INLINE COHERENT IMAGING
OF LASER KEYHOLE WELDING

by

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For Mark and Sylvia
Abstract

Laser keyhole welding is an emerging materials processing technique offering many advantages over more conventional joining methods. High intensity laser light is applied to a sample, melting and evaporating the metal in its path. The resulting recoil pressure drives a narrow capillary (a ‘keyhole’) of vapour into the metal, allowing delivery of laser energy deep beneath the surface. The resulting weld seams are deep, narrow, precisely positioned, and often require no filler material. However, the process is inherently unstable and its underlying physics are not straightforward. The keyhole has traditionally proven difficult to measure, which hinders efforts to model, understand, and control this process. Inline coherent imaging (ICI), a laser-based ranging technique, has previously been demonstrated as an effective tool for in-situ measurement of the keyhole depth. In this work, I seek to improve our understanding of ICI’s measurement of the keyhole, and enhance its utility. A new algorithm that tracks keyhole depth with zero resolution loss is demonstrated. Mechanisms responsible for signal losses in the weld image are explored, and a modified ICI system producing doubled line-rates near 600 kHz is realized. Active imaging beam scanning is implemented, increasing the resolving capability of the ICI system to three spatial dimensions. With this new capability, I measure keyhole morphology in-situ—an entirely novel way of observing this elusive and volatile physical system.
Acknowledgments

I have been fortunate in my studies with the Queen’s Ultrafast group, to be surrounded by extremely talented, driven, and competent colleagues. I have many more tall shoulders to stand on than I do feet with which to stand. It has been a pleasure and a privilege to be taught and mentored by, to share knowledge and experience with, and to work alongside such exceptional people. The experimental work carried out in our group, as well as the upkeep and development of the apparatus, is often undertaken in a collaborative manner. Any of the work presented in this thesis that was not directly aided by my colleagues was performed with the benefit of their knowledge and support, and credit is due to each of them for its completion.

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Contents

Abstract ii

Acknowledgments iii

Contents iv

List of Tables vii

List of Figures viii

List of Abbreviations x

Chapter 1: Introduction 1

Chapter 2: Background 9

2.1 Introduction ............................................. 9

2.2 Inline Coherent Imaging ................................. 10

2.2.1 The Michelson Interferometer ........................ 12

2.2.2 The Interference Signal ................................ 13

2.2.3 Derivation for a Gaussian Spectral Envelope ............ 17

2.2.4 Discretization of the Measurement ..................... 20

2.3 Imaging Artifacts ........................................ 21

2.3.1 Autocorrelation, Multiple Reflection, Dispersion, and Saturation 21

2.3.2 Motion Artifacts ....................................... 23

2.4 Laser Keyhole Welding .................................... 26

2.4.1 Features of the Keyhole .............................. 28

2.4.2 Existing Diagnostics .................................. 33

2.4.3 Analytic and Numerical Modelling Approaches .......... 40

2.4.4 Defects & Instability ................................ 46

2.5 ICI and the Keyhole ..................................... 47
List of Tables

3.1 Measured power output of the process laser . . . . . . . . . . . . . . 53

5.1 Estimated effective integration time of the camera . . . . . . . . . . . 108

5.2 Focussing optic collection geometry . . . . . . . . . . . . . . . . . . 122
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Schematic diagram of the Michelson interferometer</td>
<td>12</td>
</tr>
<tr>
<td>2.2</td>
<td>Schematic keyhole in cross-section</td>
<td>29</td>
</tr>
<tr>
<td>2.3</td>
<td>A sectioned weld bead</td>
<td>32</td>
</tr>
<tr>
<td>2.4</td>
<td>Power flow into the keyhole</td>
<td>33</td>
</tr>
<tr>
<td>3.1</td>
<td>Schematic diagram of the macroprocessing station</td>
<td>50</td>
</tr>
<tr>
<td>3.2</td>
<td>Schematic diagram of the ICI system</td>
<td>55</td>
</tr>
<tr>
<td>3.3</td>
<td>Output spectrum of the superluminescent diode</td>
<td>56</td>
</tr>
<tr>
<td>3.4</td>
<td>Processed ICI noise floor</td>
<td>61</td>
</tr>
<tr>
<td>3.5</td>
<td>Example ICI image</td>
<td>63</td>
</tr>
<tr>
<td>3.6</td>
<td>Signal intensity rolloff of the ICI system</td>
<td>65</td>
</tr>
<tr>
<td>3.7</td>
<td>Drawing of the mounted galvanometer scanners</td>
<td>69</td>
</tr>
<tr>
<td>3.8</td>
<td>Calibration of the galvanometer scanners</td>
<td>71</td>
</tr>
<tr>
<td>3.9</td>
<td>Measured field curvature of the galvanometer scanner system</td>
<td>73</td>
</tr>
<tr>
<td>4.1</td>
<td>ICI images</td>
<td>80</td>
</tr>
<tr>
<td>4.2</td>
<td>ICI details</td>
<td>86</td>
</tr>
<tr>
<td>4.3</td>
<td>Decimated ICI data</td>
<td>91</td>
</tr>
<tr>
<td>4.4</td>
<td>Group-based depth tracking flow chart</td>
<td>94</td>
</tr>
<tr>
<td>4.5</td>
<td>Depth-tracked ICI</td>
<td>96</td>
</tr>
</tbody>
</table>
4.6 Keyhole initiation in carbon steel ........................................ 97
5.1 The axial motion artifact in ICI ........................................... 104
5.2 Signal intensity v. interface speed ..................................... 107
5.3 Fitting the effective camera integration time ...................... 108
5.4 Signal intensity v. interface speed with corrected integration time 109
5.5 Mean signal intensity for different camera timings ............... 112
5.6 Signal fill factor for different camera timings .................... 113
5.7 Initial keyhole interface signal intensity v. speed in different materials 114
5.8 High-speed multiplexed ICI images ................................. 118
5.9 Signal intensity and fill factor through a 100 mm lens .......... 121
5.10 Off-axis backscatter from the keyhole ........................... 122
6.1 Transverse and longitudinal keyhole profiles ..................... 129
6.2 Interpolated transverse keyhole scan ............................... 132
6.3 Top view of a longitudinal keyhole scan ......................... 133
6.4 Super-Gaussian fit function settling times .......................... 138
6.5 Keyhole width v. feedrate ............................................. 140
6.6 ICI & X-ray keyhole profile .......................................... 142
6.7 Signal characteristics for different surface states .............. 145
## List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D-ICI</td>
<td>Three-dimensional ICI</td>
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<tr>
<td>A-line</td>
<td>Amplitude Line</td>
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<tr>
<td>CCD</td>
<td>Charge-Coupled Device</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary metal-oxide-semiconductor</td>
</tr>
<tr>
<td>CT</td>
<td>Computed tomography</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DFT</td>
<td>Discrete Fourier Transform</td>
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<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
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<tr>
<td>FWHM</td>
<td>Full Width at Half Maximum</td>
</tr>
<tr>
<td>I/O</td>
<td>Input/Output</td>
</tr>
<tr>
<td>ICI</td>
<td>Inline Coherent Imaging</td>
</tr>
<tr>
<td>IFSW</td>
<td>Institut für Strahlwerkzeuge</td>
</tr>
<tr>
<td>IR</td>
<td>Infra-red</td>
</tr>
<tr>
<td>LDD</td>
<td>Laser Depth Dynamics Inc.</td>
</tr>
<tr>
<td>NA</td>
<td>Numerical Aperture</td>
</tr>
<tr>
<td>NIST</td>
<td>National Institute of Standards and Time</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>--------------</td>
<td>----------------------------</td>
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<tr>
<td>OCT</td>
<td>Optical Coherence Tomography</td>
</tr>
<tr>
<td>PSO</td>
<td>Position-Synchronized Output</td>
</tr>
<tr>
<td>PSU</td>
<td>Penn State University</td>
</tr>
<tr>
<td>QCW</td>
<td>Quasi-Continuous Wave</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
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<tr>
<td>ROI</td>
<td>Region of interest</td>
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<tr>
<td>SD-OCT/ICI</td>
<td>Spectral-Domain OCT/ICI</td>
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<tr>
<td>SLD</td>
<td>Superluminescent Diode</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>SS-OCT/ICI</td>
<td>Swept-Source OCT/ICI</td>
</tr>
<tr>
<td>TD-OCT/ICI</td>
<td>Time-Domain OCT/ICI</td>
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<tr>
<td>USAF</td>
<td>United States Air Force</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

The evolution of laser technology in the latter half of the twentieth century is an extraordinary achievement of human ingenuity. In little more than fifty years since its invention, the laser has altered the world substantially. The ability to command directed beams of light has captured our collective imagination in culture and entertainment. In practical terms, this technology has captured the physical sciences even more completely. Today it is difficult to name a branch of experimental science that does not employ lasers in some capacity. They have been ubiquitous for decades in data transfer: within optical drives in consumer electronics, barcode scanners, and telecommunications networks. The future of optical computing as an impending successor to electronic circuit elements looks bright. At this juncture, it is within reason to compare humankind’s harnessing of coherent light to that of fire, electricity, or agriculture, and its work is just beginning. The advance of the laser in industry as tool for material modification is already well underway, but the potential for further expansion is immense.

Lasers are already applied in material modification processes too numerous to
recount here. Among them are cutting, drilling, welding, cladding, additive manufacturing of metals, sintering, heat-treating, marking, etching, photopolymerization, and solubilization of photoresist in semiconductor production. Nearly any combination of materials or tasks employed in production of goods is a viable candidate. Every one of these processes calls for a different type of specialized laser light to achieve the desired effect on the material. The physics involved in each light-matter interaction is different, and characterization and optimization of each process constitutes a significant research effort spanning from factory floor to university laboratory.

Among the laser processes of growing interest to industry is laser keyhole welding. This is a method for welding metals using a continuous-wave or long-pulsed laser beam at high power densities (> $10^6$ W/cm$^2$). The name of this process (which has no explicit link to locksmithing) refers to the formation of a capillary or ‘keyhole’ of evaporated metal as the beam bores into the workpiece. This capillary allows the laser to deposit energy deep within the material, forming a melt volume several times deeper than it is wide and resulting in a precise and narrow weld seam. The vapour capillary is, by all accounts, inherently unstable. Due to its high aspect ratio and violent thermodynamics, as well as the intensity of the process laser, few techniques are capable of directly measuring its geometry. Many aspects of this process (the penetration depth of the keyhole, for instance) are not straightforward functions of the input parameters. In present-day practical applications, laser keyhole welding is accessible to industry at the cost of broad engineering tolerances, high part scrap rates, and exhaustive parameter space exploration. There is a pressing need for better experimental tools to clarify the process behaviour and physics.

Inline coherent imaging (ICI), is a near-infrared, laser-based ranging technique
derived from optical coherence tomography (OCT), a widely-used medical imaging method with a steadily-growing breadth of applications. Using a low-power laser, ICI measures the distance to optical interfaces along the beam path by comparing the frequency content of the backscattered radiation to that of a fixed reference path. The ICI measurement beam is superimposed spatially with a high-power process beam, used for cutting or welding, and measures the depth of the material surface in the light-matter interaction zone. With its high spatio-temporal resolution, this technique allows us to capture detailed images of material morphology changes during many laser processes, including keyhole welding.

To date, ICI has been demonstrated as a viable tool for measuring and controlling keyhole depth in laser welding applications. However, the millisecond time scales on which such measurements and control loops act only make use of a fraction of the temporal resolution available from ICI. In addition, the data reduction and processing steps involved can iron out useful information containing a more detailed and subtle view of the physics taking place. The fine spatio-temporal resolution and high sensitivity of ICI are still partially untapped as a window into the laser keyhole welding process.

An ICI image of a weld keyhole contains a great deal of detail and clues about the dynamics taking place, with potential to go far beyond depth measurement. Qualitative insights may be drawn by an experienced user that can shed new light on many un- or under-explored aspects of this academically fascinating and industrially relevant stochastic system. The importance of the interaction between the ICI measurement light and the laser keyhole welding process as a whole cannot be overstated. In addition to being a relatively fast, energetic and volatile macroscopic system, the
weld keyhole itself is an optically-induced phenomenon, which is critically dependant on the propagation characteristics of the light which drives it.

The role of the process light in maintaining even quasi-stable welding operation goes far beyond straightforward optical absorption in metal. Fresnel absorption angle, multiple reflections, plasma attenuation, scattering from vapour and particulate matter, and waveguiding all play roles in the light-matter interaction. This interaction plays out through a high-temperature, high-aspect-ratio volume of gases and (sometimes) plasma enclosed within a precarious, constantly-shifting envelope of molten metal. It follows that attacking such an optically rich system with an all-optical measurement method leads to a host of quirks and complexities affecting the interpretation of the resulting data. To fully utilize the impressive capabilities of this nascent imaging technique in a scientific setting, emphasis must be placed on understanding the interplay between the measurement and the system measured.

In Chapter 2, I address the current understanding of the weld keyhole and its relationship to the process beam. I introduce the relevant characteristics of the keyhole system, including the various defects and instabilities to which it commonly succumbs. I discuss the physical operating principles of ICI, and describe relevant aspects of its interaction with a material subjected to high-power laser radiation. Finally, I review the current state of measurement and monitoring of laser keyhole welding in industry and academia. In Chapter 3, I discuss and characterize the experimental apparatus used throughout the remainder of the thesis.

The richness of keyhole welding ICI data is apparent from even the most stable processing regimes in the most straightforward imaging configuration. With the imaging beam aligned coaxially to the process beam, the keyhole depth profile as a
function of time is collected and displayed as an image. Some aspects of the weld behaviour are intuitively clear from qualitative examination of the image, and quantitative analysis techniques have previously been implemented to assess time-averaged keyhole depth. This form of interpretation is extremely useful for development of industrial applications. However, enough artifacts and variability exist within the image that depth measurements must be extracted with care. Some treatment of the image data is necessary. The sheer volume of data produced often hinders more sophisticated analysis. To fully harness ICI’s potential to resolve the keyhole, reduction of raw data and extraction of desired metrics must be performed with care to preserve the measured signal correctly.

In Chapter 4, I address qualitative interpretation and quantitative treatment of static-mode ICI of keyhole welding. In static-mode imaging, the ICI beam is aligned coaxially to the process beam. I discuss qualitative interpretation of this form of ICI data for two drastically different keyhole systems. I examine the consequences of data decimation and depth tracking algorithms on the accuracy and precision of extracted measurements, and explain the necessity of such data reduction methods. I implement a more sophisticated tracking algorithm that measures the keyhole depth while significantly reducing data volume, filtering undesired artifacts and noise, and avoiding sacrifice of spatial or temporal resolution. As an example application of this technique to physical analysis of a weld keyhole, I examine the initiation of a keyhole in carbon steel over the first millisecond of laser exposure, and extract velocity and acceleration trends.

Close examination of static-mode ICI welding images reveals that the keyhole measurement is not continuous. The signal from the keyhole root (its lowest point)
disappears and reappears on timescales faster than milliseconds. This problem is ubiquitous in imaging of the weld keyhole, and its severity often results in more than 90% of measurements from the keyhole containing no useful data. This is a significant feature of the ICI signal that is not well understood. The loss of signal severely hampers the ability of ICI to measure keyhole dynamics in a detailed—as opposed to purely statistical—manner. These signal gaps occur on the same timescales as the irregular oscillations of the keyhole, and are intimately tied to the behaviour of the entire optical system. In practice, this problem detracts from the temporal detail of the measurements taken for process monitoring. It effectively reduces the time resolution of the measurement by orders of magnitude if the application requires knowledge of the keyhole on regular intervals. Furthermore, any study relying on time-series analysis to characterize the stochastic oscillations of the keyhole cannot be performed without an accurate continuous measurement series. If these signal losses can be understood and remedied, ICI might become a more powerful tool on both applied and academic fronts.

In Chapter 5, I examine different hypotheses regarding the underlying cause of the signal losses in ICI of keyhole welding. I explore the axial motion artifact, a phenomenon by which the motion of a brightly backscattering interface may cause complete attenuation of its signal in the image, in the context of ICI. First, I determine whether the effect occurs as theory predicts for a continuously moving interface. I then extend the analysis to observation of the keyhole with ICI through variation of relevant acquisition timing parameters. I implement a high-speed, multiplexed ICI system capable of unprecedented line rates for ICI and search for new understanding of keyhole dynamics. Finally, I observe the effects of optical geometry on the ICI
signal measured from the keyhole through a change of focusing optics in the laser head.

When addressing the physics of keyhole formation and behaviour, the complete keyhole geometry (not just its depth) is extremely important to the absorption of the process beam. The keyhole thermodynamics and fluid dynamics are a consequence of the process beam absorption pattern, which in turn depends on the shape of the keyhole. An ideal process measurement tool to enable testing of theoretical models of this system would continuously monitor the general keyhole morphology in three spatial dimensions with high temporal resolution. ICI might be capable of achieving at least part of this goal.

In Chapter 6, I discuss the implementation of a set of galvanometer scanner mirrors to steer the imaging beam in real time. This addition introduces two dimensions of lateral spatial resolution to the depth profiles generated by static-mode ICI. Using this new capability, I produce two-dimensional keyhole profiles (slices) to prove the concept of ICI as a high-precision tool for measurement of more general keyhole morphology. The—to my knowledge—first in-situ measurements of the transverse aspect of a steady-state keyhole are presented here. This data is used to construct time-resolved three-dimensional images of the evolution of the keyhole profile. Next, I develop a routine that extracts keyhole widths based on ICI profile data, to prove the concept of adding a dimension to keyhole geometry extraction from the ICI image. I assess the practical time resolution limits of this approach. In order to verify the accuracy of these ICI keyhole profiles, I present measurements of a keyhole captured simultaneously using transmission x-ray imaging and transversely-resolved ICI. Finally, I identify and measure several ICI signal characteristics linked to the physical
state of the sample surface. These metrics could enable automated surface state detection from ICI data—granting the ability to algorithmically segment and measure the extent of the molten pool surrounding the keyhole, for instance.

In Chapter 7, I address the results of these lines of inquiry, and discuss directions for future research encompassing ICI and laser keyhole welding. The versatility of this tool for monitoring the difficult-to-measure weld keyhole is extremely promising, and much of the experimental data that already exists has potential to pay continued dividends as our understanding of the nuances of the signal improves.

Certain portions of the work presented here are the result of collaborative efforts both within our group and with other academic institutions, and are indicated as such. In this work, I have pushed toward a more complete understanding of inline coherent imaging and the weld keyhole as a coupled system. Although ICI has been proven for the measurement of keyhole depth when accumulated over longer timescales, many open questions stand regarding the exact appearance of the measured signal and what it can tell us about the keyhole geometry and dynamics.
Chapter 2

Background

2.1 Introduction

This thesis attempts to shed light on the complicated interplay between two key elements—the laser weld keyhole and inline coherent imaging (ICI). In this chapter, I provide sufficient background physics to grant the reader an understanding of each element in isolation, and then introduce some of the complications that are anticipated to arise when the keyhole weld system and measurement system are brought together. I will also provide context for the use of ICI to monitor the weld keyhole, in terms of other techniques that have been applied for this purpose and the current state of numerical modelling of the keyhole system in the literature.

The tremendous practical potential of laser keyhole welding has generated a lot of interest in both industry and academia. In recent years, computer modelling has produced sophisticated physical models of the keyhole system, but the phenomena involved are numerous and their interactions often unpredictable. In addition, the keyhole geometry and dynamics have proven challenging to measure directly. The
result is that self-consistent and computationally expensive models are difficult and expensive to verify and improve upon. There is a pressing need for better and more accessible experimental tools to study this system. I believe that ICI is capable of filling this role. This chapter sets the stage for a more thorough investigation of the relationship between ICI and the weld keyhole than has previously been attempted.

2.2 Inline Coherent Imaging

Inline coherent imaging is a near-infrared, interferometric ranging method. The technique is based directly on optical coherence tomography (OCT), which was invented and first published in 1991 by David Huang et al. under the supervision of James G. Fujimoto at the Massachusetts Institute of Technology [19]. A near-infrared laser beam travels through an interferometer and impinges on a sample. Backscattered intensity from the sample re-couples into the interferometer and optical path length information is encoded in the resulting spectral interference pattern. The technique allows measurement of optical interfaces along the probe beam path with micron precision. Optical coherence tomography has since grown into a juggernaut in the field of bio-photonics and sees broad clinical use in ophthalmology. Many applications for OCT have taken root outside of the biomedical application space for which it was originally intended [44]. ICI may be counted among these.

Inline coherent imaging refers to the implementation of an OCT system such that the probe beam is superimposed coaxially with a second laser beam used for material modification. The goal of ICI is to directly measure the positions of material interfaces along the process beam path with high speed and precision. The ICI beam enters the work-piece along the same path as the machining light, granting direct
access to the dynamics of light-matter interactions in laser machining. Since the measurement requires no motion of the beam or triangulation, ICI is well-suited to measurement of processes that produce high-aspect-ratio features. In addition, the coherent nature of the detection scheme makes ICI robust to radiation produced by thermally-mediated processes. ICI has been in development at Queen’s University since 2007 [50]. Since then, it has been applied to process monitoring and control of micromachining [48, 33, 54, 53, 21], larger-scale high-power machining [58, 49, 59], ultrafast machining [51], cutting of hard tissue [34, 40], laser additive manufacturing, and laser keyhole welding [51, 5, 7]. The latter is the focus of my thesis.

The application of ICI to these various laser processes has primarily focused on measurement of the sample interface in the beam path as a function of time, allowing drilling progress or the depth of a laser weld to be recorded. More recent efforts have involved the implementation of ICI measurements as a closed-loop feedback mechanism. An algorithm that controls the laser based on the measured machining progress allows automatic optimization of stochastic processes and compensation for material inhomogeneities. Depth control in laser drilling as well as keyhole welding has been demonstrated [52, 51].

The minutiae of ICI system design and characterization have been covered in Paul Webster’s Ph.D thesis [47]. I have endeavoured to address only the aspects necessary to an understanding of the imaging technique as it relates to laser keyhole welding. While some overlap is inevitable, few of the details of hardware selection and alignment are necessary. I refer the reader to the aforementioned thesis for more technical detail.

A description of the physics of our spectral-domain ICI (SD-ICI) system follows.
2.2. THE MICHELSON INTERFEROMETER

The SD-ICI system is built on a Michelson interferometer. Light from the laser source passes through a beam splitter, travels down separate reference and sample arm paths, back-reflects and re-combines at the splitter. The recombined light forms an interference signal that is measured by the spectrometer. A schematic diagram of the interferometer geometry is shown in Figure 2.1. The reference mirror is fixed in position during the measurement, and the interference pattern depends on the relative optical path delay between the reference and sample arm reflectors. The spectrometer makes use of a diffraction grating and line camera to resolve the intensity of the interference signal as a function of wavelength.

Figure 2.1: The Michelson interferometer. Light from the broadband source is separated by the beam splitter. The light travels down the reference and sample arms, back-scatters, and is recombined at the beam splitter forming an interference pattern. This pattern is measured by the detector.

This schematic illustrates the basic operating principles of any spectral-domain
2.2. INLINE COHERENT IMAGING

OCT (SD-OCT) apparatus. For SD-OCT, the light source is broad-band, and different frequencies are measured simultaneously using a camera and diffraction grating [16, 55]. In swept-source (SS-) OCT, a frequency-swept source of narrow instantaneous bandwidth is used. A high-speed photodiode in the detector arm resolves the intensity as a function of frequency to form the interferogram temporally, through synchronization with the light source [9].

Another OCT variant is time-domain (TD-) OCT. The original OCT system design calls for a rapidly translating reference mirror and a single-frequency source. The interference signal is measured by a photodiode as a function of reference mirror position. Thus, the ranging of reflective interfaces in the sample arm depends on physically matching the optical path delay in the interferometer. This reliance on moving parts is a serious hindrance to performance. The more modern SS- and SD-OCT schemes yield significant advantages to imaging speed and sensitivity [11].

A multitude of potential variations on this theme exist [44]. One example is the use of a balanced detection scheme, in which the interference signal that returns toward the light source from the beam splitter (typically discarded) is diverted to a second detector by an optical circulator and subtracted from the primary signal. This scheme yields a theoretical 3 dB increase in signal-to-noise ratio (SNR).

2.2.2 The Interference Signal

In SD-OCT and ICI, the main processing step comprises conversion of a spectrally-resolved backscatter signal to extract depth information from a sample. The following derivation demonstrates the transformation of a spectral interferogram to a plot of backscatter intensity as a function of optical path length. We begin by considering
the case of a continuous-wave source entering the interferometer with $N$ partially-reflective interfaces in its sample arm. The light throughout the interferometer will be assumed to propagate as a plane wave in the direction of the optical axis. Additionally, we will neglect dispersion and assume all reflection coefficients are explicitly real. Assuming infinite spectral bandwidth, the electric field component of this wave is expressed

$$E(z,t) = \varepsilon e^{i(\omega t - k(\omega)z)}, \quad (2.1)$$

where $\varepsilon$ is the complex field amplitude, $\omega$ is the angular frequency, and $k$ is the wavenumber.

The signal returned to the detector arm is a superposition of light reflected from all optical interfaces along the reference and sample arms. Assuming the interferometer is well-designed, reference arm scatter other than the reflection from the terminal mirror is minimal. In addition, multiple reflections between interfaces along both arms are neglected here. Typical sample arm interface reflectivity coefficients (in terms of intensity) are on the order of 0.1 or lower for glass and turbid media. Therefore, a beam that is multiply-scattered on-axis to return to the interferometer will be attenuated by roughly three orders of magnitude. Reflectivity is of course higher for metallic media (such as alloys used in welding), but the shallow metallic skin depth at near-infrared wavelengths precludes the inclusion of multiple scattering in this context. The electric field in the detector arm is written:

$$E_{\text{det}} = E_{\text{ref}} + \sum_{i=1}^{N} E_i, \quad (2.2)$$
where the subscripts on $E$ to the right of the equals sign denote electric field returning from the reference mirror and the $i^{th}$ of $N$ interfaces in the sample arm, respectively. The intensity of the light measured by the spectrometer is:

$$I_{det} = \frac{ncc_0}{2} \left[ |E_{ref}|^2 + \sum_{i=1}^{N} (E_{ref}^* E_i^* + E_{ref}^* E_i) + \sum_{i=1}^{N} \sum_{j=1}^{N} E_i E_j^* \right] , \quad (2.3)$$

where $n$ is the refractive index of the propagation medium and $c$ is the speed of light. Tracing the possible paths through the interferometer in Figure 2.1 we note that reflection-induced phase shifts in intensity components contributing to the interference signal in the detector arm will always be a multiple of $\pi$. Therefore the relative phase shift between that reference and sample arm signals is contained in $k(\omega)z$, and the complex field amplitude of Equation 2.1 may be replaced by a real amplitude $A$ without any loss of generality. The constants in front of the brackets in Equation 2.3 will be denoted by $I_0 \equiv cc_0/2$, where we assume vacuum propagation such that $n = 1$. Breaking up the third term in Equation 2.3, we get:

$$I_{det} = I_0 \left[ A_{ref}^2 + \sum_{i=1}^{N} A_i^2 + 2 \sum_{i=1}^{N} A_{ref} A_i \cos(k\Delta z_{ref,i}) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} A_i A_j \cos(k\Delta z_{i,j}) \right] , \quad (2.4)$$

where $\Delta z_{i,j} \equiv |z_i - z_j|$. In this form, the separate components of the interference signal are explicitly visible. The first term in Equation 2.4 is the DC intensity from the reference mirror, while the second is the sum of DC intensity scattered from all interfaces in the sample arm. The third term is where the desired information is found; namely, the optical path delay between the reference mirror and the $i^{th}$ sample arm interface, $\Delta z_{ref,i}$. The diffraction grating in the spectrometer spreads the
interference signal across the line camera array, displaying this third term as a set of fringes in \( \lambda \)-space, whose frequency is proportional to the optical path delay. An interpolation step re-distributes the interference fringes as a function of \( k \) before the Fourier Transform is applied. The fourth term also describes a set of fringes, caused by the interference signal from different interfaces within the sample arm. These autocorrelation fringes appear as an artifact in the final image, described below.

Conversion of the measured interferogram into a plot of backscatter intensity as a function of optical path delay requires an inverse Fourier transform from \( k \)- to \( z \)-space. If we subtract the DC components of the interference signal, the inverse Fourier transform of the remaining oscillatory terms yields the following expression:

\[
\tilde{I}(z) = \frac{I_0}{2\pi} \left[ \sum_{i=1}^{N} A_{ref}A_i(\delta(z + \Delta z_{ref,i}) + \delta(z - \Delta z_{ref,i})) \\
+ \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} A_iA_j(\delta(z + \Delta z_{i,j}) + \delta(z - \Delta z_{i,j})) \right].
\] (2.5)

Equation 2.5 is the analytic expression describing a single amplitude-line (A-line or A-scan), in which the intensity of reflected signal from the sample arm is plotted as a function of optical path delay relative to the reference arm. This A-line contains a set of paired delta functions, evenly spaced around \( z = 0 \), with the center position of each given by the relative path delay of the corresponding interface. In practice, the amount of signal returned from the sample arm is highly variable. A calibration routine that is performed prior to measurements (discussed in Chapter 3) removes the DC component from the reference mirror, but the DC sample arm signal remains. This appears as a spike in the A-line at \( z = 0 \), representing the position of zero delay between the arms of the interferometer. This zero-delay signal may be exploited to
determine the total intensity of light reflected from the sample arm.

### 2.2.3 Derivation for a Gaussian Spectral Envelope

So far, this derivation has rested upon an implicit assumption that the frequency bandwidth of the source light is infinite. For a real light source with finite bandwidth, the Fourier transform of the fringe pattern will display peaks which are correspondingly broader than the delta functions arrived at in Equation 2.5. For a more realistic result, let us consider a continuous-wave source of finite bandwidth, with a Gaussian frequency envelope. Equation 2.1 then becomes:

\[
E(z, k) = \varepsilon e^{-\frac{(k-k_0)^2}{\Delta k^2}} e^{-ikz},
\]

(2.6)

where \( k_0 \) is the source centre wavenumber, \( \Delta k \), is a width parameter proportional to the spectral bandwidth, and \( \varepsilon \equiv E_0 e^{i\phi_k} \) is the complex field amplitude. The Gaussian envelope function carries through to the interference pattern of Equation 2.4. This common Gaussian factor acts on all terms in Equation 2.4 and may be factored out. The DC-subtracted interference pattern in k-space is then:

\[
\tilde{I}(k) = I_0 e^{-\frac{(k-k_0)^2}{\Delta k^2}} \left[ \sum_{i=1}^{N} A_r A_i \cos(k \Delta z_{r,i}) + \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} A_i A_j \cos(k \Delta z_{i,j}) \right].
\]

(2.7)

We will obtain the analytic Fourier transform of this expression from k- to z-space using the following definition of the transform:

\[
I(z) = \frac{1}{2\pi} \int_{-\infty}^{\infty} dk \tilde{I}(k) e^{ikz}.
\]

(2.8)
Substituting Equation 2.7 into 2.8, we obtain:

\[ I(z) = \frac{I_0}{4\pi} \int_{-\infty}^{\infty} dk e^{-\frac{(k-k_0)^2}{\Delta k^2}} \left[ \sum_{i=1}^{N} A_r A_i \left( e^{ik(z+\Delta z_{r,i})} + e^{ik(z-\Delta z_{r,i})} \right) + \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} A_i A_j \left( e^{ik(z+\Delta z_{i,j})} + e^{ik(z-\Delta z_{i,j})} \right) \right]. \] (2.9)

We can multiply the Gaussian envelope through all terms inside the brackets to get a sum of exponential functions with exponents that are quadratic in \( k \), all inside of the integral over \( k \). Completing the square in the exponent, we can separate exponential terms having \( k \) dependence and move the others outside the integral, leaving a sum over integrals of Gaussian functions with complex translational offsets. Making use of the following result,

\[ \int_{-\infty}^{\infty} dx e^{-\frac{(x-q)^2}{r}} = \sqrt{r\pi}, \] (2.10)

and taking the modulus, we arrive at the following expression for an A-line produced by a Gaussian source spectrum:

\[ |I(z)| = \frac{I_0}{2\sqrt{\pi}} \Delta k \left[ \sum_{i=1}^{N} A_r A_i e^{-\frac{\Delta k^2}{4}(z+\Delta z_{r,i})^2} + \sum_{i=1}^{N-1} \sum_{j=i+1}^{n} A_i A_j e^{-\frac{\Delta k^2}{4}(z+\Delta z_{i,j})^2} \right]. \] (2.11)

The result is a sum of Gaussian peaks, with centres displaced from zero by \( \Delta z_{x,x} \). This is the analytic expression for an A-line generated by a Gaussian-spectrum source.

The first term of Equation 2.11 contains a pair of peaks for each scattering interface along the sample arm path. The peak displacement is given by the absolute value
of the relative optical path difference between the reference mirror and each sample interface. The second term contains a peak for each pair of interfaces along the sample arm, with centre offsets equal to the optical path difference between the sample interfaces alone. This term describes an artifact known as autocorrelation, which can be quite difficult to separate from the desired signal [2]. An interference peak produced by autocorrelation may resemble the primary interface signal in nearly every way. However the lengths of both contributing paths are unknown and the resulting offset measurement generally cannot be registered to other interfaces in the sample. The width of each peak given by this equation is inversely proportional to the spectral bandwidth of the light source. This feature—the width of the transformed peaks—is a standard measure of the axial resolution of an OCT/ICI system. Thus, all else being equal, a broad source spectrum (in $k$-space) is desirable. Importantly, the amplitude of the peaks is also directly proportional to the source spectral width. Use of a narrow-band source results in both broadening and attenuation of the intensity peaks in the analytic transformed signal.

In practice, the fringe pattern measured by the spectrometer (after conversion to $k$-space) is multiplied by a Gaussian to ensure that the tails of the spectral envelope go smoothly to zero at the ends of the array. The resulting envelope in $k$ has a FWHM of roughly half the width of the region of pixels used. This step is necessary to reduce artifacts that would arise due to sharp drops at the edges of the field during the (discrete) Fourier transform stage of image processing. The result is that the simple form above is a passable approximation to the underlying form of a measured A-line, even in the likely event that the imaging light source does not natively produce a Gaussian spectrum.
Finally, I must stress that the $\Delta z$ values throughout the preceding derivations are optical path lengths, given by $z = nx$, where $n$ is the refractive index and $x$ is the actual propagation distance. Having assumed vacuum propagation, this is not relevant to the derived ICI signal. Experimentally, elements such as unmatched optics between the two arms of the interferometer or plasma produced by the laser process may introduce distortions to the distances that ICI measures.

2.2.4 Discretization of the Measurement

In practice, the interference fringes measured by the spectrometer are discrete rather than continuous. The equivalent implementation of a discrete Fourier transform (DFT) adds (typically unwanted) features to the final image. The discrete measurement of intensity as a function of $\lambda$, and resulting discrete set of $k$-values, sets the limit on the range of relative path lengths that may be measured.

Perhaps the most obvious limitation imposed by discretization of the measurement is a limit on the number of depth bins which are output by the DFT. This imposes an additional hardware limit on the resolution of the spectrometer. In practice the spectrometer is tuned so that the transformed pixel spacing is half the point spread function full width. This allows the spectrometer to effectively perform at the fundamental limit imposed by the transform. Interpolation of the measured intensity values to account for nonlinear spacing in $k$ introduces shoulders to the transformed peaks, as discussed in section 3.2.

Unlike the continuous derivation outlined above, the discretized case places an upper limit on the frequency of interference fringes that may be resolved by the spectrometer. As the relative path offset increases, so does the fringe frequency in $k$. 
Eventually the Nyquist limit is approached on the detector, and the real frequency can no longer be properly resolved. This effect limits the depth of the imaging field to a few millimetres, and contributes to weakening of the signal intensity as a function of distance from zero-delay (known as ‘roll-off’). This feature of the ICI system is characterized in section 3.2.4). Beyond the ends of the imaging field, aliasing causes the transform to primarily register the beat frequency between the fringes and the pixel spacing, rather than the fringes alone. In the image, the signal from an interface translated beyond the end of the field wraps around the end of the field and produces shortened, broadened peaks within the field of view.

\section*{2.3 Imaging Artifacts}

\subsection*{2.3.1 Autocorrelation, Multiple Reflection, Dispersion, and Saturation}

Complete isolation of the third term in Equation 2.4 is not possible for a real-world ICI system. A calibration step can remove the reference-arm DC level, but the sample DC level is rarely constant from one A-line to the next, and cannot typically be subtracted from the signal. Certain single-arm imaging artifacts that appear as fixed-pattern noise (false interfaces) in the ICI image may be subtracted based on the reference arm signal alone during calibration. However, due to the variability of the sample backscatter intensity, when such artifacts originate in the sample arm they appear as false sample interfaces in the final image.

As stated earlier, the fourth term in Equation 2.4 contains an interference due to the interaction of components backscattered by different interfaces within the same
arm. Many elements in the sample arm beam path may contribute to such features. Quite commonly, the optical thickness of glass elements beyond the focussing optics (e.g. cover glass) is registered as a fixed-pattern signal within the imaging field. Any sample with partial transparency and multiple scattering interfaces is also susceptible. In the case of welding metals, the contribution of the optics is usually the only one visible.

In a similar vein to autocorrelation originating between the surfaces of glass elements in the beam path, multiple reflections of the returning signal may also introduce false interfaces to the image. The result is usually a fainter echo of the main interface peak, offset from it at a distance equal to twice the optical thickness of the offending glass element. These signals do not always land within the imaging depth of field, but since they are not static relative to the zero-delay point, their removal in post-processing is much more problematic than autocorrelation artifacts.

In the design of an interferometer, care must be taken to match the distance travelled through free space, fibre, and glass in each arm. Any mismatch in the dispersion between the two arms results in an imbalanced frequency-dependent phase shift which distorts the interference fringe pattern. The result is that different regions of the wavelength spread in the spectrometer will register slightly different path lengths. The resulting A-line will display attenuation and broadening of the main signal peak. In addition to hardware-based dispersion-matching, this phenomenon may be remedied to a certain extent in code, as discussed in Chapter 3.

The most insidious imaging artifact encountered in ICI of laser welding is saturation ringing. Liquid metal surfaces have very high reflectivity, and depending on the surface geometry encountered by the imaging beam, the intensity re-coupled into the
optics may be much greater than the interferometer is tuned to handle. When the fringe pattern from a reflecting interface saturates the detector, a number of things can happen to the final image. For gentle saturation, in which the peaks of the fringes are cut off, the effect is equivalent to clipping in an audio amplifier. The squaring of the fringe peaks contributes frequency components to the pattern at harmonics of the fundamental. This results in a characteristic ‘ringing’ artifact that produces extra peaks at regular intervals around the primary peak in the A-line. Information can usually be salvaged from these A-lines, since the primary peak is still the brightest. More severe saturation of the detector results in complete destruction of useful interference fringes. The signal on the line camera may resemble a flat-topped peak with few (if any) intensity oscillations present on the slopes at its edges. In this case the transformed line is dominated by the peak at zero-delay, whose shoulders may absorb any peaks produced by the small amount of fringe content available.

2.3.2 Motion Artifacts

In Fourier-domain OCT, motion of the interface has a measurable effect on the processed image. This effect, called the motion artifact, manifests itself differently in spectral-domain and swept-source systems, as a result of the manner in which the data is acquired. For both system types, a different motion artifact exists when the sample is translated in either the axial or transverse direction relative to the imaging beam. All four flavours of motion artifact (permutations of SD, SS, and axial, transverse) are described theoretically and verified experimentally in a paper by Yun et al. [60]. The ICI systems in use throughout my thesis are configured for spectral domain measurements, so the swept-source artifact will not be considered here.
In addition, the transverse motion artifact is mainly predicted to affect signal from biological samples possessing significant surface heterogeneity. The theoretical loss of SNR due to transverse motion of the sample goes to zero for an ideal mirror-like surface [60]. Measurements carried out on molten steel approach this limiting case, and relative transverse motion of the ICI beam in my experiments is of limited speed. Thus the transverse effect will be neglected.

The axial motion artifact for SD-OCT may be intuitively understood through consideration of the fringe pattern measured by the spectrometer (as described in Equation 2.4). If the reflecting interface in the sample arm is translated by 1/4 of the centre wavelength over the course of the integration time of the camera, the measured fringe pattern washes out, leaving only the DC intensity level. This (worst) case translates to a complete loss of SNR in the processed OCT image, resulting in complete blindness to a highly reflective interface.

Yun et al. found the axial motion artifact in SD-OCT results in an approximately uniform attenuation factor acting on the A-line signal intensity. The attenuation factor is given by:

$$\sin^2\left(\frac{k_0 \delta z}{k_0} \right)$$

where $\delta z = |v_z T|$ is the axial displacement of the sample interface, equal to the product of the interface velocity, $v_z$, and the integration time, $T$. This expression holds as long as the distance from the interface to the zero-delay point is much larger than its axial displacement during an integration [60]. This factor displays a gradual rolloff of the SNR coupled with periodic dips to zero.

Intuitively, the periodic signal attenuation coupled with gradual rolloff can be
2.3. IMAGING ARTIFACTS

understood in terms of the fraction of an integration time over which the fringe pattern washes out. For instance, an interface displacement of $\frac{1}{4} \lambda_0$ results in 100% wash-out. If the interface axial velocity is increased by 1.5 times so that the displacement is $\frac{3}{8} \lambda_0$, then the first $\frac{2}{3}$ of the integration time will wash out while the remaining $\frac{1}{3}$ produces useful signal. However, the pattern measured by the camera over the effectively reduced integration time is correspondingly weaker.

In a paper published shortly after the first, the same authors describe and test two basic schemes for remediation of the motion artifact using an SD-OCT system [61]. The first scheme involves a simple switch to a short-pulsed light source. While the camera requires the same amount of time to acquire a frame, signal is only incident for the duration of the laser pulse. The principle is similar to the use of a flash to illuminate dark foreground objects in a long-exposure photograph. In this manner (referred to as stroboscopic OCT/ICI) the effective integration time of the OCT system can be reduced by orders of magnitude below that attainable with a state-of-the-art CMOS camera under continuous illumination. The second scheme makes use of a frequency-swept light source with an SD-OCT spectrometer to briefly illuminate each region of in the camera individually over the course of an integration. This hybrid SS/SD-OCT mode is still susceptible to distortion and blurring due to motion, but at least partially remedies the attenuation problem. With a change of light source, either of these schemes could feasibly be implemented on existing laboratory ICI systems.

The expectation is that, given the highly dynamic nature of laser machining processes in general, the axial motion artifact will cause significant signal attenuation for ICI. Experimental characterization of the axial motion artifact for our ICI system are compared to the results obtained by Yun et al. in section 5.2. This signal loss
2.4 Laser Keyhole Welding

The use of lasers as a heat source for welding of metallic materials has been relatively common practice for decades. As early as 1989, laser beam welding was established as a manufacturing option offering simple automation, high throughput, and high energy concentration [12]. The narrow weld seams made possible by this tight energy confinement minimize contamination and thermal stress. Various material modification effects may be achieved with a high-power laser, largely through control of the energy concentration and rate of delivery. Taking into consideration the broad range of wavelengths, pulse schemes, and beam shaping options available today in high-power industrial lasers, the parameter space for this family of processes has become quite broad. The welding process that is of primary interest to myself and other users of ICI is known as laser keyhole welding.

The preferred laser sources for keyhole welding can be broadly classified as CO$_2$ and solid-state. CO$_2$ gas lasers produce infrared light at a wavelength of 10.6 µm. Solid-state technologies, based around the Nd:YAG or Yb:YAG emission wavelengths, mostly produce light at wavelengths between 1000 and 1100 nm (and are commonly referred to with the shorthand ‘YAG’). This group comprises diode-pumped fibre and disk lasers. In each of these classes of laser, light in the cavity resonates within a solid, transparent gain medium doped with ions. The respective names of these classes refer to the physical form of this gain medium. Both CO$_2$ and solid-state lasers are capable of producing ample power for welding (outputs between 1 and 20 kW are common), and the keyhole behaviour is governed by the same basic principals for
2.4. LASER KEYHOLE WELDING

each. The difference in wavelength is important, as 10 µm light produces and interacts with plasma much more readily, while the shorter wavelengths may be focused more tightly to produce higher energy densities at the material surface given equivalent power.

Laser keyhole welding occurs when the laser power density incident on the surface of the metal workpiece exceeds the threshold for vaporization. The high-power laser beam, at normal incidence, melts and evaporates the metal in its path, forming a narrow channel of metal vapour that extends millimetres below the surface of the workpiece. The vapour channel—the keyhole that is the namesake of this welding method—allows the beam to deliver energy deep into the sample, overcoming the typical metallic skin depth of tens of nanometers for near-visible wavelengths of electromagnetic radiation. The keyhole is surrounded by a volume of molten metal which constitutes the weld seam after cooling. Confined within the melt volume, the keyhole is held open by a balance of laser-induced evaporation recoil pressure, surface tension, and hydrostatic pressure. Typical keyhole widths are on the order of the beam diameter [24, 27, 29, 17], meaning that high aspect ratios on the order of ten are the norm.

The process beam is translated across the surface of the workpiece, continuously melting and vaporizing fresh material. As the beam passes, surface tension closes the keyhole behind it. The beam is trailed by turbulent melt pool many times longer than the width of the keyhole (usually several millimetres). At the tail end of this pool, the melt cools and re-solidifies to form the weld seam. Typical laser keyhole welding is autogeneous—the joint is back-filled with the material of the parts to be joined, and requires no extra filler material. For experimental purposes, the industry and
scientific standard is to perform bead-on-plate welds in bulk steel. A bead-on-plate weld is formed within a single piece of metal, not between separate parts. This is the simplest, most controllable test case that allows exploration of laser, material, and atmospheric parameters. The welding experiments discussed in this thesis are autogeneous bead-on-plate.

2.4.1 Features of the Keyhole

In qualitative terms, laser keyhole welding behaviour may be observed across a broad parameter space in many materials. A schematic diagram of a weld keyhole is shown in Figure 2.2.

A vapour channel up to several millimetres deep forms in the region of the process beam. This channel is predicted by theory to be 1 - 1.7 times the width of the beam at its waist [24, 27, 29, 17], with a typical beam waist measuring 100 - 200 \( \mu \text{m} \) for solid-state lasers and \( \sim 500 \ \mu \text{m} \) for CO\(_2\). For some applications, a beam as wide as several millimetres at the waist may be used to produce a wider seam. As the sample is translated relative to the beam, a pool of liquid metal trails the keyhole, measuring several millimetres long and one to two millimetres across at its widest point on the top surface.

The keyhole itself is quite thin, slightly tapered toward the bottom and curved in the trailing direction. This curve is a significant element of the light-matter interaction. At feedrates and power levels greater than 20 - 50 mm/s and a few kilowatts, respectively, curvature is great enough that only the front keyhole wall is directly exposed to the process beam [36]. The longitudinal asymmetry of the keyhole can be understood in terms of the characteristic time of welding, taken to be the beam
radius divided by the sample feedrate. If the time needed for the keyhole to form completely is less than the characteristic time of welding, the keyhole will, in theory, form coaxially to the process beam. If the formation time is greater, there will be some lag and the keyhole will trail the beam slightly [36].

Multiple reflections are a crucial element of keyhole formation and stability [12, 46]. A single Fresnel absorption event can absorb up to 40% of the power at a given location, depending on the angle of incidence [25]. Via multiple reflections, the power of the process beam is distributed over the interior walls of the keyhole. Multiple
reflections allow the majority of the incident power to be absorbed at some point within the keyhole. As a result, effective absorption coefficients for the keyhole in its entirety can be well above 50% [26]. The intensity map on the keyhole interior is uneven and highly dynamic, which contributes to the inherent instabilities of laser keyhole welding [27, 26].

Evaporation recoil pressure at the absorbing interface is the driving force keeping the keyhole open. On the front wall, any small ripple will present the process beam with an incidence angle closer to normal, and experience strong downward recoil pressure. The ripple travels down the wall, gaining amplitude as it scoops up melt and absorbing more of the process beam as a result. The keyhole provides positive feedback for such perturbations. Depending on process parameters, such waves may regularly travel down the front keyhole wall with frequencies in the hundreds of Hertz [57]. This phenomenon is referred to as ‘humping’ [4].

As a result of the dynamic instabilities that occur during constant power keyhole welding, the depth of the keyhole often fluctuates over hundreds of microns on sub-millisecond time scales. The melt pool is subject to ‘spiking’ defects as a result of this keyhole motion. Spiking of the melt pool is typically of smaller amplitude and on longer length-scales than that of the keyhole, since thermal conduction through the bulk has a smoothing effect on the final solidified seam.

The melt flow around the keyhole is longitudinally asymmetric. The layer of melt leading the front keyhole wall is much thinner than the trailing portion of the melt volume. The leading melt flows downward and outward, moving around the vapour channel toward the trailing melt pool. The net vertical flow at the keyhole surface is downward [13]. The region of the melt pool immediately trailing the process beam
spans the entire depth of the keyhole. Flow in this region is turbulent [13] and convection plays a large role in heat transfer throughout the melt pool. Numerical models suggest pressures as high as six atmospheres exist in regions of the melt neighbouring the keyhole [26].

The atmosphere inside the keyhole consists of a mix of evaporated metal, ambient atmosphere (typically inert shield gas), and—primarily for CO$_2$ laser welding—plasma produced by the intense energy of the laser [57]. Sites on the keyhole walls where the laser is strongly absorbed produce jets of evaporated metal. Due to the high pressures induced by this evaporation, a plume of exhaust gas and plasma develops above the keyhole. This plume plays an important role in CO$_2$ welding, as the plasma can attenuate the process beam significantly [12]. Plasma absorption within the keyhole is an important energy transfer mechanism for long-wavelength radiation.

The back wall of the keyhole, not being under constant, direct exposure to the process beam, is liable to produce larger protrusions of melt as the pressure distribution on its surface shifts. These may completely pinch off the keyhole at any depth beneath the sample top surface, entraining a bubble containing some combination of metal vapour and ambient gas within the melt pool. Some of these bubbles condense or ride on currents of liquid metal to be expelled at the melt pool surface, but many remain and become trapped in the re-cast steel of the weld seam. Instabilities in the rear keyhole wall may also result in expulsion of melt droplets from the top of the keyhole. Expulsions can re-join the melt pool or be deposited on the virgin surface as spatter.

The melt pool grows significantly wider and longer near the surface of the sample. This leads to a characteristic ‘wineglass’ profile to a keyhole-mode weld, as shown in
2.4. LASER KEYHOLE WELDING

Figure 2.3. If a transverse section is cut through a welded plate, the topmost region of the weld seam will be wider and roughly triangular, with a narrow, straight-sided ‘stem’ extending to the full depth of the weld.

![Keyhole weld cross-section](image)

Figure 2.3: An ex-situ transverse cross-section of a keyhole weld bead in stainless steel. The ‘wineglass’ profile of the bead and multiple pores are visible. From [5].

Considering the roles of Fresnel absorption through multiple reflections and plasma plume damping, it is clear that there is an intimate relationship between the keyhole shape and the thermal distribution in the bulk. In order to accurately model keyhole dynamics one must take into account the many possible paths for the laser energy. Figure 2.4 shows a schematic flow of energy from the laser source to the keyhole walls via different interaction mechanisms. It is apparent that formulating an accurate model of the physics involved in this system is not a trivial undertaking, and will not be attempted in this thesis.
2.4. LASER KEYHOLE WELDING

Figure 2.4: A characteristic hierarchy for consumption of laser power by the keyhole. The various absorption processes involved are indicated in a darker shade of grey. In this picture, six different modes of energy transfer from laser to workpiece must be independently accounted for. Adapted from [24].

2.4.2 Existing Diagnostics

The weld keyhole is a physical system of which many aspects are still poorly understood. As a light-matter interaction, keyhole welding involves high energy and complicated thermo- and fluid dynamics. The system presents mechanical complexities and sustained, high-speed stochastic behaviour that differentiates it greatly from the clean, deterministic behaviour of ultrafast ablation commonly studied in the field of laser physics. Due to a combination of the violence of the light-matter interaction, the high aspect ratio of the vapour channel, and the impermeability of bulk steel to
most transmissive measurement techniques, experimental study of the weld keyhole has so far proven challenging.

In a 2009 review on the vapour phase in the keyhole, John Dowden aptly describes the broad level of understanding of this system in recent years. He writes,

The broad qualitative aspects of what happens in the keyhole in laser keyhole welding are reasonably clear, but the details are complex and are not too well understood. Experiments show that the keyhole is usually not in a steady state, even in a frame of reference that is stationary with respect to the laser beam... \[13\]

Dowden alludes to a still-present gap between theoretical models of keyhole welding and verifiable data. My sense is that the pace of numerical modelling has outstripped experimental methods. While such models are theoretically sophisticated and their results self-consistent, they are computationally expensive and lack concrete verification. The field of laser welding suffers from a dearth of experimental methods that enable direct observation and assessment of the keyhole behaviour, rather than correlation of indirect measurements to theoretically predicted events. I will present here a brief summary of existing reported measurement techniques employed in the study of keyhole welding.

In a 2014 review of laser weld monitoring technologies, You, Gao and Katayama write about four representative detection structures in common use to measure aspects of the weld keyhole behaviour \[57\]. The list offered in this review is somewhat incomplete, likely representing a more industrial than academic perspective. The methods enumerated are straightforward and established enough to be readily accepted in industry. More sophisticated methods are in use in academia, but the body
of work surrounding the detection structures outlined in the review is substantial enough to warrant discussion. I will describe them in brief here.

The first class of detection technique is coaxial optical radiation detection. Using a beam splitter, radiation originating from the welding site in the visible and near-IR bands is separated from the process light within the machining head. This light is primarily blackbody radiation and plasma emission from the plume. A set of notch filters and photodiodes allow real-time spectral analysis of these emission signals. The experimental method involves correlation of certain classes of weld feature, identified by ex-situ analysis, with changes in the emission in one or more bands [56, 28]. For example, in certain materials an increase in the emission associated with plasma formed from the metal of the sample often coincides with a large melt ejection event.

The typical implementation of an optical detection scheme involves simultaneous collection of signals associated with the melt pool temperature (T-signal), back-scattered process beam (R-signal), and plasma emission (P-signal) [39]. Eriksson et al. found that under certain circumstances, the thermal (T) signal is largely mixed with the plasma emission [14], and that subtraction of the T- and P-signals might be more useful. In the case of fibre and disk laser welding around 1 µm, the laser-generated plume may be very weakly ionized, and the plasma signal can be dominated by thermal emission from the melt pool and metal vapour [57].

The second class described by You et al. is coaxial visual detection. These techniques also use a beam splitter to separate the process beam wavelength from visible or near-IR light from the weld site. A CCD is used to capture a two-dimensional image of the sample surface. Additional illumination is often necessary to mitigate blinding due to the other strong sources of radiation intrinsic to the process. These techniques
2.4. LASER KEYHOLE WELDING

focus on qualitative assessment of weld progress. An operator may view the shape of the keyhole and melt pool at the top surface, or in the case of full-penetration welding verify that the keyhole reaches through the workpiece.

Na et al. demonstrated an algorithm for feedback control on the melt pool width in laser welding, using a high-speed camera to measure the top-surface pool geometry [38]. This was implemented for conduction-mode laser welding, an inherently more stable process in which no keyhole is formed. However, such a system could feasibly be extended to keyhole-mode welding, if the material parameters were well-controlled.

The third class of monitoring is paraxial sound and temperature detection. Stress-induced vibrations in the workpiece may be measured via contact methods, or a remote microphone can be used to monitor sound from metal evaporation and plasma formation. Surface temperature at various points in the melt pool may be measured remotely with a pyrometer. Similarly to the coaxial optical detection group of techniques, these sensors are most effectively used for process optimization via ex-situ correlation with finished weld characteristics. The acoustic methods are usually too slow to be viable candidates for process control via a live feedback loop [57].

Fang et al. made use of a contact acoustic sensor to detect thermal stress crack propagation during welding [15]. Huang et al. employed a non-contact microphone to monitor laser keyhole welding progress [20]. They found a correlation between the amplitude and frequency content of the weld tone and keyhole depth, as well as some defect formation events. Their system was able to detect loss of breakthrough in full-penetration keyhole welding in-situ with good accuracy. Interestingly, experienced laser welding operators are rumoured to be capable of distinguishing ‘good’ from ‘bad’ welding by ear. However, I have not found a scientific study attempting to
2.4. LASER KEYHOLE WELDING

decipher the acoustic queues that human hearing might respond to for this purpose.

The fourth and final group of technologies covered in You’s review revolve around measurement of the electronic properties of the plasma plume. Contact probes on the sample and machining head measure the potential difference across the plasma plume directly. This allows a combination of plasma concentration and temperature to be calculated, quantities that bear a connection to what is happening within the keyhole. In my opinion, the correlations derived from plasma monitoring may confuse cause and effect, as the plasma plume both responds to and influences the behaviour of the keyhole (the latter through attenuation of the incoming laser radiation). In any case, this technique is more useful for CO$_2$ laser welding at 10.6 µm wavelength than for fibre or disk lasers in the region of 1 µm, since plasma is less consistently generated at these shorter wavelengths, and has a much weaker effect on the propagation of the process laser [57].

In 1996, Li et al. implemented a voltage sensor for monitoring of laser-induced plasma temperature in keyhole welding. Through theoretical arguments, they link the plasma temperature directly to weld penetration depth. They also lay claim to a learning algorithm that combines data from the plasma sensor with acoustic signals to flag seven different types of weld defect with greater than 90% accuracy [35]. Independent verification of these results was not found.

In all of the aforementioned detection schemes, the metrics investigated are largely expected to respond to the general, time-averaged behaviour of the keyhole system. Trends in the signal are compared to parameters that may be measured by ex-situ sectioning, i.e., resolidified melt volume depth and width, seam underfill, and pore size and density distributions. With such broad correlational monitoring approaches,
2.4. LASER KEYHOLE WELDING

strong emphasis is often placed on Fourier analysis of signal oscillations attributed to the keyhole and melt pool. Deviations in the frequency content of the keyhole emission spectra can indicate melt ejections, defects, and other perturbations [57]. The treatment of the keyhole as a stochastic oscillatory system presents a fascinating physical problem and constitutes an open research question in the weld literature [10, 30]. The possibility of addressing this question using ICI data is a rich direction for future work.

Techniques that make direct quantitative measurements of the keyhole along the direction of the beam axis are conspicuously absent from You’s review [57]. While the weld monitoring techniques discussed above have been thoroughly tested, those that do not rely on extensive inference are limited in perspective to what is arguably the less useful and interesting perspective of the weld keyhole—looking downward at the top surface of the sample. The subsurface geometry of the keyhole is crucially important to its behaviour. Several techniques that allow direct measurement of the keyhole dimensions in a more useful way have been developed and are actively used in research laboratories around the world.

The use of X-ray transmission imaging to capture keyhole geometry and dynamics in the plane of the beam axis continues to be extremely important. Such techniques require the use of a powerful X-ray source (sufficient to penetrate \( \sim 5 \) mm of metal) and a relatively sophisticated detection apparatus. Laser keyhole welding is carried out along the edge of a plate only slightly thicker than the weld bead, and the X-ray system captures high speed video of the process.

In 2011, Abt et al. reported the development of an X-ray system for weld monitoring, displaying 2D images with 250 µm resolution at frame rates of up to 5 kHz.
X-rays with wavelength on the order of 1 Å are projected from an X-ray tube through the sample. On the other side of the sample, the transmitted X-rays hit a scintillator plate. These transmitted rays form a shadow pattern according to differences in the attenuation factor at different positions in the sample. Light from the scintillator is amplified by an electronic intensifier and captured by a high-speed CCD. Hollow embedded structures in the target (such as the weld keyhole or trapped pores) cause less attenuation than the surrounding steel. The image contrast scales exponentially with feature size, limiting the minimum feature size that may be effectively resolved [1].

The X-ray transmission technique allows direct observation of the evolution of the keyhole geometry at high speed, including the occurrence of defects and keyhole collapse. The formation of pores and their propagation through the melt pool are also readily visible. The addition of tracer materials (e.g. Tungsten particles) allows melt pool dimensions and velocities to be recorded.

One solution for experimental investigation of the weld keyhole adopted by several groups is the use of transparent materials as a proxy for metals. Jin et al. observed formation of stable keyholes in CO$_2$ welding of a high-temperature glass (GG17—described elsewhere as a Chinese brand similar to Pyrex) [23, 22]. Zhang et al. modified this experiment to more closely represent CO$_2$ welding of metals by including a thin layer of aluminum between two layers of GG17 to act as a plasma source and enable inverse Bremsstrahlung as an energy transfer mechanism to the molten glass. More recently, Cheng et al. used a high-speed camera to perform direct observations of a keyhole produced along the interface between a plate of aluminum alloy and a plate of GG17. Of course, mixed-material studies of this sort really only relate to
welding of pure metals in a qualitative sense.

The absorptivity of water at the CO$_2$ emission wavelength of 10.6 µm is quite high. This property enables an interesting offshoot of keyhole welding of transparent materials—ice block welding. A keyhole and melt pool may be induced in water ice using comparatively low intensity light. Since there is no plasma formation or visible blackbody radiation, quality images and video of the keyhole profile are easy to obtain. Phenomena such as pore formation, keyhole oscillation, and melt depth spiking have been clearly observed and qualitatively described in ice welding [3].

Although the field of experimental weld keyhole measurement has spanned three decades, the goal of accurate measurement of the keyhole behaviour has remained elusive. The most effective measurement technique for keyhole geometry characterization under realistic conditions, x-ray transmission videography, allows accurate measurement of the gross shape of the keyhole but lacks the spatio-temporal resolution to capture most instabilities and defects. More detailed understanding is needed in order to build models and theory that can accurately predict the behaviour of this complex physical system. ICI has the potential to answer many questions about the keyhole, but the accurate interpretation of its data is not trivial. The need for thorough understanding of our measurement technique as it applies to keyhole welding is a key motivation for this thesis.

2.4.3 Analytic and Numerical Modelling Approaches

Significant effort has been made to model the underlying physics of laser keyhole welding. Various approximate solutions have been implemented, often excluding certain experimentally-observed phenomena to keep solutions manageable. The rapid
improvement in power and accessibility of computers as numerical modelling tools in the past decades has yielded great advances in the sophistication and accuracy of keyhole models.

Swift-Hook and Gick published a line-heat-source model of deep penetration laser welding in 1973 [46]. This simple model allowed some relationships to be explored between input parameters and weld seam dimensions for deep laser and electron-beam welding. Steen et al. modelled absorption of laser power in keyhole welding as a combined point and line heat source within the bulk [43]. They justify this simplified model by pointing to its avoidance of an actual energy transfer mechanism solution and the unknown shape of the keyhole as an advantage. Ignoring the presence of the keyhole, and assuming constant thermal conductivity and diffusivity, Steen et al. model a uniform line heat source through a bulk steel sample, translated through the sample at constant velocity. A point source at some distance beneath the surface is added as a correction to allow the model to reproduce the characteristic ‘wine-glass’ profile of a laser keyhole weld seam. An analytic solution for the temperature distribution is found allowing approximate calculations of the expected melt volume geometry for this simplified case.

Prior to the more recent coming-of-age of solid-state industrial lasers, welding was carried out primarily using CO$_2$ sources. These gas-tube lasers can be made extremely powerful (∼10 kW) with excellent beam quality, and still see common use in industrial cutting and welding applications, in spite of losing out on reliability to more modern solid-state units. The CO$_2$ laser produces a strongly ionized plume within the keyhole and above the workpiece during welding. The long emission wavelength of CO$_2$, at 10.6 µm, means the process radiation is susceptible to significant attenuation in the
plasma plume. This becomes an important energy transfer mechanism, as the hot plasma conducts heat into the keyhole walls. Rigorous analytic models of plasma absorption effects based on assumed keyhole geometry have been developed [12].

In 1993, Kroos et al. developed a self-consistent model based on a keyhole that is constrained to cylindrical geometry, concentric to the axis of a Gaussian process beam [29]. The width and surface temperature of the keyhole are allowed to vary with the process parameters to balance pressure and energy at the gas-liquid interface. Their results allowed them to extract a theoretical threshold power for stable keyhole formation as a function of workpiece composition and thickness. Their model doesn’t specify an absorption mechanism, assuming all power that enters the keyhole is transferred into the keyhole walls through some combination of direct absorption and transfer from the plasma.

In 1994, Kaplan published an iterative numerical solution for a two-dimensional keyhole profile in the longitudinal plane, based on a point-by-point energy balance on the keyhole wall [24]. This model marked a departure from prior efforts that assumed rotational symmetry of the keyhole, extending its applicability beyond the regime of very low processing speeds. The keyhole profile is discretized into small, flat, angled elements. Fresnel absorption for each element is calculated, and the angle is adjusted to balance the absorbed intensity against the heat flow necessary for evaporation of the metal. The shapes of the leading and trailing walls of the keyhole are solved separately in this manner, with the angle at each point calculated consecutively, beginning far from the process beam axis. The velocity of the bulk steel introduces an asymmetry in the heat flow that results in different profiles for the front and back walls. Nearly all of the beam falls on the front wall. It is here that the first Fresnel absorption
event takes place. Kaplan treats all subsequent reflection events as isotropic heating. The model allows the back wall to exhibit an experimentally realistic undercut, but appears to be limited to angles less than the divergence of the phase fronts for a Gaussian beam focussed at the sample surface. This model predicts experimental weld depths for a CO$_2$ process beam in mild steel with moderate success. Kaplan proposes a simple method for estimating the likely number of multiple reflections a ray of light entering the keyhole will undergo before escaping, as a function of the mean wall angle.

In 1996, with then-current models still unable to predict the crucially important keyhole depth in a satisfactory manner, Lankalapalli et al. developed a procedure for computation of weld depth based on the process parameters and measured melt pool width [31]. This model still assumes an axisymmetric, conical keyhole profile, justified by the need for computational efficiency. The authors found a satisfactory level of agreement between predicted and measured weld depths, and attributed the visible discrepancy to errors in the power calibration of their laser. Tellingly, they found that the dependence of keyhole depth on power and feedrate is much stronger than that of the keyhole width, and admit that the keyhole width cannot sufficiently index weld penetration depth.

Until the mid-1990s, all models treated the keyhole in a quasi-steady-state manner. Some assumptions regarding the geometry were usually necessary, and thus the effects of multiple reflections and Fresnel absorption events, though consistently noted to be crucial to energy transfer from the laser [12, 46, 24] were poorly addressed. These models analysed Fresnel absorption at the keyhole walls and inverse Bremsstrahlung absorption in the plasma. Once a thermal distribution was established the extent of
the weld seam was determined by simply setting an appropriate isotherm.

In 1997 Matsunawa and Semak published a theoretical paper marking an important departure from the quasi-steady-state treatment of earlier efforts. Their model assumes high welding speeds, and describes the dynamics of the front keyhole wall, assuming keyhole tilt is great enough that all incident power is applied there [36]. Their calculation of arbitrary front wall profiles is quite similar to the method of Kaplan, but is based on different fundamental assumptions about mass and heat transport away from the absorption site. They begin with the premise that the dominating factor in keyhole behaviour is the transport of molten material out of the beam path due to recoil pressure, as opposed to evaporation as was previously assumed. This model is notable for its incorporation of realistic melt hydrodynamics. According to experimental data, local melt velocities in the weld pool may exceed the feedrate by several times, something not addressed by previous models. Additionally, this model gives a better attempt to follow experimental data indicating a high degree of keyhole asymmetry in the longitudinal plane. The front wall, as modelled by Matsunawa and Semak, is a dynamic entity capable of exhibiting significant horizontal velocities relative to the process beam axis. The formation and propagation of ‘hump’ instabilities (discussed below in section 2.4.4) is clearly exhibited, providing a potential explanation for keyhole depth oscillations. In 1999 Semak extended this same approach to a model of a complete keyhole geometry, rather than just the front wall [41].

In 2002, Ki et al. published a pair of modelling papers that, in my opinion, mark the first successful effort to completely capture the numerous complexities of the keyhole [27, 26]. The evolution of the keyhole shape is framed as a liquid-vapour boundary problem, approached computationally using the level-set method [27]. The
level-set method turns the motion of the Keyhole boundary interface into a partial differential equation. This method deals well with splitting and joining of multiple interfaces, and enables straightforward calculation of surface normals and curvature. These advantages make for a very general model of the keyhole geometry, and facilitate calculation of the light-matter interaction across the surface. Beam propagation within the keyhole is modelled using the ray-tracing method.

This simulation was able to demonstrate the transition from conduction-mode to keyhole mode welding, as well as the effects of different keyhole wall phenomena on the process, in a self-consistent manner that displayed qualitative agreement with experimental data. The transition from conduction- to keyhole-mode welding was found to depend primarily on the role of evaporation recoil pressure. They found that keyhole fluctuation was an intrinsic consequence of the sensitive energy absorption pattern. The beam is distributed over many rapidly shifting absorption sites, driving perturbations in the keyhole walls. As a result of the dynamism of the multiple reflection paths, the effective absorptivity of the keyhole was found to fluctuate strongly during quasi-steady-state operation.

The results of the model were compared against CO$_2$ welding experiments with identical input parameters. The top surface of the melt pool was recorded with a high-speed CCD camera, and good agreement was found with measured top-surface melt geometries and velocities. This model excelled in its sophistication, but the computational expense was described by the authors (in 2002) as “tremendous” [27]. The code was vectorized and run on a supercomputer platform at the American National Center for Supercomputing Applications at Urbana-Champaign, IL. Moreover, and in spite of the computational power devoted to this project, no experimental verification
of the subsurface activity was carried out.

The primary difficulty facing any finite-element approach to keyhole modelling is the close interdependence between the keyhole geometry and the spatial distribution of laser energy. At each step, the geometry must be re-calculated, followed by the beam path and absorption map, before the thermodynamics may be addressed. Self-consistent models may be developed in such a manner at high computational expense, but even minor inaccuracies in the keyhole shape and its response to welding conditions will have a strong effect on the results produced. In theory, accurate, high-speed, in-situ measurements of the complete keyhole geometry have the potential to change the way such modelling is approached.

2.4.4 Defects & Instability

The tendency of the modelling community to make simplifications that treat keyhole welding as a static process in the frame of the machining laser represents a gap between experimental observation and theoretical understanding of this system. Real observations of the keyhole indicate that it is anything but static. As John Dowden states,

The keyhole... ...is known to be a writhing, tortuous entity, far from dynamically stationary, with a great many of the characteristics commonly associated with turbulence. [13]

He also notes that,

The bottom end of a blind keyhole may move around erratically, and its boundary deform, in a manner reminiscent of chaotic behaviour; although
its shape and position are given deterministically it appears to behave randomly.[13]

The keyhole behaves in a stochastic manner. A number of defects and perturbations can and do occur under normal operating circumstances. The laser welding literature describes front wall ripples (humping), irregular depth oscillations (spiking), ejecta and spatter, pinch-off, underfill and overfill of the finished seam, and porosity. Humping and spiking are common to the point that referring to them as defects is slightly misleading. The natural state of the keyhole is not static in the process beam frame of reference. In practical welding, reduction of the keyhole mobility is part of the effort to control levels of under- and over-fill, spatter, and porosity—all of which have direct bearing on finished part quality.

2.5 ICI and the Keyhole

In measuring laser keyhole welding using ICI, we have married two optical systems of which our understanding is incomplete: the weld keyhole and the novel imaging capabilities of ICI. Regarding the extent of subtleties in the resulting data, the whole certainly exceeds the sum of its parts.

Experimental measurements of the keyhole have posed a challenge for years. ICI is in many ways an ideal technique to accomplish this task. It uses a probe beam with an 840 nm centre wavelength, and spatially superimposes the two. Thus, the probe effectively sees what the process beam sees, granting it access to laser-material interaction regions deep within the sample. However, one can also make a compelling argument against the use of ICI for this purpose. Quasi-stable keyhole welding is
characterized by strong absorption via multiple scattering of the process beam. Intuitively, the odds of retrieving a coherent signal from the inside of the keyhole are low, and experiment confirms this. The characteristic ICI signal from the bottom of the weld keyhole is both low in intensity and sporadic. It is due to the high dynamic range of ICI—upwards of 60 dB—that it can be successfully applied to this problem at all. All else being equal, signal is retrieved most readily when the net absorption of the keyhole is at its lowest—arguably only during times when the keyhole is in a non-ideal state.

In the coming chapters, I will explore the ICI signal from the weld keyhole in the context of the imaging characteristics described in the previous sections. The strengths and limitations of ICI as a tool for practical weld monitoring and exploration of the underlying physics will be addressed. Particular attention is paid to factors responsible for pervasive signal losses from the keyhole root, in Chapter 5. In Chapter 6, I implement and characterize an extension of the original one-dimensional ICI measurement technique to three spatial dimensions. I discuss the ability of this technique to produce a more general view of the keyhole morphology, and its viability as a means to further our understanding of the physics of keyhole welding.
Chapter 3

Experimental Apparatus

The laser welding apparatus used throughout the experiments discussed here is the kilowatt laser macroprocessing station designed by former graduate student Paul Webster. The specifications of the system in its original configuration are described in some detail in Webster’s thesis [47]. Significant modifications to the sample arm beam path were carried out as part of my research, to enable dynamic positional control of the ICI beam on the sample surface. This capability introduces transverse resolution to the ICI image, opening the technique to a host of new potential applications.

3.1 The Macroprocessing Station

The macroprocessing station consists of a high-power laser source, an interlocked safety enclosure for machining, a beam delivery head, work-piece fixturing with three-dimensional motion control, auxiliary air and assist gas management, and a dedicated, portable ICI system built into a rack-mount case. This setup is designed to allow us to experimentally replicate laser machining conditions commonly seen in industrial
settings. This combination of laser and delivery head is well-suited to laser keyhole welding and a range of larger-scale laser cutting tasks. Figure 3.1 is a schematic diagram of the macroprocessing station.

![Diagram of the macroprocessing station](image)

Figure 3.1: Schematic diagram of the macroprocessing station, including the process beam delivery optics and ICI system components.

### 3.1.1 The Process Laser

The machining source is a diode-pumped, Ytterbium-doped fibre laser (YLS-1000-IC) made by IPG Photonics. The nominal maximum output power is 1100 W, with a typical centre wavelength of 1070 nm and a bandwidth of 3 nm. Since high power is desired, this laser is multimode. The laser is built into a case approximately the size of a chest freezer, containing the gain media, pump diode sources, power supplies, liquid cooling systems, and electronics for control and safety. The unit contains three independent gain modules, each responsible for roughly one third of the output power.
After the gain stage, the beam is coupled into a 5 m feeding fibre with a core diameter of 50 µm. This fibre is, in turn, coupled to a 5 m delivery fibre with a 100 µm core, through which the beam travels into the laboratory to the macroprocessing station enclosure. All inter-fibre coupling occurs via specialized, water-cooled collimators, as even a small amount of thermal lensing at these power levels can have destructive consequences.

Where the beam reaches the enclosure, it is coupled horizontally into the machining head (Laser Mech Accufiber PLYDH0209) through a 60 mm-focal length water-cooled collimator. The process beam is reflected from a 45° dichroic mirror, pointing it straight down toward the workpiece. The ICI beam couples into the machining head through a camera vision port above the dichroic. This optic is coated to allow the 840 nm-wavelength ICI beam to pass while reflecting the process beam at 1070 nm.

The Laser Mech head has interchangeable cartridge-mounted final focussing optics, with options for 100, 150, or 250 mm working distances above the sample. All lenses are anti-reflection coated, spherical, and plano-convex. Below the lens is a second cartridge that holds sacrificial cover glass meant to protect the lens from machining ejecta and vapour. The cover glass cartridge is sealed with a rubber O-ring, and the chamber immediately below it has an inlet for assist gas and threading for mounting of a coaxial-delivery gas nozzle. In addition to the direct delivery of assist or cover gas to the sample along the beam axis, these components allow the volume below the cover glass to be kept at positive pressure, helping to prevent material ejected from the machining site from reaching the optics.
3.1. THE MACROPROCESSING STATION

The 150 mm lens is suitable for both cutting and welding applications, and therefore sees common use in this setup. When the laser and head were commissioned, a beam profile measurement for the 150 mm optic was taken using a PRIMES beam diagnostic system. The process beam through this optic has a waist of 210 µm, a single-sided Rayleigh length of 3.7 mm, and an $M^2$ value of 9, with a slight ‘top-hat’ intensity profile. Unfortunately, the hardware required to capture a profile of a laser beam of this power is not regularly accessible to us. Thus, spot sizes for the 100 and 250 mm optics (acquired at a later date) must be calculated based on the beam waist and $M^2$ value measured for the 150 mm lens.

Assuming the process beam is collimated where it meets the focusing lens, I calculate the spot size on the lens from the PRIMES commissioning data. Knowing the beam quality parameter, $M^2$, for a non-Gaussian beam, I use

$$w_m' = \frac{M^2 \lambda f}{\pi w_0},$$

(3.1)

where $\lambda$ is the wavelength and $f$ the lens focal length, to relate the focused beam waist radius $w_M'$ to the (collimated) beam radius on the lens $w_0$ [37]. Based on the data for the 150 mm lens, I find a collimated beam radius of 8.8 mm at the focusing optic. Using this value, I calculate expected beam waist diameters of 140 µm and 340 µm, respectively, for the 100 and 250 mm focusing optics.

The process laser is operated using IPG’s LaserNet software. The software handles alarms and logging, allows the laser to be armed and fired manually or set to respond to an external electrical trigger or modulation signal, and sets the nominal output power of the laser. Along with fellow graduate students Jordan Kanko and Matthew Windeler, I checked these values for accuracy using a water-cooled
thermopile (Laserpoint-W-1500-D40-SHC). The thermopile is fixed to the macroprocessing enclosure floor, and the laser head is translated to the upper limit of the z-axis travel, in order to spread the spot out as much as possible on the absorbing surface of the thermal head. Tap water is run through the cooling lines at a rate of 4 L/min, and the temperature is observed (with an alcohol thermometer) to be stable at 20 ± 1 °C before power measurements commence. The power meter requires approximately thirty seconds to stabilize when the laser power is changed. Errors are estimated based on the observed range of variability of the measurement. Nominal laser power is increased from 110 W to 1100 W in 110 W steps. The results of this calibration are reported in table 3.1.

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Table 3.1: Nominal output power of the macroprocessing laser as reported by IPG’s LaserNet control software, and actual output power as measured by a thermopile power meter.

3.1.2 Motion Control

Control of the workpiece position relative to the process laser beam is handled by three ball-screw-bearing linear motion stages. The x-axis stage (Aerotech PRO-165)
is bolted down to the floor of the macroprocessing enclosure (an optical table). This stage bears the y-axis stage (Aerotech PRO-115) and a custom sample bed as a cantilevered load. The combination gives positional control of a fixtured sample in the horizontal plane with sub-100 nm precision. For control of the laser focal height, the machining head is mounted on another linear stage (Aerotech PRO-115), thus affording full three-dimensional control of the process laser spot position relative to the workpiece. The maximum velocity of all stages is 300 mm/s. The range of travel is 400 mm for the x-axis, and 300 mm for others.

The stages are driven by brushless motors, each with its own control and power supply unit (Aerotech Ndrive CP). Positional control and analog and digital input and output (I/O) for each axis is managed by these units. The entire motion system is controlled from a computer running Aerotech’s A3200 software suite. Automated motion programs for experiments are written in G-code (a common automated machine tool control language), or its Aerotech-proprietary derivative, Aero-basic.

3.1.3 The ICI System

The ICI system pertaining to the macroprocessing station is the first such unit built with a portable design. It comprises a fibre Michelson interferometer, light source, custom spectrometer, and open-air reference arm terminus, all built into a rack-mountable computer case. A schematic diagram of the system internals (including a modified reference arm to be discussed below) is shown in Figure 3.2. Input and output signalling are handled by a National Instruments DAQ. The system is paired with a dedicated computer for image acquisition and processing, which pulls data from the spectrometer via a National Instruments camera-link card.
3.1. THE MACROPROCESSING STATION

Figure 3.2: Schematic diagram of the macroprocessing station ICI system. The four arms of the interferometer, including a) the source, b) the reference arm, c) the spectrometer, and d) the sample arm, are implemented through single-mode optical fibre. The light source, a superluminescent diode (SLD), couples into the interferometer through a faraday isolator (circ) to protect against damage from backscatter. An evanescent wave coupler (50/50) splits and merges light from the different arms. The spectrometer consists of a collimator, diffraction grating (DG), and line camera (cam). Polarization control (PC) in the reference arm is adjusted to optimize the strength of the interference fringes. The reference arm path length is adjusted with a manual stage, and reference arm power is controlled by defocussing a lens with a micrometer stage.

At the core of the interferometer is a 50/50 evanescent wave fibre coupler (Thorlabs FC850-40-50-APC). Interferometer elements are connected to the coupler via 5 μm core-diameter single mode optical fibres. The light source is a superluminescent diode (Superlum BLM-S840) with a nominal output power of 30 mW, centre wavelength of 843 nm, and 25 nm bandwidth FWHM. The nominal output spectrum is shown in Figure 3.3. A Faraday optical isolator (AC Photonics) separates the light source
from the beam coupler, preventing back-reflected radiation from the interferometer from damaging the diode. The spectrometer comprises an output collimator, volume phase holographic transmission grating (Wastach, 1800 lines/mm), objective lens (Zeiss planar T 85/1.4 ZF-IR), and high-speed CMOS line camera (Basler Sprint spL4096-140km). The camera array comprises two horizontal rows of 4096 pixels. The reference and sample arms of the interferometer travel through a length-matched pair of 10 m single-mode fibre jumpers (Oz Optics SMJ-A3A,3A-780-5/125-3-10-SP).

![Linear plot.](image)

Figure 3.3: The nominal output spectrum of the superluminescent diode. From [45].

The reference arm terminus originally consisted of an output coupler, a 50 mm focussing lens, and a fixed silver mirror. The lens is used to adjust reference arm power ($I_r$ in Equation 2.3) through confocal gating, to correct for changes to camera integration time or soften the signal from a highly reflective sample. The open-air portion of the reference arm is designed to match both the path length of the sample arm and dispersion due to the sample arm optics as closely as possible. To accompany modifications that I make to the sample arm (discussed below in section 3.4), I have
constructed a second reference arm terminus, external to the ICI system case. This new reference arm has the output coupler and reference mirror mounted on a manual translation stage, with the beam path folded once, to allow adjustment of the relative path delay without realignment of optics.

The sample arm fibre terminates at the top of the machining head, where it is coupled into free space and aligned coaxially, through the dichroic mirror, with the process beam. A polarization controller is placed in the reference arm. This is adjusted to optimize the amplitude of interference fringes observed from a flat reflector, correcting for any polarization changes in the ICI beam delivery fibre. The spectrometer is calibrated using an Argon lamp. The incident wavenumber as a function of camera pixel is calculated from a 4th-order polynomial fit to the known near-IR emission peaks of argon. The wavelength calibration of the spectrometer is thus NIST-traceable.

3.1.4 Operation and Synchronization

Operation of the laser, motion control, and ICI system is centred on the A3200 software suite. Both the laser and the ICI system are wired to receive a digital trigger signal from the position-synchronized output (PSO) line of the x-axis nDrive unit. This trigger is synchronized with the motion of the stages such that laser exposure and imaging may be commenced and terminated by the operator at desired points on the sample. The triggering is written into a G-code motion program by the user. Laser timing is directly linked to this trigger, and may be gated by it if multiple runs or quasi-continuous-wave (QCW) pulsed operation is desired. For most imaging applications, the ICI system responds only to the rising edge of the initial
PSO pulse, and the subsequent frame acquisition timing is handled independently by the DAQ internal clock. Auxiliary systems including a solenoid valve to regulate assist gas flow and a fume extractor are also wired to the digital I/O of the nDrive units and controlled from G-code. The capability to automatically control z-axis height (autofocus), or horizontal axis position (seam-tracking) based on ICI data are also in place, however these do not see use in this thesis.

3.2 Processing ICI Images

Images presented throughout this thesis are captured using Laser Depth Dynamics’ proprietary software. The program controls camera parameters and timing, processes the measured interference patterns, manages some communication with the Aerotech hardware, and saves ICI images in National Instruments’ TDMS file format.

Each line of camera data, containing integrated backscatter intensity as a function of wavenumber, is processed into a single A-line, which represents the intensity as a function of relative optical path length. The processing can be performed in one of two ways, as outlined below. The first method follows the Fourier-transform-based derivation of section 2.2.2. The intensity as a function of camera pixel is converted to intensity as a function of wavenumber \( k \), based on the spectrometer calibration, by a linear or cubic spline interpolation (whether optimizing for speed or image clarity, respectively). This step is necessary to produce intensity measurements that are evenly-spaced in \( k \) for the fast-Fourier-transform (FFT) algorithm, since the mapping of \( k \) to pixel number is not linear. The new set of interpolated intensity fringes is then Gaussianized to ensure that the boundaries go smoothly to zero. The interpolation step ignores the nonlinearity between \( k \) and \( \lambda \). This effectively introduces an artificial
intensity shift toward one end of the $k$-space interpolated data set. However, since the spectral fringes are immediately subjected to another artificial shaping step, this inaccuracy is not accounted for explicitly. An FFT transforms the intensity data from $k$-space (wavenumber or spatial frequency) to $z$-space (optical path length).

The modulus of the output from the FFT is taken. This results in a single real intensity value for each optical path length, and shortens the range of the set to half the number of pixels read from the camera since the result is symmetric about zero. This step also introduces an ambiguity between signals from either side of the interferometer zero-delay point. The result of the complex conjugate ambiguity is that there are two imaging fields on either side of the zero-delay point which are, all things being equal, indistinguishable except for inversion of the image. Care must be taken when imaging to keep track of on which side of zero-delay the interface of interest falls.

A sequence of A-lines arrayed as columns in chronological order constitutes an ICI image. A-lines are displayed on a $20 \log_{10}$ decibel scale. The factor of twenty is applied because the interference fringe strength depends on the square root of the sample arm intensity (see Equation 2.3). Since the reference arm intensity is held constant during a measurement, the intensity of the sample arm is what determines the relative amplitudes of measured peaks. This square root scaling—in theory—results in effective doubling of the line camera dynamic range for sample backscatter intensity. The FWHM of the transformed peak for a perfect reflector—its point spread function—is taken as the axial resolution of the system. For the macroprocessing ICI system, the minimum measured PSF width on clean steel is $22 \ \mu m$. In OCT literature, it is common to quote axial resolution values on the order of nanometers,
derived from the precision with which a peak may be fitted to the measured data. However, these figures are not a correct measure of the system’s ability to distinguish two nearby interfaces from one another. The point spread function FWHM is more appropriately conservative, especially when no a-priori knowledge of the sample is assumed.

3.2.1 Noise Floor Subtraction

Whenever a run of experiments is commenced, the system is recalibrated to subtract the spectrometer noise floor and remove any fixed-pattern artifacts in the field of view, resulting from multiple reflections within transmissive optical elements in the interferometer (see section 2.3.1). This step requires measurement of a sample of lines from the spectrometer, with the sample arm of the interferometer blocked so that only the reference arm intensity is present in the signal. First, the sample of raw camera lines is averaged by pixel. The result of this average—the reference arm power spectrum—is subtracted from all subsequent lines read from the camera, effectively removing the second term, the reference arm DC level, from Equation 2.3. Once the DC level has been subtracted, the sample of camera lines is processed into a set of A-lines, and the RMS variation of each depth pixel is calculated. The RMS noise floor forms a vector the same size as an A-line, and is subtracted from the measured (dB-scale) intensity as a function of depth. This step removes any fixed-depth noise in the image, as well as providing the zero-point for the intensity decibel-scale at each height. An example RMS noise floor is shown in Figure 3.4.
3.2. PROCESSING ICI IMAGES

3.2.2 Homodyne Filtering

In the case of ICI data acquired by the LDD software, the traditional interpolation and FFT steps of the image processing chain are replaced by a homodyne processing method [52]. Homodyne filtering allows most of the computational load to be shifted to pre-processing. This decreases the resources necessary to process the data during fast acquisitions. It also reduces artifacts that result from the interpolation of the raw data required for the FFT approach, namely the growth of shoulders on intensity peaks as the Nyquist limit is approached at greater relative path lengths (see [47]). The homodyne filtering process essentially involves generation of a lookup table of synthesized interferograms for each depth bin that would be produced by the FFT (called a homodyne matrix). The depth profile is then drawn by mixing of the measured interferogram with the set of synthesized ones. Implemented with GPU-based parallel processing, this method is much faster than the equivalent FFT-based procedure [47]. The homodyne matrix is defined as a function of camera pixel number and relative optical path length. The mapping of k to pixel number
is determined during the spectrometer calibration. Homodyne filtering also allows any dispersion mismatch between the reference and sample arms to be compensated during the generation of the matrix. Second- and third-order wavelength-dependant phase-shift terms are added to the synthetic interference patterns. The second-order dispersion correction affects the PSF width, while the third-order correction affects its symmetry. The dispersion coefficients can only optimize the PSF shape over a certain range of depths. Inclusion of dispersion correction tends to offer a sharper PSF on one side of the zero-delay point at the expense of broadening on the other side. A more detailed description of this processing method can be found in Webster’s thesis [47].

3.2.3 Display of Data

Once processed, ICI data is displayed with the A-lines concatenated into an array. The vertical axis corresponds to relative optical path length, and the horizontal to time. In the interpretation of these images, the beam is assumed to propagate through air, and the y-axis is mapped directly to interface position (depth). Backscatter intensity at each depth pixel is represented by a gray-scale colour map. The colour map is set to a logarithmic scale with limits to match the system’s dynamic range. Figure 3.5 shows a simple artificial representation of an ICI image. This image is an approximation of what is seen when ICI is continuously recorded while the distance between the process optics and the reflective interface increases. The height of the sample surface (the brightest peak in each column) moves smoothly downward as its distance from the optics increases. This is a very simple example of the behaviour one sees in a sample as it is machined. The surface on which the imaging and process
3.2. PROCESSING ICI IMAGES

beams simultaneously impinge descends into the sample as time progresses.

Figure 3.5: A simplified, artificially generated ICI picture of a descending interface. Time increases along the x-axis, while the y-axis indicates optical path length. Increasing backscatter intensity is scaled from black to white. As the interface portrayed here moves away from the optics, the measured intensity peak descends.

3.2.4 Sensitivity Rolloff

As can be seen in Equation 2.3, backscattering interfaces at greater absolute path lengths relative to the zero-delay point produce interference fringes with higher frequency in $k$. These fringes are resolved on a camera array with fixed pixel width. As the fringe frequency across the line camera pixels approaches the Nyquist limit, the spectrometer is no longer able to properly resolve the fringes. This results in attenuation and broadening of the backscatter peak in the transformed A-line. In theory, the rolloff rate as a function of distance depends on the number of camera pixels and the spectral resolution of the spectrometer. In practice, sample-dependent
confocal effects also play a role. To account for both effects, I measure the backscatter from a coated steel surface and a white business card, while translating the laser head through the entire single-sided field of view of the ICI system. The resulting data sets are represented in Figure 3.6. The imaging focus is located at 2 mm path offset. The peak amplitude begins to decrease beyond this point. This is due to a combination of both the camera-resolution-induced roll-off described above, and confocal gating of the imaging beam on its return trip to the optics. A similar roll-off pattern is observed for the (relatively) specular metal surface and the diffuse paper surface. The peak-to-peak intensity range for each is 18dB, and the highest intensity occurs between 1200 and 1300 µm. Both the confocal effect and spectrometer rolloff contribute to the asymmetry of the observed peak intensity about the focal point at 2 mm.

3.3 Multiplexed High-speed ICI

The maximum imaging line rate is limited by the speed of the CMOS camera. This limit may be pushed slightly by using a smaller portion of the pixel array. However, a desire for much improved imaging speeds requires a change to the interferometer design. To this end, industrial collaborator Paul Webster and I designed and implemented a multiplexed arrangement of ICI systems that doubles the imaging speed attainable with a single camera.

The multiplexed high-speed ICI system takes advantage of the fact that interference signals are returned along both the spectrometer and source arms of the interferometer. Under normal operation, the light returning to the source is diverted by an optical isolator and sent to a beam dump to protect the superluminescent
Figure 3.6: Measured signal from a coated steel surface (top) and white paper (bottom), at various relative offset distances. Signal rolloff is visible in the decreasing peak signal heights toward the upper end of the path offset range. Each curve is a single A-line (plot of backscatter as a function of optical path delay) extracted from an ICI image of a sample interface slowly translated toward the process optics. The A-lines are extracted at regular time intervals, and are distinguished by colour. The imaging beam focus is 2000 µm from zero-delay.

diode. This signal is equally capable of producing an ICI image. The multiplexed system is implemented using two commercial LD-600 ICI systems from Laser Depth Dynamics Inc. The first is run in its standard configuration, while the spectrometer of the second is disconnected from the fibre coupler and hooked up to the output of the protective isolator in the first interferometer (the point marked “cap” in Figure 3.2). In this manner, the two different interference patterns returned from the coupler in the first interferometer (differing by a phase shift of π), are measured by two separate spectrometers. The signals from the line cameras are captured by two different Camera Link cards in separate computers, and the data sets are combined after the fact.
3.4. THE GALVANOMETER SCANNER HEAD

Triggering of camera acquisitions is synchronized using a multi-channel function generator (Tektronix AFG 3022-B). The PSO output signal from the Aerotech Ndrive controller is used to trigger the function generator. Pulsed output signals to each camera are configured for the desired line rate and integration time, and set to fire on the rising edge of the trigger signal. The timing of these two outputs is verified using an oscilloscope (Tektronix DPO 3034), for both simultaneous and interlaced (\(\pi\) phase-shifted) timing configurations.

The spectrometer line cameras are set to a 576-pixel area of interest (the usual value is 896), centred on the array. With fewer pixels to read out, the maximum line rate for the camera increases to 294 kHz (as opposed to 232 kHz for 876 pixels), at the cost of reduced axial resolution (288 depth bins after processing as opposed to 448). To optimize imaging speed from the multiplexed system, the cameras are fired alternately at this rate. The ICI images generated by the two systems are then interlaced to produce a single image with doubled temporal resolution. Images of laser welding obtained with this apparatus are presented in Chapter 6.

3.4 The Galvanometer Scanner Head

In laser welding, the behaviour of the process is governed by the morphology of the sample in three dimensions. It therefore stands to reason that many relevant and interesting dynamics occur away from the process beam. The extent of the trailing melt pool and the motion of waves across its liquid metal surface, for instance, or the point of onset of the melt pool just leading the beam are important pieces of the laser welding puzzle. It is possible to capture these dynamics with ICI by deliberately misaligning the imaging beam to lead or trail the process beam. A
3.4. THE GALVANOMETER SCANNER HEAD

technique which allows the beam displacement to be controlled quickly enough to repeatedly interrogate multiple regions of the sample during a single weld is desirable. To this end, I introduce a pair of galvanometer scanning mirrors to the imaging beam path, enabling electronic control of the transverse position at which the ICI beam strikes the sample.

Such scanning mirror sets are ubiquitous in OCT, but the integration of this modification into a commercial welding head proved to be challenging. The scanning mirrors used are a paired set (Nutfield Technology QS-10) in a mounting block that ensures orthogonality of the mirror rotation axes. The scanners are connected to a matching set of servo drive boards (Nutfield Technology QuantumDrive 1500) each of which sets the mirror position in response to a single-sided analog voltage input. This galvanometer system has a total scan range of ± 22.5°.

The scanner apparatus has to mate to the existing macromachining head and fit within the safety enclosure without compromising the range of the motion axes. The scanners also cannot interfere with the process beam path, and have to function through the focussing optics shared with the process beam. The scanner system must provide sufficient degrees of freedom to allow full coaxial alignment to the process beam with the mirrors in a neutral position (i.e. adjustment of the imaging beam angle and position). In addition, the system must be resistant to dust and debris as its operating environment is frequently filled with airborne particulate metal and combustion by-products. To avoid compromising the user-friendliness of the existing system, I further required that the in-line CCD camera and microscope that allows top-down viewing of the sample bed through the process optics be kept in place.
3.4. THE GALVANOMETER SCANNER HEAD

I designed a covered aluminum mounting interface to port the galvanometer scanning mirror pair onto the Laser Mech head. The block is affixed to a removable clamp assembly, which connects to four quarter-inch posts already in place to anchor the ICI beam collimator. The block is designed around a technical drawing from Nutfield technologies, indicating the beam path through the paired mirrors in neutral position. The mounting block has one-inch apertures for the optical path input and output, oriented at 90° relative to one another. The input aperture is centred between threaded holes to receive four quarter-inch posts as a new mounting position for the input collimator, upstream of the scanning mirrors. Figure 3.7 shows a photograph of the original macroprocessing head, along with an isometric view of a SolidWorks drawing of the mounting block in context, and a photograph of the finished scanner mount attached to the laser head vision port.

This design is susceptible to a number of potential issues that stem from the use of expressly non-ideal optics for beam-scanning applications. The focussing lens in the laser head is plano-convex with a spherical top surface. Thus light passing through it is theoretically vulnerable to spherical aberration. Moreover, the response of ray position in the focal plane to input angle is not linear, resulting in barrel distortion of the imaging field. The focal plane of the lens is not flat, curving back toward the lens with increasing transverse distance from the optical axis. Finally, since ICI measures optical path length, and the optic in question is a thick lens, the changing thickness of glass as the beam is translated off-axis is also considered as a possible source of depth field distortion. All told, the prospects for high-quality imaging through such an optical system appear uncertain.
3.4. THE GALVANOMETER SCANNER HEAD

Figure 3.7: a) The macroprocessing station laser head prior to insertion of galvanometer scanners in the ICI beam path. Red Circle indicates the mounting region for the scanner hardware. b) Solidworks drawing of the machining head vision port, modified to accept galvanometer scanning mirrors (includes drawings by Thorlabs, and Nutfield Galvos, provided as sales material; and Paul Webster). The ICI beam path through the mirrors is indicated by orange arrows. c) The finished mounting assembly, attached to the vision port. The dovetail at the bottom of the picture is used to affix the assembly to the lower part of the machining head.
Before imaging of materials processing is carried out using the galvanometer-enabled ICI system, I characterize the distortion of the plano-convex lens imaging field in both the transverse and axial dimensions. The imaging field is small by necessity, since the optical path passes through hardware not intended for scanning applications. The coaxial cover gas nozzles employed on this apparatus during welding have minimum clear apertures less than 10 mm. As a consequence, the galvanometer mirrors are restricted to small scanning angles about the optical axis if the ICI beam is to clear the machining head. The conversion from input voltage to transverse position in the focal plane is not necessarily expected to follow a simple functional form. Accordingly, I directly calibrate beam displacement to input voltage using ICI images of a target of known geometry.

I acquire three-dimensional images of a microscope calibration slide (Edmund Optics) placed in the path of the beam. The slide is transparent and roughly 1.5 mm thick, and the pattern—a standard USAF 1951 pattern grouping—is coated on its surface in chromium. Contrast in surface reflectivity is visible between the coated and uncoated regions. The ICI beam position is controlled using analog voltage output signals from the Aerotech Ndrive units, adjusted by a G-code script. The voltages may be set in steps to produce a (nominally) rectangular grid of pixels. The voltage step is initially set to match the nominal output resolution of the NDrive (305 µV), and is scaled up according to the desired image dimensions. An A-line is taken at each point in the grid, resulting in a volume image of reflectivity as a function of optical path in the vicinity of the process beam focus.

A calibration value mapping galvanometer input voltage to ICI beam position on the sample is calculated by fitting an overlay of the known slide pattern to a
single horizontal slice of the ICI image. This process is demonstrated in Figure 3.8. The results of this calibration procedure are tabulated below. The surfaces shown in Figure 3.8 are located 1 mm below the imaging beam focus. This position was chosen to prevent an autocorrelation signal from inside the glass slide from interfering with the image of the top surface. It is important to note that since the imaging beam is not completely parallel to the optical axis when it is displaced, some magnification of the scaling factor as a function of depth is expected to occur. Since the angle of inclination of the imaging beam tends to be small, this effect is expected to be minimal. The effect of angle is included in the calibration factors quoted in table 2.

Figure 3.8: Top-down view of a USAF 1951 pattern microscope calibration slide, imaged using a three-dimensional ICI scan pattern through 150 mm (left) and 100 mm (right) focussing optics. The slide is glass, with silvered pattern elements on its surface. Groups two and three of the pattern are primarily visible here. A square bounding the set of three stripes in the upper left corner of the pattern seen here would measure 557 µm to a side. A fit pattern is overlaid to determine the scaling of the image in microns.

Given that the optics in use are not ideal, one expects distortion of the imaging field to occur as the angle of the ICI beam relative to the optical axis is increased. Most importantly, the optical path length of a beam at the edge of the imaging
field is expected to be longer than that of an on-axis one, which will distort the depth measurement as a function of transverse position. To measure the degree of curvature, we observe the three-dimensional scan of the glass calibration slide from the side. The degree of curvature of a flat surface across the field of view may be used to correct future images to a flat field, if necessary. In Figure 3.9, I present profile views of the flat glass surface of the calibration slide. Starting with a vertical slice of the three-dimensional image, I crop the depth scale to a region around the top surface of the glass slide, and plot the brightest pixel in each vertical line (typically corresponding to the backscattering interface depth) in green.

Although strong saturation ringing is visible near the centre of the image, the distribution of brightest pixel depths gives a good sense of the measured surface curvature. The 100 mm lens is observed to produce stronger field curvature than the 150 mm lens. The curvatures in the x- and y- scan directions for each lens are comparable. The horizontal displacement scale is given by the calibration factors given above.

Interestingly, the curvature opposed the anticipated direction if one considers only the physical path length of the beam. An angularly displaced beam travels farther to reach the surface of the slide than one on-axis. However, the decreasing thickness of the lens away from the optical axis correspondingly reduces the optical path length travelled by the displaced beam. The measured result shows a relatively gentle upward curvature of the imaging field. Typically, I correct weld data sets for sample tilt and curvature by subtraction of depth from a pre-scan of the motion path. In the case of images incorporating motion of the scanner mirrors, the same approach is employed. Thus, the imaging field curvature need not be explicitly included as a correction. It is
Figure 3.9: The curvature of the flat top surface of the USAF calibration slide as measured by the galvanometer-equipped ICI system through a spherical planoconvex lens. The upper pair of images shows scans through the 100 mm focussing lens in the $x$ and $y$ directions, respectively. The lower pair shows the same measurements taken through the 150 mm lens. As the beam is displaced from the optical axis, the increase in physical path length is offset by the decreasing thickness of the lens away from its centre. Due to the high reflectivity of the silvered portions of the glass slide, saturation broadening of the measured interface is visible in some regions of each image.

still of importance that the distortion from the optics is small compared to the depth ranges typically explored in laser keyhole welding.

As can be seen in Figure 3.8, the scan field is small enough that barrel distortion is not readily apparent through the 150 mm lens, while a moderate amount is visible through the 100 mm lens. For this optic to be put to use in 3D imaging of laser welding, more confidence in the accuracy of the of the ICI beam positioning is desired. Rather than rely on a reference measured using ICI, I directly measure the beam
3.4. THE GALVANOMETER SCANNER HEAD

position as a function of time.

A high speed Indium-Gallium-arsenide (InGaAs) line camera (Goodrich SUI 512 LDV-1.7RT-0500/LX) is bolted to the sample bed in the macroprocessing enclosure, its sensor facing upward. The camera has a pixel pitch of 50 µm and a (full array) maximum line rate of 19.10 kHz. The centre pixel is aligned to the process beam focal position using the inline camera on the welding head. The line camera is aligned to the x and y scanning axes in turn, in order to measure the position of the ICI beam in response to a single galvanometer input at a time.

Voltage inputs are given by a function generator (Tektronix AFG 3022-B). A triangle input wave is used for a nominally linear, two-sided sweep pattern. Based on the previous calibration step, voltage amplitude and DC offset are chosen to yield scan patterns appropriate for capturing profiles of the weld keyhole. Scan patterns up to 500 Hz frequency and 5 mm peak-to-peak amplitude are tested. With the imaging light source on, the line camera and the function generator that controls the scanners are triggered by the same voltage pulse. The position of the ICI spot as a function of time is measured on the line camera array. The data is recorded using a simple Labview program that acquires lines from the camera and fits a Gaussian function to each to find the beam centre. The output is a vector of peak positions (pixel numbers) as a function of time.

A triangle wave is fit to the measured beam position using a least-squares regression. The linearity of the measured signal is quite good except in the outermost 5% of the amplitude for scanning frequencies greater than about 100 Hz. The pattern of observed residuals to the fit indicates that the error is dominated by the pixel pitch of the line camera. This is primarily visible at slower scan speeds, in which several
consecutive measurements will land on the same pixel. The positional error of a given measurement taken during such a scan is small enough to be neglected in comparison to the spot size of the imaging beam (45 $\mu$m minimum average waist diameter). Three scans are measured for each set of parameters tested. The vast majority of points coincide exactly when data are overlaid on the same axis. That is, the scans are consistent to within the spatial and temporal resolution of the line camera.

When measuring keyhole profiles, the system is configured to reproduce the results measured with the line camera. The function generator and trigger wiring from the Ndrive unit is kept intact to ensure that resulting scan patterns are consistent with the characterization procedure. The results of these scan patterns, applied during imaging of laser keyhole welding are presented in the Chapter 6 of this thesis.
Chapter 4

Static-Mode ICI

4.1 Introduction

In optical coherence tomography, an image formed by continuously acquiring A-lines at a fixed transverse location is referred to as a motion-mode (M-mode) scan. As the sample moves, a time-resolved recording of its path is built up over successive A-lines. This philosophy is the basis of static-mode ICI imaging. The imaging beam is typically aligned coaxially to the process beam, so that it enters the keyhole and backscatters from the interface deep at the bottom before returning to the optics. The dynamics observed in keyhole welding are faster, richer, and require a greater amount of analysis than the motion of a medical patient or biological sample, however.

The high spatio-temporal resolution of ICI proves to be both a blessing and a curse for imaging of the weld keyhole. While the micron- and microsecond-scale precision of ICI is necessary to resolve the very fastest keyhole dynamics, the sheer volume of data produced when imaging at high line-rates, combined with the number of potential artifacts and the scarcity of viable signal, makes reduction of these data to
a useful form challenging. In this chapter, I introduce the reader to interpretation of weld dynamics from ICI data, and discuss some of the approaches for data reduction and algorithmic extraction of information. I describe a novel method for tracking the keyhole depth that solves problems inherent to earlier approaches. This approach reveals dynamics throughout the keyhole with new clarity, as well as a region of unexpected determinism during the first millisecond after the laser begins to fire.

### 4.2 ICI Images

The crux of this thesis is that the laser weld keyhole involves some very rich physics, which result in complicated ICI data. To fully motivate the work presented in the following chapters, I begin by introducing the features that constitute an ICI weld image and discuss some of the difficulties present in developing best practices for their display and interpretation. I review the approaches typically employed within our group for visualizing and extracting information from these data. I show that the most straightforward of these can obscure or distort the underlying dynamics and hinder thorough understanding of the weld data. In response, I develop a more sophisticated approach to extracting useful information from an image of the keyhole depth as a function of time. I then perform a phenomenological interpretation of weld physics gleaned from static-mode keyhole imaging processed using this new approach.

Most of the data in this chapter are drawn from experiments performed in collaboration with Penn State University (PSU), in which PhD student Jared Blecher provided samples of several engineering alloys of interest to the laser welding community for ICI imaging tests. During September 2013, Jared and I produced autogeneous
bead-on-plate welds in these materials with our 1.1 kW fibre laser (IPG YLR-1000-IC). We ICI-imaged every weld in-situ, and Jared returned with the samples to PSU where he performed ex-situ X-ray CT imaging of the completed welds, as well as sectioning and bright-field microscopy. The ex-situ tests yield direct measurement of pores entrained in the solidified weld bead, and verification of the weld bead extent beneath the sample surface, respectively. Some of the finished results of this effort are presented in a joint publication [5]. ICI imaging discussed in this chapter is static-mode—that is, the imaging beam is aligned coaxially to the process beam, and is fixed in the frame of reference of the process optics throughout the weld.

### 4.3 Decimated ICI Data

When imaging a weld keyhole, a profile of backscatter intensity as a function of depth, or A-line, is produced for each line captured by the camera in the spectrometer. A-lines are displayed as columns side-by-side to produce an image of scattering interface depth as a function of time. The CMOS line cameras used in current-generation ICI systems are capable of line rates of hundreds of kilohertz. At these rates, image data accrues at gigabytes per second. A typical test weld might last one or two seconds, resulting in an image upwards of $10^5$ pixels wide. If the entire weld image is to be viewed at once, some form of data compression must be employed for this number of A-lines to be rendered gracefully by (for example) MATLAB or Labview and displayed on a monitor.

The first step in processing an ICI data set for display is typically to call an algorithm that combines A-lines to reduce the density of the data—often by two or three orders of magnitude. This allows a full ICI image to be displayed on several
4.3. DECIMATED ICI DATA

hundred columns of pixels quickly and consistently and is very useful for ascertaining gross weld characteristics like average keyhole depth, degree of instability, and the like. The most basic approaches involve discarding the majority of A-lines, or averaging the signal at each depth within a bin of A-lines. Where signal is scarce, such methods perform poorly. The more sophisticated ‘ceiling’ method (invoked by former postdoctoral fellow Cole Van Vlack) finds the maximum signal intensity at each depth across a time bin a number of A-lines wide, and combines the results into a single line. This has the advantage of reducing the size of the data set while preserving the brightest points—an asset in weld imaging, where strong signals are present in roughly one-tenth of A-lines.

Complete weld images in carbon steel and an aluminum/magnesium alloy are shown in Figure 4.1. Each image is decimated by a factor of 800 for display on the page. Dark pixels in these images represent the presence of a reflective interface at a given optical path length. The process laser is incident from the top of the frame; laser exposure begins at $t = 0$ ms and terminates at $t = 2032$ ms (both $\pm 1$ ms). The dynamic range of ICI data is too great for intensity detail to be perceived well in a printed image (even using logarithmic scaling). Therefore, the intensity scale in the figures presented here is restricted to a range that shows good contrast in the keyhole root (bottom) signal. The method used flattens all values outside of the desired range to the extrema of said range. All values below the lower threshold are mapped to zero.

Even in this decimated form, the data display a good amount of complexity. Most obviously, the gross evolution of the keyhole depth as a function of time may be directly ascertained from these images. Focusing on the carbon steel weld data
Figure 4.1: ICI pictures of welds in carbon steel (upper) and 5052 aluminum (lower). Both welds were carried out at 25 mm/s feedrate over 50.8 mm distance, with a process laser power of 1100 W and a spot size of 210 µm. The process laser is incident from the top of the frame; exposure commences at $t = 0$ s and terminates at $t = 2.032$ s. Images are ceiling decimated by a factor of 800, top-subtracted using surface pre-scans, and nonzero intensity is compressed to within the ranges specified on the greyscale bars at right. Values below a threshold of 12 dB (for the carbon steel data) or 15 dB (for the aluminum data) above the noise floor are discarded to reduce visible noise in the image.
in the upper frame of Figure 4.1, we can directly estimate an average steady-state keyhole depth between 2 200 and 2 400 microns, and a delay of between 200 and 400 milliseconds before the system reaches equilibrium. The keyhole root appears as a band of strong signal, primarily consisting of short vertical spikes (a feature of decimated data to be discussed below). Some slow-moving average depth fluctuations are apparent in the shifting of this band.

The region above the keyhole root displays short-lived, bright speckles which appear to the untrained eye to be noise. However, their non-uniform depth distribution and their intensity (often more than 30 dB) relative to the noise floor of the detector suggest that they are real signal. These features are ubiquitous in static-mode weld keyhole imaging. They are characterized by short duration (less than a 5 microseconds), shallow depth relative to the keyhole root, and signal intensity that is significantly stronger than the noise floor, but weaker than that obtained from a flat reflector. This type of short-lived signal will be referred to as ‘sidewall’ signal, as this is its most common source. However, depending on keyhole geometry, this type of fleeting backscatter may originate from nearly anywhere within the keyhole.

My hypothesis is that sidewall signal results from temporary perturbations in keyhole geometry that encroach on the path of the imaging beam. The interaction may result in a direct backscatter to the focusing optics, or a multiple reflection path within the keyhole. While consistent with observed trends in data, this hypothesis will likely prove very difficult to test experimentally. This issue will be discussed in more detail in Chapter 6.

An important imaging artifact, caused by detector saturation, is visible in both the carbon steel and aluminum images. The ICI system used to produce these images
has a dynamic range of more than 60 dB. However, the range of backscatter intensities collected from a mobile liquid metal surface is even greater than this can accommodate. Saturation occurs when the backscatter intensity is high enough that the peaks of the fringe pattern measured by the line camera reach the top of the camera range. This results in flat-topped fringes that, when transformed from k-space to optical path length, produce ‘ringing’ or harmonics in the depth profile. The ringing appears as additional peaks in the A-line, regularly-spaced in depth about the real peak. This phenomenon is analogous to the loss of signal fidelity brought about by clipping in an audio amplifier. Depending on the severity of the saturation, significant attenuation of the real peak and distortion of the depth profile may occur. In some cases it is impossible to determine the location of the real peak within a badly saturated A-line.

Saturation is visible intermittently throughout the aluminum weld in Figure 4.1. It is evidenced by vertical bars of strong signal outside of the region in which most real backscatter is anticipated—between the sample surface at 0 mm depth, and the variable band of signal from the keyhole root. Some of these bars display periodicity with depth, characteristic of the harmonics described above. Others appear as solid lines—the result of multiple saturated A-lines combining during ceiling decimation.

There is only one instance of the saturation artifact visible in the carbon steel image. When the laser is shut off just after the two second mark, the surface tension and hydrostatic pressure in the melt volume force the keyhole shut. When the keyhole closes, a shallow concave bowl of liquid metal is left at the sample surface, which then solidifies. This characteristic bowl-shape can often be observed on the top surface of completed welds, at the last point of contact of the process laser beam. The existence of this solidified feature indicates that the melt cools more quickly than the liquid
metal can re-flow to completely fill the depression left by the keyhole. The shape of this feature, combined with the high reflectivity of liquid metal, results in efficient back-reflection of the imaging light and a high probability of recording saturated lines for a short time after the process laser is terminated. The saturation artifact is a generally undesirable feature of welding data.

It is also possible to gain a sense of the keyhole stability from full-scale weld images. The breadth and stability of the keyhole root signal depth band, as well as the prevalence and distribution of sidewall signal, are indicators for the stability of the keyhole geometry and its aspect ratio. While individual keyhole depth fluctuations occur too quickly to be observed from heavily decimated images such as these, the range of keyhole root depths displayed is a good indicator of the amount and severity of depth spiking (to which porosity and other instabilities are attributed). The presence of what appears to be significant amounts of sidewall signal at greater depths than the keyhole root in the aluminum weld is consistent with a wide and unstable keyhole.

After an examination of the two weld images in Figure 4.1, someone of limited familiarity with ICI data should be able to assess that the aluminum weld is qualitatively different from the carbon steel one. The keyhole seen in the lower figure is shallower, the amount of depth spiking in steady-state is greater, the sidewall signal is stronger, and events occur that intermittently break the steady-state behaviour of the weld. These interruptions to steady-state are marked by a sharply increasing keyhole depth, as well as loss of sidewall signal, and can last up to 100 microseconds. The interruptions were found to correspond to melt ejections, clearly visible as underfill in the finished weld bead. The increase in measured depth and decrease in sidewall
signal are consistent with runaway swelling of the keyhole root, which is purported to undermine the melt pool and cause expulsion of large fractions of the liquid metal volume [7].

Aluminum alloys exhibit high thermal conductivity and high reflectivity in the liquid state relative to ferrous alloys [42]. The combination of these features mean that it is more difficult to couple laser energy into an aluminum sample than a steel one, especially once the surface is molten, and that once energy is coupled into the bulk the heat diffuses more quickly. The result of the latter is that the conditions of localized heating necessary to support a keyhole are harder to achieve in aluminum. The net result is that creation of a stable keyhole in aluminum costs more power than it does in steel. While a relatively stable keyhole is produced in carbon steel at 1.1 kW of power, this appears to be insufficient for aluminum. Swift-Hook and Gick state that anywhere between four to ten times the amount of power is required to weld aluminum [46]. In my experience, industrial welding experts recommend powers upward of 4 - 5 kW for keyhole welding of aluminum alloys (a spot diameter of a few hundred microns and feed rates between 50 - 100 mm/s are typical).

The decimated data sets presented in Figure 4.1 have proven useful so far in this example interpretation of weld keyhole behaviour. This type of data presentation allows gross-scale trends such as time-averaged keyhole depth and general process stability to be assessed at a glance for seconds of weld data at a time without great delay or computational expense. Qualitative information about the keyhole can be inferred by an experienced user. For ICI to be applied to quantitative evaluations of the weld keyhole as a physical system, more detail is needed. The goal is to progress from understanding ICI data in terms of existing knowledge to development of better
physical descriptions of the keyhole system based on novel ICI data. It is therefore imperative that post-processing methods used for scientific purposes preserve as much information as possible about the keyhole dynamics captured by ICI.

In Figure 4.2, I present a more detailed image of the two welds displayed in Figure 4.1. These images have not been decimated, and so represent the maximum temporal resolution available from these data sets. That is, there is a one-to-one correspondence between columns of pixels in this figure and frame read from the line camera. In fact, the entire 4 ms extent of Figure 4.2 is compressed into the first column of each image in Figure 4.1 by the ceiling decimation algorithm. It is immediately clear how much information is lost to this process.

The short vertical lines that are typical of the keyhole root signal in Figure 4.1 are a product of data decimation. Sloping features containing rich dynamics of the keyhole root are washed out and only the range of depths present within the bin is preserved. The first few milliseconds of the weld images seen in Figure 4.2 are interesting for a number of reasons. Strikingly, the initial formation of the keyhole in carbon steel is deterministic and well-behaved. The interface progresses smoothly downward into the sample, accelerating slightly up to the 1 ms mark (discussed in more detail in section 4.5). Below approximately 1 mm of depth, an abrupt change in the mode of keyhole behaviour occurs and the progress of the vapour channel into the sample is slowed by periodic breaks. The aluminum keyhole, in contrast, requires 0.5 ms to break below the surface, and the depth is immediately unstable with no deterministic break-in period visible.

The set of aluminum welds produced in these experiments represent an interesting
Figure 4.2: Details of the same keyhole welds in carbon steel (upper) and 5052 Aluminum (lower) presented in Figure 4.1, with no decimation applied. Each image here is contained within the first column of pixels in Figure 4.1.

region in the laser welding parameter space. In conduction-mode laser welding, introduced in section 2.4.3, the incident laser intensity is too weak to form a keyhole. The laser beam may be approximated as a moving point heat source at the sample surface, the temperature distribution in the sample depends primarily on diffusion, and the resulting weld bead is broad, shallow, and roughly hemi-cylindrical. The aluminum welding process that we have imaged here results in a vapour channel that extends below the sample surface, so it is not truly conduction welding. Meanwhile, sections
of the aluminum welds show a finished bead that lacks the characteristic ‘wineglass’ profile of keyhole welding. The aluminum welds are shallow relative to other alloys, and much wider below the surface.

The in-situ ICI data from the aluminum welds indicate that the sample initially resists formation of a vapour channel, and that once formed, the channel is not dynamically stable in the same sense as in other materials welded with the same process parameters. Referring back to Figure 4.1, the presence of apparent sidewall signal at depths greater than the aluminum keyhole root raises questions. A possible explanation is the temporary existence of a multiple reflection path within the keyhole, resulting in a round trip path length noticeably greater than the linear distance from the process optics to the keyhole root and back. In a high-aspect-ratio keyhole (such as that formed in steel), such a path would typically require many reflections, reducing both the probability of the ICI beam coupling back into the optics and the intensity remaining to contribute to the signal in such an event. Density of sidewall signal at what would seem to be too great a depth is again consistent with a lower aspect-ratio (and consequentially geometrically unstable) vapour channel. The evidence points to a process that falls between conduction and keyhole-mode laser welding.

Both the carbon steel and aluminum weld images in Figure 4.2 exhibit intermittent gaps in the signal. This effect is ubiquitous in ICI imaging of keyhole welding. Its origins are crucial to our understanding of how the measurement beam interacts with the keyhole, and it will be discussed in detail in the next chapter. These gaps tend to be hidden by ceiling decimation. The pattern of missing signal coincides with the existence of keyhole depth fluctuations, as seen throughout the steady-state region of a keyhole weld. The keyhole root is visible to ICI almost exclusively while it is
moving away (deeper); events in which the root moves toward the process optics are only rarely recorded. A notable exception is welding of aluminum in the quasi-keyhole parameter space discussed above. In such cases an upward-moving keyhole root is more commonly visible (as in Figure 4.2 at approximately 1.75 ms and 2.25 ms).

The existence of continuous fluctuations in the keyhole depth is indicative of a dynamic equilibrium. As discussed in section 2.4.3, the force holding the keyhole open is evaporation recoil pressure. This force is sustained by continued absorption of laser energy at the liquid-vapour interface. It follows that stable keyhole geometry would depend on a relatively even distribution of laser intensity over the keyhole interior, in just the right amount to balance the action of the closing forces (surface tension and hydrostatic pressure). Insufficient intensity at any point within the keyhole will result in localized closing of the keyhole surface. As the interior surface area of the keyhole increases, closing forces will inevitably dominate at certain points. For a typical keyhole geometry, process beam absorption favours the keyhole root over the sidewalls (although for CO$_2$ lasers at 10.6 $\mu$m wavelength, multiple reflections may act to mitigate this [25]. As a consequence, keyhole depth is likely to increase until the sidewall stability is compromised. Complete closure (‘pinching-off’) of the keyhole above the root may occur. The volume of the vapour channel below this point either condenses and collapses, or becomes entrained in the melt volume as a pore. A new keyhole root has been formed at a shallower depth, and will bore down into the sample until the process repeats itself.

This description of keyhole depth spiking is consistent with numerous literature descriptions of keyhole instability and pore formation. A full-resolution ICI picture matches this understanding of the process well. The carbon steel keyhole progresses
smoothly to greater depths until it reaches a point at which closing forces overbalance evaporation pressure over a large enough region of the sidewalls to cause a pinch-off. The keyhole then continues to deepen at a much slower rate until the entire vapour channel/melt pool system reaches the dynamic equilibrium we refer to as steady-state welding. In the case of aluminum, for the reasons discussed above, the keyhole is always quasi-stable and similar depth fluctuations are visible immediately after its initiation. The depth fluctuations appear to be closely tied to the signal losses described above, and this will be addressed in more detail in Chapter 5.

Clearly if an in-depth examination of keyhole dynamics is desired, the detailed images of Figure 4.2 are vastly preferable to the heavily decimated data of Figure 4.1. This brings us back to the problem of volume of information. For ICI images to be maximally useful in qualitative and quantitative analysis of weld physics, and to reduce the associated computational costs, steps must be taken to increase the density of relevant data.

4.4 Tracking Keyhole Depth

4.4.1 Brightest-Pixel Tracking

Since the skin depth in metal is on the order of nanometers for near-infrared wavelengths, it is unlikely that more than one scattering interface will contribute to any given A-line. Thus of the hundreds of pixels that compose the A-line, the norm is for only two or three (the width of the system point spread function) to contain backscattered signal from the sample, assuming a relatively flat metal interface. Ideally, the
4.4. TRACKING KEYHOLE DEPTH

solution would be to take the centre position of the tallest peak in each A-line (well-approximated by the position of the brightest pixel) to be the position of the keyhole root interface at a given point in time. In theory this approach allows a large array of ICI intensity data to be reduced to a one- or two-column vector (depending on whether depth and intensity as a function of time are to be kept).

In practice, multiple imaging features discussed in the past few pages complicate the matter significantly. Saturation of A-lines due to excessively bright backscatter frequently hinders effective keyhole depth tracking by the method outlined above. Severely saturated A-lines often display intensity peaks in locations other than the real interface depth, easily fooling a straightforward brightest-pixel approach. Even more troublesome is the presence of sidewall signal in a weld image. While these signals are brief, they are often bright, and are broadly distributed as a function of both depth and time while the keyhole is in steady-state (where saturated A-lines are generally rare). Especially given the sporadic nature of the keyhole root signal, sidewall pixels often bias brightest-pixel tracking data to artificially shallow depths, and dramatically increase the variability of the measured depth.

The problems posed by both saturation artifacts and sidewall signals can be partially remedied by decimation of the data set before depth tracking. We have already established that decimation of a complete ICI image destroys useful information about keyhole dynamics, and its effect on a depth-tracking vector is predictably similar. In the left column of Figure 4.3, I present the familiar carbon steel and aluminum weld data sets, decimated by a factor of 50, and overlaid with the output of an algorithm that tracks the depth of the brightest pixel in every decimation bin. The approach of decimating prior to tracking relies on the assumption that the keyhole root interface
will produce bright signal often enough to dominate the other forms of signal over a span of many A-lines. In practice this method works moderately well, at the expense of multiple orders-of-magnitude losses of temporal resolution.

Figure 4.3: Weld data ceiling decimated by a factor of 50 (left) with the corresponding un-decimated data (right), for the carbon steel (upper) and aluminum (lower) welds of the last two figures. Green dots overlaid are the output of a simple depth tracking algorithm which searches for the brightest depth pixel in each bin of decimated A-lines.

The right column of Figure 4.3 shows the same tracked points overlaid on the un-decimated ICI image. These points provide useful information if long-term weld depth and a rough idea of process stability are the desired outputs. Better compensation for the effects of sidewall signal and saturation artifacts may be achieved without
excessive decimation by choosing an algorithm (other than just finding the brightest pixel) that is biased toward deeper signals, for instance. For weld imaging, this patch does not address the underlying problem of resolving fast keyhole dynamics. We are left with a similar issue to that presented by decimation of full ICI images. Undesired artifacts are mitigated, and data volume reduced to manageable amounts, but temporal resolution—arguably one of the strongest assets of this imaging modality—is sacrificed.

4.4.2 Group-Based Tracking

I have devised a more sophisticated method to extract the keyhole root depth as a function of time, without sacrificing the maximum temporal resolution available from the ICI image. My algorithm is based on the following general observations of ICI weld imaging:

- The overwhelming majority of pixels in a well-aligned weld image contain no backscatter signal, and may be excluded if an image of the keyhole root is desired.

- Signal from the keyhole root, while not always bright, is generally continuous over multiple A-lines, whereas sidewall signals are transient and are only very rarely seen spanning more than one 5 µs line period when imagining at 200 kHz.

- For laser powers up to 1.1 kW, and feedrates up to 175 mm/s, in all materials addressed in this thesis, observed keyhole root interface speeds are on the order of 1 m/s and lower.
This group-based keyhole tracking algorithm begins by finding the depths of the brightest pixel in every A-line. A flow chart of the steps involved is shown in Figure 4.4. Data from the keyhole root is then filtered from this set based on the signal groupings in time and depth. Prior to tracking, the ICI image is cropped to exclude the pixels closest to the zero-delay point, and a threshold of at least 8 dB above the noise floor is applied to the image. It is important to note that only a fraction of A-lines will contain signal with intensity greater than the threshold. The first step is to find groups of consecutive A-lines that display a signal. The minimum number of A-lines that constitutes a group may be varied depending on the image characteristics, but a value of three gives good results in the majority of cases. This step finds signal that may be from the keyhole root, given that root signal tends to be continuous when it appears. The identification of what is understood to be ICI signal from the keyhole root has been confirmed by comparisons with ex-situ destructive analysis of weld seam depths as well as in-situ transmission x-ray imaging of weld keyholes [5, 51, 7].

The second step is to search within the horizontal groupings (found by the first step) for any elements that differ too greatly in depth to be consistent with a single moving interface. Elements that differ from their immediate neighbours by more than a set amount are discarded. If this process causes the grouping to fall below the minimum number of lines specified for filter step one, it is ruled out. Correct implementation of filter step two depends on the imaging frame rate used. A value for change in depth corresponding to 10 m/s between any adjacent A-lines typically works well. It is best to set a healthy margin above the actual interface speeds expected. This step is intended to prevent multiple sidewall signals—that is, backscatter from
4.4. TRACKING KEYHOLE DEPTH

Figure 4.4: A flow chart detailing major steps in the group-based keyhole depth tracking algorithm. The core of the algorithm is a pair of filters that search for groupings of signal characteristic of backscatter from the keyhole root interface. The points that do not pass the filters are determined to be sidewall signal, and are output as a separate data set.

disparate interfaces closely grouped in time—from being interpreted as a continuous moving interface. Optionally, an additional step may be added before filter step one to fill small gaps between A-lines displaying signal, to account for breaks in an otherwise continuous feature.

I have written a MATLAB function to implement this algorithm. It accepts an ICI image (as a two-dimensional array) as input, and produces vectors of intensity and depth as a function of time as output. The points passed by the two filtering steps compose a data set containing the measured depth of the keyhole root as a function of time. The data blocked by the filters is output as a separate set containing only the sidewall signal. Thus a roughly complete picture of the original ICI image may
be reconstructed as needed for qualitative analysis, while a data set comprising the
dynamics of the keyhole root, largely free of unwanted artifacts, is readily-accessible.
Crucially, time resolution is not compromised, and the position of points as-measured
is faithfully represented.

The combined outputs represent a reduction of data volume by a factor on the
order of $10^3$. If further reduction is desired, decimation may be carried out on the
tracked data without compromising positional accuracy of remaining points. The
program is vectorised to improved performance, and can typically process $10^5$ A-lines
in less than half a second, although the number of calculations required depends
directly on the specific data set.

The results of the group-based keyhole root tracking algorithm, applied to the first
10 ms of the carbon steel weld data of Figure 4.1, are shown in Figure 4.5. Tracked
keyhole root signal and sidewall signal are shown, overlaid on the original ICI image
with a 2 mm vertical offset for comparison. The initial steps of the group-based
algorithm produce tracking points similar to those in Figure 4.3. The key difference
is that the group-based approach involves brightest-pixel tracking of every A-line to
begin with. The novel component is the ability to filter out the keyhole root signal by
observing consecutive A-lines. The filtering steps are what allow the ICI data set to be
accurately depth-tracked without decimation, yielding the excellent correspondence
to raw image data demonstrated in Figure 4.5.
4.5. **KEYHOLE INITIATION**

Amid the general instability and stochasticity that marks the behaviour of the weld keyhole, there is a small feature that persistently exhibits surprising levels of determinism. The progress of the initial keyhole interface into the sample, immediately after laser exposure begins is extremely consistent. For any combination of material and process parameters for which a quasi-stable keyhole is formed, the first millisecond of welding behaves predictably. The interface moves downward into the sample, until the first instability of the keyhole occurs, and signal is momentarily lost. The path of the keyhole over this interval, as well as the point in time (and depth) at which instability sets in, is repeatable.

In the left pane of Figure 4.6, I show group-based tracking output from the initial interface of five different welds in carbon steel with identical process parameters. The correspondence between successive data sets is so close that some data are barely

![Figure 4.5: The result of the group-based tracking algorithm applied to un-decimated ICI data from the carbon steel weld.](image)
visible. The sets are truncated at the first keyhole instability event (marked by a loss of signal and a discontinuity in the movement of the keyhole interface—see Figure 4.2 for context). The timing of this event, like the motion of the interface, is largely consistent from one weld to the next.

I extract the interface speeds from each of these data sets by least-squares fitting a third-order polynomial curve to each individually. I then take the first time derivative to get an expression for velocity as a function of time. The results of this procedure are displayed in the right pane of Figure 4.6. The physically interesting results here is that the keyhole initially accelerates on its way into the sample, at rates on the order of 1000 m/s$^2$. This is consistent with increasingly efficient absorption of the process beam by the keyhole as it deepens, facilitated by the greater likelihood of multiple reflections trapping the beam at higher aspect ratios.

Figure 4.6: Group-based depth tracking algorithm outputs from five welds in carbon steel, with a process laser power of 1.1 kW, and a feedrate of 25 mm/s. The left pane displays the tracked depth data as a function of time, with sets truncated after the first instability-induced signal loss event. The right pane shows the first time derivative of a 3$^{rd}$ order polynomial fit to the depth data.

A trend in the behaviour of the keyhole at later times may be extrapolated from
this data set. The tendency of the keyhole root to accelerate toward greater depths is prevalent in the shorter, ‘spiking’ interfaces measured at times above 1 ms in Figure 4.2. My hypothesis is that the keyhole root accelerates into the sample as the beam trapping efficiency improves with increasing depth. This continues until the process beam overreaches, spreading over too large an area to sustain sufficient evaporation pressure on the entire keyhole interior. At this point the keyhole pinches shut at an intermediate depth, forming a new root, and the process repeats itself.

4.6 Conclusions

With practice, a great deal of qualitative information may be gleaned from ICI images of the weld keyhole. The keyhole depth, and a general sense of the process stability are clearly visible from large-scale, decimated data, and this method provides a useful means of assessing weld behaviour quickly. Large-scale defects such as melt ejections may also be identified in this type of image, and material-dependant behavioural changes are readily visible. Decimation ultimately discards some of the most interesting dynamics that ICI is capable of resolving, however, creating a trade-off between detailed analysis and manageable data volume. I have devised a more sophisticated algorithm that allows the depth of the keyhole root interface to be tracked while filtering out undesired noise and artifacts, and reducing the data volume by orders of magnitude. As an example application of this method, I extract keyhole initiation velocities from carbon steel welds, and demonstrate that the keyhole repeatably accelerates into the sample during its formation. This appears to extend to the oscillations of the keyhole depth that occur at later times. In addition to fluctuations of the measured depth, the oscillatory keyhole regime presents a challenge in the form
of aperiodic loss of the ICI signal. The relationship between the keyhole behaviour and these signal losses will be explored in the next chapter.
Chapter 5

Signal Losses in ICI of Welding

5.1 Introduction

In the previous chapter, we saw that ICI of laser welding is capable of measuring keyhole depth with micron-scale spatial resolution on microsecond timescales. Different pieces of information regarding keyhole dynamics may be measured directly or inferred from such images. The ability to extract these data from within this thermodynamically active, high-aspect ratio system presents new opportunities to interpret the underlying physics. More specifically, the direct measurements of keyhole depth and root velocity potentially provide a new source of external verification for finite-element analysis, and may enable accurate treatment of the keyhole as a physical oscillator.

The most glaring issue with this imaging solution is sporadic, unexplained, persistent loss of signal from within the keyhole. These losses appear in ICI of welding in stainless and mild steel, titanium, aluminum, and nickel-based alloys, shortly after the keyhole forms. For a keyhole in dynamic equilibrium, the percentage of A-lines
containing no signal above threshold is usually around 90%. The regions of loss are seen to coincide with the oscillations of the keyhole. The transitions from bright to dark A-lines occur in tandem with the depth fluctuations. Signal from the keyhole root is almost entirely measured from downward moving interfaces, while the motion between these downward spikes (whether it be pinching of the keyhole or upward motion of the root) is largely unobserved. The short-term morphology of the keyhole—through geometry or dynamics—must have a strong effect on the successful measurement of interfaces in the beam path.

Physical analysis of the keyhole system would benefit greatly from continuous information about the keyhole depth, on timescales shorter than the oscillations. Time series analysis of continuous depth or velocity data would enable discussion of the keyhole as a chaotic oscillatory system [10, 30], for instance. With the aim of eventually remediating the losses, or at least understanding the limitations brought about by them, I examine the effect of possible signal loss mechanisms on the ICI signal.

5.2 The Axial Motion Artifact in ICI

Optical coherence tomography, ICI’s progenitor, is designed primarily for medical contexts in which the subject is—ideally—stationary. Of course, when examining a living organism, some movement is inevitable. However in medical imaging with OCT, images are generally captured with the express goal of examining static morphology, and subject motion is usually small and slow enough to not pose a serious problem. Arguably the main motivation for the application of this imaging technique to laser processing (as ICI) is the ability to resolve dynamics. If the evolution of the
sample morphology during processing is not of interest, many other techniques exist to examine static topography. A notable exception to this philosophical distinction is the Doppler-OCT modality used to measure the axial component of the blood-flow velocity field in a patient [8].

Sample motion becomes increasingly important as the speed of the interface in question increases. In general, backscattering interfaces that move at speeds on the order of the imaging wavelength divided by the imaging frame-rate introduce complications (see section 2.3.2). As the interface moves, wavelengths that initially experience constructive interference switch to destructive, and the fringe pattern ‘washes out’ while the camera integrates. Artifacts are produced that, depending on the imaging modality, may attenuate, broaden, or displace the measured peaks in the processed image. In the context of spectral-domain OCT (and ICI), interface motion along the imaging beam axis can cause partial or complete signal attenuation. Although signal from the sample arm may be strong, a motion-induced phase-shift of the interference fringes can cause the pattern to wash out while the camera integrates. This effect is described in more detail in my summary of the results of Yun et al. [60, 61], in section 2.3.2.

This phenomenon has been well documented in spectral-domain OCT [32, 60, 61], and is expected to manifest in much the same manner in ICI imaging. In brief, for a given camera integration time and imaging source centre wavelength, the signal attenuation as a function of velocity is expected to take the form of a gradual roll-off punctuated by periodic dips to zero. The theoretical attenuation obeys the relationship described by Equation 2.12. The signal dips correspond to zero-crossing points
of the sinc function. For our typical range of imaging parameters, these dips are expected to occur at speeds on the order of 0.1 m/s. Our ICI images of laser processes frequently display slopes many times greater than this, and should therefore be susceptible. In the case of the keyhole root depth oscillations ubiquitously observed in laser welding, the axial motion artifact is a theoretically justifiable cause for extensive signal losses.

In order to verify the model proposed by Yun et al., and confirm its relevance to ICI, a series of experiments was carried out by undergraduate researcher Seth Todd during the summer of 2013. Todd’s experiments explore the response of ICI to interfaces in motion along the axial direction of the measurement beam. A 4” speaker is affixed flat to the x-y motion stage inside the macroprocessing station enclosure. A flat, thin piece of steel shim of approximately 4 mm$^2$ is fixed to the center of the speaker cone as a reflector. The speaker is connected to a stereo amplifier that accepts an input signal from a function generator (Agilent 3322OA).

The interface velocity (the independent variable of interest) is determined by fitting a sine wave to the interface depth as a function of time from the ICI image and calculating the derivative. It is therefore desirable to use a large portion of the imaging field of view to ensure good resolution for the fitting step. Oscillation frequencies are selected to allow recording of many cycles over roughly one second of imaging, while maintaining a smooth response of the speaker up to appropriate amplitudes. This tuning process may be accomplished straightforwardly using ICI to view the speaker displacement directly. The lack of visible distortion of the speaker response is taken as evidence that the reflector does not have an appreciable effect on the oscillation. An approximate frequency and speaker displacement amplitude of
100 Hz and 1 mm, respectively, give good results.

In Figure 5.1, I present a short section of ICI data of the speaker oscillating at 90 Hz, captured with a nominal camera integration period of 4.0 μs at a framerate of 185.2 kHz. The upper pane is an un-decimated image of the speaker motion. Some saturation ringing (dark, horizontal lines) is visible around the extrema of the speaker’s motion. Dips in signal intensity are also visible, distributed symmetrically in time around the extrema.

To obtain the velocity as a function of time, the full data set is ceiling decimated by a factor of ten and brightest-pixel tracked with a high threshold (25 dB). The tracked interface is fit with a sine function. Upwards of 40 cycles are included in the fit, and the standard deviation of the residuals from the tracked points is 0.3% of the
5.2. THE AXIAL MOTION ARTIFACT IN ICI

fit peak-to-peak amplitude. Assuming smooth motion of the speaker, the derivative of this function gives the interface velocity as a function of time.

To quantify the influence of the motion artifact on this image, we extract the maximum signal intensity from the speaker surface as a function of time. In order to prevent saturation artifacts (and in the case of regions of weaker signal-noise) from interfering, the signal intensity of each A-line is filtered as a function of depth, by a Gaussian mask of FWHM 232 µm (25 depth pixels), centred on the fit sine wave depth at each time interval. Thus signals far from the speaker surface interface are attenuated. This masked, un-decimated ICI image is then brightest-pixel tracked once more, and the value of the brightest pixel in each A-line as a function of time is plotted in the lower pane of Figure 5.1 (in blue). A theoretical curve is added to this pane (in red), using the nominal camera integration time (4 µs) and imaging centre wavelength (840 nm) and the velocity calculated from the fit curve as inputs to Equation 2.12.

The signal intensity as a function of time exhibits a few interesting features. The positions of the intensity peaks line up nicely with the extrema of the speaker’s displacement, which was somewhat clear from the symmetry of the signal dips in the upper plane. Between peaks, the coarse attenuation of the measured signal is greater than that predicted by theory. A more subtle discrepancy between the measured results and the curve predicted by theory is visible in the spacing of the signal dips away from the displacement extrema. The horizontal correspondence is best near the interface speed minima, and worst near the speed maxima.

The issue here is that the integration time used to calculate the theory curve is a nominal value. ICI imaging involves running a CMOS line camera sensor at rates
approaching its upper limit (microsecond frame periods and integration times). In this operation range, the sensor rise time is non-negligible, and the effective integration time—the value that contributes to the occurrence of the motion artifact—is less than the nominal value requested of the camera.

The spacing inconsistency becomes clearer when the intensity data are presented as a function of interface speed rather than time. In Figure 5.2, the data from the 90 Hz speaker oscillation image are sorted into speed bins of 3 mm/s width. The intensity values from the tracked interface in each bin are averaged and plotted in blue. The mean sample size for this bin width is 485 points, and the standard error of the mean ranges from 0.03 to 0.5 dB. The intensity values predicted by theory are plotted in red. The speeds at which signal minima are expected to occur are given by Equation 5.1. The measured signal dips are seen to be regularly distributed as a function of speed, but the gaps are wider than predicted. This is consistent with an integration time shorter than the specified value, and suggests a method for estimating the effective camera rise time.

The signal dips correspond to the minima of the sinc-squared function of Equation 2.12. The spacing in velocity, \( \Delta v \), is given by

\[
\Delta v = \frac{n\pi}{k_0t_{\text{int}}},
\]

where \( k_0 \) is the light source centre wavenumber, \( t_{\text{int}} \) is the camera integration time, and \( n \) is a positive integer. The spacing is inversely proportional to the camera integration time. The local minima in the measured intensity data are extracted by applying a minimum value search to a manually-segmented area around each dip. The speeds at which the minimum intensity values occur are plotted as a function of
5.2. THE AXIAL MOTION ARTIFACT IN ICI

Figure 5.2: The intensity of the ICI signal from the speaker foil as a function of velocity (blue dots) along with the maximum intensity predicted by Yun’s theory (red lines). The standard error of the mean intensity represented by this set of points ranges from 0.03dB to 0.5dB. Velocity is binned in 3 mm/s increments, and the average sample size per point is 485.

The indexing value, \( n \), in Figure 5.3. Data are extracted from images of the 90 Hz speaker oscillation taken at nominal integration times of 4, 6, 8, and 10 \( \mu \text{s} \). A linear least-squares fit is applied to each set using MATLAB’s polyfit function. From the slope of the fit, the effective integration time for each data set may be estimated. The resulting estimates for each nominal integration time setting are given in Table 5.1. Errors are estimated standard deviations of the linear fit slope based on the estimated covariance matrix for each set of fit parameters. These errors appear to be artificially small based on the spread of the effective integration time estimates. However, since this effective integration time is itself an approximation of a more complex temporal behaviour of the camera sensitivity, further speculation as to the source of this variation is not presented here.

As a cursory verification of the self-consistency of this effective integration time estimate, the measured signal intensity as a function of time data from Figure 5.2
5.2. THE AXIAL MOTION ARTIFACT IN ICI

Figure 5.3: Speeds at which signal dips occur v. signal minimum indexing value, with linear regression fit lines. An estimate for the effective integration time accounting sensor rise and fall time is calculated from the slope of the fit.

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>5.4</td>
<td>4</td>
<td>3.46 ± 0.01</td>
</tr>
<tr>
<td>7.4</td>
<td>6</td>
<td>5.43 ± 0.03</td>
</tr>
<tr>
<td>9.5</td>
<td>8</td>
<td>7.72 ± 0.02</td>
</tr>
<tr>
<td>11.5</td>
<td>10</td>
<td>9.33 ± 0.03</td>
</tr>
</tbody>
</table>

Table 5.1: Estimated effective camera integration times, based on the measured dependence of signal minima on velocity.

are plotted again in Figure 5.4, along with a new theory curve calculated using the corrected integration time. As expected, the measured and theoretical intensities now agree in the horizontal aspect.

The above experiments confirm that the motion artifact appears in an expected manner in ICI—at least in the case of an interface exhibiting smooth axial motion, as well as providing a useful means of estimating the error in the nominal integration time of the line camera. In the past, when imaging a weld keyhole, the generally accepted practice within our group has been to choose the shortest integration time available (2 µs ). It was implicitly assumed that minimizing the effect of the axial
5.3. THE MOTION ARTIFACT IN ICI OF WELDING

Figure 5.4: Measured and theoretical maximum signal as a function of velocity. The data presented here are the same as those in Figure 5.2, but the integration time used to calculate the theoretical curve is adjusted according to the results of the fit shown in Figure 5.3.

motion artifact was important to obtain a strong signal. At this integration time, the signal dip spacing is expected to be 0.2 m/s, while measured keyhole root speeds in most metals reach 1 m/s or higher. The maximum keyhole root signals observed in most alloys (welding at 1.1 KW of laser power with a 210 µm spot size and 25 mm/s feedrate), tend to fall near 25dB, so an attenuation of 10dB to 20dB will be enough to push the bulk of the signal below threshold. It is therefore reasonable to assume that the motion artifact should be pervasive in ICI of welding, and responsible for significant signal losses. The next section will address this hypothesis.

5.3 The Motion Artifact in ICI of Welding

Broadly speaking, if attenuation due to the motion artifact accounts for significant signal losses in ICI of welding, it should be possible to induce a change in both the amount of signal measured from the keyhole, and the intensity of the signal
5.3. THE MOTION ARTIFACT IN ICI OF WELDING

by changing the integration time. Considering only the gross attenuation described by Equation 2.12 (that is, the envelope), and ignoring the signal dips, the range of intensities measured from a given spread of interface velocities will scale inversely with the integration time squared. This only holds for velocities on the order of the signal dip spacing and above. For small values of $k_0 v_z T_{\text{int}}$ (i.e. where $\sin(\theta) \sim \theta$ holds) the attenuation approaches zero.

Across seconds-long timescales, slow relative to the oscillations of the keyhole, and for different welds with identical parameters, the average backscatter intensity and interface velocity distributions should be similar. Therefore, assuming the same optical returns from the keyhole over time, welding with different integration times ought to produce the following effects:

- Assuming a spread of velocities at least on the order of the signal dip spacing (given by Equation 5.1), increased integration time should cause signal attenuation by roughly $(1/T_{\text{int}})^2$.

- With the attenuation, as more signal is pushed below threshold (or into the noise floor), the signal fill factor (the fraction of A-lines showing strong signal) should decrease.

The former effect should be measurable in the average level of signal intensity measured from within the keyhole once the weld process has reached quasi-steady-state operation. The latter effect will result in a net decrease in the keyhole signal fill factor. However, the functional form of this effect is much harder to predict, depending on the specific distribution of the backscatter intensity returning from the keyhole. Changes in fill factor may still serve as a satisfactory secondary check.
To examine the effects of the motion artifact on keyhole measurements, I produce welds in stainless steel at nominal integration times ranging from 2 µs to 18 µs. A laser power of 1100 W (continuous) is used with a material feedrate of 25 mm/s, 150 mm focussing optics, and Ar cover gas at 20 psi for all welds. The upper frame in Figure 5.5 shows the mean signal level above a 10dB threshold as a function of integration time (in blue) as well as the mean signal level of the keyhole root as determined by the group-based tracking algorithm (in red). Each point is the mean of the relevant quantity taken over three different welds. Data is only sampled from the middle 80% of each weld, to isolate the keyhole in dynamic equilibrium. Error bars show the standard deviation of each set of three welds. The trend in mean signal observed here is a net decrease of less than 1dB.

As seen in Equation 2.11, the intensity of a measured peak in an A-line is proportional to $\sqrt{I_{\text{ref}}I_{\text{sam}}}$, where $I_{\text{ref}}$ and $I_{\text{sam}}$ are the backscattered intensities from the reference and sample arms, respectively. When the integration time is changed (from $t_1$ to $t_2$, say), the reference arm power is adjusted to negate the change. The change in integrated intensity from the sample arm cannot be compensated, and this results in scaling of the measured intensity as $I_2/I_1 = \sqrt{t_2/t_1}$. The tenfold increase in integration time in displayed in Figure 5.5 ought to result in a $\sqrt{10}$ increase in signal, or 10 dB in our $20\log_{10}$ decibel scale. Meanwhile, the signal intensity distribution from a fast-moving set of interfaces would be expected to decrease as $1/T_{\text{int}}^2$ due to the motion artifact. For an order-of-magnitude increase in integration time, this should result in attenuation by $10^{-2}$ (or -40dB on our ICI intensity scale). There is thus an approximately 30 dB discrepancy displayed here between the measured and expected behaviours of the motion artifact in keyhole weld data.
5.3. THE MOTION ARTIFACT IN ICI OF WELDING

Figure 5.5: Mean welding signal as a function of camera integration time with 150 mm focussing optics. Blue points represent values taken from brightest-pixel tracking of the entire ICI image, red points represent keyhole root signal as determined by the group-based tracking algorithm.

The change in integration time also has a collateral effect on the sensor duty cycle. The role that this quantity plays in the results above cannot be discounted completely, but it should not have a significant effect on the measured intensity of an individual A-line, especially in the case of the long, continuous signals measured from the keyhole root. The result above suggests that the motion artifact is not the factor that dominates the intensity of signals from deep within the keyhole. The real functional relationship of weld keyhole signal intensity to integration time is likely much more complex than the simplified model above. While more rigour could certainly be applied to isolating variables if this study were to be repeated, based on the results obtained here it is not anticipated that increased accuracy would yield a satisfactory explanation for the ICI signal losses in the keyhole.

A corollary of any strong relationship between signal intensity and integration time (or duty cycle) would be some corresponding dependence of the signal fill factor (fraction of A-lines containing signal above a given threshold) on the same. Figure 5.6
shows the signal fill factor for the same set of welds discussed in the preceding pages, as a function of integration time. There is a slight downward trend in fill factor. The behaviour is consistent with only a weak dependence of fill factor on integration time.

Figure 5.6: ICI signal fill factor as a function of integration time with 150 mm focusing optics. Blue points represent values taken from brightest-pixel tracking of the entire ICI image, red points represent keyhole root signal as determined by the group-based tracking algorithm.

Neither the dependence of average intensity nor signal fill factor on integration time appears to be strong enough to justify the absence of signal from the keyhole bottom in more than 90% of A-lines. These experiments point away from the axial motion artifact as the dominant cause of signal losses in welding. In spite of this, it is still of interest to examine whether the expected behaviour of the motion artifact, as observed under smooth motion of a speaker, may be conclusively witnessed in the context of laser keyhole welding.

In Figure 5.7, we revisit the keyhole initiation data from the previous chapter. The figure shows intensity data from the initial keyhole interface as a function of velocity, as calculated from a third-order polynomial fit to the interface depth. The measured intensity as a function of speed is superimposed on the theoretical maximum signal
intensity given by Equation 2.12. Each pane shows data from a different material, and each set of intensity data is a superposition of data from five welds produced with identical parameters.

The data in Figure 5.7 display some interesting features. Strikingly, there are no readily visible dips in signal intensity at the predicted speeds—in fact, no periodic attenuation structure on the correct scale is visible here. All materials shown here do display a common gross pattern in signal intensity. Signal is initially sporadic with high maximum intensity, then decreases sharply and levels off as the initial keyhole interface descends into the sample.

The lack of regular signal dips suggests that although the motion of this interface appears to ICI to be smooth, the data do not adhere to the model as expected. According to Equation 5.1, errors in the horizontal distribution of intensity levels
5.3. THE MOTION ARTIFACT IN ICI OF WELDING

relative to theory could stem from inaccuracies in the camera integration time, light source centre wavelength, or interface velocity. Variation of the center wavelength or the integration time, especially on timescales as fast as milliseconds, would produce serious and far-reaching problems with our imaging system, and all evidence suggests that these values are stable. It is, however, entirely feasible that the surface velocity at any given point might differ significantly from the fit value when measuring a molten interface. While the gross motion of the keyhole root follows a smooth trajectory, these data suggest that on timescales similar to the spectrometer frame period and integration time, the interface upon which the imaging beam impinges is not moving in the same manner as the speaker from the previous section.

One of the challenges in our observation of the motion artifact in welding data is that the phenomenon depends on intra-frame dynamics. In the case of the moving speaker, velocity data is inferred based on the assumption that the motion is smooth on timescales smaller than the integration time. The design of the speaker should damp out any higher-frequency noise components that may be present in the driving signal. When a continuous interface is observed at the keyhole root, velocity data must still be acquired by interpolation between A-lines. In the case of keyhole welding the assumption of smooth motion is likely no longer valid due to the high energies, fast dynamics, and general instability inherent in the process. Literature descriptions of waves on the keyhole walls corroborate the idea that the interface observed by ICI would be unstable over short distances and timescales even during a relatively smooth gross motion.
5.4 High-Speed Imaging

The idea that fast keyhole dynamics might stymie efforts to measure certain effects with ICI is intriguing, given that framerates available to us are already orders of magnitude faster than keyhole depth oscillations. Additionally, in the interest of a thorough examination of camera timing effects on the ICI signal, it would be interesting if any qualitatively new features were revealed by a brute-force increase in imaging speed and duty cycle.

With the aim of realizing faster imaging speeds for welding, and with the help of industrial collaborator Paul Webster, I devised a combination of two commercial ICI systems into a single multiplexed high-speed imaging system. The first ICI system operates normally. The spectrometer of the second ICI system is used to collect the fringe pattern returning from the beam splitter toward the light source in the interferometer of the first. This signal is usually diverted by an optical isolator and dumped to protect the imaging light source.

The second spectrometer is connected via a fibre optic jumper in place of the beam dump at the output of the isolator. A function generator is configured to trigger the respective cameras alternately, allowing the maximum speed attainable by a single camera to be effectively doubled. A consequence of this configuration is that the imaging duty cycle is also doubled. Additionally, a smaller region of the camera array (576 pixels instead of 896) is used to boost readout rates and further increase speed. This setup is described in greater detail in section 3.3.

This multiplexed system is used to take the fastest ICI images ever recorded of laser keyhole welding, at a total frame rate of 588 kHz. Data are collected separately from each spectrometer and the images are interlaced by a MATLAB script after the
5.4. HIGH-SPEED IMAGING

fact. Figure 5.8 shows a multiplexed ICI image of a weld in stainless steel. The weld is 30 mm long, with a material feedrate of 25 mm/s. The laser is turned on at 0 ms and terminated at 1200 ms.

The top frame shows the entire image of the weld, ceiling decimated by a factor of 500. The middle frame shows a region of steady-state keyhole oscillations over a time span of 20 ms, decimated by a factor of 5. The third frame is a 1 ms sample of the region shown in frame 2, displayed at maximum time resolution. Alternate A-lines are mapped in different colors to distinguish the signals from the two multiplexed spectrometers.

The response of long, continuous interfaces to the doubled imaging rate is largely unchanged. It is perhaps not surprising that interfaces that are resolved continuously at 200 - 300 kHz do not demonstrate qualitatively new behaviour when imaged at 600 kHz. In certain respects there are limitations to what can be gained from the image by doubling the line rate. However, this system does theoretically have the ability to resolve dynamics that would be intra-line at lower rates. Now that the detection concept has proven viable, greater gains could be realized through effective shortening of the exposure time—either through improved camera technology or stroboscopic illumination.

Tellingly, several instances of sidewall signals spanning two A-lines are visible in the full-resolution frame of this figure, a phenomenon not typically observed at imaging rates near 200 kHz. This suggests that sidewall signals are not necessarily much shorter than 1-2 µs.

Figure 5.8 shows ICI of Keyhole welding in unprecedented temporal detail. However, no glaringly new dynamics or image features are observed as a result of this
Figure 5.8: Imaging a welding stainless steel at 588 kHz using the high-speed multiplexed ICI setup. Left frame: the full weld, ceiling decimated by a factor of 500. Middle frame: a detail of 20 ms of weld data from the weld center. Right frame: A 1 ms detail of the image displayed without decimation. Red and blue colour maps distinguish data from two different spectrometers.
configuration. In spite of this, the apparatus demonstrates a sound proof-of-concept for multiplexed-spectrometer ICI imaging. Potential further uses for such a system are discussed in the future work section of Chapter 7.

The gaps in ICI signal from the weld keyhole stubbornly persist through various permutations of the image timing parameters. The dependence of signal strength and fill factor on integration time is weak, implying that the axial motion artifact does not dominate losses. The camera duty cycle is seen to have an even weaker effect on these metrics. A simultaneous multiplicative increase of ICI frame rate and duty cycle did not yield much in the way of signal gains, although the increased detail afforded by the design used may see other uses. The data seem to indicate that acquisition timing parameters are not the dominating factor controlling signal losses in welding. In the next section, we will examine the effects of sample and optical path geometry on keyhole signal levels.

5.5 Geometric Signal Losses

The data discussed in the previous sections of this chapter show that although ICI imaging in general is subject to signal losses depending on sample motion and camera timing, the conclusive observation of these effects in imaging of keyhole welding remains elusive. The effects of camera timing, and specifically the axial motion artifact, do not account for the large fractional signal losses present in weld imaging. In this section, we turn our attention to the geometry of the keyhole and the properties of imaging light backscattered from within it as possible culprits for the sporadic nature of ICI measurements of the keyhole.

If we discount the influence of motion-related effects, there are generally four ways
in which the instantaneous sample geometry might cause complete signal loss in ICI. The backscattered beam may be prevented from re-coupling into the collection optics through attenuation within the keyhole, attenuation due to wavelength-scale surface texture, distortion of the spatial structure of the beam, or complete diversion of a spatially-intact beam. The first three possibilities are remediated to an extent by the large dynamic range (60dB) of the imaging system. Attenuation by several orders of magnitude is tolerable, as are the diffractive consequences of back-scattering only a fraction of the beam. As discussed in section 2.4, the keyhole system is a narrow, molten, conducting waveguide in which multiple reflections of the process radiation are continuously present. It is reasonable to expect that the backscattered imaging beam will frequently be diverted from the optic axis.

As it happens, large improvements in signal fill factor may be realized by simply adjusting the numerical aperture of the collection optics. Figure 5.9 shows the mean signal and fill factor obtained from a nearly equivalent weld to those produced for Figures 5.5 and 5.6. The only difference in parameters is that the data in Figure 5.9 were obtained through a 100 mm final focussing optic as opposed to the 150 mm one employed in previous experiments. The mean signal is increased by approximately 1 dB, but the fill factor is more than doubled.

The numerical aperture, NA, of a lens, assuming small angles, is

\[ NA \sim \frac{nd}{2f}, \]  

(5.2)

where \( n \) is the refractive index of the lens material, \( d \) is the clear aperture diameter and \( f \) is the focal length. The 100 mm optic has a numerical aperture 1.5 times greater than the 150 mm optic. Therefore, the solid angle through which it may collect light
is greater by a factor of $1.5^2 = 2.25$. For matching integration times, the signal fill factor is on average 2.8 times greater for the 100 mm lens than the 150 mm lens, with a standard deviation of 0.1. This is slightly greater than the increase predicted by the collection solid angle. That the fill factor more than doubles in step with the lens solid angle of acceptance, while the signal strength does not, suggests that the intensity and spatial structure of the ICI beam returning from the keyhole do not vary as much as the angle at which it backscatters. The limiting factor appears to be the angular distribution of the beam relative to the incident optical axis over time.

To carry the analysis further, I construct a simple model. I assume that at any point in time, the imaging beam is returned from the keyhole intact, but with a random direction somewhere in the $2\pi$ steradians above the sample surface. A schematic illustration of this model is shown in Figure 5.10. The solid angle of acceptance for the 150 mm lens is $5.4 \times 10^{-2}$ sr, centered on the optical axis, while for the 100 mm lens it is $2.0 \times 10^{-2}$ sr. The results of this model are shown together in Table 5.2.

If the beam direction leaving the keyhole were truly random within the upper
Figure 5.10: Schematic illustration of a potential imaging beam path in and out of the keyhole, resulting in an off-axis returning beam and loss of signal.

<table>
<thead>
<tr>
<th>Lens focal length [mm]</th>
<th>Acceptance half-angle [°]</th>
<th>Acceptance solid angle [sr]</th>
<th>Percent of upper hemisphere [%]</th>
</tr>
</thead>
<tbody>
<tr>
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<td>6.89</td>
<td>0.054</td>
<td>0.72</td>
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<tr>
<td>150</td>
<td>4.59</td>
<td>0.020</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Table 5.2: Calculated geometry values for the 100 mm and 150 mm focusing optics in the macroprocessing laser head.
hemisphere, I would expect the signal to couple back into the lens only 0.32% of the
time for the 150 mm lens, and 0.72% of the time for the 100 mm lens. The signal
fill factors measured for these two lenses are much higher, consistent with a more
center-biased angular distribution of the ICI beam returning from the keyhole.

5.6 Conclusions

It is important to note that the imaging and process beams share final focussing op-
tics. If keyhole geometry is in fact the dominating factor behind ICI signal losses,
care must be taken to account for the fact that the final focussing optics also directly
determine the spot size and Rayleigh length of the process beam. The differences
in signal level observed from a change of lens NA may not be attributed entirely to
backscatter collection angle unless a contribution due to changing keyhole geometry
can be accounted for. This problem will be revisited in the context of off-axis imaging
of the keyhole in the next chapter. Additionally, any meaningful discussion of signal
loss involving attenuation or diffractive effects requires a more thorough understand-
ing of the keyhole geometry under different welding conditions. In the next chapter
I explore the extension of ICI imaging capabilities to a more general view of sample
and keyhole morphology in laser welding.
Chapter 6

Transversely-resolved ICI

6.1 Introduction

In the previous two chapters, I have discussed the utility and some of the limitations of ICI as a tool for in-situ process monitoring, quality assurance and control in laser keyhole welding. The understanding of the keyhole system that results from one-dimensional imaging is fundamentally limited. When the effects of keyhole geometry on both the process and the ICI measurement come into question, it becomes clear that depth is only part of the picture. To move toward a more general understanding of the system and to approach modelling its physics based on ICI data, a two- or even three-dimensional view of the keyhole is potentially much more useful.

6.2 Three-dimensional Imaging of the Keyhole

With respect to our understanding of ICI measurements, in the last two chapters we have run into barriers where our analysis would benefit from knowledge of the entire
keyhole shape when assessing the response of our image to dynamics and geometry. In this section, I explore imaging of the keyhole with the newly introduced ability to dynamically steer the ICI beam using a pair of galvanometer scanning mirrors. This grants two-dimensional control of the imaging spot position on the sample surface, allowing regions away from the machining beam axis to be queried, and expanding the resolving power of ICI from one to three dimensions.

The three-dimensional implementation of ICI marks a return toward the technique’s roots in medical optical coherence tomography. The scanning mirrors are mounted at the top of the machining head, where the ICI fibre would normally couple into free space via a fixed collimator. I have designed new mounting hardware that allows the scanning mirrors to be introduced into the beam path. Due to the design of the machining head, the galvanometer pair is located above the focal plane of the process beam by approximately 50 cm. As a consequence, angular displacements of the imaging beam are necessarily small. This beam steering capability allows beam angle to be controlled by an analogue electronic signal, which in turn translates into transverse displacement of the imaging spot in the focal plane of the process optics. Since both the angles involved and the target field of view on the sample are small, adequate performance is achieved in spite of the use of a simple spherical lens to focus the beam. The particulars of this apparatus are discussed in more detail in section 3.4. The output of this new implementation of ICI is a time-resolved, three-dimensional field-of-view approximately centred on the process beam focal position.

A cursory consideration of the potential applications for dynamic beam steering results in the conclusion that its introduction increases the imaging parameter space vastly. In order to prove the new imaging capabilities in a manner that will build
directly on the work discussed in previous chapters, and lend itself to straightforward interpretation, I aim to understand the keyhole geometry in terms of two representative scanning geometries. Both involve the use of a triangular waveform to drive just one of the scanner motors in a repeating sweep pattern during imaging of a weld. The first pattern is a repeated transverse sweep of the imaging beam, perpendicular to the material feed direction, in a plane containing the process beam axis. In the reference frame of the sample, this scan pattern produces a ‘zig-zag’ pattern over time. The images that result contain information from the keyhole and the narrow melt pool and virgin surface to either side of it. The second scheme is a longitudinal sweep in the direction parallel to the material feed, again in a plane containing the process beam axis and produced by a triangle input waveform. This pattern contains information from the virgin surface leading the keyhole, and the melt pool and re-solidified weld bead trailing it. I often offset the range of the longitudinal scan pattern to the rear, since the behaviour of the static solid material ahead of the keyhole is of less interest than that of the dynamic melt pool in its wake.

For a single-pass keyhole profile to be viewed as a detailed image, it is preferable that it comprise a number of A-lines on the order of one hundred. To this end, scanning of the imaging spot is performed here at rates much slower than the imaging frame rate. Of course, there are limits on the response of the galvanometers that also play a role (typically on the order of kHz and higher, depending on scan angle). Scan patterns presented in this thesis reach as high as 500 Hz. The relative imaging spot displacement as a function of change in galvanometer input voltage is calibrated using ICI images of a microscope calibration target (Edmund Optics) in section 3.4. However, for precision measurements of the keyhole on 100 Hz timescales, more accuracy
is desired, particularly with respect to the fidelity of the beam displacement waveform in the focal plane to the input analogue waveform. Rather than rely on a general calibration value for ICI of the keyhole profile, I directly measured the position of the beam as a function of time for a given galvanometer input signal, using a high-speed line camera fixed in the focal plane of the process beam. I then use the same input signal to drive the scanning mirrors when producing a weld image. Measurements of the same nominal waveform show excellent repeatability, often to within the limits of the line rate and pixel pitch of the camera, as discussed in section 3.4.

The process beam axis position is registered to the line camera via the aligned centre position of the imaging beam. A vector of imaging spot displacement as a function of time is interpolated from the line-camera-measured map of each scan pattern. The interpolation step size is matched to the ICI camera line period, so that each A-line acquired is assigned a position relative to the process beam. Weld images are acquired using pre-mapped scan patterns to produce keyhole profile images. The weld data sets are brightest-pixel tracked, and A-lines are mapped to spot position on the sample surface as a function of time. The timing of the galvanometer input signal, produced by a function generator (Tektronix AFG 3022-B), is synchronized to the process laser and imaging system via an initial electrical trigger produced by the Aerotech motion stage drivers (Ndrive). The resulting data set is a three-dimensional cloud of points with coordinates in time, ICI beam offset in the frame of the process beam, and depth relative to the process optics.

An additional processing complication arises when the beam is translated into the trailing melt pool. Significant saturation is present in A-lines captured from these regions, as the molten surface has high reflectivity and the backscatter produced is
extremely directional. A summing filter is found to be most effective for saturation removal in the extreme cases witnessed here. A-lines in which the total signal from all depth bins sums to an amount greater than a specified cut-off value (usually 300 dB) are removed entirely. The value of the cut-off must be tuned depending on the specific imaging conditions. Ringing causes strong signals to appear from improbable depths (i.e. much greater than the skin depth of the metal). The cut-off value is decreased until such signals are not prevalent in the brightest-pixel-tracked data set.

The three-dimensional point cloud produced from profile-scanning ICI may be visualized in many possible ways. Among the more intuitive outputs are cross-sectional images of the air-metal interface that constitutes the keyhole surface, henceforth referred to as ‘profile views’. In Figure 6.1, I present transverse (inset) and longitudinal (main) profile views of two welds in mild steel with identical process parameters. The horizontal axis is the ICI beam centre displacement in the frame of the process beam, and the vertical axis is brightest-pixel tracked depth. The colour scale represents signal intensity. Each profile is a superposition of successive sweeps over a period of 10 ms. In total, 60 sweeps over the keyhole are included in each set.

In order for the profile to accurately depict successive superimposed sweeps, the top surface depth of the material must be subtracted to negate material curvature. Before each weld, I acquire an ICI image of the virgin surface using the same imaging parameters and scan pattern. The top surface data are processed and tracked in a similar manner to the weld data. A flexible-surface fit (algorithm) is applied to the top surface point cloud, and the height of the sample surface at each beam position is interpolated from the result. The fit and interpolation steps are applied in order to isolate and correct for large-scale sample curvature while leaving smaller-scale texture
Figure 6.1: Transverse (inset) and longitudinal keyhole profiles for welds in mild steel. For both sets, the process laser power is 1100 W, the material feedrate is 25 mm/s, and Ar cover gas is fed through a coaxial nozzle at 25 psi.

The depth error is given by the ICI point spread function full-width at half maximum. For this system, the value on steel is typically 22 µm. The ICI beam centre position error relative to the process beam axis is given by the compounded errors of the various steps in the alignment procedure. I estimate a value of ± 25 µm. Error in relative ICI beam position from one point to the next is a function of the galvanometer pointing error (which is small; see section 3.4) and the width of the ICI beam itself.

Looking closely at the transverse and longitudinal keyhole profiles in Figure 6.1,
we observe a difference of roughly 300 µm in the maximum measured depth of the keyhole between the two scan types. These sets were acquired from different welds with the same parameters. Given that the span of time represented in this figure is much greater than typical keyhole oscillation periods for this parameter space, such a marked difference in real maximum keyhole depth is not expected. The greater depth in the longitudinal scan is attributed to keyhole tilt. It is common for the keyhole root to trail behind the process beam axis (see section 2.4). For the parameters in use here, this effect is expected to be slight. The difference in imaged keyhole root depth is consistent with the greatest depth occurring to the trailing side of the optical axis, and therefore being visible to the longitudinal scan (variable trailing displacement) and not the transverse scan (fixed trailing offset of zero).

A characteristic feature of keyhole profile images is a pair of dense clusters of signal just below the shoulders of the weld keyhole. These are measured slightly below the top surface height of the sample, and are seen in both longitudinal and transverse scan images of higher-aspect-ratio keyholes (e.g. those produced at 1100 W power and feedrates less than 75 mm/s). These clusters are visible in Figure 6.1 centred near 250 µm depth and ± 100 µm offset. At first glance these features seem to indicate that there is some type of radially-symmetric shelf formation just below the keyhole shoulders. However, this is inconsistent with weld keyhole theory, as well as transmission X-ray data and welding of transparent media. A probable explanation is that these points result from a multiple reflection path involving a single traversal of the keyhole width, with the beam reflecting from both shoulders of the keyhole in the process. The measured depths within these groupings, relative to the surrounding melt, are consistent with such a path. These signals are generally of low intensity
(<20 dB), which is consistent with losses from the polarization changes that such a path would likely induce.

Three-dimensional ICI is, to my knowledge at the time of writing, the first and only technique capable of directly imaging the keyhole profile in the transverse aspect. X-ray transmission produced images of the keyhole profile, but due to constraints on the thickness of material which may be imaged in this manner, only the longitudinal aspect is accessible. To give a sense of the keyhole evolution as a function of time, the transverse data may be interpolated to give a time-resolved image of the keyhole width profile. Figure 6.2 shows the results of an interpolation carried out on the point cloud data from a (50 Hz) transverse scan of a weld in mild steel. Points are arrayed in a space with dimensions of time, ICI beam displacement from the process beam axis, and brightest-pixel-tracked depth.

The depth values as a function of time and offset are interpolated using a Delaunay triangulation (MATLAB’s ‘TriScatteredInterp’ function). Points are joined by straight line segments in such a manner that no triangular face bounded by three connected segments contains a point. The result is a segmented surface contained within the hull of the point cloud. This triangulated surface is then re-sampled on a rectangular grid of 100 by 300 points for plotting. The relative scaling of the time and transverse displacement axes is not directly based on the material feedrate. Scaling of the horizontal axes affects the results of the triangulation algorithm. The scaling chosen yields an easily interpreted image for qualitative use, and does not accurately represent the physical separation of points in the sample frame of reference. This presentation of the data provides an intuitive way to visualize the evolution of the transverse keyhole profile over the duration of the weld. A similar treatment may be
Figure 6.2: A triangular interpolation of a continuous transverse scan of the keyhole produces a map of the keyhole profile as a function of time. These measurements are taken in a plane containing the process beam axis and perpendicular to the welding direction. The weld shown here is produced in mild steel at a feedrate of 25 mm/s.

applied to the longitudinal scan data, however the interpretation is less intuitive as there is no direct spatial analogue to the time axis.

Another interpretation of the three-dimensional keyhole images is shown in Figure 6.3. Top views of a weld in mild steel at 25 mm/s are shown with ICI spot displacement on the horizontal axis, time on the vertical axis, and colour scales representing depth (left frame) and signal intensity (right frame). Due to the broad scan width of over 3 mm, detail in the keyhole is limited in this view. The black dashed line shows the position of the starting point of the weld as a function of time, beginning at (0,0). The angle of this line indicates the motion of any fixed point in the sample frame of reference within this figure.

The interesting aspect of the data that is visible here is the extent of the trailing
melt pool. The region of the trailing melt pool is visible in both frames, to the left of the keyhole (at zero µm offset). The melt pool is marked by a scarcity of signal in both frames (potentially removed at both ends of the intensity range due to the threshold and saturation filter) and a high apparent variability of the signal intensity visible in the right frame. The sudden transition in backscatter characteristics at the trailing (left) edge of this region marks a change in surface state, in this case from liquid to solid. These differences in backscatter characteristics might be harnessed to identify the state of the sample surface in ICI data from the weld and melt pool algorithmically. This is investigated in more detail in section 6.5.

Figure 6.3: Longitudinal scans of a keyhole in mild steel at 25 mm/s. Colour is mapped to brightest pixel depth (left) and backscatter intensity (right).

Since the displacement axis in Figure 6.3 coincides with the direction of material feed, we can plot the sample feedrate along with the data. The trailing edge of the
melt pool is seen to match the material feedrate for a short time (about 50 ms), indicating a delay before the front of recast metal begins to move relative to the sample surface. The pool extent reaches a local maximum just after 150 ms. The melt pool length proceeds to fluctuate by as much as 800 um over the remaining duration of the weld. It is not until this first maximum is reached that the keyhole system can be truly said to have reached dynamic equilibrium. Interestingly, this is two orders of magnitude slower than the initial deterministic break-in observed in section 4.5, which lasts approximately one millisecond.

The melt pool dimensions affect the fluid dynamics and heat-transfer properties of the keyhole system, which in turn influence the keyhole geometry and process beam coupling efficiency. Most accurately, the terms ‘steady-state’ or ‘dynamic equilibrium’ should describe a state of the keyhole and melt volume in which neither the process parameters nor the gross system geometry varies systematically. Therefore, a full-length melt pool (and not just a full-depth keyhole) is necessary for the system to truly be in steady-state. Interestingly, the observed melt pool length varies on rates much slower than the keyhole oscillations. This suggests multiple-timescale oscillatory behaviour of the system.

The data presented in this section prove the concept of transversely-resolved ICI of the weld keyhole, and scratch the surface of the new opportunities it presents for visualization of the keyhole. The timescales of keyhole evolution are still much faster than those of human perception. Any online process monitoring and control, or comparisons with numerical modelling results that could stem from multi-dimensional keyhole imaging will require a quantitative treatment. With this in mind I seek to demonstrate the algorithmic extraction of a straightforward metric from keyhole
profile data, analogueous to the measurement of keyhole depth from static, zero-offset ICI presented in Chapter 4. Whether such information can be accurately measured on timescales that meaningfully represent the evolution of the system is a crucial factor in the potential future utility of this mode of imaging. In the next section, we will examine the extraction of a new keyhole metric from longitudinal and transverse keyhole sweep data—the keyhole width.

6.3 Keyhole Width Measurement with ICI

The simplest approach for quantitative analysis of the new keyhole geometry information afforded by multi-dimensional ICI is to attempt to boil the transverse aspect down to a single metric, as with keyhole root depth from on-axis ICI images. To this end, I explore the feasibility of extracting a characteristic keyhole width as a function of time from the transverse and longitudinal sweep images. Eventually, combined keyhole width and depth monitoring may be capable of producing a much-improved in-situ process stability assessment than depth alone. The keyhole width is not commonly reported in the literature, at least in a quantitative sense. This may be in part due to the difficulty inherent in measuring the keyhole geometry in the past. I have encountered claims that the value ranges between 1.0 - 1.7 times the process laser spot diameter [24, 27, 29, 17].

As always, some complicating issues must be considered. First, the (automated) measurement of a self-referential geometric quantity such as the width is inherently more complex than the measurement of an interface position relative to the process optics. The measurement of width involves successful registration of at least two depth values as a function of both time and offset, whereas measurement of the root
6.3. KEYHOLE WIDTH MEASUREMENT WITH ICI

depth only requires one depth value as a function of time. All of the complications surrounding whether a given depth point is the correct one to use (see Chapter 4) still exist.

Second, the time resolution with which width may be measured is fundamentally limited by the rate at which the galvanometer scanners are able to scan. Assuming perfect, continuous ICI signal, keyhole profiles sweeps may only be acquired at kHz rates, which is two orders slower than the theoretical time resolution of on-axis measurements. In practice the signal is not perfect. When imaging within the keyhole, the root signal is sporadic. Depending on galvanometer frequency, missing keyhole signal can and does result in entire sweeps without any signal from within the keyhole. Even a sweep with ample signal from within the keyhole may display gaps as a function of ICI beam offset where no depth is measured (particularly in the keyhole sidewall regions). The position and magnitude of such gaps are unpredictable. Therefore an approach involving continuous monitoring of a given subset of pixels is likely to prove ineffectual. The only clear solution is to apply a fitting procedure to a set of points collected from all offset values in a given sweep of the beam, or some appropriate time interval. If a fitting procedure is used to extract characteristic width values, the rate at which the measurement is taken must be limited to ensure sufficient signal is collected for results to be accurate.

It is of course unrealistic, given the nature of the physical phenomena at play, to assume that the keyhole profile will ever assume an analytic functional form. However, a form that matches the profile well enough for the fit parameters to match trends in actual geometry should suffice for this exercise. To this end, we desire a function of peaked form with a preference to steep walls and a flattened peak, to accommodate
the high aspect ratio shape observed in the keyhole profile in Figure 6.1. A super-Gaussian of moderate order, as given by

$$y = y_0 \exp \left( -2 \left| \left( \frac{x - x_0}{w} \right)^n \right| \right), \quad n \geq 2,$$

(6.1)

should be appropriate, where $n$ is the order of the function, $y_0$ the amplitude, $w$ the width parameter and $x_0$ the horizontal offset. Setting $n = 2$ reduces the function to a typical Gaussian.

In Figure 6.4, I show the results of a super-Gaussian fitting procedure to extract characteristic widths from longitudinal scan data taken of a weld in mild steel. The process laser power is 1100 W, the material feedrate is 125 mm/s, and the focal length of the final focussing optic is 100 mm, and the ICI scanning rate is 500 Hz. The data are grouped into bins of a given duration, depth values are plotted as function of ICI beam displacement, and a 4th-order super-Gaussian is fit to the resulting two-dimensional distribution using a least-squares regression. The fourth order fit consistently yields good stability in resulting parameters when compared head-to-head with other orders of super-Gaussian fitting to the same weld data. The third and fifth order functions also behave well, whereas the second (a natural Gaussian) and seventh orders functions were markedly less stable. Filters are applied to automatically remove fits that clearly failed to produce accurate results. Any fit that results in negative amplitude, amplitude much greater than the feasible keyhole depth, or width greater than that of the scan field are discarded.

The upper frame of Figure 6.4 shows the $1/e^2$ width of the keyhole as calculated from the fit parameters, for time bin durations ranging from 1 ms to 15 ms. Data was
Figure 6.4: Fitting a 4th order super-Gaussian to longitudinal weld scan profiles to determine keyhole width. The results shown are from a weld in mild steel at 1100 W power, 125 mm/s feedrate, with a 150 mm focussing optic. The imaging beam scan pattern is a triangle wave at 500 Hz. Fits are applied to brightest-pixel depth-tracked data as a function of ICI spot displacement, split into bins based on acquisition time. The $1/e^2$ full width of the resulting curves are plotted in the upper pane as a function of time. The lower pane shows a cumulative average of the same width data, giving a sense of the measurement settling time.

taken with a galvanometer input frequency of 500 Hz, so the 1 ms bin size corresponds to half of a scan period, or a single sweep across the keyhole. The high amount of variation on display in this set is the result of inaccurate fit results. Most individual sweeps at this rate contain signal too sparse for the fit procedure to perform well. More consistent and stable width values are seen for bin sizes of 10 ms and up. To give a sense of the time for this measurement to settle to a relatively stable value, the cumulative average of the same width results as a function of time is shown in the lower frame. Reassuringly, the widths obtained with different time bin durations appear to converge toward the same average value. This suggests that the volatility
observed in the upper frame is indeed the result of random variance of the fit results when too few data points are included.

Not shown here is the result that the width measurement settling timescale does not vary appreciably with ICI beam scan frequency (I have also tested 200, 100, and 50 Hz). This suggests that the factor limiting the keyhole width measurement rate is the temporal density of the signal returning from the keyhole, rather than the rate at which the beam is scanned. The scan period of course becomes the limiting factor at sufficiently low frequencies. Once the timescale over which sufficient signal may be collected is established, the best approach is to apply this value as the minimum bin duration for the fit procedure. This is advantageous because good input data will increase both the accuracy of the fit parameters generated and the speed with which the algorithm converges. In the case of varied-feedrate welding in mild steel at 1100 W, the width may be measured with a fair degree of confidence at rates on the order of 100 Hz (based on the observed measurement stability). This value is expected to vary with material and process parameters, as the relationship between keyhole geometry and collection optic numerical aperture has been shown to influence signal fill factor appreciably (section 5.5).

As proof of concept for this procedure as an in-situ weld keyhole diagnostic, I measure the keyhole width in a set of welds in mild steel, for which the material feedrate varies between 25 and 175 mm/s. Scan patterns are longitudinal triangle waves, and scan frequencies of 100, 200, and 500 Hz are shown here. A fourth-order super-Gaussian fitting procedure is applied with a 15 ms bin duration. The resulting measured widths are averaged for each weld and presented in Figure 6.5, with errors given by the standard error of the mean of each set. Since the welds are of a standard
length (30 mm), the number of time bins contributing to each average width point scales inversely with the feedrate. The keyhole and melt pool are expected to elongate at higher feedrates, a trend which is absent from this data set. A possible explanation for this is the limited parameter space of the apparatus used for these experiments. The laser powers and material feedrates available to us are both at the lower end of the parameter ranges typically employed for laser keyhole welding.

Figure 6.5: The longitudinal keyhole width from the super-Gaussian fit procedure, plotted as a function of feedrate for welds in mild steel. Each point is the average of 4th order super-Gaussian $1/(e^2)$ widths for a single 30 mm weld, binned in 15 ms time steps. Error bars are standard error of the mean width for each weld.

This fitting method for measuring keyhole width in-situ is capable of reporting relative changes in the keyhole width for a given set of process parameters. However, the question of its absolute accuracy, and indeed that of the more general keyhole profiles measured by multi-dimensional ICI, is important if these results are ever to be applied to the absorption profile of the process beam on the keyhole walls. It becomes
necessary to consider the fact that the ICI beam has a non-negligible width on the scale of the process beam and keyhole. More advanced applications of this type of data will require confidence in the position of an observed backscattering interface relative to the process beam, not just the position of the ICI beam centre.

6.4 Comparison with In-situ X-ray

With the aim of obtaining external verification of the keyhole geometries produced by scanning the ICI beam, in March 2015 I carried out a series of experiments with PhD student Meiko Boley at the University of Stuttgart’s Institut für Strahlwerkzeuge (IFSW). These involved welding different alloys while imaging with both ICI and a transmission X-ray system [1, 6, 7, 18], as introduced in section 2.4.2. These experiments allowed comparison with one of the only (if not the only) other techniques capable of directly measuring keyhole geometry in-situ, as well as providing an opportunity to observe materials and welding power regimes not accessible in our laboratory.

Using the X-ray system, bead-on-plate welds are produced along the edge of 4 mm thick plates. An X-ray tube passing through a pinhole illuminates the plates from the side in the region of the keyhole. Opposite the X-ray tube is a detector system culmination in a two-dimensional high speed camera array for measurement of the transmitted rays. The transmission is increased in regions where the metal sample is thinner, which serves as the contrast mechanism for distinguishing the vapour channel from the surrounding solid material. The analysis of these data will constitute a fascinating direction for future work. To give an example of its utility I present a direct comparison of X-ray and ICI keyhole geometry measurements in
6.4. COMPARISON WITH IN-SITU X-RAY

Figure 6.6: A longitudinal ICI scan (black dots) of a keyhole in stainless steel overlaid on an X-ray transmission image of the same keyhole. The ICI and X-ray data sets were captured simultaneously. The X-ray image is an average of 800 frames taken at 1 kHz, while the ICI profile is an accumulation of points from 60 sweeps at 100 Hz.

The weld in Figure 6.6 was produced on the edge of a 4 mm thick plate of stainless steel, with 2 kW of laser power (TRUMPF TruDisk 5001), a spot size of 400 µm and a material feed rate of 50 mm/s. The X-ray image is an average over 800 ms of data, while the ICI profile is accumulated for 600 ms at the weld centre. The longer time frame for the X-ray image was used to get the maximum amount of contrast possible for this image. The X-ray system provides a clear view of the keyhole profile, but its resolution (at 100 µm) is rather limited for a keyhole of this size. As a result, the root of the keyhole is difficult to locate in the X-ray data. It appears to be shallower.
than the ICI measurement indicates by about 10%. This is perhaps not surprising. When imaging a fluctuating keyhole wall, the edges of the profile taken by the X-ray will be biased inward by the averaging process, whereas the set of tracked ICI points will have sharply defined edges at the extremes of the keyhole extent.

In a strictly qualitative sense, the keyhole geometry measured by scanned ICI appears to agree well with that imaged by transmission X-ray. This is presented here as evidence for the accuracy of the keyhole width and profile measurements of the preceding sections.

6.5 Surface State Identification

Returning briefly to the discussion of Figure 6.3 above, I observe that there is information about the surface state of the sample encoded in the multi-dimensional ICI data. This information is immediately evident to the human eye—an exercise in distinguishing patterns in an image. The eye is drawn to the contrast at the left of the frame, attributed to the trailing edge of the melt pool. The signal to the right of this line appears to be patchy, with large variability in signal intensity. The signal to the left is continuous and bright. There is clearly a sharp boundary in the backscattering characteristics of the sample at this point.

The surface state of the workpiece at different points around the keyhole (perhaps largely by virtue of accessibility), is information that commonly sees use as a process monitoring metric for laser keyhole welding. The temperature and extent of the melt pool are used to extrapolate subsurface melt pool dimensions, and indirectly estimate keyhole depth. In practical joining geometries such as lap welds, an increase in the melt pool length can indicate loss of fusion. As a consequence of the reduced volume
for the heat of the melt to diffuse into, more heat diffusion occurs across the material surface, resulting in greater melt pool area. Other imaging modalities (such as high-speed infrared cameras) are likely better-suited than ICI to the task of measuring melt pool geometry. However, the opportunity to identify the surface state for free while imaging the keyhole profile is intriguing. Access to multiple, simultaneous in-situ measurements can only offer a more complete understanding of the evolution of the keyhole system.

To investigate the response of ICI to different material surface states in a realistic welding scenario, I carry out fixed-offset imaging of welds. The welds are in mild steel, carried out at 1100 W power and 25 mm/s feedrate, through a 100 mm focal length optic. Images are recorded with the ICI beam at a different fixed offset position in the longitudinal plane of each weld. Three characteristic fixed-offset images are selected to represent the characteristic regions of the sample. An image leading the process beam by 370 µm observes solid virgin steel prior to the passage of the keyhole. An image at 0 mm offset shows the keyhole. A 740 µm trailing offset distance is used to observe the melt pool behind the keyhole.

The resulting images are processed in an effort to extract metrics which may be used to quickly distinguish surface state in-situ. That is, on timescales at least an order of magnitude shorter than the galvo scanning periods used, so that surface state as a function of offset may be determined. The ICI data are binned in time intervals of 1 ms. Mean depth, mean signal intensity and fill factor are calculated, along with RMS variation of the depth and intensity, for each bin. In Figure 6.7, I present four metrics which, combined, could potentially allow keyhole, melt pool, and solid metal to be distinguished algorithmically on millisecond timescales. Unexpectedly, the RMS
variation of the signal intensity does not exhibit a strong dependence on the different surface states examined here. The metrics included in Figure 6.7 are the mean depth of the brightest pixel, the RMS variation of depth, the mean signal intensity above a 10 dB threshold and the signal fill factor.

Figure 6.7: Surface state detection metrics for static-offset ICI images of the virgin surface, the keyhole, and the trailing melt pool. The signal is binned into groups of 200 A-lines, for statistical analysis of the measured depth and signal intensity. Metrics shown are those demonstrating the best distinction between weld regions. 200 kHz data at 1 ms bin length.

The behaviour of these four metrics for the keyhole and virgin steel images is largely as expected. The results from the melt pool merit a closer examination. Within the melt pool image, the brightest pixel is frequently detected much deeper than is realistic. This is attributed to saturation ringing. The backscatter from the
exposed melt pool at the sample surface is intense and highly directional. Therefore the signal is sporadic, as shown by the low fill factor. When signal from the melt pool is measured, however, it is frequently bright enough to strongly saturate the camera. The result of this strong saturation is that the brightest pixel often occurs at depths much deeper than the actual surface of the sample. Unexpected consequences follow, such as an average melt pool depth (in unfiltered data such as this) registered at values between the virgin surface and the keyhole root, and an RMS variation of measured melt pool depth greater than in either of the other images. Due to the strong effects of saturation, the measurements of the melt pool in this form are not an accurate depiction of the workpiece surface topography. They are, however, theoretically capable of facilitating automated workpiece surface state detection. The data can always be filtered subsequently in order to present a more accurate picture of the melt pool depth.

6.6 Conclusions

The results outlined in this chapter, even more so than those of the preceding two chapters, leave ample opportunity for future work to build on our understanding of ICI of laser keyhole welding. My hope is that the work presented here may pave the way for more involved investigations of the physics of what has heretofore proven to be a slippery system in terms of complete and accurate experimental characterization. There is work to be done toward closing the gap between self-consistent numerical modelling of the weld keyhole and real-world results. A better understanding of the relationship between ICI and the keyhole will advance the ability of this imaging tool to monitor and control laser processing, as well as facilitating its use in increasingly
quantitative study of this physical system. In the final chapter I will draw conclusions from the results presented, and suggest future research directions of primary interest.
Chapter 7

Conclusion

My work with ICI of laser keyhole welding has contributed to a better understanding of both the imaging technique itself and its relationship to the vapour channel. This system has proven difficult to precisely characterize experimentally for decades. The results described here will allow better understanding of its underlying physics, and improve our ability to control it for practical purposes. This work has included multiple international collaborations (PSU, IFSW) and conference presentations (COLA 2013, ICALEO 2014), as well as contributing authorship on two publications [5, 51] and authorship of a third (pending publication).

I have demonstrated an algorithm for extracting the depth of the keyhole, filtering out imaging artifacts specific to the keyhole while reducing data volume by orders of magnitude, with no loss of spatio-temporal resolution. Keyhole dynamics may be more precisely and efficiently resolved and studied with this approach. This algorithm has potential for integration into existing and upcoming commercial ICI applications in the immediate future.
I have explored hypotheses regarding ICI signal losses that are ubiquitous in imaging of the keyhole. In collaboration with undergraduate researcher Seth Todd, I have characterized the effects of the axial motion artifact on ICI imaging of moving interfaces. Conclusive observation of this effect was found to be much more elusive in the context of keyhole welding, with the corollary that keyhole geometry is likely to play a more significant role in these signal losses. This hypothesis is supported by the strong dependence of signal fill factor on the collection solid angle of the focusing optics. The effects of the motion artifact

With industrial collaborator Paul Webster, I have realized a multiplexed-spectrometer ICI scheme by which the imaging rate may be doubled, setting a new speed record for ICI imaging of the weld keyhole (588 kHz). Such a system could be extended to more than two spectrometers to realize 100% imaging duty cycle and arbitrary speed gains up to the limit imposed by the light source power and the camera sensitivity. This same hardware scheme, with the spectrometers set to acquire lines simultaneously, could also be used as a balanced detector to double the SNR of the imaging system. The possibilities for such a system in a miniaturized, on-chip spectrometer configuration are truly exciting.

I have designed, characterized and implemented a scanning-mirror apparatus for extending the imaging capabilities of ICI to three dimensions, through an existing commercial laser processing head. Using this new three-dimensional capability I capture in-situ profiles of the keyhole and demonstrate the viability of ICI as a tool for monitoring general keyhole morphology in laser welding. This initial proof of concept has since led to commercialization by industrial collaborators Laser Depth Dynamics Inc., and this technology is currently seeing use in industrial production settings. I
made use of one such system for a collaboration with the University of Stuttgart’s Institut für Stahlwerkzeuge (IFSW). The data stemming from these experiments comprises simultaneous x-ray and ICI measurements of keyhole profiles. These data serve to verify the accuracy of the transverse aspect of 3D-ICI measurements, and will provide a means to still better understand the strengths and limitations of our imaging technique for a broad parameter space including multiple alloys and violently unstable welding regimes.

My hope is that the results and analysis laid out in this thesis will pave the way for more complete and accurate measurement of the keyhole, simpler verification of numerical modelling outputs, multi-dimensional closed-loop control of laser welding processes, and the application of ICI to similar thermally-mediated laser processes.

As a young imaging technique, the potential uses for ICI in laser materials processing are legion. The gains in processing efficiency, imaging speed, and multidimensional resolution described here, as well as the contributions to image interpretation and analysis, will extend its utility still further.
Bibliography


