Evaluation of aging effect on Mild Steel (E 6013) welded Areas using Hilbert Huang Transform.

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Approval Page

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List of Abbreviations

CSD	Chirplet Signal Decomposition
DT	Destructive Testing
ECT	Eddy Current technique
EMD	Empirical Mode Decomposition
HAS	Hilbert Spectral Analysis
HHT	Hilbert Huang Transform
IMF	Intrinsic Mode Function
LT	Laser Technique
MFL	Magnetic Flux Leakage
MPL	Magnetic Particle Technique
MS	Mild Steel
NDT	Non-Destructive Testing
PARCO	Pak Arab Refinery Ltd.
PSO	Pakistan State Oil
RT	Radiographic Technique
RUL	Remaining Useful Life
SDMS	Sonatest Data Management Software
SSGC	Sui Southern Gas Company
SWG	Standard Wire Gauge
UT	Ultrasonic Testing

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Abstract

The welding inspector ensures the integrity of weld joints since the structural stability mainly depends on it. Welded joints are tested for the prediction of remaining useful life using different Non-Destructive Testing (NDT) schemes such as Ultrasonic Testing (UT). In this proposed study, possible classification of UT signals acquired from weld areas in terms of different levels of thermal fatigue were explored using Hilbert Huang Transform (HHT). In this study the HHT was employed for the determination of aging effect by characterizing the ultrasonic backscattered echoes of scanned welded materials. The HHT being an empirical based method can generate meaningful representation of data from non-stationary and nonlinear system. Firstly, the ultrasonic signals were broken into a set of simpler signals named Intrinsic Mode Functions (IMF). Based on the Hilbert spectrum of these IMF, time-frequency analysis was conducted. Energy Frequency distribution based feature extraction was proposed for determining the aging effect of the welded material at particular locations.

Chapter 1 Introduction

Key ideas

1.1. Background information and motivation

1.2. Problem Statement

1.3. Aim of Research

1.4. Objectives

1.5. Relevance to National Needs

1.6. Advantages

1.7. Area of Application

1.1 Background and motivation

Welding is an essential manufacturing process of repairing or creating metal structure by joining the pieces of metals. Welding process is performed in almost every major industry because the products and structural stability mainly depends on it. The philosophy that often guides “Without welding there would be no vehicles on the road and no buildings, machines, instruments would cease to exist”. There are approximately 35 different welding, brazing processes and soldering methods, are being used in the industry depending upon the structures and applications. There are various ways of classifying the welding processes, they may be classified on the basis of source of heat which depends upon material and conditions of application. Some most popular types of welding processes are mention here.

I. Arc Welding
II. Gas Welding
III. Resistance Welding
IV. Solid state Welding
V. Thermochemical Welding
VI. Radiant Energy Welding

The critical point, as far as the weld is concerned, is the “Quality of welding” which plays an important role for joining the parts of material or structures. Quality of weld can be tested using different methods and techniques. There are two basic approaches commonly used in industries to evaluate the quality of weld.

I. Destructive Testing (DT)
II. Non-Destructive Testing (NDT)

I. Destructive Testing:

Destructive test is the basic testing method where the test specimen is broken down to find its mechanical properties. Test objects are destroyed in this process. This technique is used for assessing the strength of material. These tests are generally easy and no requirement for high skill to operate its instrument. Some important destructive test used in the local workshop and manufacturing industries are mention below

a. Break Test
b. Tensile Testing
c. Hardness testing
d. Impact testing
e. Bend testing

II. Non-Destructive Testing:

Non-Destructive Testing (NDT) is considered as an important inspection method, which involves a group of analysis techniques, used in industries to characterize a material or system without damage. NDT is an industrial technique that help the Maintenance personal to examine the weld part without causing damage to it. The other uses of NDT technique are characterization of a material, flaw detection, lifecycle (Aging) and thickness gauging *etc*. The test produces accurate results with less investment and time. Some important types of NDT processes are mentioned below which are based on a particular scientific principle.

a. Eddy Current Technique (ECT)
b. Magnetic Flux Leakage (MFL)
c. Magnetic Particle Technique (MPL)
d. Ultrasonic Testing (UT)
e. Laser Technique (LT)
f. Radiographic Technique (RT)

1.2 Problem Statement

It has been reported that most of the weld joint failures occur because of thermal aging effect after long service life. These effects may become dangerous under critical weather as well as in different stress conditions [1]. Due to this reason the welding inspectors focus to ensure the integrity of welds. According to expert point of view, the inspection of welded material is very critical especially in term of aging factor prediction. Therefore, there is a need to evaluate (aging).

1.3 Aim of Research

Welded joints are tested using different Non-Destructive Testing (NDT) schemes such as Ultrasonic Testing (UT). Therefore, the aim of the research is to evaluate the aging effect on welded joint specimen by using advance signal processing technique, because it plays a vital role to prevent the unexpected failures of welded joints. It also enables maintenance personnel to plan preventive actions well in time and reduce the machine down time.

1.4 Objectives

The NDT Center of PNEC NUST has been continuously involved in the development of NDT for weld and pipeline gauge inspection to enhance the quality of testing and safety of the material. The proposed study will be helpful to evaluate the aging effect on the welded material using advanced signal processing techniques.

1.5 Relevance to National Needs

The inspection of aging effect on weld joints is very important in the industries because the structural stability mainly depends on it; if weld joints fail often the complete structure fails.

M/s. Sui Southern Gas Company (SSGC), M/s. Pakistan State Oil (PSO) and M/s. Pak Arab Refinery Ltd. (PARCO) operate their businesses in the southern provinces of Pakistan with a transmission and distribution pipeline network systems. They need to check the quality and life of weld joints for pipeline network in the critical weather and stress conditions.

As per international practice/recommendations oil and gas pipelines and weld joints should be inspected at an interval of 5 years using the latest technology available and advanced procedures. NDT technique is also used by different industries of Pakistan; such as:

a. Civil Airline and Airforce industries
b. Maritime Services and Pak Navy
c. Pipeline inspection
d. Railway
e. Pakistan Steel Mill
f. International Industries Limited (IIL)
g. Peoples Steel Mill

1.6 Advantages

Quantification of aging effect will not only help to develop confidence on the strength of alloys and material but also help to acquire other mechanical properties. In addition, aging factor evaluation helps to prevent unexpected failures of metals. UT can be used to test thickness and length up to 30 feet, these tests would be highly accurate in combination with advanced signal processing tools for determining the lifecycle (aging) more accurately *etc.*

The depth of penetration for measurement is excellent as compare to other NDT methods. It is nonhazardous for operators and does not affect the testing material.

1.7 Areas of Application

Lots of public organization as well as private sectors are involved in the NDT inspection of weld joints according to international standards and specifications. Transportation of liquids or gases through metallic pipelines, ship building department, aircraft manufacturing, heavy mechanical industries, metallurgy, fabricators, tools and dies industries, chemical and biomedical industries *etc*. are the potential areas of its application.

Chapter 2 Literature Review

Key ideas

2.1. Previous Work

2.1.1. Non-Destructive Testing (NDT)

2.1.2. Common NDT Techniques and their Applications

2.1.3. Evaluation of Artificial Aging through Hilbert Huang Transform (HHT)

2.1. Previous Work

NDT is an inspection process which involves a group of analyses techniques used in industries to characterize a material or system without damage [2]. This type of testing is an economically reasonable technique being used for material inspection. NDT testing is a quality assurance tool that helps to determine safety and reliability of the product [3-4].

2.1.1. Common NDT Techniques and their Applications

Most widely used NDT technique is Ultrasonic Testing through Pulse Echo scanning method. The technique also requires one sided surface preparation [5]. Using ultrasonic pulse echo technique, the attenuation of UT signal can be calculated and UT signal's behavior may be observed in different materials like Mild Steel (MS), Pearlitic Steel, Copper and many composite materials *etc*. In this technique, attenuation can be measured in both longitudinal and transverse directions. Mostly in the UT process, Pulse Echo Technique is being used with a 5 to 10MHz transducer depending upon the specimen specification [6]. The application of Pulse Echo UT includes corrosion testing, flaw detection, weld inspection, chemical exposure, bond inspection, material characterization, depth gauging, surface discontinuities, life (aging) *etc*. [7].

With the help of signal processing tools, UT can also be used as a strong method for predicting remaining useful life of materials during in-service inspection. Artificial Aging (life) through introduction of thermal stress to study the aging effect on the test specimen material [8]. Internationally the process of artificial aging is performed with the help of heat treatment [9]. Heat treatment is an industrial process used to alter the physical and chemical properties, which accelerate the aging effect in the artifacts. Generally, artifacts may be treated on different temperature in the control and calibrated environment within furnaces and ovens [10].

2.1.2. Signal Processing Techniques

Artificial aging can be evaluated by using different signal and data processing techniques. Generally, all traditional signal processing techniques or methods of data-analysis were based on linear and stationary assumptions. Unfortunately, in most real systems, it is not possible. Therefore, an engineering spectrum analysis tool Hilbert Huang Transform (HHT) was used to characterize the UT signals in most of the research work [11]. Applications of HHT include structural health monitoring, RADAR, characterization of under-water electromagnetic environment, meteorological and atmospheric applications *etc*. However, despite of some critical mathematical problems needed to be solved, HHT methodology is considered successful and used in different applications [12].

Some authors published their research on the application of HHT using different NDT techniques [13-14]. They have compared the performance of HHT with Chirplet Signal Decomposition (CSD) technique. They observed that HHT is an effective tool for dispersive echoes and ultrasonic signal analysis accounting for nonlinear signals. It is evident from the literature that the algorithm was successfully utilized for signal classification, flaw detection, pattern recognition and material degradation (remaining life) [15].

Lot of NDT researchers carried out their research on HHT theory, its applications and development. The background theory of HHT was also discussed and compared with other spectral analysis tools. Numbers of applications were used to demonstrate the capability for HHT to dissect and analyzed the periodic components of different oscillatory data and then a new algorithm was presented which expands HHT ability to analyze discontinuous data [16].

In this study, the HHT is utilized for the characterization of ultrasonic backscattered echoes and their performance has been estimated. Feature based extraction has been proposed for location in the Hilbert region.

Chapter 3 Theoretical evaluation

Key ideas

3.1. Introduction of Ultrasonic Testing

3.2. Advantages of UT Testing

3.3. Disadvantages of UT Testing

3.4. Data Representation

3.4.1. Amplitude Scan (A Scan representation)

3.4.2. B Scan Representation

3.4.3. C Scan Representation

3.5. Calibration Procedure

3.6. Interface of Ultrasonic Equipment and Data Format Analysis

3.7. Mild Steel E 6013

3.1. Introduction of Ultrasonic Testing

Ultrasonic Testing (UT) uses high frequency sound waves (0.5 to 15 MHz) to perform measurements. The working principle of ultrasonic testing is based on this fact the materials are good conductors of sound waves but, the waves are not only reflected at the end surfaces but also on any flaw in between them. Ultrasonic signal can be used to detect flaw in the material, crack, flaws growth evaluation, dimensional measurements, material characterization and useful life *etc*. There are two methods commonly used for receiving of ultrasound signals: i- reflection wave ultrasonic technique and ii- attenuation wave ultrasonic technique.

In reflection waves (or pulse-echo) mode, UT consists of only one probe transducer (transmitter/receiver) and a display device. A transducer is an electronic device that can produce/receive electrical pulses. Driven by the transmitter, the transducer generates high frequency ultrasonic energy. The ultrasonic energy is introduced and propagates in the form of waves. When there is a discontinuity (crack or any flaw) in the wave path, part of the energy will be reflected from the flaw surface. The reflected energies are transformed into an electrical signal by the transducer and displayed on a screen shown in Figure 3.1. Remaining part of ultrasonic energies will be reflected from the backwall surface and it's called backwall echo.

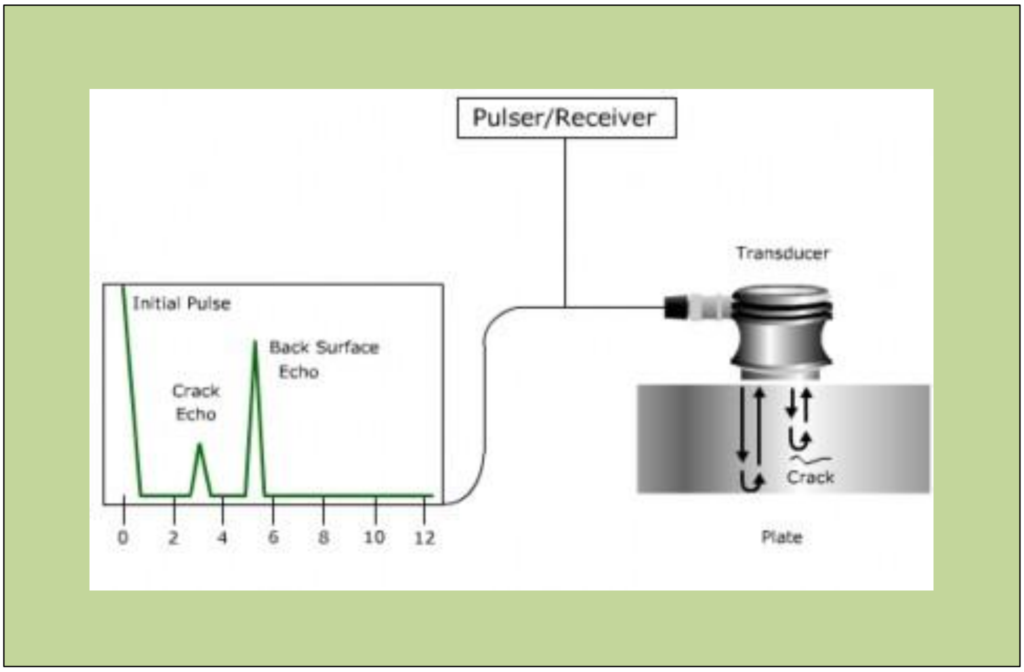

Figure 3.1: Pulse Echo UT

A transmitter sends ultrasonic signals in attenuation (Through-transmission) mode through one surface, and another separate receiver detects reflected signals from back wall after traveling through the medium. Generally, Couplant jell is used between the ultrasonic probes (transducers) and test specimen to increases the efficiency of the UT process by reducing the losses in the ultrasonic wave energy due to separation between the surfaces shown in Figure 3.2

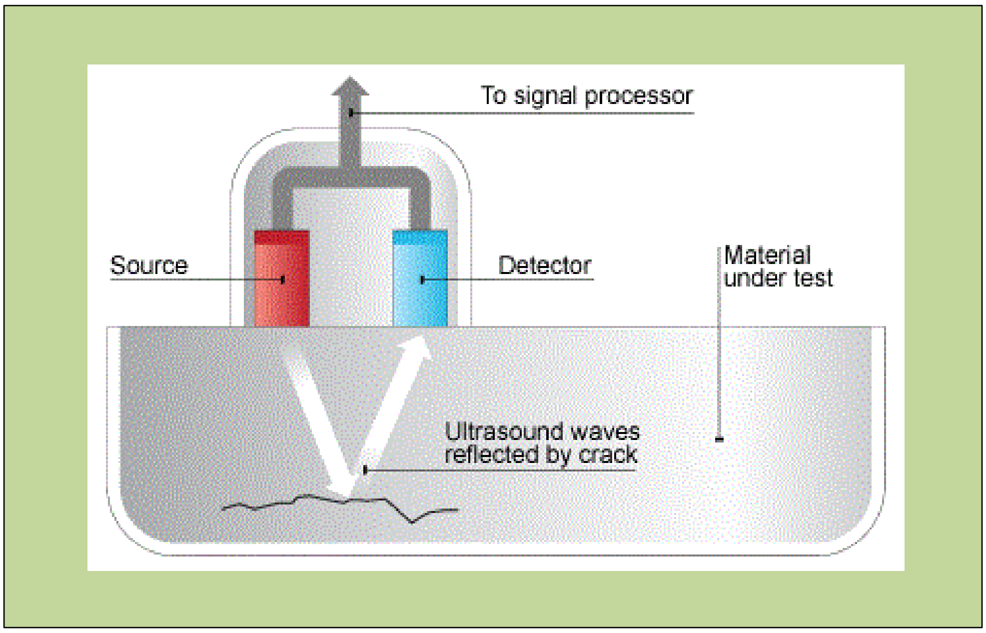

Figure 3.2: Two Probe UT Testing

3.2. Advantages of UT Testing

The principal advantages of UT testing over other NDT methods are:

- It is sensitive to surface and subsurface (cracks/flaws)
- The depth of penetration for flaw detection or measurement is excellent as compare to other NDT methods.
- single-sided access is required when the pulse-echo technique is used (simplicity).
- It is highly accurate in determining crack position and estimating size and shape.
- Minimal part preparation is required (fast processing).
- It is nonhazardous to operators (Safety).
- Test Objects are not destroyed during process.
- Its equipment can be highly portable and cost effective.

3.3. Disadvantages of UT Testing

Some disadvantages of UT testing are described below:

- Restriction in material for UT testing (accessible to transmit ultrasound wave).
- High level of skill and training required as compare to other NDT methods.
- Rough materials, irregular in shape, thin or not homogeneous are difficult to inspect.
- Cast iron and other coarse grained materials are difficult to inspect because of low signal transmission and high level of noise .
- Linear defects oriented parallel to the sound beam may go undetected.
- Reference standards are required for calibration and flaws characterization.
- Calibration certificate is also required with the UT instrument from the manufacture or accredited calibration/testing laboratory.

3.4. Data Representation

Ultrasonic data can be displayed in different type of formats. The three most common formats are listed below:

1. A-scan presentation
2. B-scan Presentation
3. C-scan presentation

The above presentation mode provides a different way of viewing and evaluate the region of inspection depending upon the nature and condition of test.

3.4.1. Amplitude Scan (A Scan representation)

The A-scan representation, the received ultrasonic signals treated as a function of time. The received UT signal is plotted along with the elapsed time (which depends upon the traveled distance). The A-scan is also called one dimensional presentation of ultrasonic signal amplitude with respect to time. The vertical axis displays the ultrasonic signal amplitude while the horizontal axis is the time taken by the ultrasound energy to travel within the material.

3.4.2. B Scan Representation

The UT B-scan presentation is a linear scanning system which represents a cross-sectional view (Two-dimensional representation) of the test specimen. In this case, the time-of-flight of the ultrasonic sound energies are displayed along the vertical axis and the position (distance) of the transducer is displayed along the horizontal axis.

3.4.3. C Scan Representation

This presentation is a two-dimensional ultrasonic scanning systems that provides a plan-type view of the position and size of test specimen. The plane of the image is parallel to the scan pattern of the transducer. The C-scan presentation provides a critical view of the features that reflect and scatter the sound wave within and on the surfaces of the specimen. It is high resolution ultrasonic scanning system which produced very comprehensive images.

3.5. Calibration Procedure

Calibration is required in almost all electronic instrument for their precision and accuracy. According to ISO procedure, Manufacturers generally recommend calibration once in a year from accredited calibration lab because the calibrated equipment are used for testing due to authenticity of the results [17]. There are few accredited laboratories in Pakistan which does this type of calibration like PCSIR and NPSL Islamabad. For ultrasonic testing calibration process is essential requirement before conducting the test. At the start of experimental work, the operator must know the depth (thickness) of the specimen to be inspected. Secondly the sound velocity of the material should be known. Change and set the parameter according to the test requirement. Calibration blocks are provided with each flaw detector to calibrate the range of depth before each inspection for depth measurement. The ultrasonic setup is sensitive to environmental conditions such as heat, dust, humidity *etc*. [18]

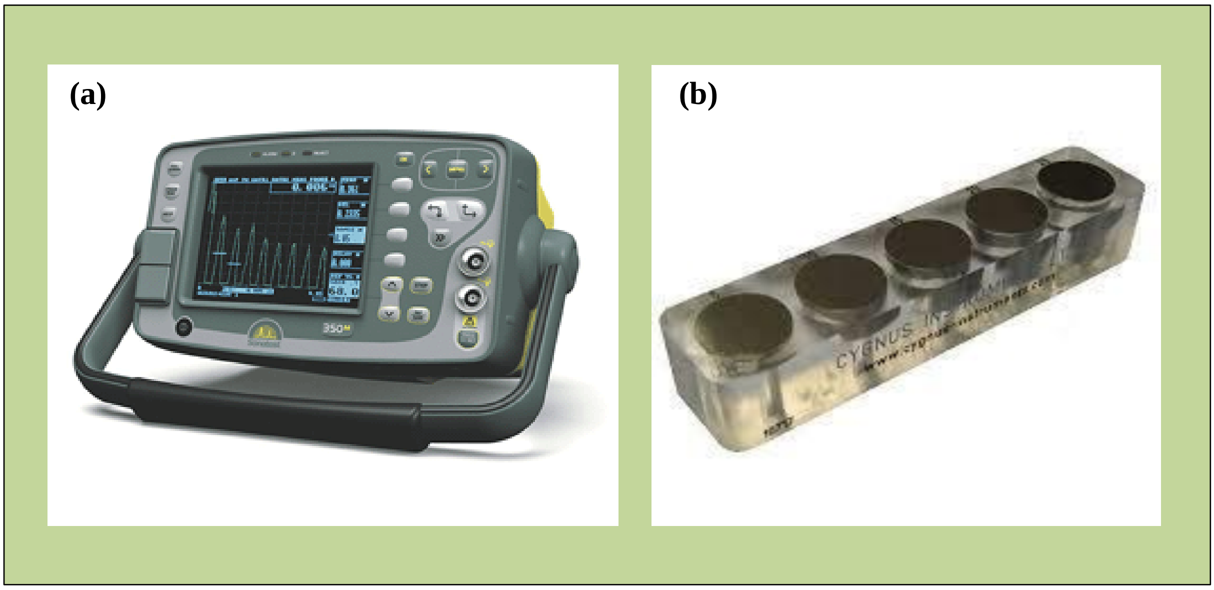

Figure 3.3 (a): Ultrasonic test instrument (b): Calibration Block

3.6. Interface of Ultrasonic Equipment and Data Format Analysis

Master Scan 350 M is used for ultrasonic testing. Calibration block and different type of sensor probes are the accessory parts with this instrument. Master scan UT is easily interfaced with computers. Operators can extract and read the data format for further analysis. Sonatest Data Management Software is used to extract the data from equipment using serial port of the terminal, acquired data may be saved in the following three formats:

i. .dat type file,

ii. .csv file, and

iii. .dfd type format.

.dat type format for algorithms development was used during this study. In the data file there were 5 header lines which give the test parameters information and 255 data lines which provide the amplitude of the UT signals.

3.7. Mild Steel E 6013

The electrode used in this proposed study is Mild Steel E-6013 with a 10 SWG. E-6013 relates to AWS2 standard which is a code that describes about the type of coat, current etc. It is a four or five digits code and each digit refers to a property.

Table 3.1: AWS Classification

E	+	+	+	*	-
		+	+	*	-

where

+ indicates the maximum UTS in psi (for e.g., E 60** has UTS of 60 000psi)

* indicates welding position (flat, horizontal, vertical and overhead)

– indicates the coating and current

E-6013 electrode can be used in all welding process with AC and DC (straight or reverse polarity). It is a general-purpose electrode which is preferred over 6012 electrodes because of its bead surface and less spattering. The slag is thin and easily removable. It is mainly used for repair maintenance of large ship, tanks, sheet metals, machine guards, storage tanks and general light fabrication etc. (20). The chemical composition of MS E 6013 is described in Table 3.2:

Table 3.2: Chemical Composition of Mild Steel E 6013

Elements	Composition (%)
Carbon	0.12
Manganese	0.50
Silicon	0.30
Phosphorus	0.13
Sulphur	0.09

SWG = Standard Wire Gage; higher the number, thinner the electrode.
AWS = American Welding Society

Chapter 4. Experimental Work

Key ideas

4.1. Design of Experiment

4.1.1. Sample Preparation

4.1.2. Heat Treatment (Artificial Aging)

4.1.3. Surface Preparation

4.1.4. Ultrasonic Testing

4.1.5. UT Data Representation

4.1.6. Equipment Used for Experimental Setup

4.1. Design of Experiment

In this research, ten (10) Mild Steel (MS) samples have been prepared with a thickness of 11mm for artificial aging on weld specimen. For welding electrode, the selected material is Mild Steel E 6013. It is a general-purpose electrode used in fabrication, repair maintenance *etc*. Each sample is welded by a single operator and on the same day to ensure that the process has least amount of errors. The selection of electrode is depended upon the thickness of test material. The samples are then heat treated in a furnace from 100 to 1000 °C. During the process, we need to alert the Melting point for the electrode ranges from 1375-1425 °C. After artificial aging and annealing process, Ultrasonic signals were observed with the help of Master scan UT Flaw Detector.

During the welding and UT process, the ambient conditions were kept constant for all samples. Adopted all necessary steps of experiment have been taken as per guideline and standard method of aging techniques. The step-wise experimental work is as appended below:

4.1.1. Sample Preparation

The electrode material used for this research was Mild Steel (MS) E 6013. Two rectangular pieces of base material Mild Steel (MS) with a thickness of 11mm were joined in the form of a lap joint (Figure 4.1). Arc welding was used for joining base material. Ten SWG (Standard Wire Gauge) electrodes were used, which is depending upon the thickness of base MS material. The samples were then grinded to prepare the surface for UT examination.

Figure 4.1: Lap joint Weld sample

4.1.2. Heat Treatment (Artificial Aging)

Normally aging effect that occurs at room temperature is stated as natural aging. Due to weathering or different stress condition, aging process can be clearly seen on the material. Artificial aging is the lab scale treatment of a metal with the increasing of temperatures to accelerate the changes in the properties of material as the result of casting and forging process. Artificial aging will speed up this change more speedily at high temperatures. Artificial aging is performed under controlled conditions. This artificial process ensures the ideal quality and accuracy in close tolerance specifications as per guidelines. It also helps manufacturers and other testing companies to calculate the machinery and electronics parts life.

As per standard procedure, the ten samples of welded material were heat treated on different temperatures which ranging from 100°C to 1000°C with a step of 100°C on each sample. The time of heating process is one hour for all samples. For this test, a calibrated furnace is used to control temperature stability. They were then air cooled to stop the aging process [19].

4.1.3. Surface Preparation

Ultrasonic testing is very sensitive to the surface conditions. Ultrasonic testing required the surface to be smooth and free from burs. In order to prepare the surface, the samples were grinded both manually and through a grinder-polisher machine using silicon carbide paper with grit size ranging from 400µ, 600µ and 1000µ, respectively using water.

4.1.4. Ultrasonic Testing

Ultrasonic testing was performed using digital Ultrasonic flaw detector SONATEST Master Scan 350 with pulse-echo technique. This technique is popular as it only requires one-sided access to the inspected object. In this case the transmitter/receiver (Tx/Rx) are placed on the same surface of the samples and back wall echoes are observed. The same transducer was used for transmission and receiving. Glycerin was used as a coupling agent between the UT probe and welded material surfaces. 5MHz longitudinal beam probe was used to determine the ultrasonic data acquisition. The ultrasonic velocity was calculated for the sample at zero degrees and was set at 5920m/s for all the heat-treated samples. The data was recorded using 200V input with full wave scan mode. Manually constant pressure was applied on the specimen via probe by a single operator under similar conditions [20].

4.1.5. UT Data Representation

A-Scan ultrasonic signals representation, welded specimen treated at 100°C is shown in Figure 4.2.

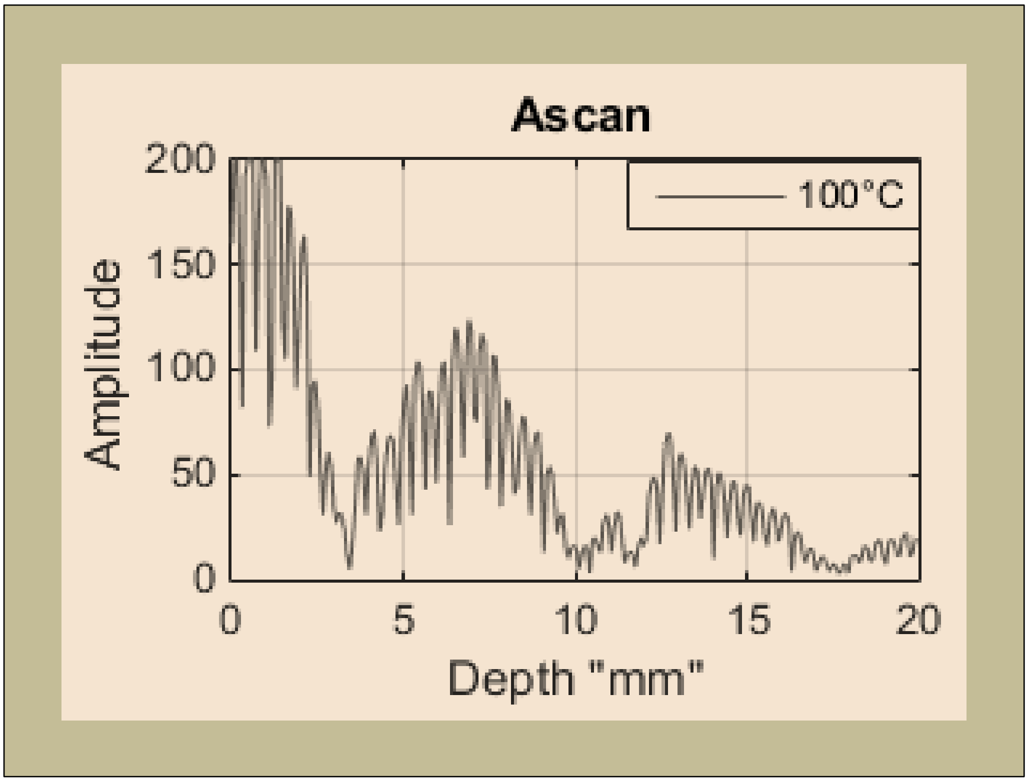

Figure 4.2: A-Scan Ultrasonic Signals

The X-axis of the graph shows the value of thickness (Distance) and Y-axis represents the amount of amplitude of UT signals. Similarly figure 4.3 shows a comparative view of A-scan Ultrasonic Signals of ten samples treated at different temperatures ranging from 100- 1000°C. The Legend in the graph shows the temperature at which the sample was treated. These UT signals were first acquired from the equipment using Sonatest Data Management Software (SDMS) in the computer system and then further analyzed it with the help of advanced signal processing technique using MATLAB.

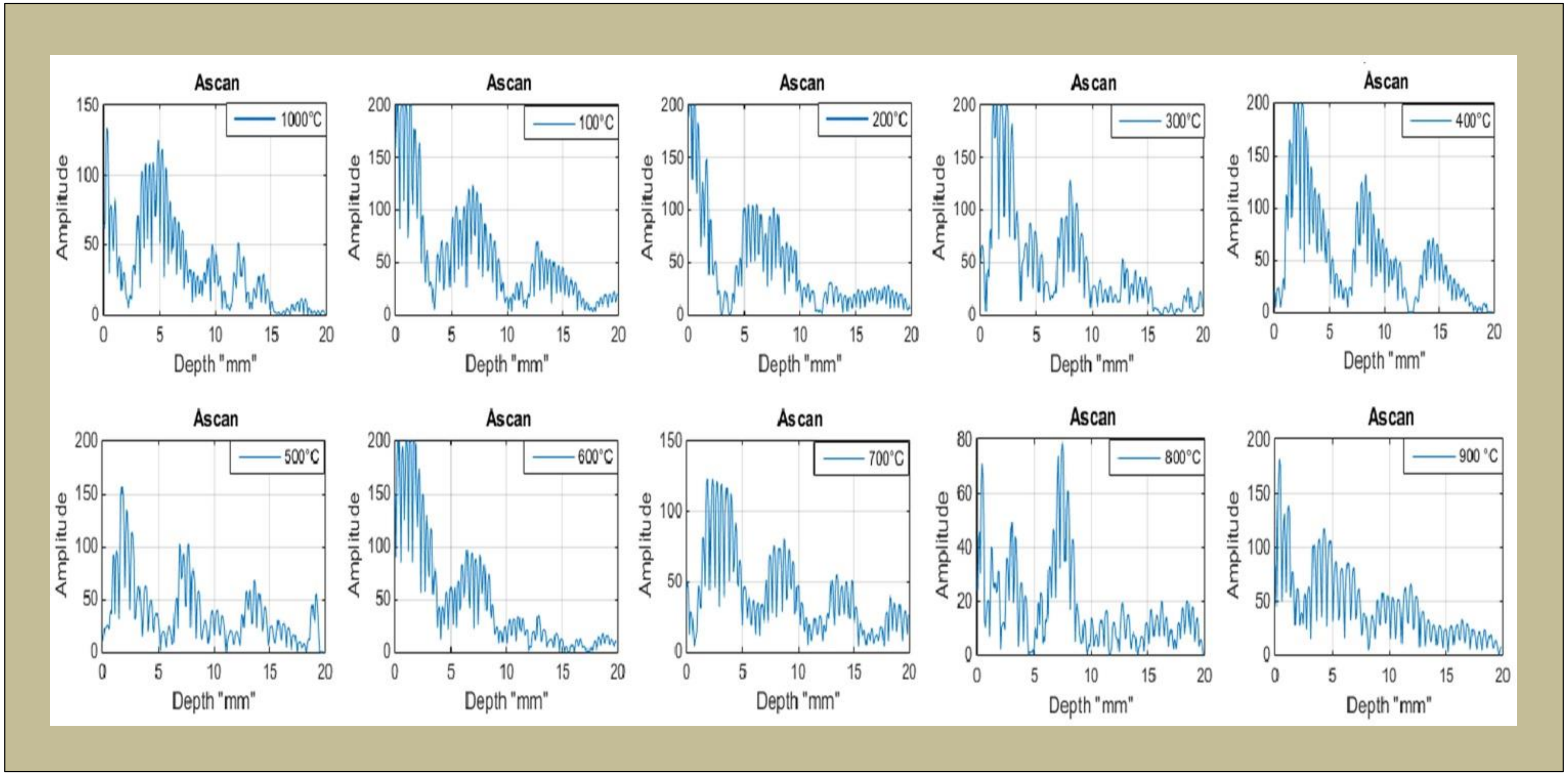

Figure 4.3: A-Scan Ultrasonic Signals of ten samples treated from 100 – 1000 °C.

4.1.6. Equipment Used for Experimental Setup

The following equipment were used during experimental work:

i. Furnace
ii. Grinder polisher machine
iii. Ultrasonic flaw detector
iv. SDMS software / MATLAB
v. Glycerin jell
vi. Sonatest Master Scan 350 flow Detector
vii. 5 MZ transducer UT Probe
viii. Electrode (E-6013), 10 SWG

Chapter 5. Methodology HHT

Key ideas

5.1. Introduction

5.2. Empirical Mode Decomposition (EMD)

5.3. Hilbert Huang Transform (HHT)

5.1. Introduction

Varies signal Transformation technique are used for analysis of signal or data in frequency domain. Frequency domain representation gives insight look of the time domain signal or raw signal resulting in some meaning full conclusion. Time domain signals are also called as raw signals due to very less information about the acquired signal being observed. therefore, it is not an easy task to get information about abrupt changes and small discontinuity etc. when considering time domain signals [21].

The Hilbert Huang transform (HHT) was motivated by nonlinear and nonstationary distorted signals, with the variations that naturally occur. All traditional signal processing techniques or data-analysis method were established on linear and stationary assumptions. Unfortunately, in real systems, it's not possible. Data may be nonlinear and nonstationary. These signals cannot be evaluated easily by applying FFT, Wavelet or any other signal processing tool.

Hilbert Huang Transform, was proposed by Professor Huang *et. al.* [22], for non-linear and nonstationary signal analysis. The Hilbert–Huang transform (HHT) is an empirically based data-analysis. Its basis of expansion is adaptive, HHT can produce physically meaningful representations of data from nonlinear and non-stationary processes. The HHT has been presented in the applications of health monitoring systems, medical imaging systems, RADAR, under-water communication, life prediction of material (material degradation) and weather condition analysis *etc*. The HHT comprises of two basic processing components, Empirical Mode Decomposition (EMD) and Hilbert Spectrum Analysis (HAS).

5.2. Empirical Mode Decomposition (EMD)

EMD is an essential data processing method that is undertaken before applying Hilbert transform. As compared to the other signal processing techniques, EMD defines oscillations, which are both nonlinear and nonstationary, more efficiently. The main objective of the EMD is to decompose the acquired signals into a set of simpler signals mode are called Intrinsic Mode Functions (IMF). This process is called sifting process, which satisfied the two following necessary condition:

1) The number of zero-crossing and the number of extreme in the entire data must either equal or differ at most by one in the test signal.

2) The mean value of the local extremes in the signal envelope is zero.

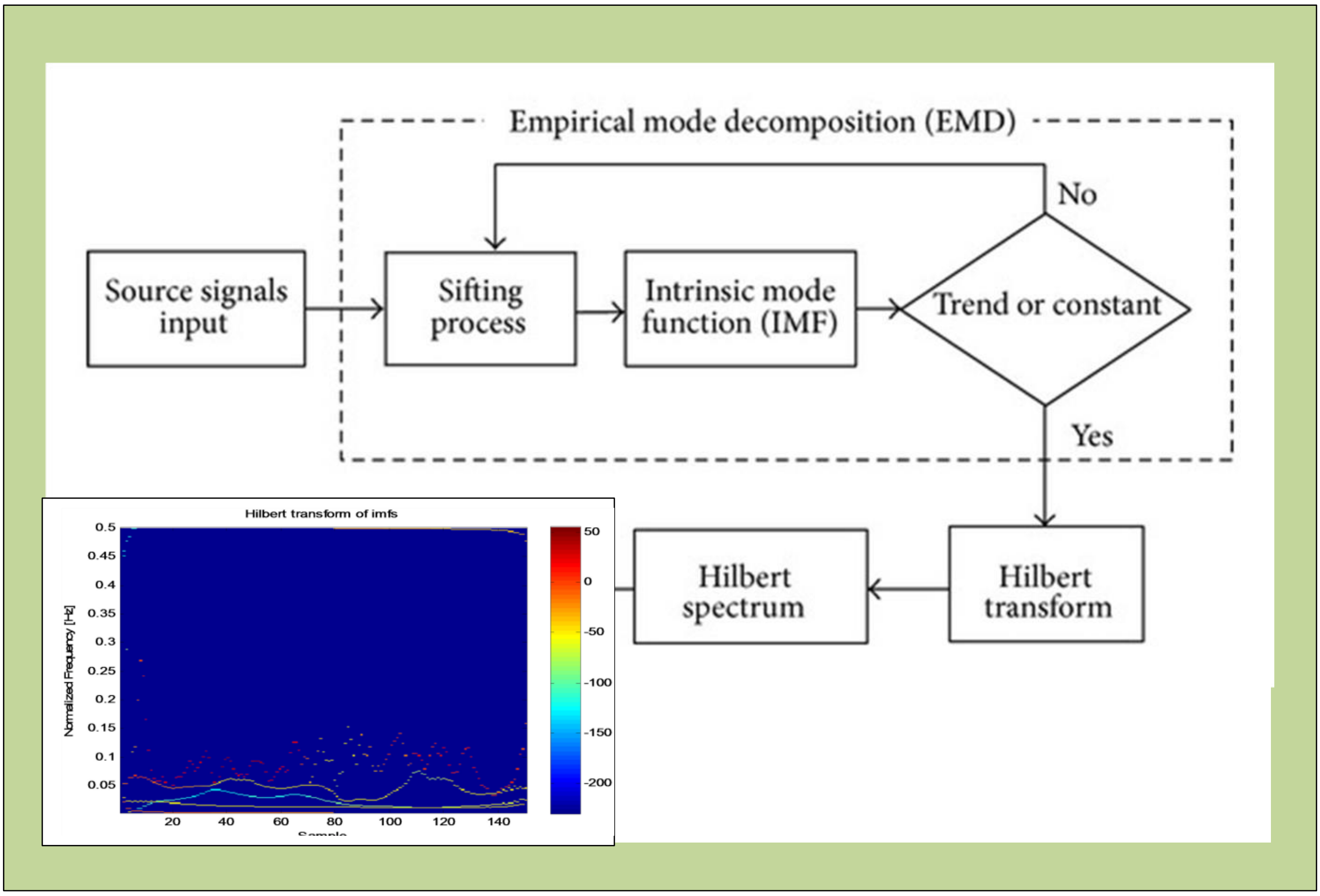

Figure 5.1: Flow graph for Hilbert Huang Transform Process

A real signal X(t) in time Domain, step wise application of EMD to compute the IMFs is a well-known technique; however, the technique is described here for better understanding of the readers.

EMD is applied as follows to obtain a set of IMFs:

1) Identify all the Extreme (maxima and minima) of the acquired UT signals by applying find peak algorithm;

2) Upper and lower envelops are generated on the UT signals as $e_{min}(t)$ and $e_{max}(t)$, by using cubic spline interpolation on the UT signal;

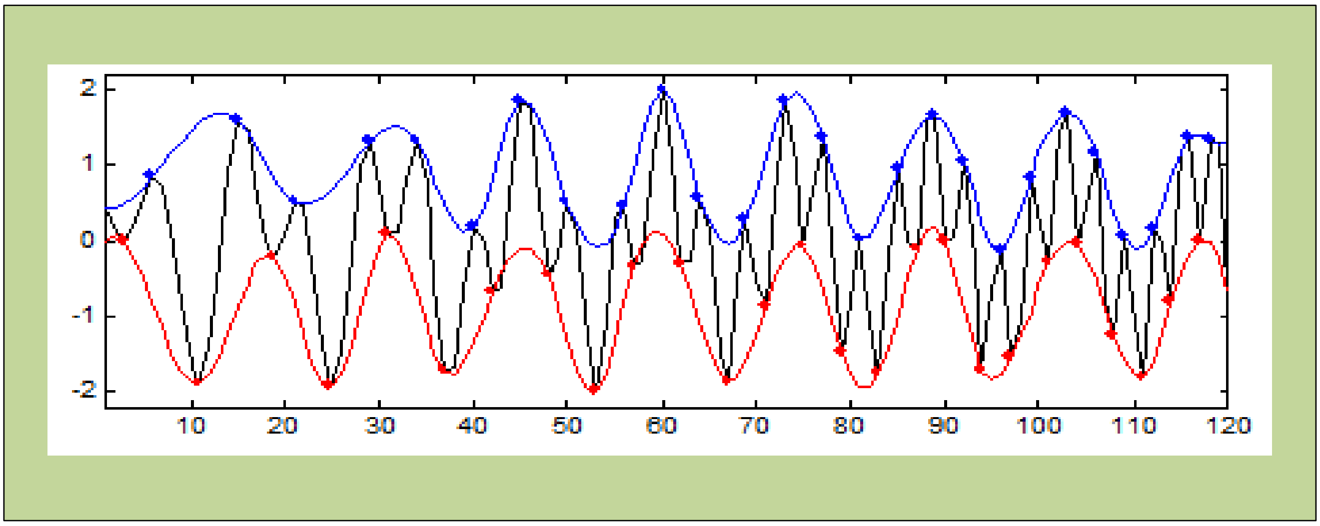

Figure 5.2: Upper and Lower envelope on UT

3) The mean value of the local maxima and local minima is calculated using eq. (1);

$$m_1(t) = \frac{e_{max} + e_{min}}{2} \qquad (1)$$

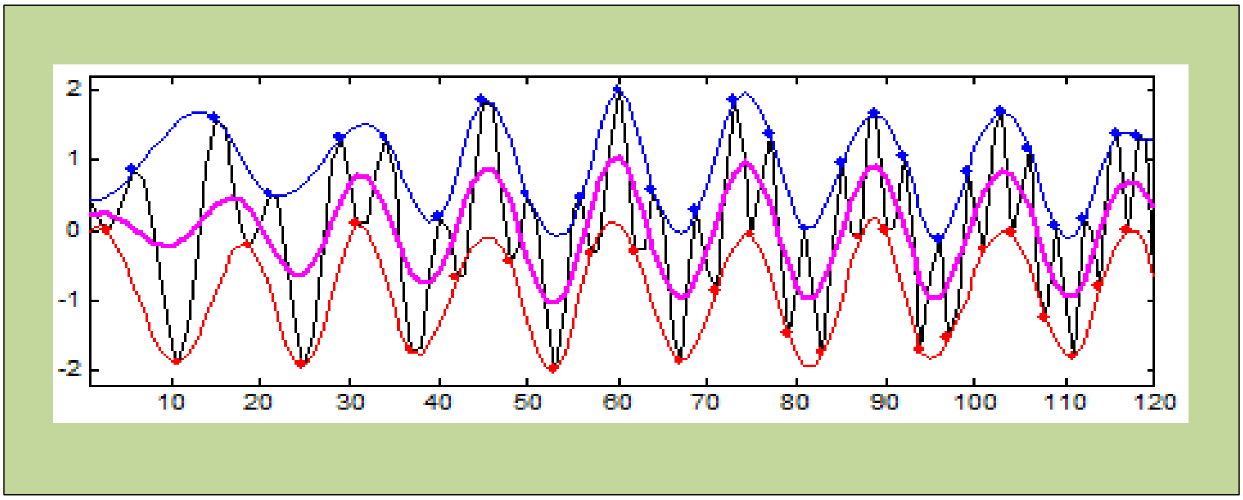

Figure 5.3: The mean value of the local maxima and local minima

4) The resulting value so computed is subtracted from the given time domain signal;

$$h(t) = X(t) - m_1(t) \qquad (2)$$

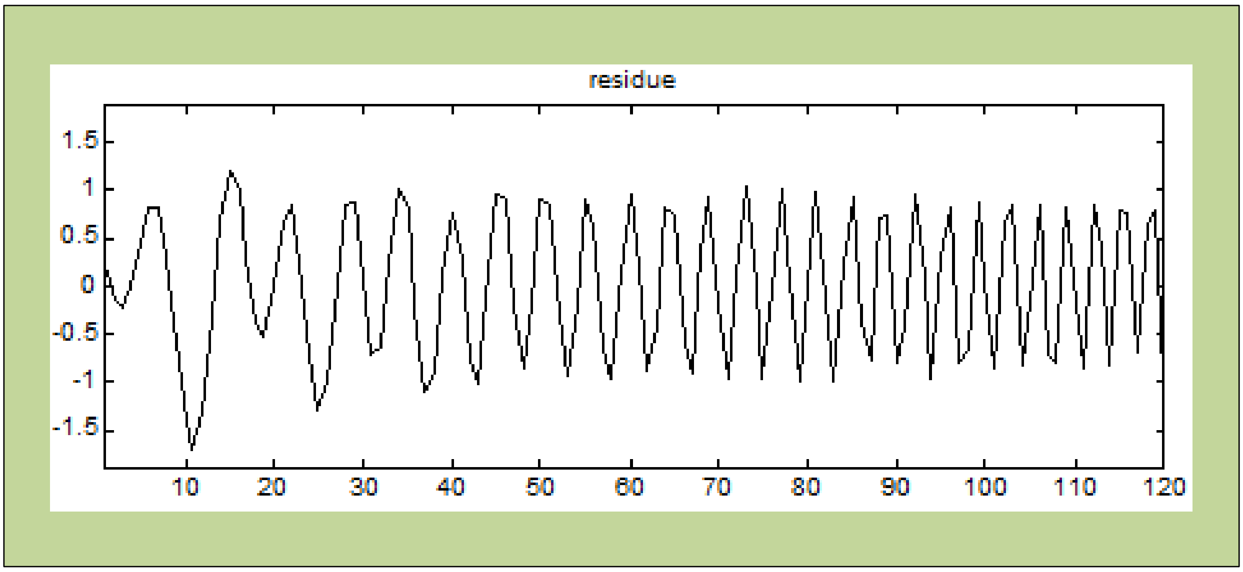

Figure 5.4: The resultant UT signals

5) The IMF conditions (mentioned above) for the computed signal $h(t)$ are investigated against the IMF conditions.

If the conditions are satisfied, step 6 is executed; otherwise steps 1 to 5 are re-executed.

6) If conditions satisfy, denote $h(t)$ as an $i^{th} IMF$ $c_i(t)$

$$r(t) = X(t) - h(t) \qquad (3)$$

The residue signals $r(t)$ still contains longer period variations;

7) The above mentioned sifting process is repeated until the stopping criterion is satisfied by the residual $r(t)$. The stopping criterion is used to verify that the signal is monotonic.

The signal $X(t)$ is finally expressed as:

$$X(t) = \sum_{i=1}^{n} c_i(t) + r_n(t) \qquad (4)$$

5.3. Hilbert Huang Transform (HHT)

The Hilbert transform is then applied on each computed IMF component to determine the respective amplitude and instantaneous frequency using

$$H[c_i(t)] = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{c_i(\tau)}{t-\tau} d\tau \qquad (5)$$

The analytic signal $z_i(t)$ corresponding to $i^{th} IMF$ is expressed as

$$z_i(t) = c_i(t) + jH[c_i(t)] \qquad (6)$$

The analytic signal can be transformed into polar coordinate system using eq. (7)

$$z_i(t) = a_i(t) e^{j\int \omega_i(t) dt} \qquad (7)$$

The phase and amplitude of the analytic signal are then computed.

$$a_i(t) = \sqrt{[c_i(t)]^2 + [H\{c_i(t)\}]^2} \qquad (8)$$

The instantaneous frequency can now be defined as

$$f_i(t) = \frac{1}{2\pi} \omega_i(t) = \frac{1}{2\pi} \times \frac{d\theta_i(t)}{dt} \qquad (9)$$

$$\theta_i(t) = \tan^{-1} \frac{H[c_i(t)]}{c_i(t)} \qquad (10)$$

Finally, the HHT spectrum is computed using eq. (11)

$$H(w,t) = \mathrm{Re} \sum_{i=1}^{n} a_i(t) \exp(j \int w_i(t) dt) \qquad (11)$$

Re {.} denotes the real part of the complex form. Equation (11) represents the Hilbert spectrum in terms of amplitude and the instantaneous frequency.

Chapter 6. Hilbert Results and Discussion

Key ideas

6.1. Evaluation UT signals

6.1.1. Determination of IMFs using HHT

6.1.2. Time Frequency Analysis

6.1.3. Intelligent Features

6.1.4. Hilbert trend with respect to aging effect

6.1. Evaluation of UT signals

The purpose of the study is to evaluate the UT signal of welded zone MS material with the help of HHT in term of their life (Aging). Therefor after received the UT signal of the ten MS welded samples, which is treated by ten different temperatures applied within constant time, samples data are ready for signal processing. The step-wise details of further processing are as under:

6.1.1. Determination of IMFs using HHT

HHT was applied on A-scan UT data acquired from the test specimen. According to HHT theory, In the first step IMFs have been obtained by applying HHT using sifting process for all ten samples (method described in the previous chapter) shown in the figures 6.1 to 6.10. Total six (06) IMF are obtained from each A scan UT of the inspected samples. In the 7^{th} stage signal is converted into monotonic component which means signal cannot be broken and no more IMF can be extracted from the UT signals.

As shown in the graphs, time scale representation, on X axis, which is the thickness of the test specimen and on Y axis representation is denoted the amplitude of received UT signal. Legend of the graph shows the samples is treated on this specific temperature.

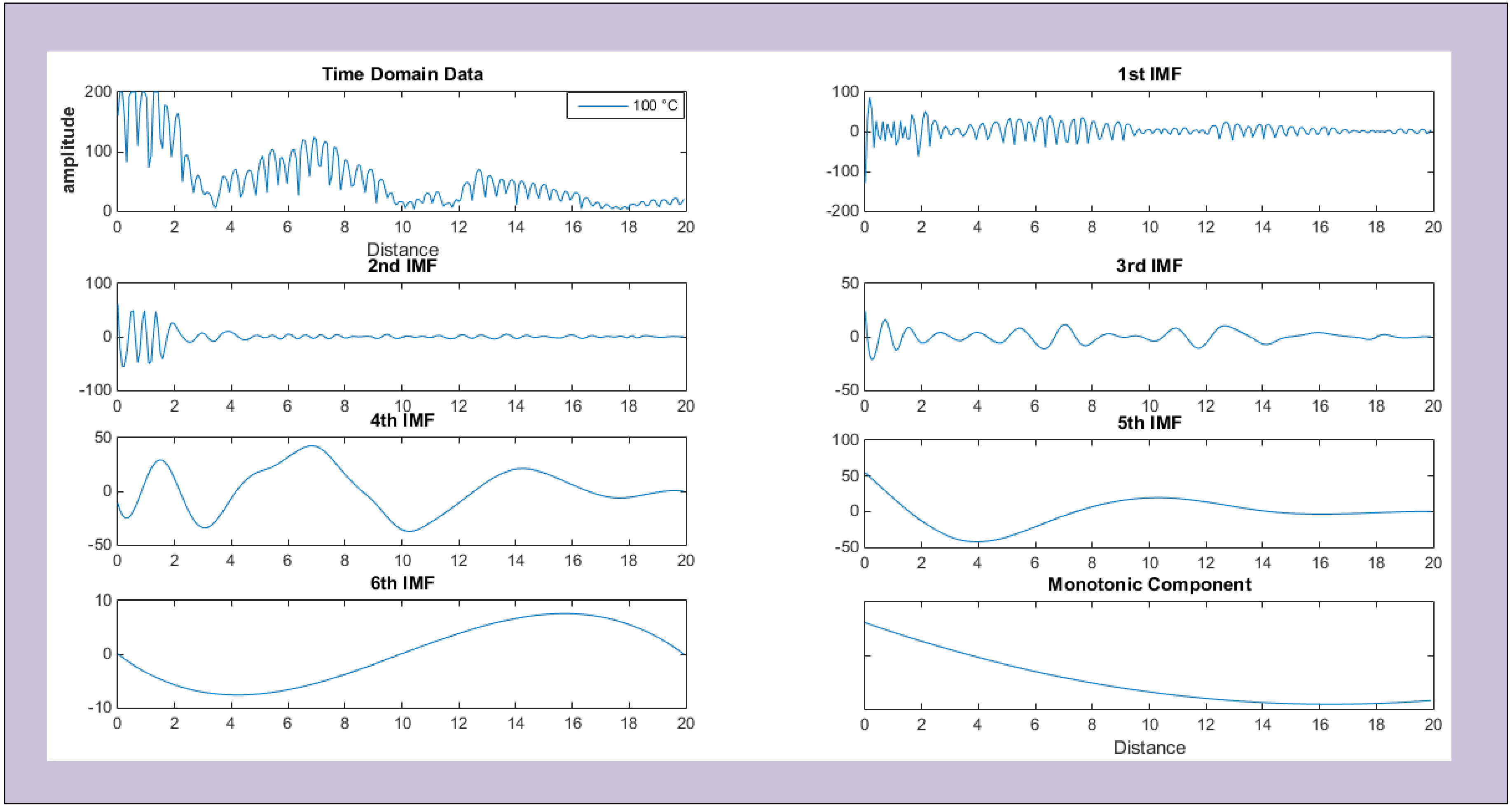

Figure 6.1: IMF for sample 1, treated at 100C

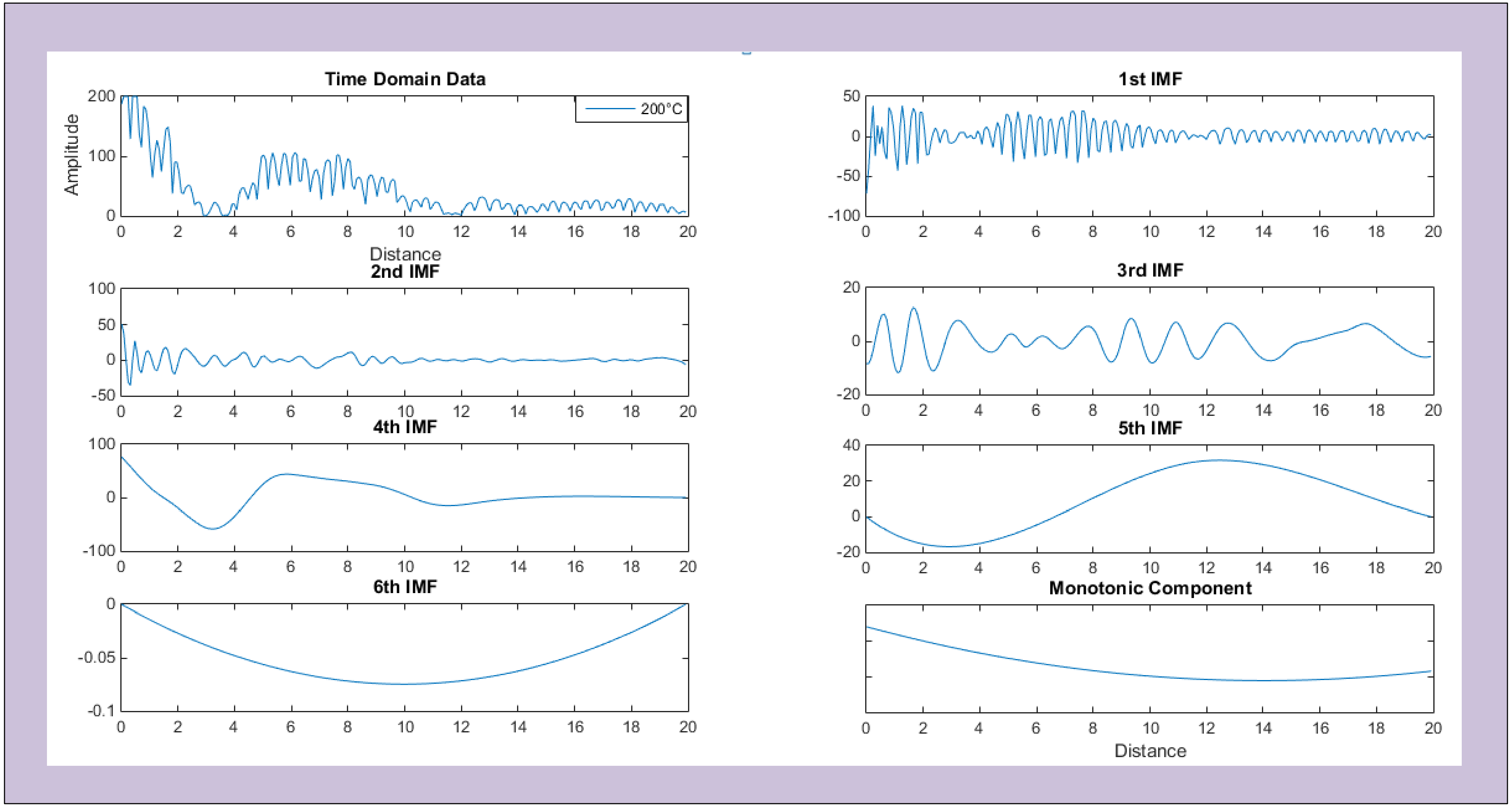

Figure 6.2: IMF for sample 2, treated at 200 °C

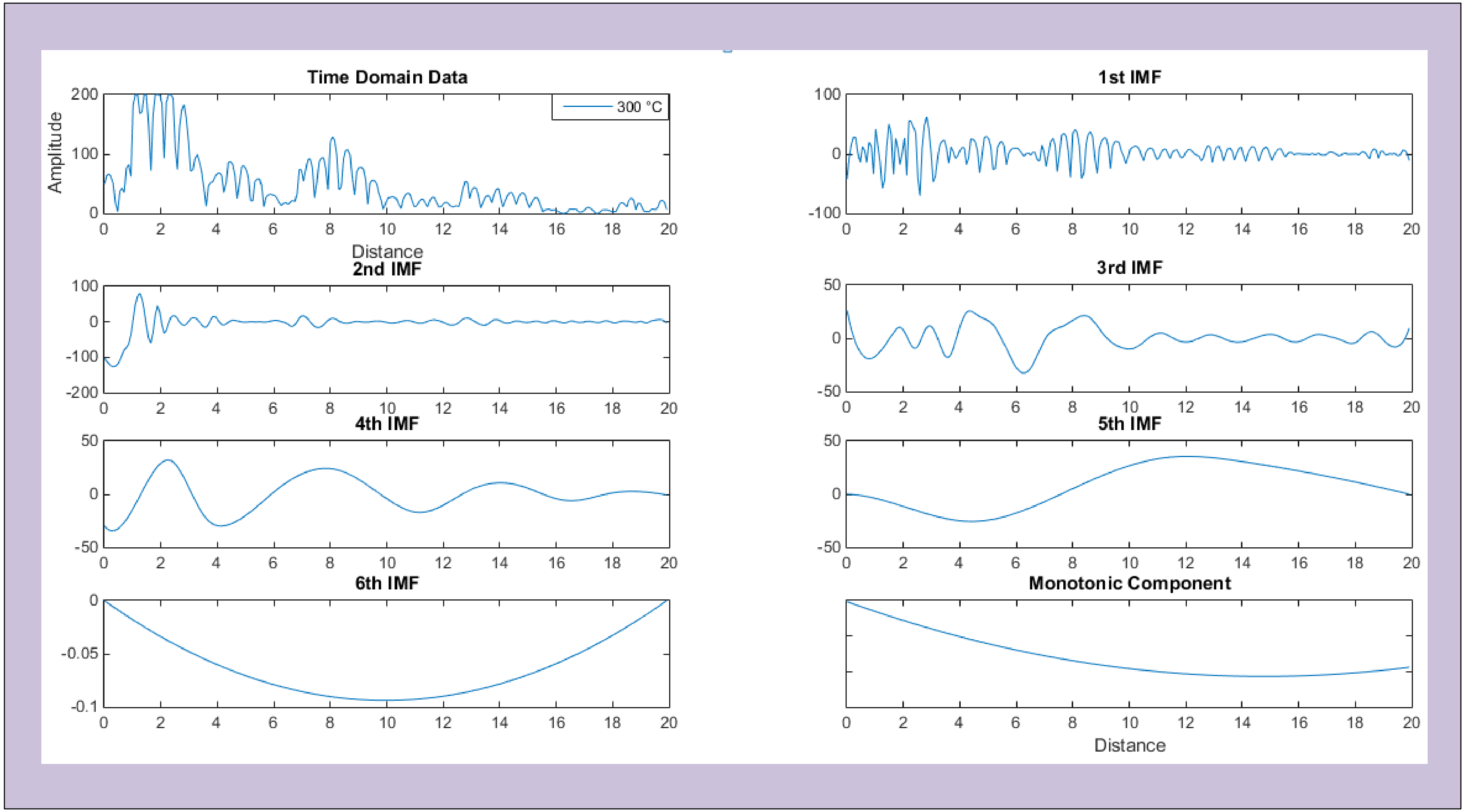

Figure 6.3: IMF for sample 3, treated at 300 °C

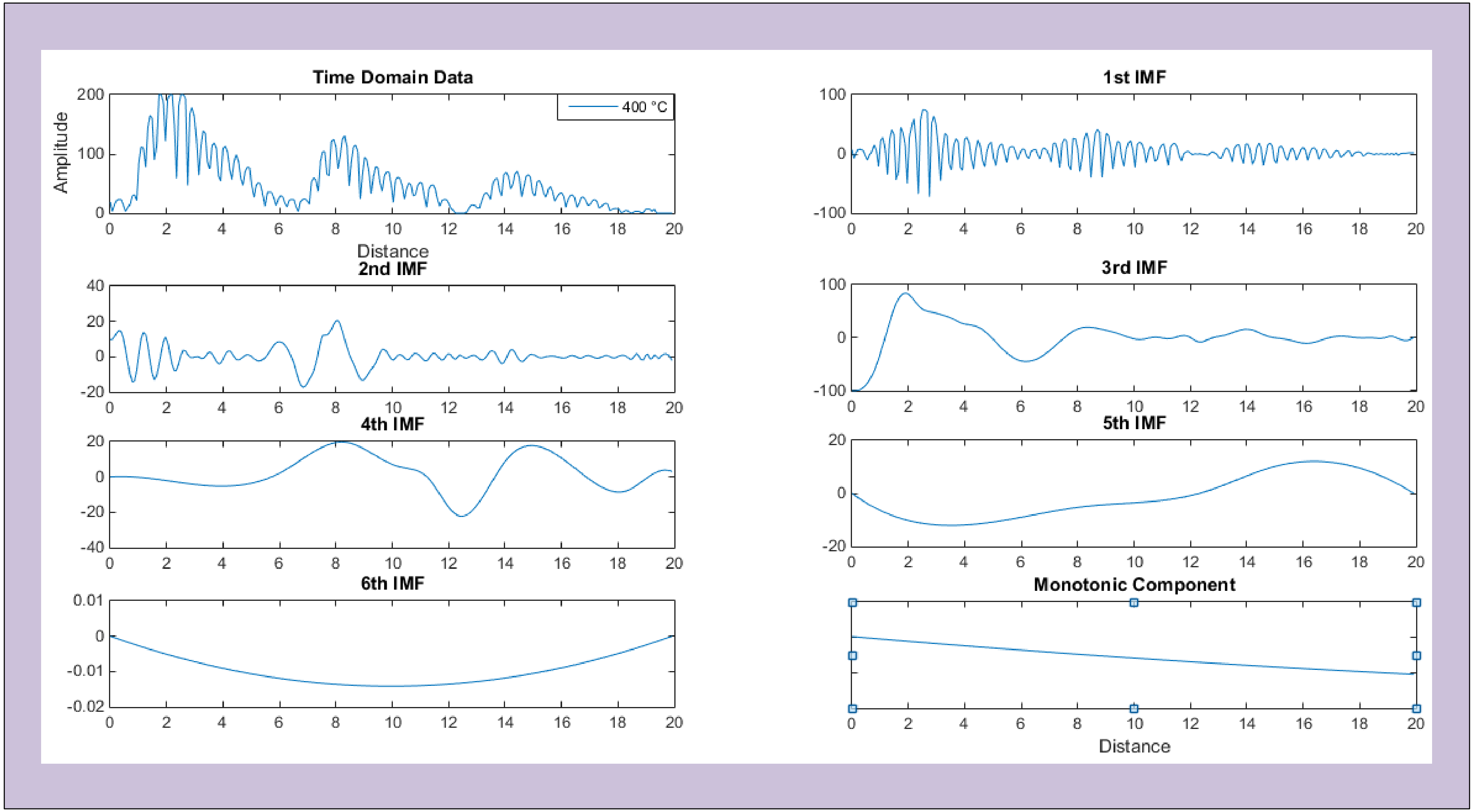

Figure 6.4: IMF for sample 4, treated at 400 °C

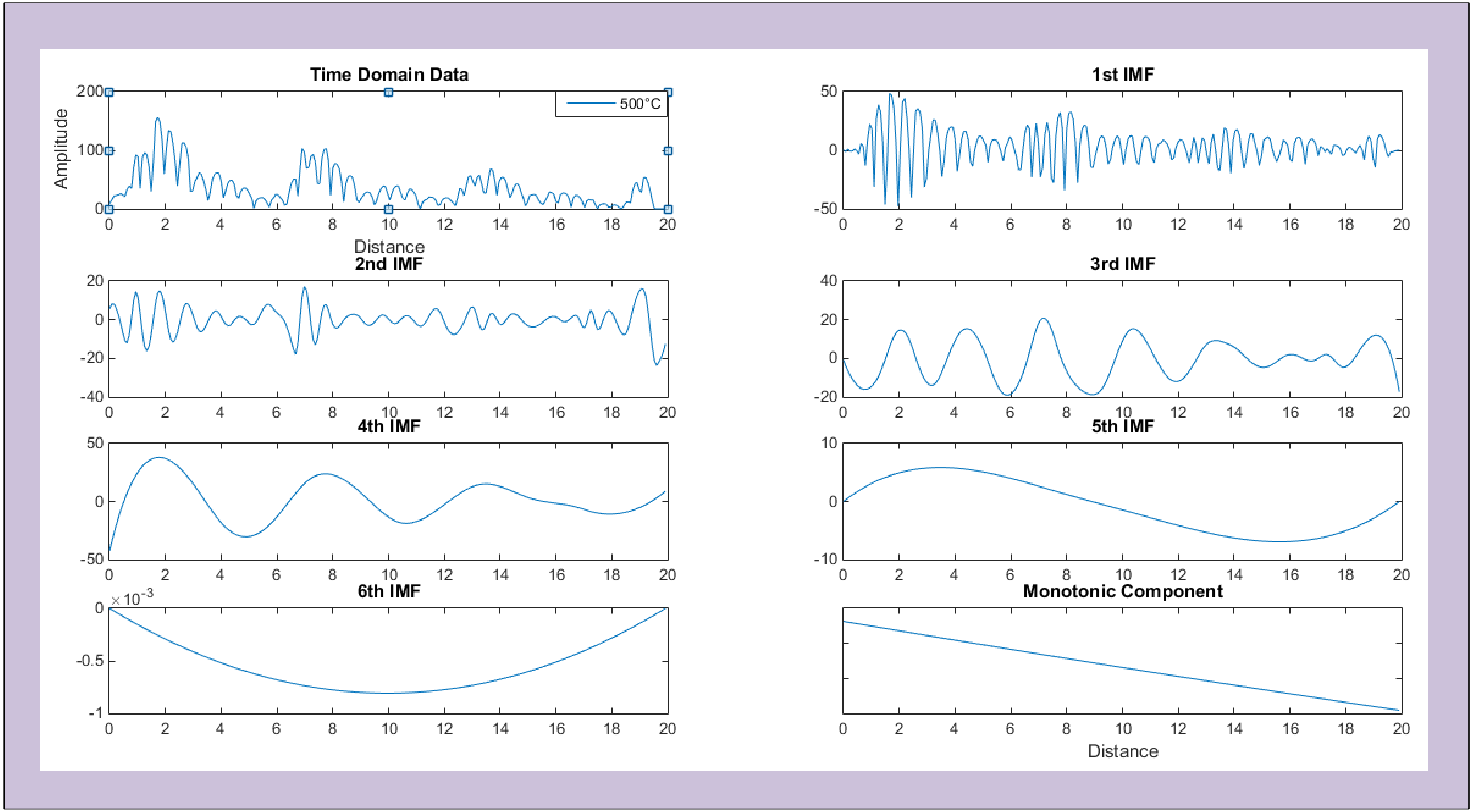

Figure 6.5: IMF for sample 5, treated at 500 °C

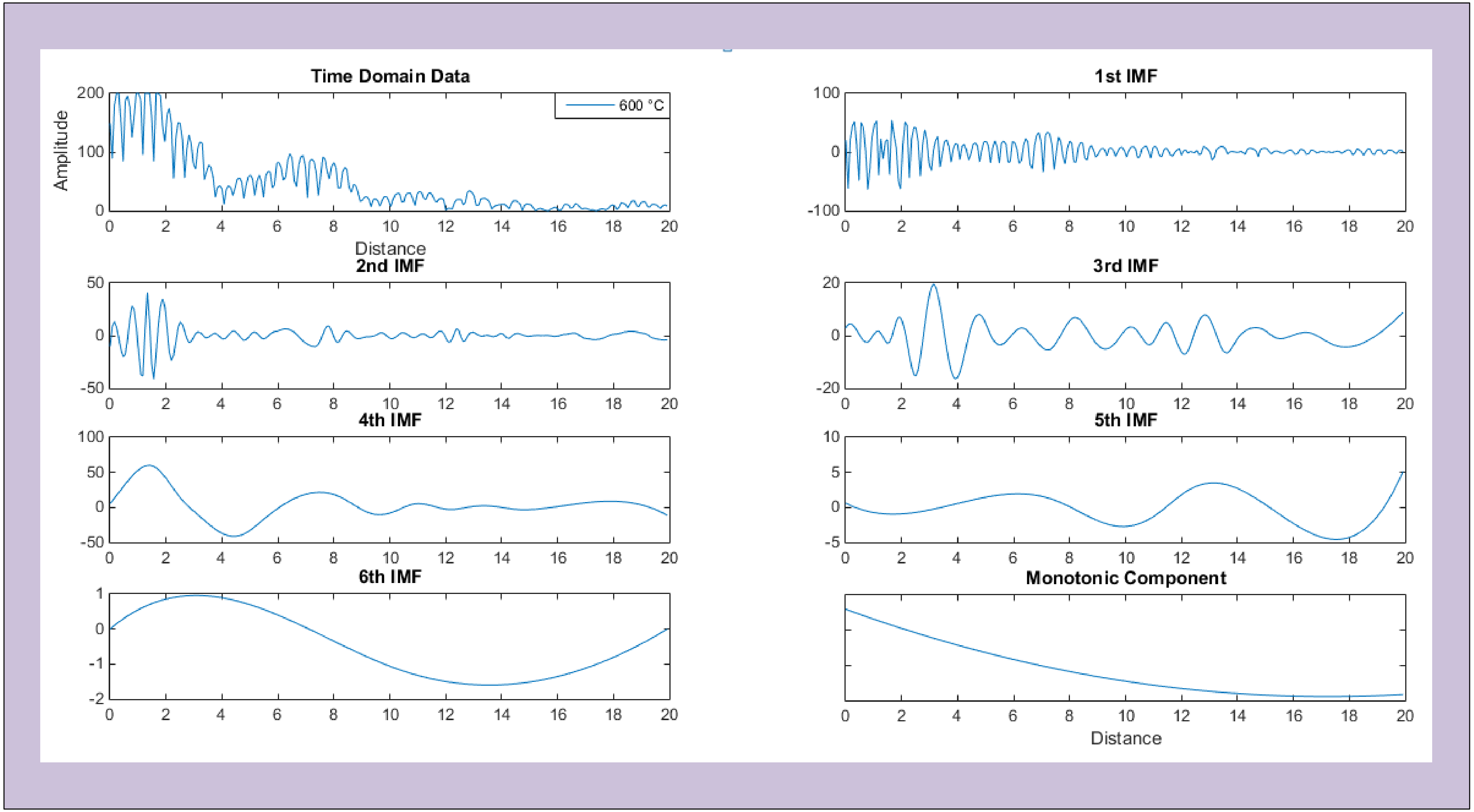

Figure: 6.6: IMF for sample 6, treated at 600 °C

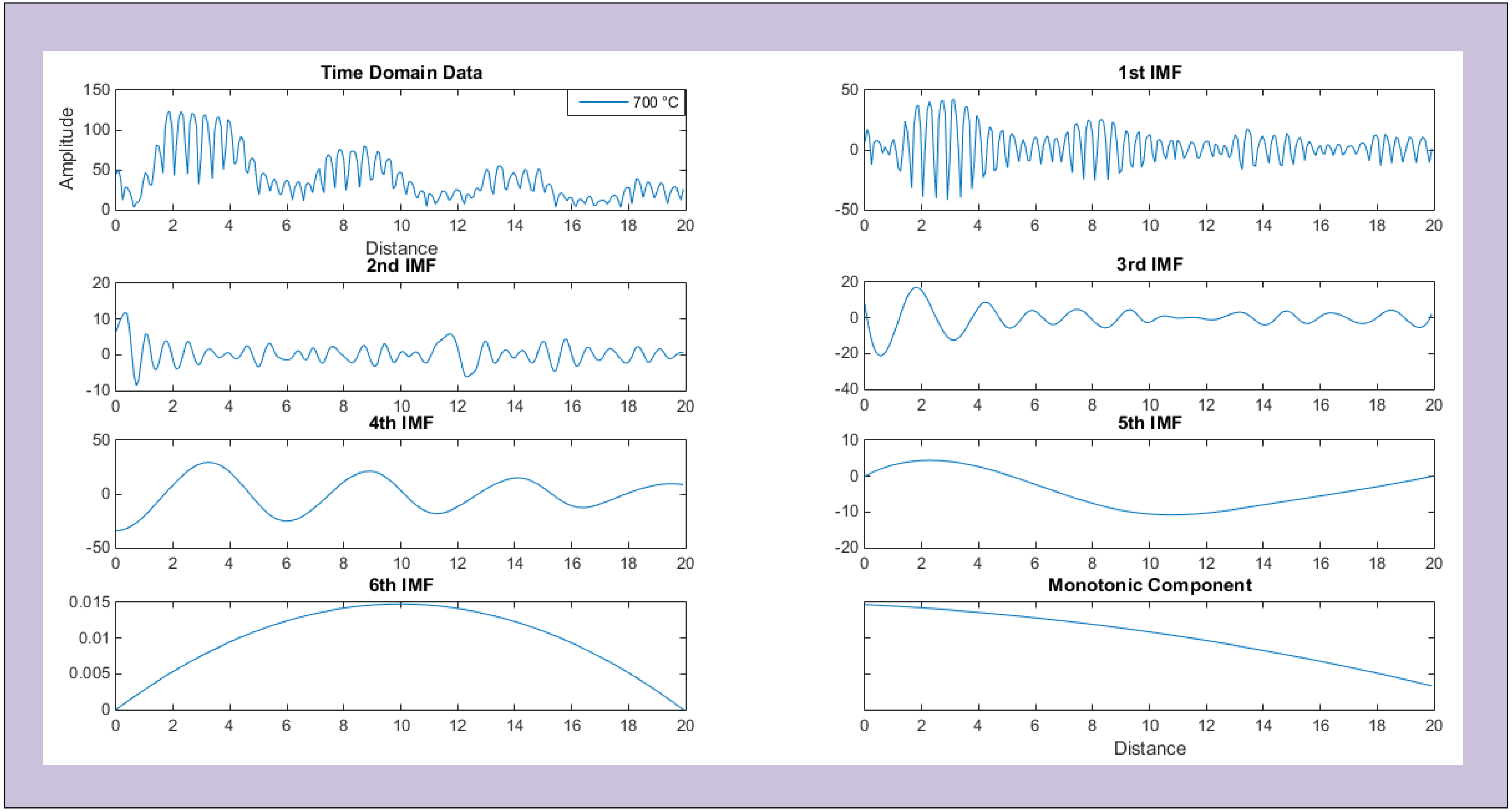

Figure 6.7: IMF for sample 7, treated at 700 °C

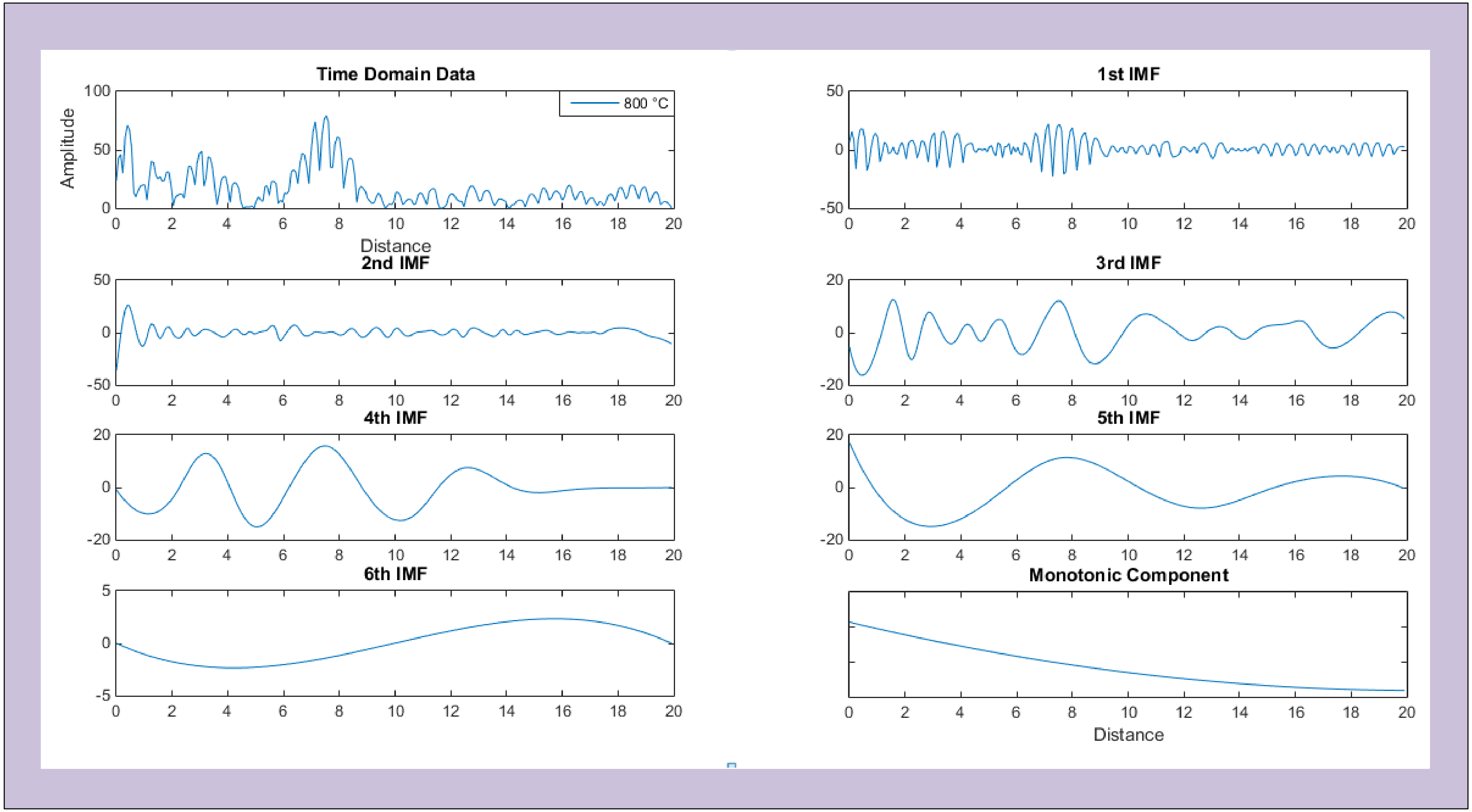

Figure 6.8: IMF for sample 8, treated at 800 °C

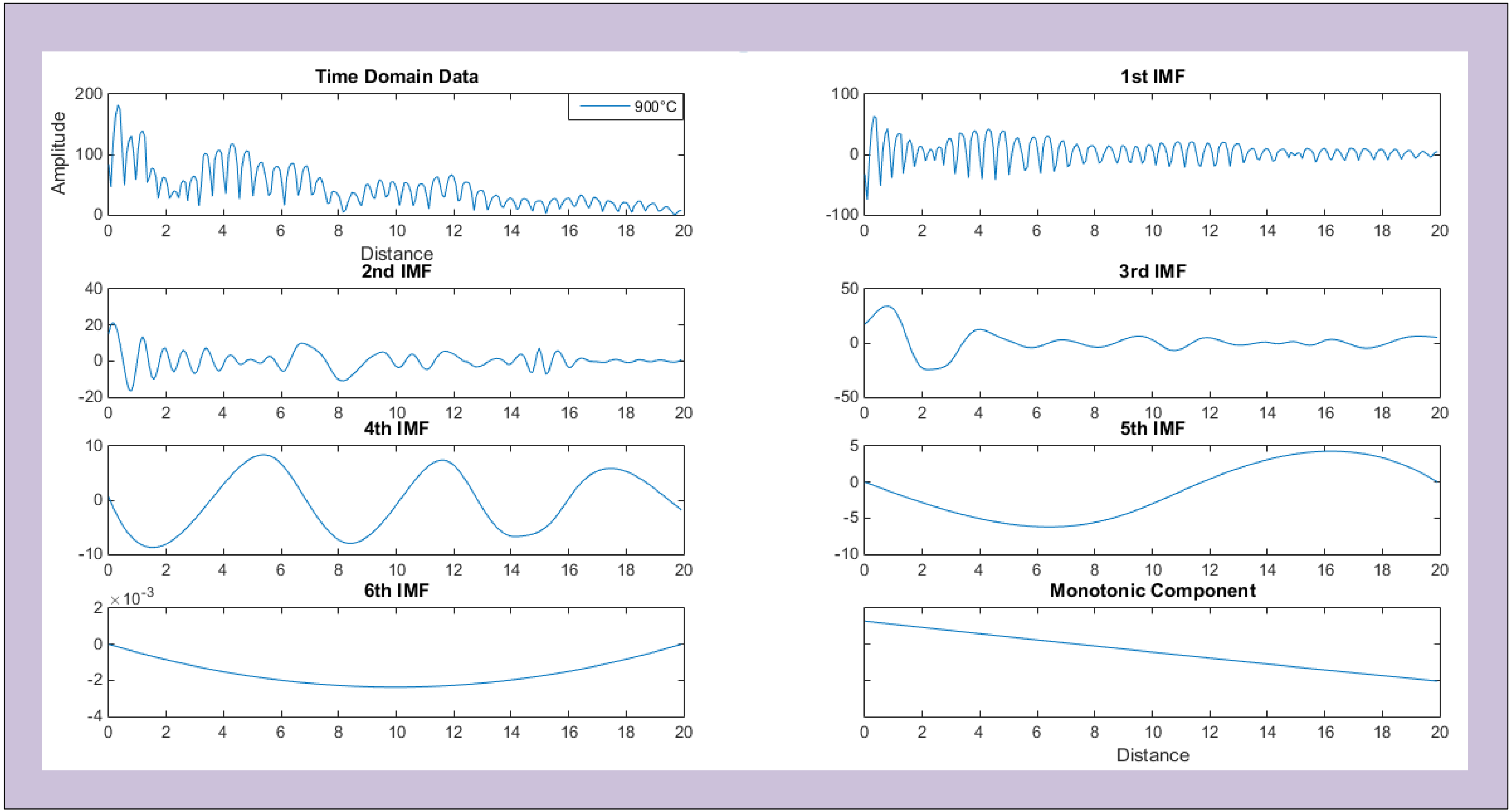

Figure 6.9: IMF for sample 9, treated at 900 °C

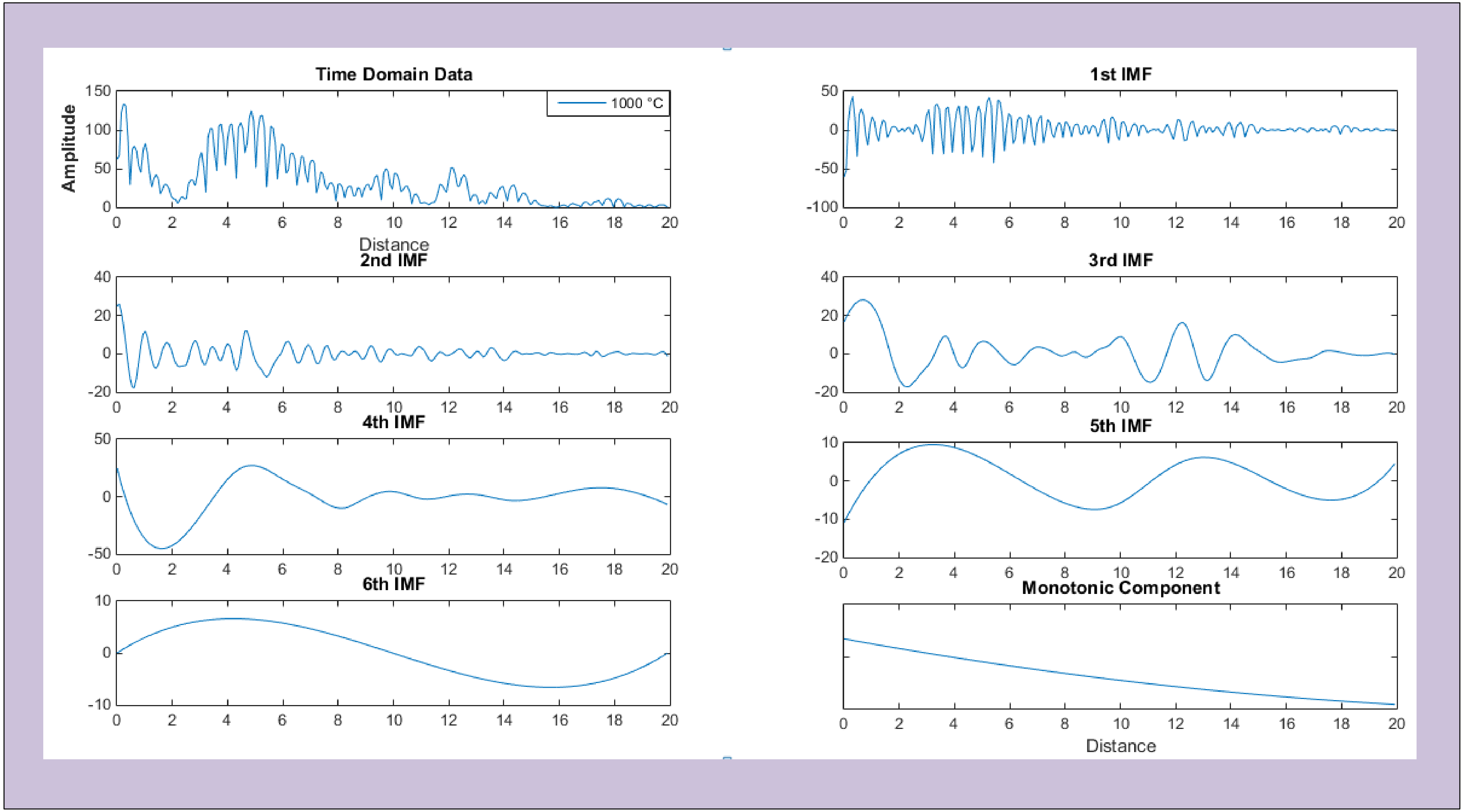

Figure 6.10: IMF for sample 10, treated at 1000 °C

6.1.2. Time Frequency Analysis

Based on these extracted IMF signals, (Discussed above) time frequency analysis is conducted. Hilbert Spectral Analysis (HSA) technique is performed to enable for examining amplitudes and instantaneous frequency as functions of time in three-dimensional plot. These plots are also called Hilbert spectrum which comprised time, frequency and energy distribution in the graph. The Hilbert Spectrum's zoomed view can be seen in Figure 6.11.

In the next stage, developed a software algorithm to find the suitable energy location in the Hilbert spectrum of all the test specimen. The algorithm result shown that, more Hilbert energy distribution is concentrated in the center of the time-frequency plot where the back-wall region located. The figure shows that the region of interest is selected at energies concentrated in normalized frequency band 0.05 to 0.3 on y-axis and 11mm to 15mm on x-axis. This selection is made after analyzing the overall HHT spectrum at each location. Selected location must be same for all specimens.

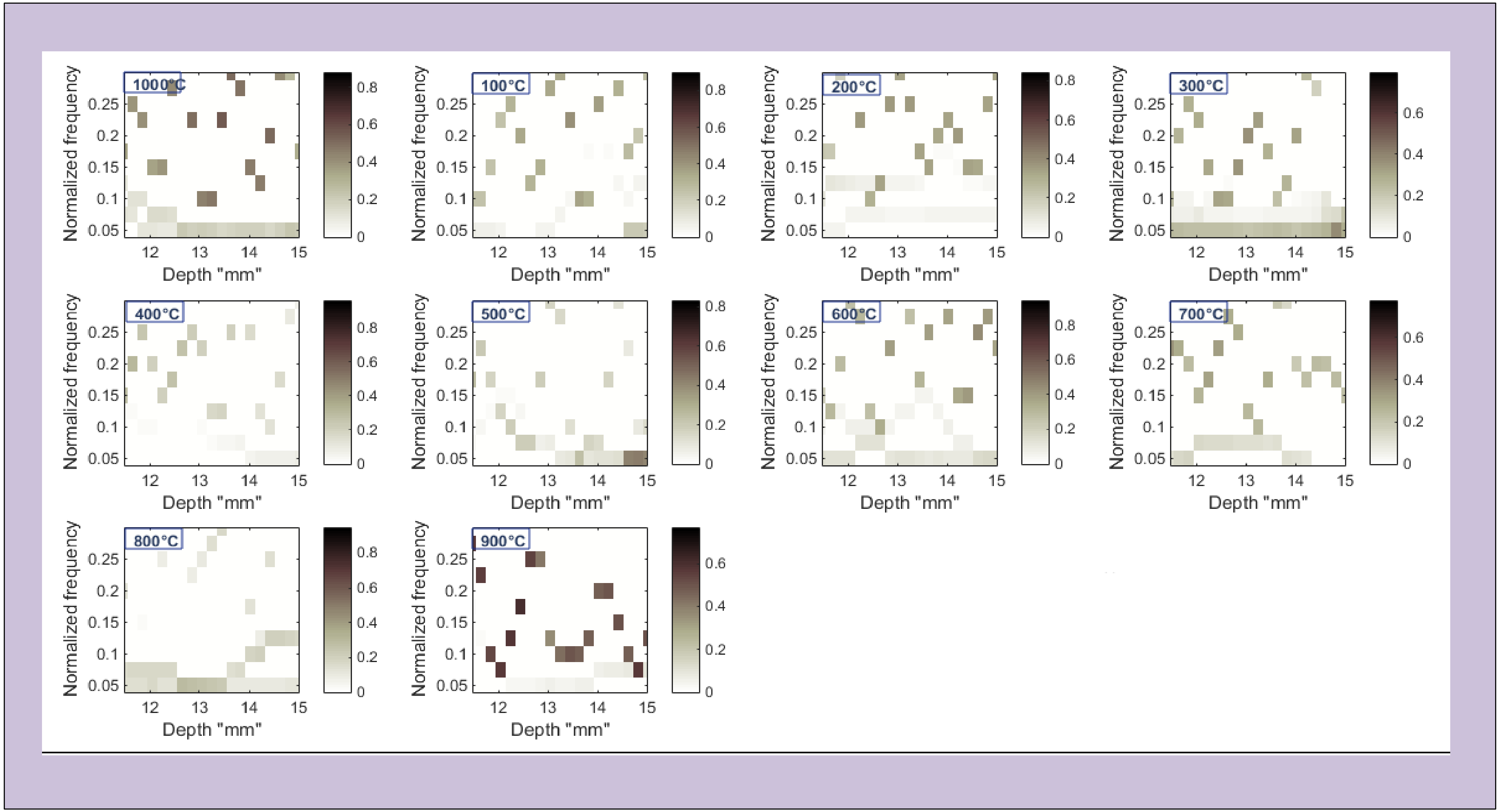

Figure 6.11: HHT spectrum zoomed view

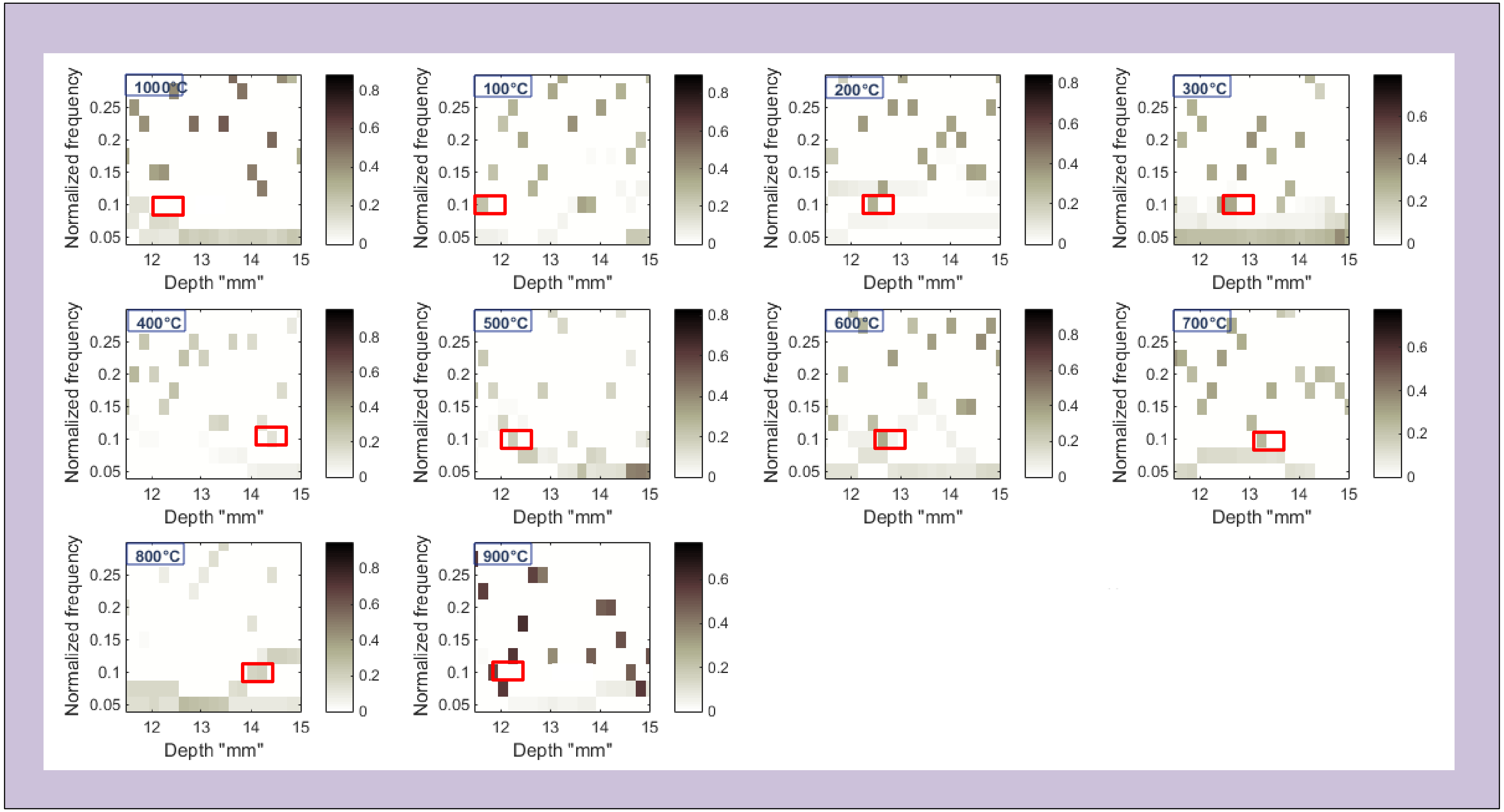

Figure 6.12: HHT spectrum zoomed view

6.1.3. Intelligent Features

In order to profile the HHT spectrum plot, energy is integrated in the region of interest to establish the relationship between artificial aging (Temperature) and energy concentrated. After selecting the region of interest, the Energy frequency distribution based intelligent feature extraction is proposed at particular locations in Hilbert spectrum plot. Therefore, a small window (approximate 1mm length) is concentrated at 0.1 normalize frequency band on the back-wall echo region has been selected which is also same for all the samples as shown in Figure 6.12.

6.1.4. Hilbert trend with respect to aging effect

The average summation of the Hilbert energies concentrated in the selected region shows in the table 6.1. According to this given information, the generation of Hilbert energy trend with respect to temperature (artificial aging) proposes a relationship for aging effect on MS welded material (E-6013) as shown in Figure 6.13. The trend establishes that the Concentrated Hilbert energy is decreasing with respect to increasing temperature (artificial aging).

Table 6.1: The average Hilbert energies concentrated in the selected region

Weld Samples No.	**Temperature in °C**	**Energy Concentrated at particular Location**
1	100	3.5063
2	200	3.4304
3	300	2.4779
4	400	2.3510
5	500	2.2461
6	600	2.2733
7	700	2.1044
8	800	1.7186
9	900	1.5666
10	1000	0.4274

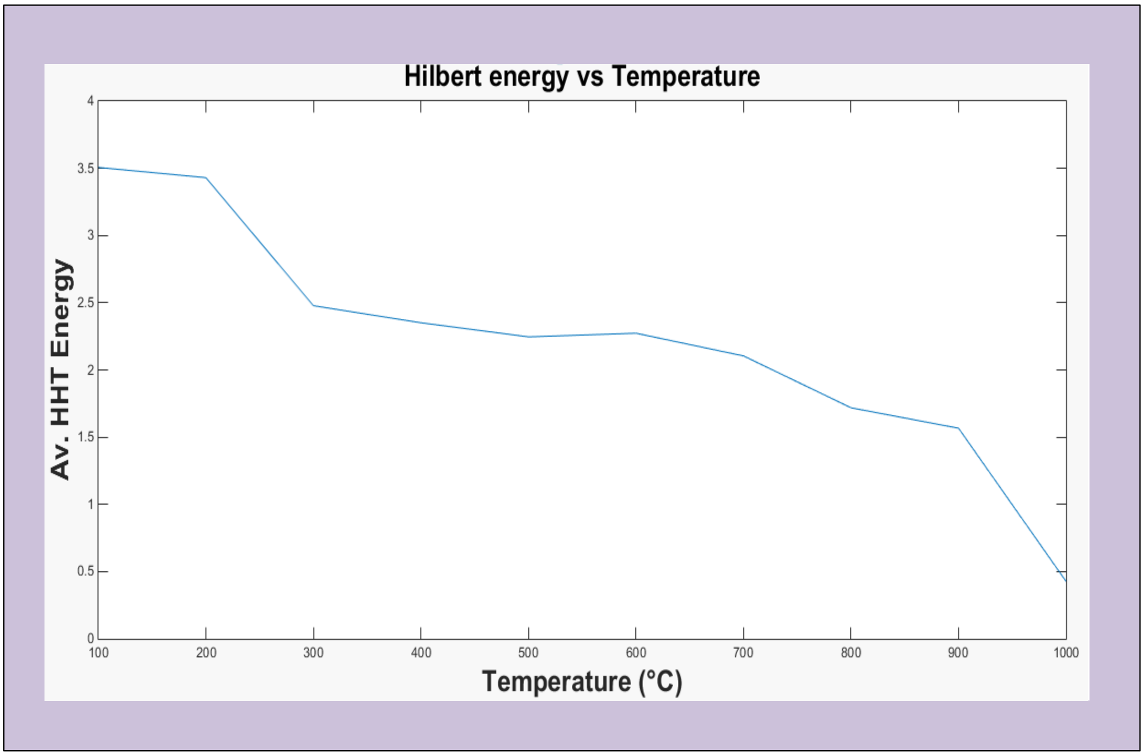

Figure 6.13: Hilbert energy trend with respect to temperature (artificial aging)

Chapter 7. Conclusions and Future Work

Key ideas

7.1. Conclusions

Ultrasonic testing is used to evaluate the aging effect, flaw detection in different material using modern signal processing techniques. In the reported research work, HHT has been used successfully to investigate the residual thermal fatigue in welded material samples through analysis of ultrasonic backscattered signals. The degree of the residual thermal fatigue is associated to the time-frequency domain features of the UT signals. Time frequency analysis is conducted, due to non-stationary and non-linear nature of acquired ultrasonic signals from weld specimen. Thus, insitu UT NDT technique can be used to assess the aging of weld samples which is treated by 100°C to 1000°C. With the help of HHT, time frequency analysis was conducted. Identify the Region of interest on the basis of the evaluation of concentrated Hilbert energy. As we know the feature based Hilbert Huang Transform offers a reliable mean for detection the aging effect of weld material. Then the Energy frequency distribution based intelligent feature extraction is proposed at particular location in Hilbert spectrum plot.

The aging information of welded samples, in turn offers the remaining useful life (RUL) of weld materials. RUL info enables the maintenance managers to exercise better maintenance strategies to reduce the down-time.

7.2. Future Direction:

Future efforts can be utilized to get more sophisticated results regarding detection of remaining useful life with the help of UT NDT using multiple transducers. Efforts can also be utilized to apply Hilbert Huang Transform to more complex data acquire from welded material using modern UT equipment's. Prognosis study and other advance signal processing technique can also be initiated with the help of current data and results to properly estimate remaining useful life of the welded material which can help to plan repair and replacement schedule efficiently.

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