittle materials it was the crack extension at the crack tip instead. The effect of peak load on fatigue crack growth rate has been reported

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Table 1. Mechanical property of Q345 steel and weld.

Parameter	$\sigma_b(MPa)$	$\sigma_s(MPa)$	$\delta(\%)$	E（MPa）
Base metal	360	560	37	206000
Weld	294	441	31	206000

σ_b = yielding stress, σ_s = ultimate tensile stress, δ = percentage of elongation, E =Young's modulus.

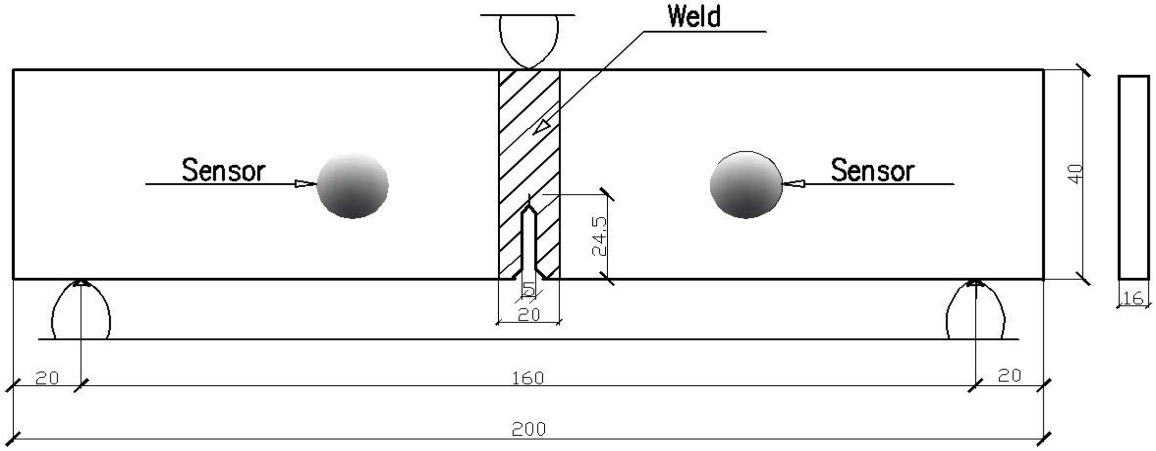

Figure 1. Welded specimen geometry.

to be insignificant (Morton et al., 1973) however the effect on the AE sources deserves in depth research.

Quantitative techniques which deal with the study of the waveform of the AE data give more precise monitoring of cracks and defects in structures. Nakagawa et al. (2009) reported that, time frequency analysis is efficient in finding small damages such as cracks on steel structure with less works. Wavelet-based analysis may have yielded some improvement over the Fast Fourier Transform because it can handle non-stationary data, but the limitation of requiring the data set to be linear is still retained (Kim and Melhem, 2004; Hamstad et al., 2002). A new innovation based on (HHT) for the analysis of non-linear and non-stationary data was discussed by Huang et al. (1996) and Li et al. (2005). This technique is a truly adaptive representation for the non-stationary processes. The HHT is used to extract damage characteristics from AE signals, and deduce defect formations in the structure. The main aim of this paper is to study the fatigue crack growth characteristics and source mechanism in steel structures and weld connections under peak loadings using the innovative signal processing method of the HHT. A clear distinction between crack growth rate in the homogeneous base metal and the welds containing heterogeneous microstructure, complex residual stress distribution and irregular shapes are clearly established using the Hilbert's spectral analysis and the constitutive ratio of the intrinsic mode function of the HHT.

EXPERIMENTAL SETUP

Specimens design

The standard three point bending specimens were designed from 345 (Chinese code) steel and weld, as representative part of a steel bridge in accordance with ASTM E647 standards. The mechanical properties of the C-Mn steel and weld used for the specimen are shown in Tables 1. The specimens were notched using electrical discharge machining (EDM). The specimens' surfaces were mechanically polished by grinding and buffing to permit observations of the crack path. The detail geometry of the specimen is illustrated in Figure 1.

Test instrument and procedure

Fatigue tests were carried out on a servo-hydraulic testing machine with maximum load capacity of 250 kN at ambient temperature (300 K) (Figure 2). All specimens were tested under sinusoidal cyclic loading at a frequency of 7.5 Hz at peak loads 10 and16 kN and load ratio (R) of 0.1. At least three specimens were tested under each condition to confirm the regularity. Initial fatigue pre-crack of 0.5 mm length was made using the MTS machine at a frequency of 10 Hz. The AE signals were detected by using four broad band piezoelectric sensors with frequency range of 10 kHz to 2 MHz from Physical acoustic corporation (PAC). The instrument settings were

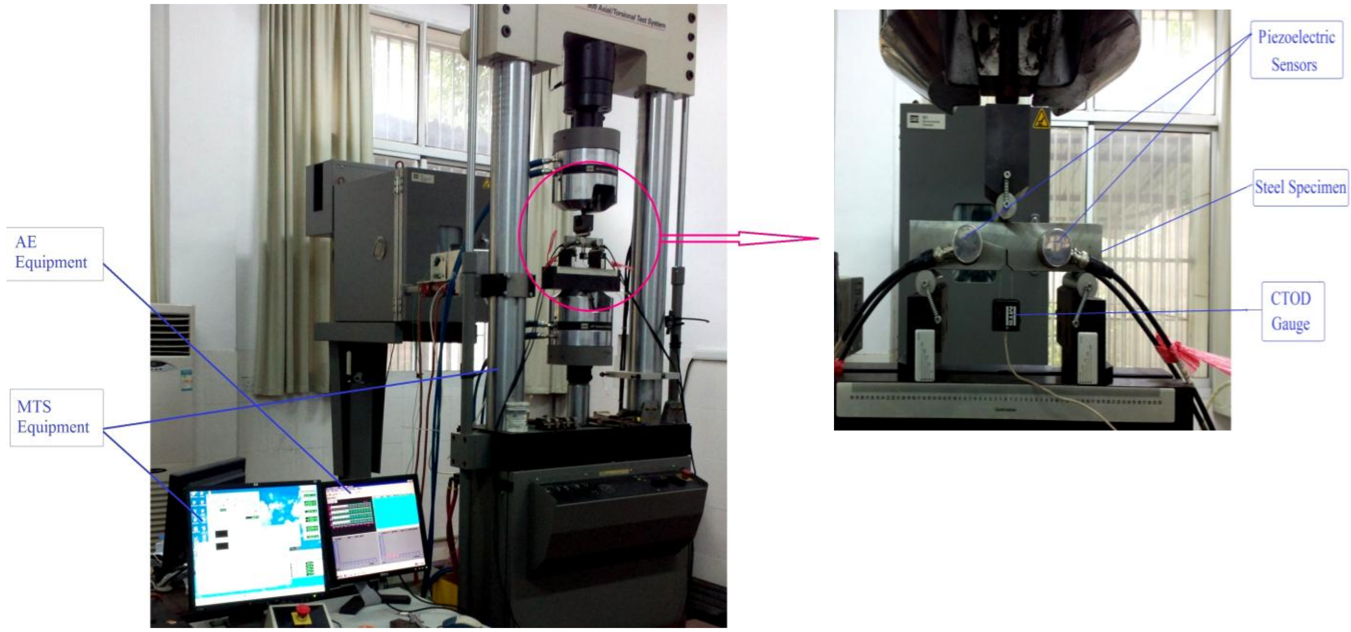

Figure 2. Experimental set up.

set at a fixed threshold level of 40 dB, a preamplifier gain of 40 dB, a sampling rate of 2 MHz, and a filter frequency range from 50 kHz to 1 MHz.

Vaseline was used at the interface between the sensors and the specimen surface to obtain proper signals. A preamplifier of 40 db gain was used to capture the AE signals. AE signals generated during the fatigue tests were recorded by SWAES full-waveform acoustic. In order to make sure that the signals were obtained from the cracked area, the linear source location was applied using the pencil lead break method (Nivesrangsan, 2007; Hamstad, 2007). The Crack-Tip Opening-Displacement Gauge (CTOD) was used to monitor the fatigue crack growth in the structure. Fatigue crack length was estimated using Equation (1).

$$\frac{a}{w} = 0.999748 - 3.9504U_v + 2.981U_V{}^2 - 3.21408U_V{}^3$$

$$+51.51564U_V{}^4 - 113.031U_V{}^5 \qquad (1)$$

Where

$$U_v = \frac{1}{\sqrt{\frac{4z_v w}{s}+1}}, \quad Z_v = \frac{BEV}{P}$$

$$V = crack - mouth - openening - displacement$$

HILBERT-HUANG TRANSFORM

Basic concept

Whereas the qualitative approach gives a general view for characterizing crack growth, a more distinctive quantitative approach is proposed. HHT is a self-adaptive signal processing method that can be applied to non-linear and non-stationary process and is arguably the most suitable technique for the fatigue crack growth characterization and source mechanism in the heterogeneous welded medium. HHT-based processing consists of two main elements: Empirical Mode Decomposition (EMD), and Hilbert spectral analysis. EMD is a process where signals produce Intrinsic Mode Functions from which instantaneous frequencies may be extracted by the simple application of the Hilbert transform and the Hilbert spectral analysis generates a “time-frequency-energy” representation of the data, based on the IMFs. EMD method is based on the direct extraction of the energy associated with various intrinsic time scales. The decomposition can be viewed as an expansion of the signal in terms of the intrinsic mode functions (IMFs). These IMFs can serve as the basis of that expansion which can be linear or nonlinear as dictated by the data, and it is complete and almost orthogonal. Most important of all, it is adaptive (Huang et al., 1998). The principle of this basis construction is based on the physical time scales that characterize the oscillation mode imbedded in signal. Using EMD the signal *x (t)* can be decomposed to a set of IMFs and expressed as follows.

$$x(t) = \sum_{i-1}^{n} imf_i(t) + r_n(t) \qquad (2)$$

Or

$$x(t) = \sum_{i-1}^{n} C_i(t) + r_n(t) \qquad (3)$$

Where $imf_i(t)$ is the i-th intrinsic mode function (IMF) and $r_n(t)$ is the residue after the n-th IMF is extracted is a monotonic function or a constant.

The characteristics of the fatigue crack growth can be further analyzed using the constitutive IMF ratio. The complexity of the IMF ratio is used to characterize each stage of fatigue cracking. A simple constitutive ratio characterizes simple source mechanism, whilst a complex constitutive ratio indicates a relatively scattered source. A comparison of the constitutive ratio for studying the AE source at the various stages during fatigue crack growth in the welded specimen is shown in Figure 8.

As illustrated in Figure 8 the constitutive ratio for crack initiation has a relatively simple mechanism whose IMF is dominated by IMF1, as crack propagates, IMF 2and 3 become relevant till final fracture.

Hilbert marginal spectrum

The Hilbert transform for on IMF $C_i(t)$ we have

$$H\left[c_i(t)\right] = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{c_i(t')}{t-t'}dt' \qquad (4)$$

Therefore an analytical signal can be defined as

$$z(t) = c(t) + jH\left[c_i(t)\right] = a_i(t)e^{j\phi_i(t)} \qquad (5)$$

Where,

$$a_i(t) = \sqrt{c_i^{2}(t) + H^2(c_i(t)]} \qquad (6)$$

$$\phi_i(t) = \arctan\frac{H[c_i(t)]}{c_i(t)} \qquad (7)$$

Instantaneous frequency can be calculated as:

$$\omega_i(t) = \frac{d\phi_i(t)}{d(t)} \qquad (8)$$

We can therefore represent the Actual Signal (AS) as follows:

$$x(t) = AS\sum_{i=1}^{n} a_i\left(t\right)e^{j\phi_i(t)} = AS\sum_{i=1}^{n} a_i\left(t\right)e^{j\int \omega_i(t)dt} \qquad (9)$$

Equation (9) represents the Hilbert spectrum H (ω, t), which offers a measure of amplitude contribution from each frequency and time.

We compute the marginal spectrum which offers a measure of the total amplitude contribution from each frequency as;

$$h(\omega)\int_{o}^{T} H(\omega, t)dt \qquad (10)$$

Where T represents the total data length

RESULTS AND DISCUSSION

Fatigue crack propagation

(Paris and Endogen, 1960) discovered the power-law Equation (11) relationship for the fatigue crack growth. The rate of cracking can be correlated with fracture mechanics parameters such as stress intensity factor.

$$\frac{da}{dN} = C\Delta K^{m},$$

$$\log\left(\frac{da}{dN}\right) = \log C + m\log\Delta K \qquad (11)$$

where a is a representative crack length, n is the number of fatigue cycles, ΔK is the applied stress intensity factor range and C and m are assumed to be constants for a particular material. Figures 3 and 4 show the relationship between crack length and number of cycles and the fatigue crack growth rates (*da/dN*) and stress intensity factor ranges ΔK respectively.

In nearly the whole fatigue live, they obeyed the Paris law for the metal and weld. It is evident in the two diagrams that crack propagate faster in weld than in the base metals using fundamental LEFM this is due to the decreased tensile properties and fatigue resistance of the weld as a results of inclusions and heterogeneous microstructure.

Acoustic emission during fatigue crack propagation

Figure 5 illustrates a comparison of the AE transition for the weld specimen and LEFM. The AE transition occurred at $\Delta K = 58Mpa.m^{\frac{1}{2}}$; there was no change in the linear relationship between (*da/dN*) and the ΔK on the Log-log axes. A significant change in slope was observed at $\Delta K = 70Mpa.m^{\frac{1}{2}}$; suggesting that rapid crack propagation might occur. This suggests that AE stage transition preceded the unstable crack propagation defined by LEFM. This agrees with previously results (Moorthy et al., 1994) that the transition from stage 2 suggested that fatigue crack propagated under a Laird mechanism which depends on the cyclic deformation ahead of the crack. The AE in stage 2 were generated from new yielding at the edge of the plastic zone. Stress increased with the increase in crack length as the plastic deformation zone.

Effect of peak load on the AE

As discussed early in Figure 4, peak load has little

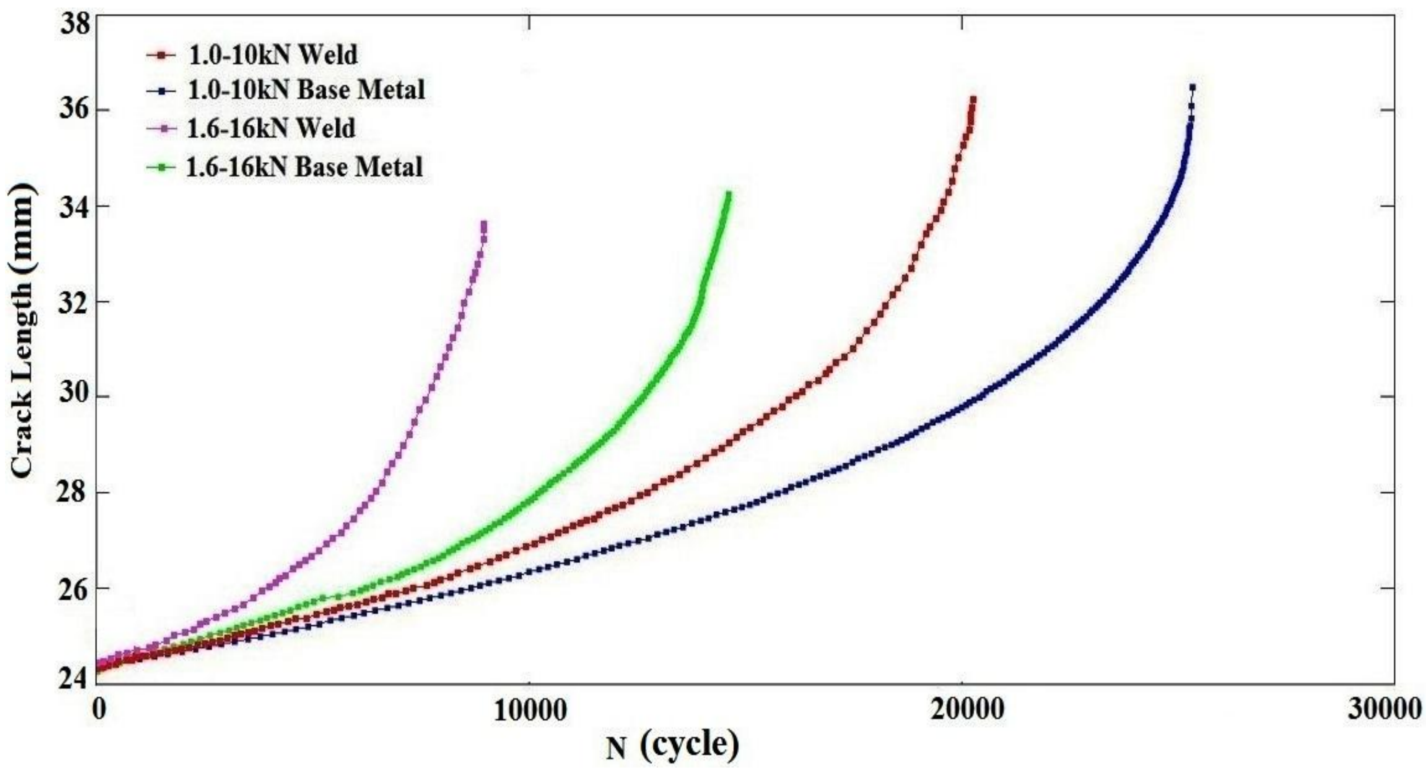

Figure 3. Relationships between crack length and number of cycle.

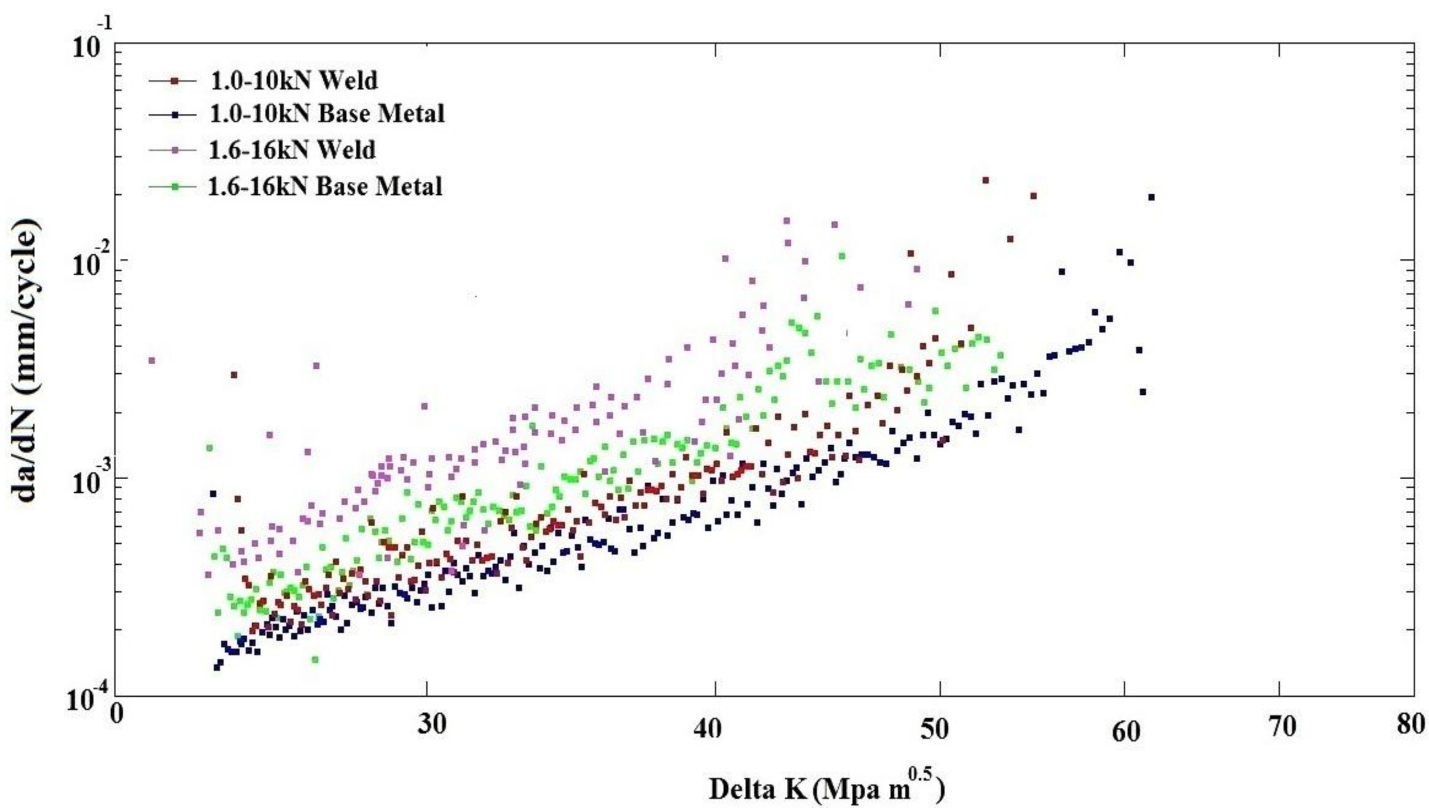

Figure 4. Relationships between crack growth rates and stress intensity factor ΔK .

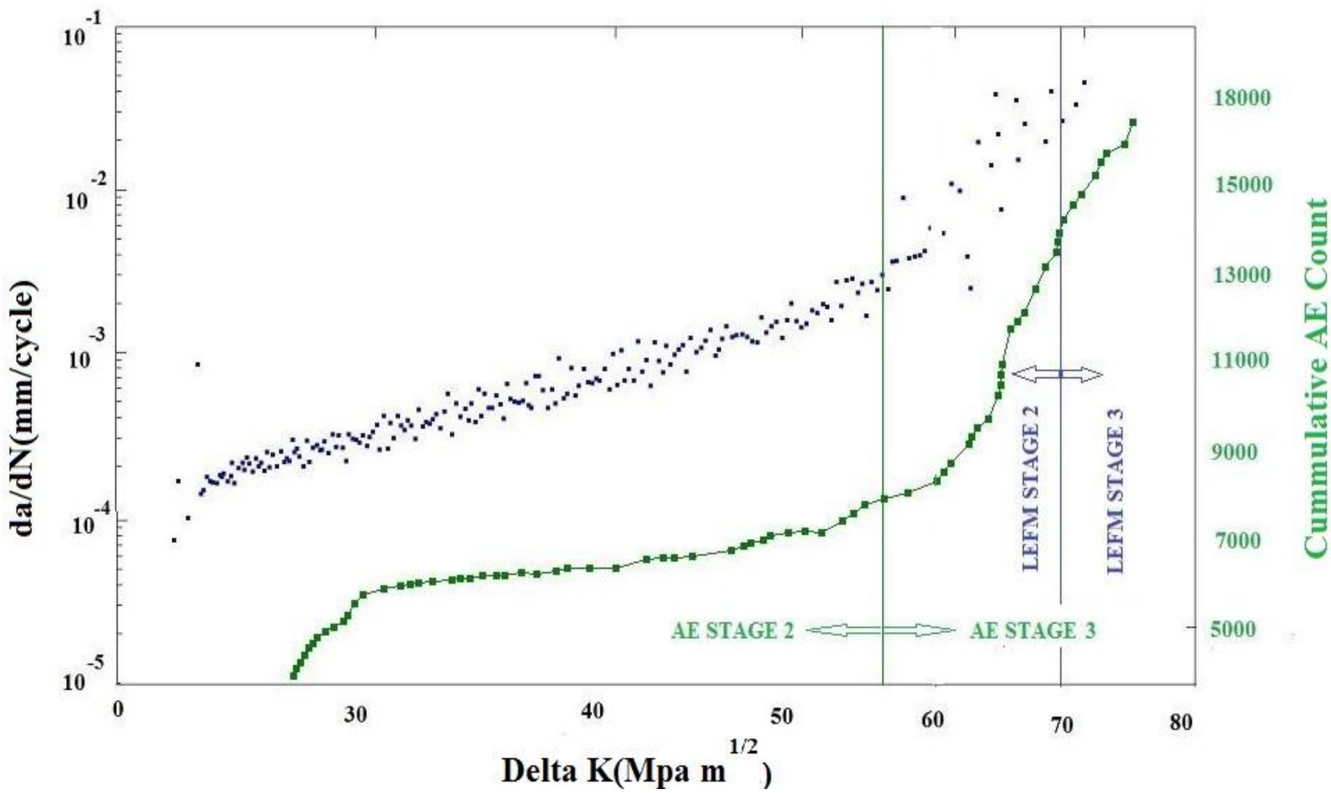

Figure 5. Comparison of the AE transitions and CTOD.

significance on the fatigue crack growth rate. This agrees with previous results (Robert and Talebzadeh, 2003; Moorthy et al., 1996) that ΔK is the controlling factor in crack and AE behavior instead of stress. Figure 5 indicates that, the values of ΔK at the transition points from Stage 2 to Stage 3 were also influenced by the peak load and micro-structure. The welded microstructure and lower peak load both decreased ΔK of the transition points. The transition from Stage 2 to Stage 3 represented the changes in AE source mechanisms due to the alteration of fracture modes. The welded micro-structure with the characteristics of the coarse ferritic grains and inclusions could not only increase the crack growth rate, but also promote the formation of micro-voids and micro-cracks, at the tip of the crack. The peak load is generally considered that has little influence on the AE transition point related to the stress state change during fatigue crack propagation. It has been shown that the transition from plane strain to plane stress crack propagation, which causes a peak of emission, occurred at certain ΔK for a kind of materials and specimen thicknesses.

However, the result in Figure 6 shows that the transition of AE from Stage 2 to Stage 3 was not only controlled by ΔK, but also by the peak load. In this study, the effects of the peak load on the AE transition may be explained by the differences in the ligament size of specimens when the transitions happen, as shown in Figure 7. For the specimens tested under lower peak load, the transitions occurred at longer crack lengths, indicating that the ligaments of specimens were decreased as compared to those tested under higher peak load. Though ΔK were still lower for these specimens, the constraints at the tip of the crack were less and the stress was at the similar level as the specimens of higher peak load. Consequently, the AE transition happened at a lower ΔK in the specimens tested under lower peak load. This result also suggests the transition may be a stress controlled rather than a ΔK controlled process.

Application of HHT

In order to obtain the characteristic frequencies of the fatigue crack growth for the various stages, Figure 9 and 10 illustrate the Hilbert spectral analysis for both specimens. A distinction between the crack growth characteristics for the base metal and welded specimen are evident for the three stages: initiation, propagation and failure.

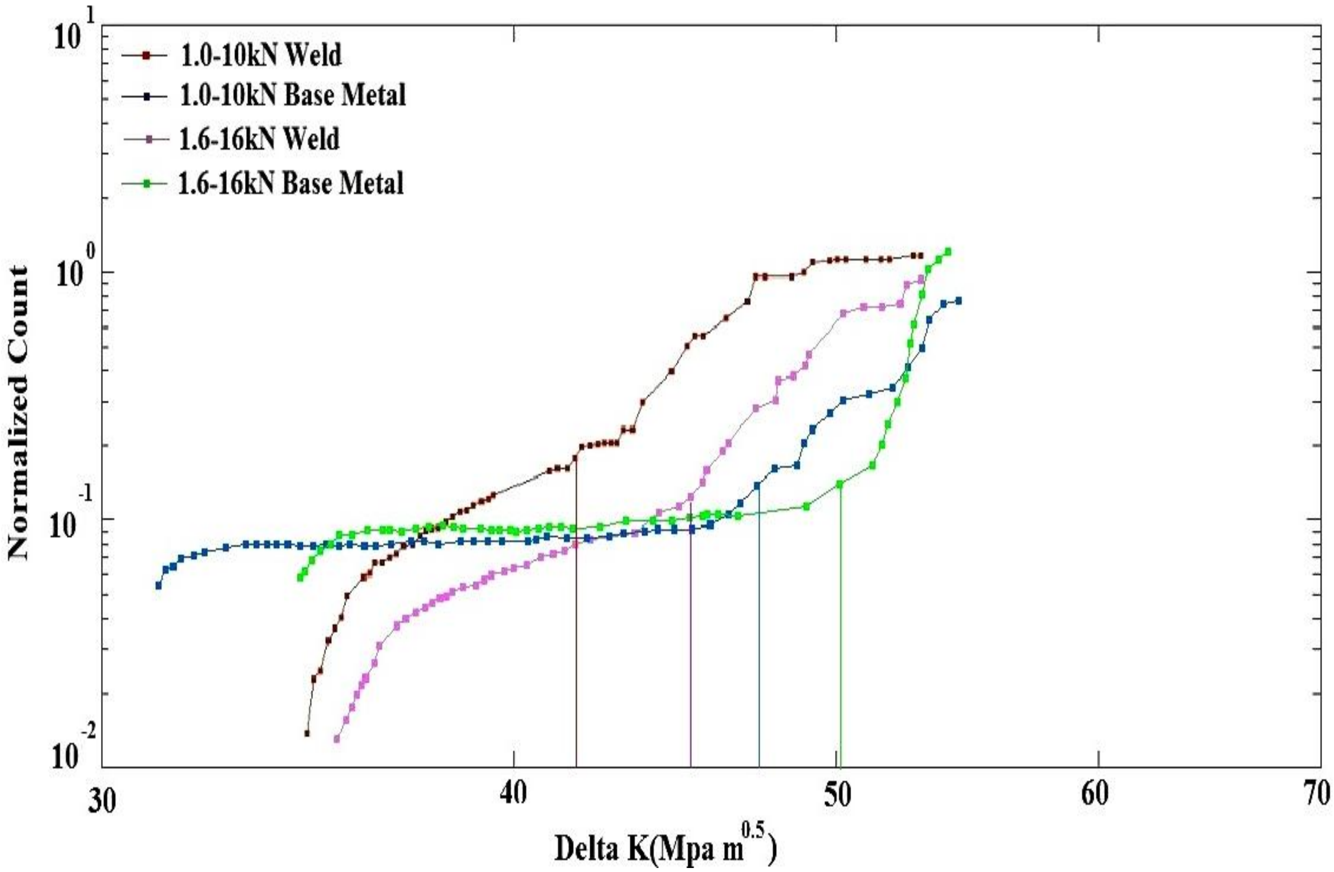

Figure 6. Normalized AE counts versus ΔK for the base metal and weld under the peak loads of 10 and 16 kN respectively.

Figures 9(a) and 10(a) show the AE waveform corresponding to fatigue source initiation for both the base metal and the weld respectively. At this stage, the AE signals are generated by the formation of crack source and plastic deformation on the tip of the notch generating AE events. The waveforms have low-amplitude, wide pulse with a narrow frequency scale, mostly located at 100 to 200 kHz. However, comparatively higher amplitude is recorded for the weld than the base metal due to the release of residual stresses.

Figures 9(b) and 10(b) show The AE waveform corresponding to fatigue crack propagation for both base metal and weld respectively. The waveforms at this stage have high amplitude, narrow pulse, with a wide energy scale, and a main frequency scale of 100 to 350 kHz for the base metal and 250 to 500 kHz for the welded specimen. The heterogeneous microstructure of the weld causes crack to propagate at a higher frequency rate and higher amplitude than base metal At the rapid crack propagation stage, the energy of the AE signal increased until the specimen completely failed, and the AE waveform amplitude is higher than preceding stages. The waveform characteristic shows that this type of AE signal is a burst signal. The fracture waveform (Figure 10a and 10c) is a high amplitude narrow pulse, with a wide energy scale, and a main frequency scale of 250 to 600 kHz.

Conclusion

1. The presence of inclusions and the heterogeneity of the welded material enhanced the fatigue crack growth rates for the welded specimen higher than the base metal.
2. AE is more sensitive to fracture mode transition than LEFM, as the transition from Stage 2 to Stage 3 indicated by AE preceded LEFM method in Figure 6.
3. The constitutive IMF ratio is a useful tool for fatigue source mechanism in steel structures. Crack initiation produced a comparatively simple constitutive ratio than propagation and fracture due as AE activities are not so intense at this stage.
4. The application of the quantitative method of analysis using HHT for damage characterization proved to be more effective as compared to the qualitative analysis using the signal parameters.

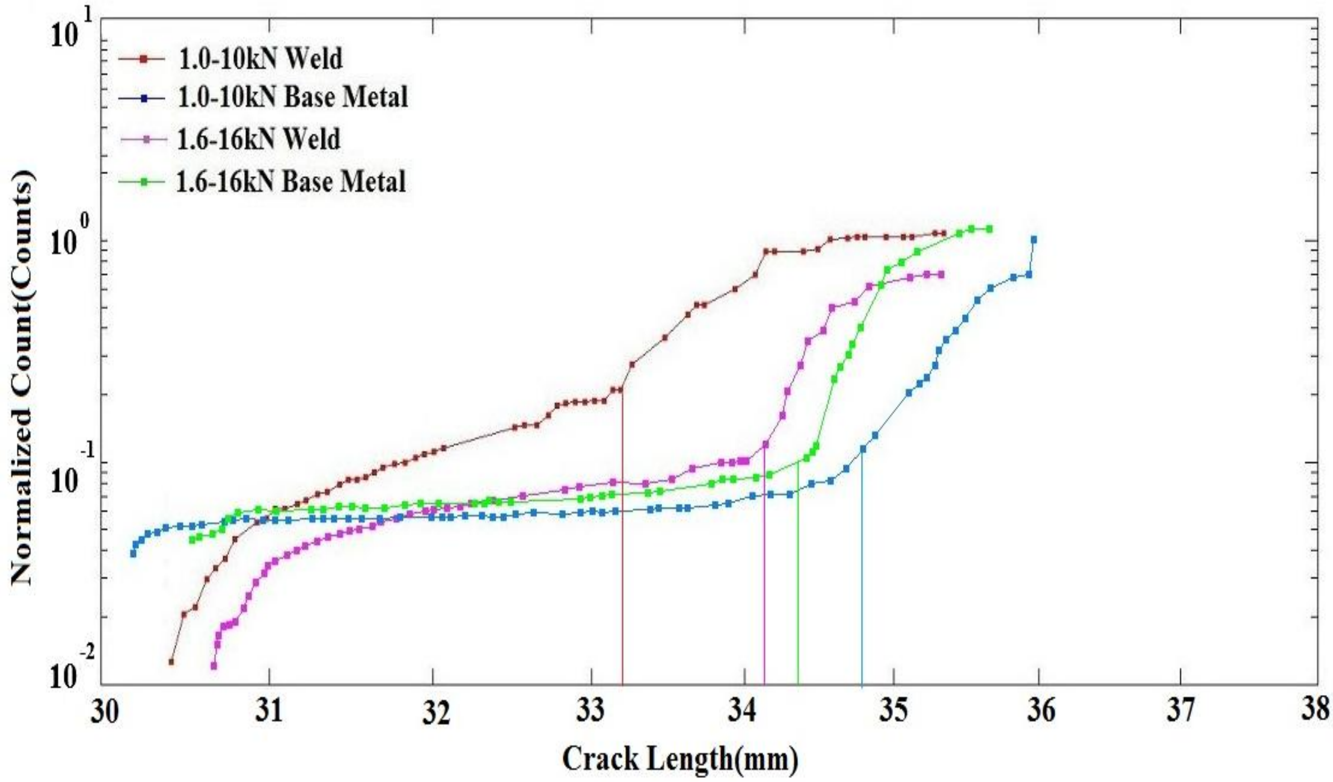

Figure 7. Normalized AE counts versus crack lengths for the base metal and weld under the peak loads of 10 and 16 kN respectively

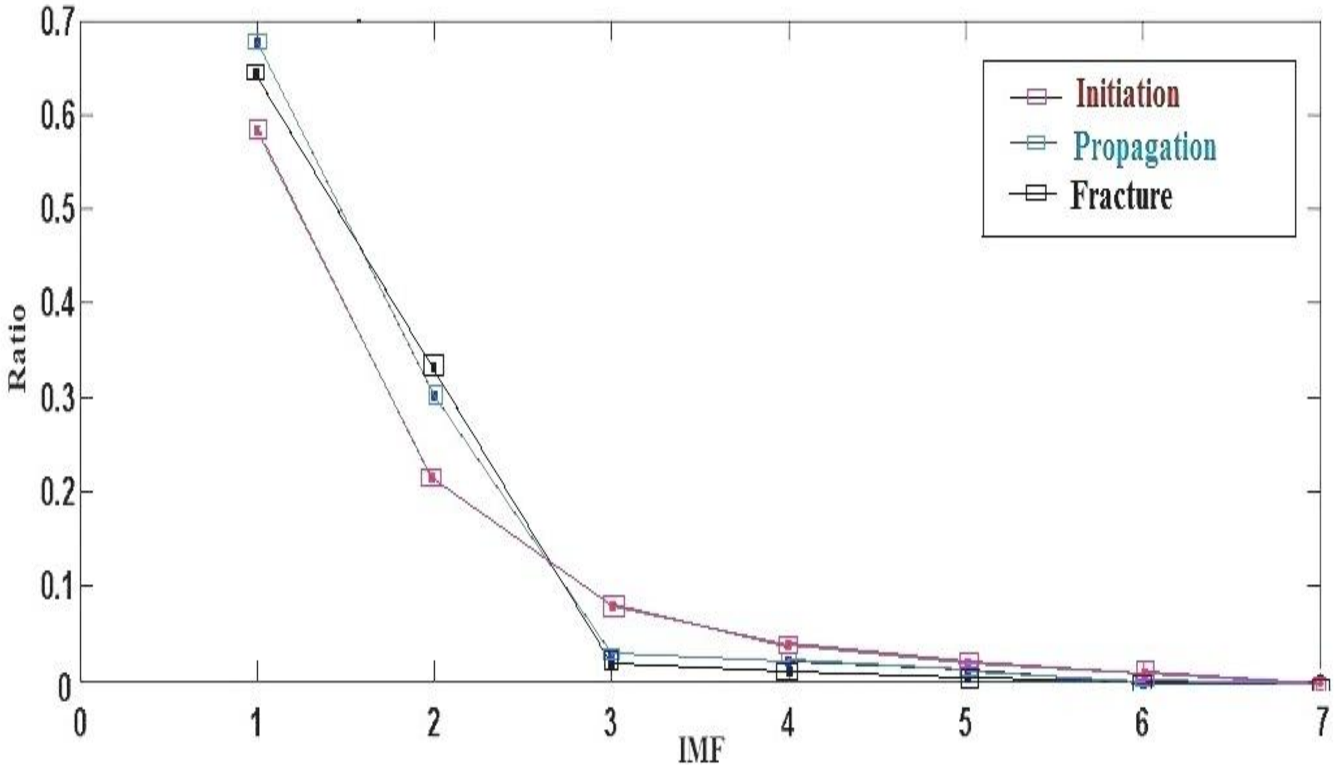

Figure 8. Constitutive ratio of the IMF for source mechanism in weld specimen.

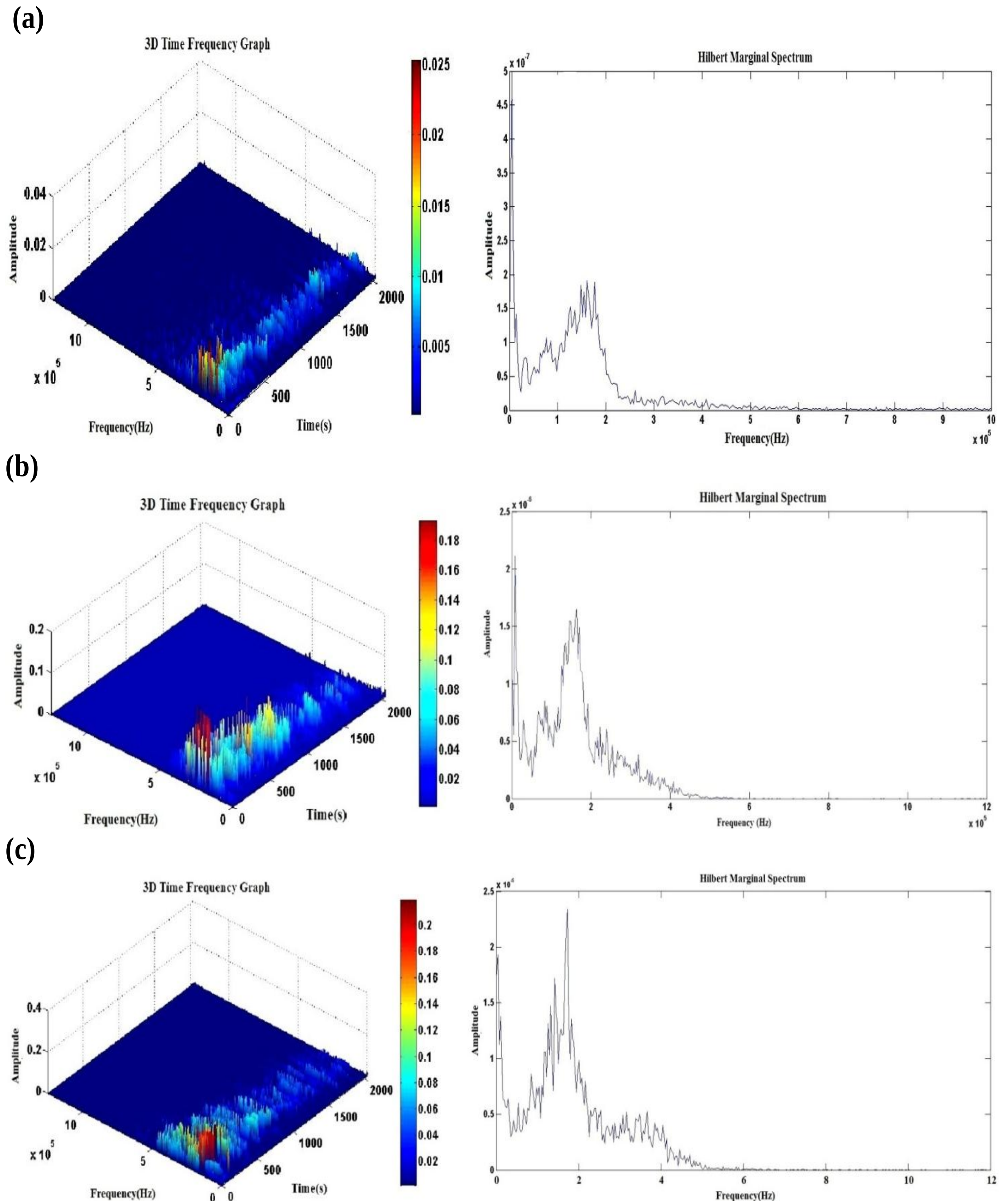

Figure 9a-c. Time-Frequency and Hilbert Marginal spectrum for base metal.

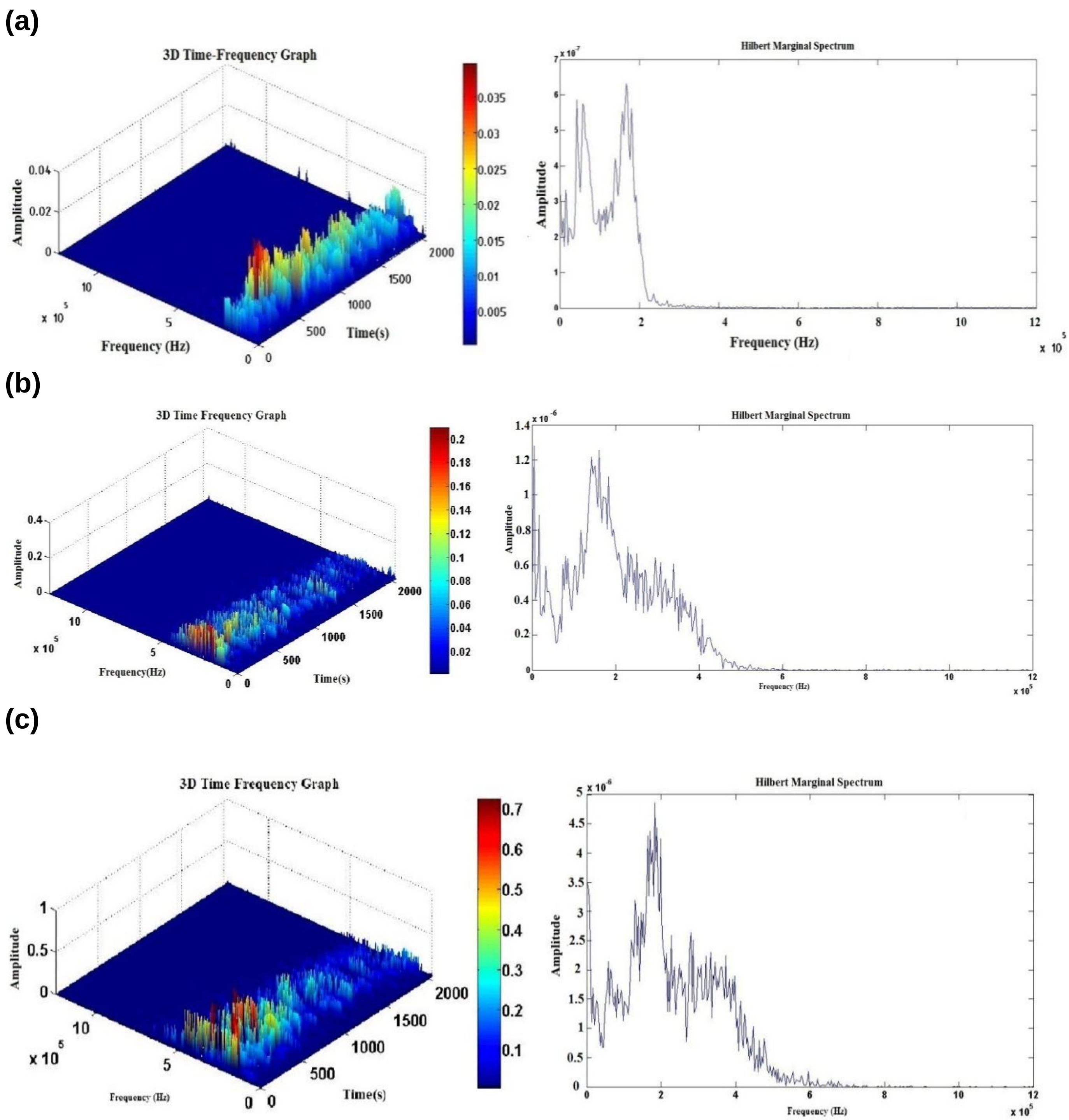

Figure 10a-c. Time-Frequency and Hilbert Marginal spectrum for Weld.

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