MULTISCALE CHARACTERIZATION OF THERMOACOUSTIC RESPONSE AND FATIGUE FAILURE OF AEROSPACE STRUCTURES

BY

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THESIS
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ABSTRACT

Sustained hypersonic flight has presented a complex problem to researchers and structural designers in recent decades as it has been seen to induce failure of thin aerospace panels in modes that had not been previously accounted for. These new and unaccounted for failure modes are attributed to the extreme and coupled loading conditions of the thermoacoustic environment prevalent in hypersonic flight. Prior research has highlighted the resonant behavior of simple structures in a combined loading environment of vibration and heating. The effects of various heating distributions on pre-thermally and post-thermally buckled plates have been evaluated in theoretical and experimental work. However, this understanding has not yet found its way into advanced thermomechanical coupled simulations, in part because fatigue failure caused by in-plane thermal gradients from localized heating, vibration, and mechanical boundary conditions has not been sufficiently addressed in the laboratory setting to validate such complex simulations. The present work seeks to add to our current understanding of this topic with a series of experiments which investigate structural response and failure at multiple length scales. Non-contact optical methods for displacement and strain measurement were used to study the resonance, broadband excitation response, and thermal loading response of structures with varying boundary conditions. Thin aerospace-type beams and plates made of a nickel super-alloy, Hastelloy X, Al 1100-O, and Al 1100-H14 were subjected to forced vibration initially at room temperature and subsequently with localized heating to examine the effects of thermal stress gradients on structural response. Coarse-grained specimens were then produced by annealing aluminum Al 1100-O (commercially pure Al) to explore the role of microstructural phenomena in the thermoacoustic environment and their influences on global behavior. Using oligocrystal samples in this fashion made the grain scale effects occur at the same scale as the sample size and thus both effects could be investigated
simultaneously. The microstructural heterogeneity of coarse-grained beams was shown to have significant effect on plastic hinging behavior at the beam root. Finally, fatigue experiments were performed in a combined loading environment to assess behavior beyond the linear elastic regime and promote plasticity and failure. Although fatigue failure was suppressed in thin beams and panels, adding a stress concentrator, such as a notch near the beam root, promoted fatigue crack nucleation.
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1.1 Motivation: Structural Challenges of Hypersonic Flight

Less than half a century after the Wright Brothers first achieved powered flight in 1903, a V-2 rocket became the first man-made object to exceed Mach 5 as it travelled into the hypersonic flight regime in February 1949 [1]. The pursuit of hypersonic flight presented researchers and engineers with demanding structural challenges. In the decades following World War II, hypersonic flight research in the United States became focused on developing vehicles which could withstand the tremendous aerodynamic heating and structural instability experienced at high speeds. Mounting interest in high-speed flight for applications such as weapons and manned space vehicles in the 1950s accelerated the development of new airframes, hot-structures, and materials. Laboratory basic and applied research as well as X-plane test flights provided a wealth of data on surviving vibration at high speeds and tolerating thermal stresses from intense heat. Nonetheless, the design of hypersonic flight structures was, and to a certain extent remains, an empirical process generally leading to overly conservative designs. In the decades since these pioneering efforts, researchers have sought to further and more precisely characterize knowledge gaps in both structural and material behavior, including failure, in the extreme hypersonic flight environment in efforts to create more efficient, and ultimately effective, high-speed vehicles. The present work seeks to bridge these knowledge gaps even further by concentrating on multiscale characterization of both thermoacoustic structural response and material fatigue failure. Thermoacoustic loading is defined as an environment in which transient or harmonic mechanical loading in the acoustic frequency range (100s to 1,000s of Hz) coexists with elevated temperature loading (100s°C to 1500°C).
1.2 Prior Work

1.2.1 Early Studies of Plate Vibration

Early research on aircraft structures produced a comprehensive body of theoretical and basic experimental work on plates, beams, and shells. Leissa’s monograph, *Vibration of Plates*, provided a detailed survey of early work in free vibration of plates [2]. After introducing the governing theory for thin, linear elastic plates, Leissa compiled results from studies of isotropic plates, anisotropic plates, plates with in-plane forces, and plates of variable thickness. Vibration characteristics of plates of different geometries, ranging from annular to rectangular with a slit, were also included. Further, Leissa considered the effects of varying boundary conditions, additional masses, and springs on the vibration of plates. Detailed derivations and results on frequencies of resonant modes for combinations of these characteristics are tabulated and plotted in [2]. This thorough review was expanded with Leissa’s second monograph, *Vibration of Shells*, in which he delivered a wide-ranging review of shell vibration in the same format as *Vibration of Plates* [3]. The curvature of shells, which separates them from plates, led to more complicated equations of motion and a requirement for additional specified boundary conditions. Additional parameters are necessary in characterizing the geometry of shells and the formulation of shell theories was not as consistent between different researchers as plate theories. Addressing these complexities, Leissa covered a wide range of shell geometries and again considered the effects of additional masses, springs, varying boundary conditions, and anisotropy on free vibration resonant frequencies and mode shapes.

Other early studies of plate mechanical behavior extended the work surveyed by Leissa and explored the effects of thermal stress on plate vibration and rigidity [4]–[8]. Produced at a time when high-speed flight was of prime interest to governments and researchers, these works were
targeted at understanding flutter of aeronautical structures in heated environments. Uniform heating, non-uniform heating, and various combinations of boundary conditions were analyzed theoretically as well as with basic experiments. These studies showed a wide array of changes to plates’ resonant modes caused by different temperature distributions and boundary conditions. Certain heating distributions stiffened plates while others increased compliance to the point of buckling. For example, the heated edge of a fully clamped plate decreased resonant frequencies (a softening behavior) while central heating or cooled edges increased resonant frequencies (a stiffening behavior) [7]. These contrasting behaviors highlighted the effects of mechanical constraints as well. Mixed free, pinned, and clamped boundary conditions showed natural frequencies of certain resonant modes to decrease with rising temperature while frequencies of other modes increase [6], [7]. As seen in Figure 1.1 and Figure 1.2, simultaneous increasing and decreasing of different resonant frequencies with elevated temperature can produce mode mixing, during which two modes occupy the same natural frequency and mode shape at a unique temperature (e.g., intersection of 2\textsuperscript{nd} and 3\textsuperscript{rd} modes in Figure 1.1).

![Figure 1.1. Changes in resonant frequencies showing mode mixing during heating from [7]](image1)

![Figure 1.2. Mixing between mode 4 and mode 5 of a free-free plate from [16]](image2)
Researchers in the mid-20th century also examined local instabilities of aeronautical structures in heated environments [8]–[10]. Theoretical results and qualitative experiments of fixed plates with heated edges demonstrated a gradual transition from local to global buckling with increasing temperature. Local buckling, shown in Figure 1.3, is an instability which affects only a subsection of the entire structure while global buckling involves the whole structure. Vibration modes were found to evolve into buckling modes as the plate occupied a lowest energy configuration. Local vibration modes mixed in the frequency spectrum with increasing temperature just as global vibration modes did. Theorists studied the relationship between thin wing buckling and span-wise stress distributions [4]. While a unique stress distribution induced equal chance of global and local buckling, stresses caused by aerodynamic heating of the leading edge of a wing were shown to be generally higher than stresses required for global buckling [9], [10]. Thus, in high-speed flight, thin wings were susceptible to local edge buckling. Further work considered the rigidity of spar and rib structures inside thin wings and their influence on buckling due to aerodynamic heating [9].

The above summarized research in the mid-20th century set the stage for achieving a basic understanding of the behavior of aerospace structures in high-speed flight environments. Since then, computational advancements and improvement of experimental facilities enabled researchers in the following decades to further build on this work with a desire to employ air and space vehicles in more extreme flight regimes.
1.2.2 Prior Work in Thermoacoustic Behavior of Panels

Research in recent decades on the behavior of aerospace structures in heated environments has been aided greatly by advanced experimental facilities. The National Aeronautics and Space Administration (NASA) Langley Research Center’s Thermal Acoustic Fatigue Apparatus (TAFA), shown in Figure 1.4, is an example of such a facility. Accommodating large panels in a 6 ft. x 6 ft. x 1 ft. test mounting section, the TAFA uses air modulators to propagate an acoustic load across the face of a test panel [11], [12]. The TAFA can generate standing wave frequencies from 40 Hz to 500 Hz. Banks of quartz lamps heat test panels up to 1093˚C. Research conducted in the TAFA has studied aerodynamic heating, shock phenomena, mechanical pre-loads, and flutter [11], [12].

Murphy et al. used the TAFA to study the dynamic response of a fully clamped, uniformly heated steel panel subject to narrow-band acoustic loads [13]. Small-amplitude excitation of the clamped, heated panel’s resonant modes showed in-plane thermal stresses decreasing the stiffness of the panel and thus lowering the natural frequencies to the point of buckling. The nine resonant modes studied all followed this behavior until the loss of static stability at the buckling temperature.

Figure 1.4. Thermal Acoustic Fatigue Apparatus at NASA Langley Research Center from [12]
Heating beyond the buckling temperature caused the frequencies of some modes to increase and the frequencies of other modes to decrease, resulting in mode mixing.

Another set of experiments probed structural response relevant to fatigue by forcing large-amplitude deflection, snap-through behavior of the panel [14]. A companion theoretical model included initial panel imperfections and imperfect boundary conditions. A static heating study of the panel detailed the pre-buckled and post-buckled behavior of a perfectly flat panel and an imperfect panel. During heating, the initially flat panel experienced a sudden bifurcation in equilibria as it buckled at a critical temperature. The initially imperfect panel, however, slowly deformed from the onset of heating. It continued to deform past the flat-panel buckling temperature until reaching a higher-temperature bifurcation where a second branch of equilibrium position appeared. Analysis of the global nonlinear response strongly indicated that the theoretical motion of the panel was highly chaotic during post-buckled vibration. Analysis of the experimental results suggested similar chaotic motion with less certainty.

Other recent theoretical and experimental studies also considered post-buckling behavior of plates, panels, and beams in both uniformly and non-uniformly heated configurations [15]–[22]. Mead conducted an insightful theoretical study of the resonance of a free-free rectangular plate subjected to non-uniform heating [16]. He focused on the role of thermal stress in relationships between different resonant modes. Coupling in a non-uniform in-plane stress state was noted to exist only if resonant modes are of the same order of symmetry. Mead also considered three different heating distributions of varying complexity. The size of the heated area relative to the size of the plate was found to be a critical parameter which governs the average central stresses and thus also significantly influenced buckling and resonant behavior. The specific heating distribution across the plate induced mode mixing as well. Research conducted at the Air Force
Research Laboratory in recent years has considered non-linear behavior of thin panels in a combined loading environment and the stochastic resonance of simple structures, where harmonic forces exert a large effect in a vibration environment otherwise dominated by random excitation [18], [19].

More recently, and more directly related to this work since a similar set-up and protocol were followed, Berke et al. numerically and experimentally analyzed the thermoacoustic response of a free-free Hastelloy X plate [23]. The first nine resonant modes were observed at ambient temperature and high temperature. A schematic of the experimental setup is shown in Figure 1.5. Apart from the rigid body modes, the natural frequencies of the plate decreased as the compliance of the heated plate increased. This comparison is seen in Figure 1.6. An image decomposition technique was used to compare the finite element and experimental results [24], [25]. Two-dimensional Chebyshev polynomials were used to characterize each resonant mode shape. Sets of Chebyshev kernels were identified for relevance to measured and finite element mode shapes. The selected kernels were then used to create reconstructed mode shapes and compared to the original mode shapes. This method allows for an efficient, quantitative assessment of similarity between...
Experimental and numerical results. Simulation and experiment were shown to agree well, demonstrating high-fidelity full-field characterization of thermoacoustic structural response.

Understanding of the thermoacoustic behavior of panels has advanced greatly in the late 20th and early 21st centuries. Researchers have shed more light on known phenomena with updated facilities and innovative techniques. New observations have been made regarding the intricacies of non-linear, post-buckled response and non-uniform heating. Still, there are challenging problems yet to be addressed in the study of thermoacoustic structural behavior. The work presented in this thesis seeks to further elucidate this topic.

1.3 Research Objectives

1.3.1 Understanding Combined Environment Structural Response

The first objective of the work presented in this thesis was to develop an understanding of structural response in a combined environment of high-frequency vibration and thermal loading representative of the hypersonic flight environment. Surveying vibration response was a critical first step in understanding structural behavior during high-speed flight. Next, the effects of localized heating and in-plane thermal gradients on vibration response were studied. In-plane stresses caused by extreme thermal gradients influence out-of-plane deflection and resonant behavior. The present work sought to collect and analyze high quality full-field data of this response. The addition of mechanical constraints was also an important facet of the present work. The boundaries of real aerospace structures induce complex changes to structural response and can cause coupled responses in combined loading scenarios.
1.3.2 Understanding the Influence of Microstructure on Deformation

The second objective of the present work was to investigate the role of microstructural effects in the context of combined environment loading. Mechanical behavior at the microscale governs initiation of fatigue damage as microstructural anisotropy leads to strain heterogeneity. Prior research of structures in the hypersonic environment have largely focused on global response in the presence of vibration and heating. Local behavior has not been studied thoroughly despite its importance in understanding global behavior. With the addition of localized heating, the interaction between thermal gradients and microstructural features, such as grain boundaries, was an important research direction.

1.3.3 Promoting Plasticity and Fatigue Failure in a Thermoacoustic Environment

The final objective of the present work was to induce a plastic response and achieve fatigue failure in a combined environment of high-frequency vibration and localized thermal loading. Previous studies are limited to exploring global behavior of pre-buckled and post-buckled structures. Inducing plasticity and fatigue are essential in understanding failure during combined loading. Again, the role of localized heating and thermal gradients was of key interest. Characterizing the effects of highly non-uniform heating on fatigue failure is crucial in studying the degradation of hypersonic vehicle structures. The present work aims to study these potentially complex, coupled fatigue failure modes in a thermoacoustic environment.

1.4 Thesis Overview

This thesis first presents the methods used to conduct experimental research. Selection of specimen materials, design of specimen geometries, and design of mechanical constraints are detailed in Chapter 2. The vibration and thermal loading apparatus and measurement methods for
collecting full-field data are also described in Chapter 2. Chapters 3, 4, and 5 address each of the research objectives. Results from vibration loading, localized thermal loading, and combined loading are considered in Chapter 3’s study of thermoacoustic structural response. The effects of different configurations of specimens, heating areas, and boundary conditions on global behavior are analyzed. Chapter 4 reviews prior research on coarse-grained oligocrystal specimens. These specimens enable efficient study of the relationship between microscale and macroscale response. Preparation procedures for the oligocrystals used in the present work are described. Results from static mechanical and thermal loading experiments on oligocrystals are discussed. The last research objective of inducing plasticity and fatigue failure is detailed in Chapter 5. The design of fatigue failure experiments and results at room temperature and high temperature are examined. Final conclusions are presented in Chapter 6 with suggestions of future research on the topics of thermoacoustic structural response and fatigue failure in a combined environment.
CHAPTER 2: EXPERIMENTAL METHODS

2.1 Specimens: Materials, Design, and Preparation

2.1.1 Materials

Following prior thermoacoustic and fatigue studies of our group [23], [26]–[29], Hastelloy X, manufactured by Haynes International, was used in vibration and heating experiments. Hastelloy X is a refractory nickel-based alloy commonly used for mechanical components of systems with high operating temperatures such as gas turbines and industrial furnaces [30]. It is capable of sustained use at temperatures of nearly 1200˚C. At room temperature, Hastelloy X sheet exhibits a yield strength of 376 MPa and an ultimate tensile strength of 783 MPa. At 538˚C, the yield strength and tensile strength decrease to 253 MPa and 628 MPa, respectively [30]. Hastelloy X sheet of 0.5 mm thickness was used to make plate and beam specimens. A small thickness was selected in an effort to best match the behavior of thin aerospace panels. The small thickness was also chosen to more easily promote thermoacoustic fatigue failure.

A second material, Aluminum 6061-T6, was also used for fatigue failure experiments due to its yield strength and fracture toughness being lower than Hastelloy X. These weaker properties permitted a plastic response and failure to be readily achieved during high-cycle fatigue experiments. A common aerospace alloy, Al 6061 offers relatively high strength with low density [31]. The T6 temper of Al 6061 exhibits a yield strength of 255 MPa and an ultimate tensile strength of 290 MPa. Al 6061-T6 sheet of 0.4 mm thickness was used to make plate and beam specimens.

Aluminum 1100, otherwise known as commercially pure aluminum, was used to make coarse-grained specimens for experiments studying influence of microstructure on global response. Al 1100 is noted for high formability, corrosion resistance, and low strength [32]. Annealed
Hastelloy X and Al 6061-T6 did not exhibit any significant grain growth. For this reason, Al 1100 was selected to produce oligocrystal specimens. The 99% aluminum content of Al 1100 allows for significant grain growth during annealing, which led to beams and plates with centimeter-sized recrystallized regions. These specimens, known as oligocrystals, are characterized by grains with sizes comparable to the length scale of the entire specimen. Oligocrystals have fewer grains than a representative volume element of the material and thus may exhibit anisotropic and heterogeneous properties. Preparation of oligocrystals is detailed in Chapter 3. Two different tempers of Al 1100 were used in the present work due to the availability of the material at the time of purchase. Al 1100-O sheet of 1.5 mm thickness and Al 1100-H14 sheet of 0.8 mm thickness were used to make plate and beam specimens.

![Figure 2.1. Cantilevered beam vibration experimental setup](image)

2.1.2 Specimens and Mechanical Constraints

Rectangular thin plates and beams were used for thermal loading and vibration experiments. These geometries have been studied in prior work and bear fundamental semblance to aerospace
structural components, particularly thin skin panels and thin bulkheads susceptible to thermoacoustic fatigue failure. Additionally, analytical solutions of linear elastic beam and plate behavior are well known and can be used to validate simple experimental results.

Cantilevered beams used to study resonant behavior were relatively large (up to 30 cm in length). The compliant nature of these specimens allowed the first several resonant modes to be observed at frequencies below 200 Hz. The large size benefitted the quality of experimental results by permitting large out-of-plane deflections during vibration loading. The experimental setup for the cantilevered beam is shown in Figure 2.1. Large doubly clamped beams, as seen in Figure 2.2, were used in initial harmonic vibration fatigue experiments with and without localized heating.

Cantilevered and doubly clamped beams were used to study broadband excitation response and fatigue failure were significantly smaller than those used to survey resonant modes. Downsizing these specimens to 4.5 cm in length promoted
plasticity and fatigue failure more quickly than with large specimens. This change in specimen size was crucial in probing behavior beyond the linear elastic regime.

Aluminum clamps, shown in Figure 2.2, Figure 2.3, and Figure 2.6 were used to secure cantilevered and doubly clamped beams. These fixtures were designed with front and back plates aligned via a sliding channel. Specimens were held between the two plates and four bolts threading into the plates’ corners were tightened to constrain the specimens. The clamps were bolted directly to an optical table. Beveled edges, which were placed facing the DIC cameras, as seen in Figure 2.3, increased the visible area of specimens during imaging. Square edges blocked the root of beams from the view of angled cameras, and the beveled edges allowed imaging closer to the fixed root of the beam.

Fully-fixed rectangular plate specimens were used for thermal loading experiments. These plates had a visible area of 5 cm x 7 cm for imaging. A border of 2 cm on each side of the plates was fixed, making the total size of each plate 9 cm x 11 cm. A steel frame, shown in Figure 2.4 and Figure 2.5 was used to fully constrain plate specimens. A front face was connected to a rear face and base with 16 bolts on the frame edges. The specimen was sandwiched between the two faces and the entire assembly bolted directly to the optical table. Like the aluminum clamps for beam specimens,
rectangular inner frame edges would have impeded the cameras’ views of the plate specimen. These edges of the frame were slightly beveled to achieve an unobscured view of the specimen during imaging.

2.2 Loading Conditions and Apparatus

2.2.1 Thermal Loading and Measurement

Thermal loading was supplied by two OEM Heaters SpotIR heaters, shown in Figure 2.7. The Model 4085 heater used a 750-watt lamp and with a heat flux density of 101 W/cm² at the target surface [33]. The Model 4150 used a 250-watt lamp with a peak heat flux density of 170 W/cm² [34]. The heaters were mounted on optical accessory posts and brackets to be easily reconfigured to match varying arrangements of specimens and boundary conditions. These infrared heaters provided localized heating on a 0.635 cm diameter circular area with a peak temperature of 430°C. Both heaters were fitted with air hoses to provide cooling for the infrared emitters. To further promote the localization of heating, each heater was operated with a focusing

Figure 2.7. OEM Heaters Model 4085 SpotIR (left) and Model 4150 SpotIR (right) from [33], [34]
cone. These attachments, seen in Figure 2.7, enhanced the thermal gradients within specimens and thus promoted out-of-plane deflection caused by in-plane thermal stress.

A handheld FLIR TG165 microbolometer with 80 pixel x 60 pixel spatial resolution was used to record thermal images during high temperature experiments [35]. The measured temperature range of the FLIR TG165 is limited to 380°C, which in some cases was below the maximum heated temperature of test specimens. This measurement cap and the relatively low resolution of the sensor restricted use of the TG165 to establishing qualitative-only views of the extent of heating area rather than measurements of the peak temperature. Because of this, K-type thermocouples were used in conjunction with the TG165 to produce quantitative temperature measurements, but at the few locations where the thermocouples were placed. Figure 2.8 shows an example of thermocouples attached to a plate during a heating calibration study. A corresponding FLIR image on the right of Figure 2.8 shows the heated plate and SpotIR heater.

Figure 2.8. SpotIR 4150 heater, K-type thermocouples on plate, and FLIR TG165 image
2.2.2 Vibration Loading and Laser Doppler Vibrometry

Vibration loading was provided by a Data Physics GW-V4 electrodynamic shaker. The GW-V4 imparted a maximum sine force of 17.8 N, maximum random force of 5.9 N, maximum sine acceleration of 892 m/s², and maximum peak-to-peak travel of 5 mm [36]. The maximum excitation frequency of the GW-V4 was 14 KHz. The shaker armature was connected to specimens with a 7 cm-long steel M4 threaded stinger rod. This length was short enough to mitigate rod bending during forced vibration of specimens and long enough to accommodate other experiment fixtures, such as lighting assemblies, infrared heaters, and mechanical boundary conditions. The shaker head sat on a trunnion, which was bolted directly to the optical table. The shaker was controlled in an open loop by a Hewlett Packard 33120A function generator.

Harmonic vibration was used in experiments which studied the resonant behavior of cantilevered beams. Fatigue failure experiments also used harmonic loading to quantify the number of cycles until failure. Harmonic vibration, however, is less relevant to real-world scenarios than broadband frequency vibration. Characterizing structural response under both harmonic and broadband excitation was important in pursuing later goals of introducing localized heating and inducing plasticity and fatigue failure. The function generator supplied 10 MHz bandwidth Gaussian noise to the shaker during broadband excitation experiments.

Laser Doppler Vibrometry (LDV) was used during vibration experiments to verify the frequency of excitation and identify resonant modes. LDV measurements have been combined with DIC in vibration studies to measure both full-field and high-fidelity single point data [37]–[40]. LDV offers a non-contact, accurate measurement of a target object’s velocity using interferometry, making it an appealing alternative to traditional accelerometers. Vibrometers operate by splitting a laser into a reference beam and a measurement beam. The measurement
beam is directed at a moving target surface, which causes a Doppler shift. The interference between the distorted reflection of the measurement beam and the reference beam is used to directly calculate the target’s velocity [41]. This process is shown in Figure 2.9 [42]. This velocity can be integrated to find displacement.

A Polytec OFV-505 single point laser vibrometer head and a Polytec OFV-5000 vibrometer controller were used in the present work to measure specimens’ out-of-plane velocity and displacement during forced vibration [43]. The OFV-505 autofocuses on the target object and the OFV-5000 output can be routed to an oscilloscope to monitor the vibrometer signal in real time.

2.3 Digital Image Correlation

2.3.1 Digital Image Correlation Fundamentals

Digital Image Correlation (DIC) is a non-contact optical technique for displacement and strain measurement [44]. It has been widely popular in mechanics research in recent decades and has been used in the present work. 2D-DIC uses a single camera to measure in-plane displacements and strains of a flat specimen which does not exhibit out-of-plane deformation. The present work used 3D-DIC, a stereoscopic DIC method involving the use of multiple cameras to measure out-of-plane and in-plane displacements and strains.

DIC works by applying a high-contrast, random speckle pattern to the surface of a specimen, recording images of the speckled specimen throughout deformation, and analyzing the
movement of the speckled region to resolve high-fidelity measurements of displacement and strain. After running an experiment and recording images of the deforming specimen, each image is processed sequentially to calculate displacement and strain.

Each image of the speckled surface is first digitally divided into a grid of trackable, overlapping subsets. A subset size is chosen so that each subset exhibits a unique image grayscale distribution. A step size is chosen to specify the overlap between subsets. These parameters are selected based on the speckle pattern. A computer algorithm calculates a functional fit for each unique grayscale distribution within a subset. Subsequent images are processed similarly as the algorithm then searches for the functional fits of the original subsets in the deformed images, as shown in Figure 2.10 [45]. Each deformed image is compared to the initial state of the experiment (selected by the user), known as the reference image. Iterating through this process for all DIC images acquired during an experiment provides quantitative information of the specimens’ surface deformation at every subset point. The full-field, high-measurement-density nature of DIC is one of the most attractive facets of the technique.

2.3.2 Speckle Patterns for Digital Image Correlation

The quality of DIC results depends heavily on the quality of the speckle pattern applied to the specimen surface. Once other testing considerations have been addressed (e.g. camera lens quality, lens focus, lighting conditions), the quality of DIC speckle pattern is the most important
factor in collecting high-quality experimental results. Generally, an optimized speckle pattern has high contrast, shows randomly distributed speckle points, and contains speckles of all roughly the same size [46]. High contrast is usually achieved by first thinly covering the specimen with either a black or white coating. The color opposite to this background is used to create the speckles. White-background speckle patterns perform well because they can be brightly and uniformly illuminated. This enables shorter camera exposure times (with a well-lit specimen), which is beneficial for recording dynamic events where motion blur can afflict DIC images. Black-background images can be useful for experiments which involve thermal imaging. While more lighting may be required to properly illuminate the specimen, the high emissivity of a black background is an advantage over a white background in these cases.

Depending on the length scale of the experiment and patterning tools available, the speckle can be applied to the specimen surface in a number of ways. Speckle patterns at the macroscale can be created with felt marker dots or laser printing. These two methods often generate very high contrast patterns. Patterns can also be applied by lightly flicking paint-covered toothbrushes or paintbrushes onto the specimen surface. At a slightly smaller scale, sprayed mist from aerosol paint cans can be used to create finer, uniformly random speckles. Experiments conducted at the microscale may employ extremely fine speckle patterns made from airbrushing, particle deposition, or UV-printing [47]. The present work used spray can misting and toothbrush paint-flicking to apply DIC speckle patterns.

2.3.3 3D Digital Image Correlation

Digital Image Correlation can be used to measure out-of-plane deformation in addition to in-plane displacements and strains. This extension of DIC has been used widely used for research
in vibration, fatigue, fracture, and biomechanics [26], [37]–[39], [48]–[51]. Whereas 2D-DIC uses one camera which cannot gauge object depth within an image, 3D-DIC (or stereo-DIC) uses two cameras to simultaneously record images of a specimen [44]. Capturing images from two camera perspectives allows for calculation of an object’s position in all three dimensions. 3D-DIC results in the present work were generated with Correlated Solutions VIC-3D software [52]. Images were recorded with Correlated Solutions Vic-Snap software. Two Allied Vision Prosilica GX 1050 cameras were used to record images during experiments [53]. They have sensor resolutions of 1024 pixels x 1024 pixels and can record at up to 112 frames per second at full resolution. The 3D-DIC setup used in the present work is shown in Figure 2.1.

The basis of the 3D-DIC method is a calibration procedure to determine the cameras’ positions relative to the test specimen. Calibration is performed with a target grid displaying target markers of known size, shape, and spacing. An independent calibration, shown in Figure 2.11, involves identifying a world coordinate system based on a specific target grid location. The positions of the cameras, known as extrinsic parameters, are then related to each 3D point of the target grid using this coordinate system. A combined system calibration procedure differs slightly by declaring one camera as a primary system and establishing a world coordinate system relative to this primary camera. The position of additional cameras is related to the primary camera with intrinsic parameters.

Figure 2.11. Independent 3D-DIC calibration from [44]
In practice, the calibration procedure begins after optimizing camera position, focus, depth of field, and lighting arrangements. The target grid can be placed directly in front of the specimen so long as it remains in focus of the cameras. The target grid is translated and rotated on all axes slightly while the cameras record images of the moving grid. Typically, 30-60 calibration images are used during calibration. The images are processed by a computer algorithm, which calculates the position of cameras. The resulting parameters are used in the subsequent DIC analysis. It is critical that the cameras are not tampered with after finishing the calibration procedure.

3D-DIC techniques have also been modified by researchers in recent years. Experimental setups involving mirror assemblies and bandpass optical filters reduce the cost of performing 3D-DIC by using only one camera while retaining the benefits of the technique [54]–[59]. These single-camera techniques have been especially attractive for high-speed 3D-DIC, where the immense amount of data recorded and synchronization issues between two cameras can thwart the success of a setup.

2.3.4 High Temperature Digital Image Correlation

2D-DIC and 3D-DIC have proven to be useful techniques for measuring displacement and strain during high temperature experiments. A number of studies have demonstrated improvements to traditional DIC which extend its usability to temperatures upwards of 1200° [23], [28], [60]–[69]. They have addressed challenges which hamper the quality of DIC images and degrade speckle patterns. Radiation from the specimen, speckle coating oxidation, and air distortion during heating are the main hurdles to overcome when performing DIC at elevated temperatures [70].

Radiation from heating can be mitigated by illuminating the specimen with monochromatic light. Because radiation is emitted in the red and infrared regimes of the electromagnetic spectrum, blue lamps are often used to illuminate experiment setups. Blue lamps, seen in Figure 2.5,
paired with blue bandpass filters placed in front of camera lenses, mitigate the glowing effect of heated specimens and thus reduce unwanted image saturation. This concept has also been extended to UV light to further lessen the impact of radiation at extreme temperatures [62]. However, 470 nm blue ring lights and blue bandpass filters were used in the present work.

Non-high-temperature speckle patterns can undergo significant yellowing during experiments involving thermal loading. Some coatings crack and peel when subjected to extreme temperatures. Degradation of speckle patterns can be resolved by applying patterns of refractory coatings which resist oxidation. Ideal coatings also exhibit reasonable ductility to handle large deformations during experiments. Alumina and zirconia ceramic adhesives combined with cobalt oxide have been shown to create speckle patterns well-suited for high temperature applications [65]. Matte black and white Very High Temperature ® (VHT) Flameproof™ automotive paints, which can withstand temperatures of up to 1093˚C, were used for all experiments in the present work. These aerosol paints were a cost-effective, easily accessible solution for creating high contrast speckle patterns.

Air distortion and heat hazing can also negatively affect the quality of high temperature DIC results. Air knives can be employed to circulate heated air and reduce unwanted image distortion. For extremely high temperatures, this problem can be addressed by conducting experiments in vacuum chambers [70]. Heat haze was not observed during the experiments.
discussed in the present work and no measures were taken to lessen its impact on experimental results.
CHAPTER 3: THERMOACOUSTIC STRUCTURAL RESPONSE

3.1 Vibration Loading Response

3.1.1 Validation of Cantilever Beam Harmonic Resonance

The first set of vibration experiments investigated the linear elastic response of a simple structure—the resonance of a cantilevered, thin Hastelloy X beam at room temperature. The cantilevered beam was a natural first step and served as a starting point for a subsequent series of experiments involving localized heating and more complex boundary conditions. The advantage of beginning with the cantilevered beam at room temperature was that its resonant behavior is governed by a simple, well known theoretical solution. Linear elastic experimental results could be compared to Euler-Bernoulli beam theory to confirm that both the experimental equipment and methods were sound. This validation process also improved practical aspects of the experiment, such as camera positions, lighting arrangements, and calibration procedures. Best practices learned during this process for achieving high quality DIC and LDV results were carried forward to subsequent, more complex experiments.

The frequencies and shapes of the first four resonant modes of a cantilevered Hastelloy X beam (30 cm x 2.54 cm x 0.1 cm) were calculated before performing experiments. Mode shape predictions were made with Euler-Bernoulli beam theory and were plotted with a MATLAB script.

Figure 3.1. First four cantilevered beam mode shapes
These shapes are shown in Figure 3.1 with the left side of the plot representing the fixed displacement and slope boundary condition.

The experimental setup for cantilevered beam vibration is shown in Figure 2.1. One end of the Hastelloy X beam was fixed with an aluminum clamp. The other end was connected to the shaker via a steel stinger rod. Five blue ring lights surrounded the camera-facing side of the beam to illuminate it during imaging. The vibrometer was directed at a non-vibration node (of non-zero displacement) location of the beam during imaging. An example of the laser vibrometer signal is included in the bottom right corner of Figure 2.1.

The cantilevered beam was externally forced to vibrate starting at 5 Hz. The frequency of excitation was then manually increased until the laser vibrometer signal reached local maxima of the beam’s velocity, signifying a resonant frequency. DIC image sets were recorded at each of the first four resonant frequencies. The Prosilica cameras did not have high-speed imaging capabilities to record time-resolved images of the vibrating beam. Thus, a phase-stepping imaging method was used instead. DIC images were taken with precise delays to capture the beam’s entire period of harmonic motion. These images were recorded over many periods of motion and were combined to create a representative period. This method assumes that each period was identical and required precise information of the beam’s motion from the laser vibrometer to trigger the cameras. This function within the Vic-Snap software is the Fulcrum Mode. The user has control over several aspects of
the phase-stepping method. For example, the degree of separation between images can be specified to choose how many images are captured to create the representative period. The recording process can also be tailored to capture a representative period beginning and ending at a certain point of the target’s oscillation.

Figure 3.2 shows a DIC image of the cantilevered beam. The long, thin geometry of the beam occupied only a small portion of the cameras’ views. This limited view required careful adjustment of the cameras’ positions and focusing to record as high quality images of the beam as possible.

The theoretical and experimental frequencies of the first four resonant modes showed good agreement and are listed in Table 3.1. The largest discrepancy was a 13% difference between theory and experiment for Mode 2. The experimental frequencies of modes 1, 3, and 4 matched closely to the predictions. Figure 3.3 shows a VIC-3D visualization of out-of-plane displacement of the cantilevered beam’s third resonant mode. The right end of the beam is fixed. The DIC results were better visualized in MATLAB. Figure 3.4 shows a set of results for the second resonant mode of the cantilevered beam. The left-most plot shows the out-of-plane displacement for every subset (represented by a filled circle) at the point of greatest displacement within the image set. The six lines in this plot are a row of subsets along the axis of the cantilever beam at a fixed width location. These width-specific values were then averaged together across each width location and the single average DIC measurement as a function of axial location is shown in the right-most plot. This view

Table 3.1. Theoretical and Experimental Frequencies of Cantilevered Beam Modes 1-4

<table>
<thead>
<tr>
<th></th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical Resonant Frequency</td>
<td>8.7</td>
<td>54.4</td>
<td>152.4</td>
<td>298.6</td>
</tr>
<tr>
<td>Experimental Resonant Frequency</td>
<td>7.5</td>
<td>47</td>
<td>153</td>
<td>304</td>
</tr>
</tbody>
</table>
is the mode 2 shape from DIC. The right side of the plot is the fixed end of the beam with zero displacement. The center plot tracks the out-of-plane displacement of the beam tip throughout the period of motion. In this case, the phase-stepped images were recorded starting and ending at the minimum displacement. The sinusoidal shape verifies the harmonic motion of the beam.

3.1.2 Broadband Loading Response

Broadband excitation experiments were performed on a doubly clamped beam made of Al 6061-T6. The greater compliance of the Al 6061-T6 beam compared to Hastelloy X was practically significant due to the lower shaker force possible during broadband excitation (17.8 N maximum during harmonic load vs. 5.9 N maximum during broadband) and the stiffening caused by a second fixed boundary. Continuing to use the stiffer Hastelloy X specimen would have at the best case exhibited little out-of-plane deflection and a poor signal-to-noise ratio, while at the worst case would have damaged the shaker.

Phase-stepping cannot be used with the broadband excitation experiments because the beam motion was no longer periodic. To overcome motion blur, camera gain was increased, lighting was moved closer to the specimen, and exposure times were reduced to 30 µs (compared to 500 µs for harmonic excitation experiments). DIC images were captured at 50 frames per second
Figure 3.5. Doubly clamped beam mode 1 shape from broadband excitation (every 20 ms) for 5 seconds, which approached the temporal resolution limit of the cameras. It has been shown that low-speed cameras yield the same average results for operational deflected shapes during broadband excitation as high-speed cameras, thus justifying the use of the Prosilica cameras in this case [71].

Broadband excitation of the doubly clamped beam resulted in generic out-of-plane deflected shapes at random points in time when imaged at 50 fps. While the transitions between these shapes were erratic since the loading frequency content was up to 10 MHz, the shapes themselves were consistent in the harmonic experimental results at given time instances, implying that during particular instances in time the response may be dominated by one or two particular mode shapes, although transition from one to the other may be rapid. Figure 3.5 shows out-of-plane displacement of the first generic shape observed during broadband excitation. Both sides of the beam in the figure are fixed. Each frame represents a DIC image set, separated by 20 ms i.e. successive frames with our imaging system rate. The sequence of frames in Figure 3.5 show a symmetric bowing of the beam center, matching the behavior of the first resonant mode shape of the doubly clamped beam. The beam quickly enters and exits this configuration within the sequence of four frames. The five-frame sequence in Figure 3.6 shows out-of-plane displacement...
of the second generic shape observed during broadband excitation. This asymmetric “S”-shape is characterized by the left and right sides of the beam deforming in opposite directions. This observed shape coincides with the second resonant mode of the doubly clamped beam. In all the observations made here, the beam predominantly occupied these two shapes resembling its first and second resonant modes. However, this does not mean that other, higher-order, modes are not present and simply cannot be captured by the 50 fps imaging rate of this system.

3.2 Thermal Loading Response

3.2.1 Heating Area and Temperature

Before conducting vibration experiments with localized heating, static thermal loading-only studies were conducted to determine the heating distribution generated by the SpotIR 4150 heater. Because localized heating was to be added to later cantilevered beam vibration experiments, heating calibration experiments were performed with the setup seen in Figure 2.12. The SpotIR 4150 was placed 1 mm away from the Hastelloy X beam and switched on at 100% power for 15 minutes. Thermocouples were placed at five locations along the beam, ranging from 0 cm to 10.16 cm from the center of heating. Figure 3.7 shows the thermocouple readings from the beginning of localized heating to 15 minutes of heating. The heating approached a steady state after approximately seven minutes. The center of heating reached a maximum temperature of 430°C.
2.5 cm away, the steady state temperature was 200°C, revealing a steep thermal gradient due to the localized heating. The temperature at 7.62 cm from the center of heating did not exceed 50°C. FLIR images of the first seven minutes of this heating study are shown in Figure 3.8. The heated area expanded quickly after the SpotIR was switched on, eventually encompassing approximately 14 cm of the beam length. This measurement corresponded well to thermocouple readings of the heated area.

3.2.2 Thermal Loading of the Doubly Clamped Plate

The thermal loading of cantilevered beam described above provided a quantitative idea of the area affected by localized heating. While a thermal gradient existed in the length-wise direction of the thin beam, the width-wise temperature did not vary. This one-dimensional thermal gradient made the thin beam a non-ideal structure for inducing a complicated, in-plane thermal stress loading which could later be paired...
with vibration loading. To generate 2D in-plane thermal stress gradients and quantify the in-plane constraint caused by localized heating, thermal loading experiments were also performed on doubly clamped Al 1100 and Hastelloy X plates (7.5 cm x 8 cm). All plates were heated by the SpotIR 4150 for three minutes at 90% power and naturally cooled for seven minutes. The SpotIR was placed directly behind the center of the plates. DIC images were recorded every 10 seconds for all 10 minutes of heating and cooling.

Figure 3.9 shows DIC contour plots of the out-of-plane displacement and in-plane strains measured at the peak of localized heating of a 1.5 mm-thick Al-1100-O plate. Localized heating, in this case, did not cause significant deformation. The out-of-plane displacement, W, contour shows noise across the plate surface and no clear indication of deflection. However, the $\varepsilon_{yy}$ contours display a peak strain at the center of the plate of 2150 µε. All three strain fields show noise at the edges of the contour, an indication that

Figure 3.11. Out-of-plane displacement (W) and in-plane strains ($\varepsilon_{xx}$, $\varepsilon_{xy}$, $\varepsilon_{yy}$) of the doubly clamped Al 1100-H14 plate at 3 mins. of localized heating.
very little deformation occurred. The out-of-plane shape of each plate was also measured before localized heating, at peak heating, and after complete cooling. This progression is seen in Figure 3.10 from left to right with little to no change in the plate shape caused by localized heating. The slightly bent free edges of the plate resulted from the shearing process with which the plates were cut i.e. this process did not induce any plastic deformation in the plates.

The same localized heating procedure was performed on an Al 1100-H14 (strain-hardened) plate of 0.8 mm thickness. Figure 3.11 shows the out-of-plane displacement and in-plane strains at the peak of localized heating in this case. There was significant out-of-plane deformation (peak of 0.8 mm) as well as increased strains at the plate center due to heating (recall no mechanical loading is present here – only localized heating). The effect of localized heating is evident in the strain fields despite measurement noise, particularly at the contour borders. Figure 3.12 shows the out-of-plane shape before, during, and after heating. A clear bowing of the plate is seen in the center plot corresponding to the peak of the heating process, with the plate center moving away from the cameras. An asymmetric residual plastic deformation is evident in the right contour plot after cooling, where the plate center remained slightly bent.

A 0.5 mm-thick Hastelloy X plate was also thermally loaded with the SpotIR 4150 in the doubly clamped configuration. The thinner Hastelloy X plate deformed more significantly than both aluminum plates, deflecting by 2.4 mm. Figure 3.13 shows out-of-plane displacement and in-
plane strains after three minutes of localized heating. All four contours clearly display the effect of the in-plane constraint caused by heating. The greater deformation of the Hastelloy X plate than the aluminum plates may be due to two main factors: smaller thickness and lower thermal conductivity. The Hastelloy X specimens were the thinnest of all plates tested (to compensate to some extent for being the stiffest material). The relatively high compliance from being thinner may have aided in producing higher deflections when thermally loaded. The difference between the thermal conductivity of aluminum and Hastelloy X is also an important factor to consider. At room temperature, pure aluminum has a thermal conductivity of 204 W/m K whereas that of Hastelloy X is only 9.2 W/m K [30], [32]. The lower thermal conductivity of Hastelloy X may have increased the effect of the localized thermal load as heat could not be dissipated away as effectively as in the aluminum plates. Another interesting difference between the 0.8 mm-thick aluminum and 0.5 mm-thick Hastelloy X plates was that the aluminum plate deflected towards the heater (see Figure 3.12) while Figure 3.14 shows the Hastelloy X moving away from the heater. This may have been caused by the plates’ initial shapes. Figure 3.12 shows the aluminum plate was bent slightly towards the heater but Figure 3.14 displays less of an initial curvature for the Hastelloy X plate. Both exhibited a residual plastic deformation.

Figure 3.13. Out-of-plane displacement (W) and in-plane strains ($\varepsilon_{xx}, \varepsilon_{xy}, \varepsilon_{yy}$) of the doubly clamped Hastelloy X plate at 3 mins. of localized heating.
3.2.3 Thermal Loading of the Fixed Plate

Fixed plates all-around were also thermally loaded. Like the doubly clamped plates, the increased mechanical constraint (compared to cantilevered beams) and greater surface area of the plate geometry promoted a multi-axial in-plane constraint caused by localized heating. The steel fixed frame, shown in Figure 2.4 and Figure 2.5, was used to enforce a fixed displacement and slope condition on all four sides of the plates. All fixed plates were thermally loaded with the same procedure used for the doubly clamped plates: heated for three mins at 90% power by the SpotIR 4150 and naturally cooled for seven minutes. DIC images were recorded every 10 seconds for all 10 minutes of heating and cooling.

A 1.5 mm-thick Al 1100-O plate fixed all-around was loaded first. The out-of-plane displacement and in-plane strains at peak loading are shown in Figure 3.15. Little out-of-plane displacement was measured. The in-plane strains display more obvious effects of the heating, most notably in the case of the shear strain,
The strain contours, however, also show elevated measurement noise at the borders of the DIC region of interest. The presence of this noise indicates that the deformation was not significant. The out-of-plane shapes measured before heating, at peak heating, and after cooling are shown in Figure 3.16 and do not exhibit appreciable change during and after heating. The large thickness, high thermal conductivity, and structural stiffness of the fixed Al 1100-O plate, similar to its doubly clamped counterpart, may have prevented localized heating from causing a measureable deflection.

A 0.8 mm-thick Al 1100-H14 fixed plate was then also thermally loaded. The out-of-plane displacement and in-plane strains at peak loading are shown in Figure 3.17. The center of the aluminum plate deflected towards the heater by approximately 1 mm. The strain contours show a clear change from those for the 1.5 mm-thick Al 1100-O plate. The $\varepsilon_{xx}$ and $\varepsilon_{yy}$ fields are symmetric, with compression at the plate center and tension at the edges. As expected, tensile strain (the red contours) in the

Figure 3.16. Out-of-plane shape (Z) of the fixed Al 1100-O plate before heating (left), at peak heating (center), and cooled (right) $\varepsilon_{xy}$. The strain contours show a clear change from those for the 1.5 mm-thick Al 1100-O plate. The $\varepsilon_{xx}$ and $\varepsilon_{yy}$ fields are symmetric, with compression at the plate center and tension at the edges. As expected, tensile strain (the red contours) in the

Figure 3.17. Out-of-plane displacement (W) and in-plane strains ($\varepsilon_{xx}, \varepsilon_{xy}, \varepsilon_{yy}$) of the fixed Al 1100-H14 plate at 3 mins. of localized heating
shorter y-direction (2940 µε) was greater than in the longer x-direction (1680 µε). Localized heating of this plate also caused a permanent residual deformation. Figure 3.18 shows the plate as it moved to its maximum deflection at peak heating and shows a plastic out-of-plane displacement of approximately 0.2 mm towards the heater.

A 0.5 mm-thick Hastelloy X fixed plate was thermally loaded in the same manner as the aluminum plates. The out-of-plane displacement and in-plane strains at peak heating are shown in Figure 3.19. The displacement and strains (except for the shear strains) were symmetric about both central axes of the plate. The shear strains were antisymmetric. The Hastelloy X plate moved towards the heater, just as the Al 1100-H14 plate did. The $\varepsilon_{xx}$ strain field shows two maxima of strain, directly to the left and right of the plate center. The $\varepsilon_{yy}$ contour displays a saddle-like distribution of strain with tension above and below the plate center and slight compression to the left and right. The out-of-plane shape throughout the experiment is seen in Figure 3.20. The plate was left with a residual out-of-plane displacement after cooling. As in the case of the doubly clamped plates, the thinner and less
thermally conductive Hastelloy X fixed plate deformed more than the pure aluminum plates. A second Hastelloy X plate was loaded identically and produced the same results.

3.2.4 Combined Thermoacoustic Loading Response

Localized heating experiments demonstrated the effects of thermal gradients on plates with doubly clamped and fully fixed boundary conditions. In the pursuit of understanding the combined loading environment of vibration and localized thermal loads, a set of experiments were performed on a Hastelloy X cantilevered beam. The beam was forced with harmonic loading, as described in section 3.1.1, and the SpotIR 4150 was placed directly at the beam center, as shown in Figure 2.12. The beam was heated to a steady state and the resonant modes of the beam were identified with the same method as section 3.1.1. The resonant frequency results of the room temperature and localized heating experiments are compared in Table 3.2. Except for the first resonant mode, the frequency of each mode increased with the addition of localized heating. While the beam center became more compliant due to localized heating, the increase in resonant frequencies with heating

<table>
<thead>
<tr>
<th></th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room Temperature</td>
<td>7.5</td>
<td>47</td>
<td>153</td>
<td>304</td>
</tr>
<tr>
<td>Localized Heating</td>
<td>7.5</td>
<td>53</td>
<td>187</td>
<td>357</td>
</tr>
</tbody>
</table>
suggests that the stiffness of the entire vibrating structure increased. This stiffening from localized thermal loading contrasts prior work which reported softening behavior with uniform heating [23]. The shapes of the second, third, and fourth resonant modes under combined loading are shown in Figure 3.21. The area heated by the SpotIR 4150 is shown as well. These shapes remained similar to those observed at room temperature.

Figure 3.21. Resonant modes 2, 3, and 4 of the cantilevered Hastelloy X beam subject to thermoacoustic loading
CHAPTER 4: INFLUENCE OF MICROSTRUCTURE ON RESPONSE

4.1 Oligocrystal Specimens: Background

Performing experiments beyond surveying thermal loading response, vibration loading response, and combined environment response at the structural scale was the second key objective of the present work. It is well known that damage to materials and structures initiates at small length scales and evolves into failure at the global scale. Therefore, when progressing towards promoting thermoacoustic fatigue failure, it is necessary to study microstructural level phenomena. Prior work has demonstrated strain localization, seen in Figure 4.1, and micro-cracking in a polycrystalline material [27], [29]. Cyclic fatigue caused interactions at grain boundaries which led to heterogeneous buildup of plastic strain without cracking. Continued cyclic fatigue showed these areas of strain localization in Figure 4.1 corresponded directly with locations of fine cracks developing in the material.

Studying the interaction of microscale and structural scale responses on damage in polycrystalline materials has not only focused on small length scales comparable to the grain size. Instead of performing experiments on as-received material with small grains, oligocrystal specimens have been used to observe “microstructural” phenomena which occur at the global scale. Such oligocrystal specimens, in some sense, enable the study of multi-scale behavior but at a single measurement scale [72]–[76]. Specimens are typically treated, for

Figure 4.1. Effective strain localization after 1000 fatigue cycles with overlaid grain map from [29]
instance annealed, to grow grains to the millimeter scale of the samples to be used in the experiments. Figure 4.2 shows an example of such a copper oligocrystal specimen with a single layer of large, grown grains [72]. This specimen exhibited a strongly heterogeneous axial strain distribution when loaded in tension (at 0.075 average axial strain), as seen in Figure 4.3. Another study performed plane strain compression tests on a pure aluminum oligocrystal [74]. The rectangular aluminum block was compressed in a channel die setup and DIC was used to measure ex-situ displacement and strains. Figure 4.4 shows the equivalent strain on the specimen surface after an 8% reduction in specimen thickness. There is a clear distinction in strain between several of the grains (boundaries are marked with white lines) while some grains appear to share a similar level of strain.
4.2 Oligocrystal Sample Preparation

4.2.1 Annealing of Aluminum

The experiments and procedures from prior work listed in section 4.1 were the basis for the oligocrystal studies in the present work. The first step in this process was creating large-grained specimens through annealing of Al 1100-O. Coupon samples of Al 1100-O (1.5 cm x 1.5 cm) were placed in a Thermo Scientific™ Thermolyne™ furnace for a series of hold times at 600˚C, following the method of [75]. The grain size of the as-received aluminum was measured with optical microscopy to be approximately 30 µm. The aluminum coupon samples were annealed for 2, 4, 6, 8, 10, 12, 24, 48, and 72 hours at 600˚C to enlarge the grains. Figure 4.5 shows the effects of these annealing times on the grain structure. In all cases, centimeter-scale recrystallized regions were created due to the heat treatment. Grain growth appeared to plateau after at least 2 hours. Little difference was observed between samples of different annealing times. Figure 4.6 shows an aluminum beam (6.5 cm x 1.5 cm x 1.5 mm) annealed for 8 hours at 600˚C and an aluminum plate (9 cm x 11 cm x 1.5 mm) annealed for 2 hours at 600˚C. Large recrystallized regions on the right half of the beam stretch across the nearly the entire beam width while a cluster of smaller grains grew in the center.

Figure 4.5. Al 1100-O annealed at 600˚C for 2 hours to 72 hours with red grain boundaries
The plate contains a mixture of grain sizes with several large centimeter-sized grains at the plate center and smaller grains interspersed throughout. Later specimens were annealed for 2 hours at 600˚C due to the plateau in growth observed around 2 hours.

4.2.2 Specimen Preparation for Microstructural Analysis

Aluminum specimens were ground, polished, and etched to reveal grain boundaries. Beam specimens, such as the one shown at the top of Figure 4.6, were attached to the contra-rotating head of a Struers DAP-V grinding and polishing machine with Crystalbond™ adhesive. Two silicon carbide papers were used to grind the specimens to be co-planar. Three polishing steps refined the specimen surface.

Table 4.1. Grinding and Polishing Steps for Aluminum 1100-O Specimens

<table>
<thead>
<tr>
<th>Paper/Pad</th>
<th>Compound</th>
<th>Lubricant</th>
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<td>250</td>
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<td>Distilled Water</td>
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<tr>
<td>Buehler Policloth</td>
<td>3 µm diamond suspension</td>
<td>Distilled Water</td>
<td>Yes</td>
<td>150</td>
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<tr>
<td>Buehler Chemomet</td>
<td>0.06 µm colloidal silica suspension</td>
<td>Distilled Water</td>
<td>Yes</td>
<td>150</td>
</tr>
</tbody>
</table>
until a mirror finish was achieved. Details of each grinding and polishing step are listed in Table 4.1. Specimens were washed thoroughly with soap and water before and after each polishing step. Specimens were then immersion etched with a 10% NaOH solution for 12 minutes to reveal the grain boundaries. The large size of the plates prevented them from being effectively ground and polished. Instead, they were directly etched to show the grain boundaries.

### 4.3 Oligocrystal Beam Bend

Bending experiments were conducted with oligocrystal beams to investigate the effect of the grown grains on local and global behavior. A bending test was selected as a simplified precursor to out-of-plane vibration loading. Companion experiments were performed on beams made from as-received material to compare to oligocrystal experiments.

![Figure 4.7. Incremental beam bending setup](image)

![Figure 4.8. Axial strain fields of oligocrystal beam from 1 – 10 mm of tip displacement with grain map overlay](image)
The beam shown in Figure 4.6 was cantilevered and incrementally bent from 0 mm to 10 mm of tip displacement using the experimental setup shown in Figure 4.7. DIC images were acquired at each step of bending. The residual shape of the beam after bending was also measured.

Figure 4.8 shows axial strain fields of the beam from 1 mm to 10 mm of tip displacement. Elevated strains are clear from the beginning of bending and become highest away from the root of the beam. This unusual behavior was compared to a beam made with as-received aluminum. The residual equivalent strain fields of both beams after 10 mm of tip displacement are shown in Figure 4.9 with line scans of the mid-width strains. The as-received beam, on the right side of the figure, displays a sharp increase in strain at the beam root, where plastic hinging occurred. This hinging at the root was not present in the oligocrystal specimen, where the heterogeneity of the oligocrystal promoted strain localization away from the root. The left side of Figure 4.9 shows the equivalent strain peaking at 0.013 within the large grain just right of the beam center. The residual axial, transverse, and shear strain fields of the oligocrystal and as-received beams are shown in

Figure 4.9. Residual equivalent strain in oligocrystal (left) and as-received (right) beams after 10 mm tip displacement with mid-width line scans
Figure 4.10. Residual axial, transverse, and shear strains of oligocrystal (left) and as-received (right) beams after 10 mm displacement

Figure 4.10. The as-received strain fields are symmetric across the width of the beam and show slight anticlastic bending. The oligocrystal strain fields are somewhat different. The dissimilarity of the responses is most evident in the $\varepsilon_{xx}$ field due to the bending nature of the experiment and the beam geometry of specimens.

The same experiment was performed with a second oligocrystal beam. The residual equivalent strain after 10 mm of tip displacement is shown in Figure 4.11. Unlike the previous oligocrystal specimen, plastic hinging occurred at the root of the beam. The strain field, however, also did not match the behavior of the as-received specimen. The heterogeneity of the oligocrystal led to strains that were asymmetric about the mid-width of...
the beam. For this beam and the as-received beam, strains away from the beam root were insignificant compared to the hinging behavior at the fixed end. DIC results of the global behavior of the beams also did not establish clear correspondence between displacement and strain fields and the grain structure. A third oligocrystal beam bend was performed with a magnified view of the beam root and with finer bending increments with the intention of finding a strong correlation between deformation and grain structure.

The magnified experiment was performed with the same setup as previous specimens and applied a maximum of 2 mm of tip displacement. The axial strain at 2 mm of tip displacement and after the experiment with a grain map overlay are shown in Figure 4.12. The maximum strain was located away from the root. Like the other oligocrystal experiments, the response differed from the as-received specimen but did not display an obvious connection between the grain structure and strain distribution.

The oligocrystal beam bend experiments shed light on the effect of grain structure heterogeneity on out-of-plane deformation. While the response of large-grained specimens deviated clearly from the as-received specimen, no clear conclusion was drawn to link deformation to the grain structure. This may have been due to the thickness of the specimens preventing the
formation of columnar large grains through the specimen thickness. Varying grain structure through the specimen thickness would have presented the impression of an oligocrystal at the surface without truly revealing oligocrystal behavior.

4.4 Thermal Loading Response

4.4.1 Doubly Clamped Plate

Oligocrystal plates were also subjected to the thermal loading experiments described in section 3.2.2. A doubly clamped, 1.5 mm-thick Al 1100-O plate, annealed at 600°C for 2 hours, was heated with the SpotIR 4150 for three minutes at 90% power and left to naturally cool for seven minutes. DIC images were recorded for all ten minutes of heating and cooling. The out-of-plane displacement and in-plane strains at peak heating are shown in Figure 4.13. Measurement noise can be seen in the out-of-plane displacement field. No correlation between the strain fields and grain structure is evident. Like the thermal
loading experiments of the as-received 1.5 mm-thick aluminum plates, the large thickness and high thermal conductivity of the specimens prevented significant deformation from localized heating. To verify whether the grown grains of this plate were columnar through the plate thickness, grains on both surfaces of the plate were mapped and are shown in Figure 4.14. Comparison of the red and green grain maps show that the surface grains do not extend through the plate thickness. With potentially several layers of grains between the front and back surfaces of the plate (and other oligocrystal specimens), the lack of connection between deformation and grain structure was unsurprising. The out-of-plane shapes before, during, and after heating of the doubly clamped oligocrystal plate are shown in Figure 4.15. A slight shape change can be seen due to localized heating. The edges of the plate were bent during machining, similar to the plate in Figure 3.10.

4.4.2 Fixed Plate

A fixed Al 1100-O oligocrystal plate, shown in Figure 4.6, was thermally loaded as described in section 3.2.3 with the SpotIR 4150. The out-of-plane strains $\varepsilon_{\text{xx}}, \varepsilon_{\text{xy}}, \varepsilon_{\text{yy}}$ of the fixed Al 1100-O oligocrystal plate at 3 mins. of localized heating with grain map overlay.
displacement and in-plane strains at peak heating are shown in Figure 4.16. The oligocrystal plate underwent greater deformation than its as-received counterpart (shown in Figure 3.15). The plate center deflected away from the heater by approximately 0.1 mm. Tensile strains were localized at the center of heating. Some distortion is apparent in the strain fields seen in Figure 4.16. It was not obvious whether the asymmetry of these fields was caused by the grain structure or simply measurement noise from DIC due to small deformation. The out-of-plane shape throughout the experiment is shown in Figure 4.17. The plate center is seen to deform away from the heater at peak localized heating and retained a residual deformation after cooling. This was a major deviation from thermal loading response of the fixed as-received 1.5 mm-thick aluminum plate (shown in Figure 3.16) which did not experience any out-of-plane deformation. This difference highlights the likely change in bulk material properties brought about by the annealing process. While the large surface grains contributed relatively little to the response of the oligocrystal plate, the entire structure behaved differently than the untreated, as-received specimen.
CHAPTER 5: THERMOACOUSTIC FATIGUE FAILURE

Achieving fatigue failure in a combined loading environment of vibration and thermal loading was the final major objective of the present work. Prior work, described in Chapter 1, has surveyed the pre-buckled and post-buckled behavior of beam and plate structures with various boundary conditions. Promoting plastic behavior and fatigue failure under combined loading conditions in the laboratory setting was the next step to enhance our current understanding of thermoacoustic failure in aerospace structures, especially thin panels of hypersonic vehicles.

5.1 Room Temperature Vibration Fatigue Failure

5.1.1 Fatigue Failure of Aluminum 6061-T6

Fatigue failure was explored with a vibration loading experiment of a cantilevered Al 6061-T6 beam at room temperature. The experimental setup was identical to Figure 2.1. A thin beam (4.5 cm x 1.5 cm x 0.4 mm) was cantilevered in an aluminum clamp. To accelerate fatigue failure, the beam, shown at the top of Figure 5.1, had an electrical discharge machined central notch (0.3 mm width) located 3 mm from the root of the beam. The notch served as a stress concentrator to promote plasticity under high-cycle loading and as a fatigue crack initiator.

The beam was excited harmonically at the first resonant mode (195 Hz) for approximately 13 million cycles. Figure 5.1 shows the cantilevered Al 6061-T6 fatigue failure specimen (top) and fatigue crack (bottom).
cycles. The Fulcrum Mode of Vic-Snap was used to record DIC images every 985 cycles at the peak displacement of oscillation. DIC results showed no change in the beam shape throughout the entire experiment. However, inspection of the beam revealed that a plastic hinge had formed at the notch at an unknown point during excitation. Two fatigue cracks were seen to have grown from the ends of the notch. The notch which grew “down” through the beam in Figure 5.1 propagated through to the bottom edge of the specimen. The notch which grew “up” in the opposite direction, shown also bottom of Figure 5.1, extended only partially towards the top edge of the beam.

Figure 5.2. Schematic of fracture surface of cantilevered Al 6061-T6 beam

Figure 5.3. SEM images of fracture surface of cantilevered Al 6061-T6 beam
The fracture surface of the beam specimen, represented by the translucent pink datum plane in Figure 5.2, was studied further with scanning electron microscopy (SEM). Four SEM images of the surface are shown in Figure 5.3, beginning with the largest field of view in the top left of the figure and moving to the micron scale in the bottom right. The locations of each magnified image are shown in the previous field of view with colored boxes. The SEM images show clear fatigue striations at multiple scales as the crack propagated through the material. In the top left (220x) image of Figure 5.3, large-scale striations form a parabolic-like pattern perpendicular to the direction of crack advancement. Small-scale striations appear as series of ridges at different angles as crack propagation was guided by grain orientations. These features contrast with the void growth seen in Figure 5.4, where the specimen was broken by hand for SEM imaging. The top of the figure shows the end of the fatigue crack. This region transitions to a thinner, necked region filled with spherical pockets, typical indicators of ductile material failure. DIC paint speckles can be also seen on the left side of the figure on the specimen surface.

5.2 High Temperature Vibration Fatigue Failure

5.1.2 Fatigue Failure of Hastelloy X

Fatigue failure experiments were performed with localized heating with a series of experimental setups and Hastelloy X specimens. Large, doubly clamped beams were subjected to harmonic excitation and localized heating, as seen in Figure 2.2. These experiments were
continuously run for multiple days with no indication of plastic deformation. Subsequently, cantilevered Hastelloy X beams with stress concentrators, such as the specimen shown in Figure 5.5, were also harmonically excited to promote fatigue failure. The stress concentrators sought to encourage plasticity and increase specimens’ compliance. DIC results from these experiments also did not show any signs of plastic deformation.

A smaller Hastelloy X beam (7 cm x 1.5 cm x 0.5 mm) with a central notch was also tested. This beam was excited harmonically for approximately 885,000 cycles at the first resonant mode (79 Hz) for over three hours. Contours of out-of-plane displacement at each half hour (147,500 cycles) during the experiment are shown in Figure 5.9. Minute changes in the out-of-plane displacement are seen throughout the experiment but no significant plasticity was observed.

A small Hastelloy X beam (7 cm x 1.5 cm x 0.5 mm) with a central notch was subjected to combined environment loading with localized heating from the SpotIR. The steady state temperature distribution shown in Figure 5.8 was measured separately with
thermocouples (which were not attached to the beam during vibration) in a heating study. The beam was excited at the first resonant mode (79 Hz) for 400,000 cycles. DIC results recorded every 100 cycles (1.27 secs.) showed no deformation as well as significant distortion from image saturation caused by glowing, seen in Figure 5.8, caused by localized heating.

These Hastelloy X thermoacoustic loading experiments, while serving to refine the fatigue failure experimental setup and specimens with stress concentrations, indicated that a change of material was necessary to promote plasticity and failure with the available experimental equipment. This issue can be resolved by performing experiments on a material of lower fracture toughness or increasing the applied vibration force with a more powerful shaker system.

Figure 5.8. Temperature distribution during thermoacoustic loading of cantilevered Hastelloy X beam

Figure 5.9. Out-of-plane displacements every 30 mins. for cantilevered Hastelloy X beam with central notch
CHAPTER 6: CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

The work presented here seeks to enhance our understanding of extreme combined environment behavior of aerospace structures. Our experiments used modern, non-contact optical methods for displacement and strain measurement to collect high-fidelity, full-field data and build on the knowledge of prior work in plate vibration behavior. These experiments were conducted to achieve three main objectives: 1) understand structural response in the thermoacoustic environment with special focus on the role of localized heating and thermal gradients, 2) investigate the impact of microstructural effects in out-of-plane deformation and any connection to thermal gradients, and 3) promote plasticity and achieve fatigue failure in a combined loading environment.

Toward the first objective, the independent vibration response of a cantilevered beam and thermal loading responses of doubly clamped and fully fixed plates were considered. The linear elastic resonance of the cantilevered beam was characterized and validated against theoretical results. The resonant behavior of a cantilevered beam with localized heating was then compared to its room temperature companion, showing an overall stiffening of the structure despite a local increase in compliance due to thermal softening. Broadband excitation of doubly clamped beams revealed the prevalence of resonant mode shapes in specimen response. Instead of exhibiting a purely stochastic response, the doubly clamped beams subject to broadband excitation showed frequently occurring out-of-plane deflected shapes which matched the resonant mode shapes of the structure. Thermally loaded plates demonstrated combined effects of mechanical boundary conditions and thermal gradients caused by localized heating. 2D thermal stress gradients were seen to cause significant plastic out-of-plane deformation. The addition of fixed mechanical
boundary conditions amplified this effect. Material differences in thickness and thermal conductivity caused notable variations in behavior between aluminum and Hastelloy X specimens. Thicker aluminum plates with high thermal conductivity showed less out-of-plane deflection than thinner Hastelloy X plates with low thermal conductivity.

The second objective was addressed with the production of oligocrystal specimens, which allowed microstructural phenomena and global behavior to be observed at the same measurement scale. Specimens of pure aluminum were annealed to create large, centimeter-sized grains. These coarse microstructures, too large to comprise a representative volume element, were shown to significantly influence the plastic hinging behavior of thin, cantilevered beams as well as the thermal loading response of doubly clamped and fully fixed plates. While the responses of oligocrystal and as-received specimens differed greatly, no clear correlation between oligocrystal grain structure and displacement and strain fields was established.

Plasticity and fatigue failure were achieved at room temperature with the harmonic excitation of a cantilevered, Al 6061-T6 beam with a central notch stress concentrator. Two fatigue cracks were grown after 13 million cycles of loading. SEM imaging revealed features of the fatigue fracture surface influenced by grain orientation. Fatigue failure experiments of Hastelloy X beams performed with localized heating failed to promote plasticity. These experiments, however, were an important step in refining the experimental setup and realizing that a change to a more compliant material with lower fracture toughness was necessary to move beyond elastic behavior.
6.2 Future work

The present work encompasses a progression of experiments which were aimed to attain a holistic understanding of thermoacoustic structural behavior with applications towards hypersonic aerospace vehicles. A number of possible directions exist for future work which would build on the experiments presented in this thesis. A first step would be to achieve fatigue failure in the thermoacoustic environment. While this goal was not accomplished in the present work, the experimental setup, methods, and materials necessary to do so are described in this thesis.

The broadband excitation response of simple structures also warrants further study. Fatigue failure, at room temperature and then with localized heating, with broadband excitation would perhaps represent a physically realistic scenario which has historically not been well characterized. This experiment would benefit from the use of high-speed imaging to capture high-fidelity DIC images and a more powerful shaker system to amplify out-of-plane deflection.

The aluminum oligocrystals described in the present work can be reproduced, but with a thinner material. The thickness of the Al 1100-O used in the present work impeded the growth of columnar grains which encompass the entire thickness of the specimen. Thinner specimens could resolve this issue and be used to demonstrate a connection between out-of-plane deformations and grain structure in high-cycle fatigue experiments. Localized heating could then be applied to potentially link thermal gradients to grain structure and deformation.

Other arrangements of non-uniform heating could be applied to these experiments. Strip and spot infrared heaters as well as induction heating could be used to study the effects of complicated localized heating patterns on linear resonant behavior, post-buckled behavior, and failure.
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APPENDIX: Fringe Projection

Fringe projection profilometry was explored as an alternative potential method of measuring out-of-plane displacements of beams and plates. Fringe projection has been used in a wide variety of scientific and engineering fields to measure the three-dimensional profile of objects [77]–[88]. The method involves projecting a sinusoidal fringe pattern onto a three-dimensional target object and a background reference plane, as shown in Figure A.1. The presence of the object alters the phase of the projected fringes. Fringe analysis techniques are applied to images of the reference plane and object with fringes to compute the phase modulation. A phase-unwrapping algorithm is then used to calculate the three-dimensional position of the object [87]. A fringe projection setup that was used in the present work is shown in Figure A.1. The system was calibrated to ensure the camera axis was perpendicular to the reference plane. A large speckled board was placed in front the reference plane.

Figure A.2. Components of a fringe projection system from [87]
plane and two images of the board were acquired by the camera at different stand-off distances. The camera was moved on a translation stage to do this. The images were correlated with 2D-DIC and the total displacement vectors were visualized, seen in Figure A.3, to find the center of displacement i.e. location of zero apparent displacement due to moving the camera. If the center of displacement was at the direct center of the “deformed” image, the camera was perpendicular to the speckled board and reference plane. Otherwise, the camera was adjusted accordingly and the calibration process was redone. Fringe projection images were processed in the JOSHUA software developed by Heredia Ortiz [82]. Figure A.2 shows each step of this process with an example image included with the JOSHUA software. The images were loaded into the software and masked to subtract the non-object background. The parameters of the fringe projection system (see [82]) were inputted and the resulting out-of-plane shape contour and three-dimensional plot could be visualized. A pair of stacked boxes were used to
further test the method and software (and refine the density of the MATLAB-generated fringe pattern). The resulting object surface profile and three-dimensional shape are shown in Figure A.4. The shape of the boxes was generally represented well but the fringe pattern can still be seen in on the 3D shape.

Fringe projection was intended to be used to measure the three-dimensional shape of vibrating beams and plates. A static bend of a cantilevered beam was

Figure A.5. Fringe projection of stacked boxes

Figure A.6. Out-of-plane shapes of cantilevered beam measured with fringe projection
performed to evaluate the accuracy of the fringe projection system. Figure A.5 shows this experimental setup. The beam tip was deflected 5 mm, 10 mm, and 14 mm. Images were captured at each step and processed with JOSHUA. Mid-width line scans of the beam out-of-plane shapes at each of these bending increments are shown in Figure A.6. The measurements did not accurately capture the displaced beam and showed considerable noise.

Fringe projection profilometry, although widely used in other fields of research, was determined to yield less accurate measurements of out-of-plane shape than DIC and was not used in the presented experiments. However it may become useful in future efforts, especially in applications where two identical cameras are not available (since fringe projection uses only one camera).