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Solid Phase By-Products of Laser Material Processing

by

Leon M. Lobo

A doctoral thesis submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of Loughborough University

July 2002

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Abstract

The analysis of the particulate generated by laser material removal processes is important not only from a health aspect but is also useful to understand the underlying process.

The mechanisms of particle formation during CO\textsubscript{2} laser cutting of mild steel have been established and the influence of the laser processing parameters on the particles is discussed. Hydrodynamic instabilities in the melt zone produce airborne particulate during cutting. Larger particulate tend to be formed by shearing of the melt film (50-100\textmu m) and by pressure gradients (>100\textmu m) within the melt. Additionally the causes of secondary droplet break-up have been addressed. The investigation of these mechanisms enables an enhanced understanding of the cutting process.

Investigation of the particle characteristics yields information regarding the health of the laser process. The size distribution of the particulate has been analysed using laser diffraction particle sizing and is shown to relate to the process parameters (cutting velocity, laser power) as well as the product quality parameters (cut surface roughness, kerf width, striation frequency, etc.). Additionally, analysis of the particle morphology using scanning electron microscopy establishes that the particulate generated are often thin-walled hollow spheres.
The information provided by the experimental data and the knowledge of the mechanisms of particle formation allows a process control methodology to be applied. In order to implement the system, a particle-sizing instrument has been designed. This instrument is based around a linescan CMOS sensor and is designed to tailor for the needs of an online, real-time control system. The system is entirely optical in nature and works on the principle of laser diffraction. Much of the mathematical processing is done offline enabling it to display size distributions in real-time.

Much of the literature, available to date, regarding the solid by-products of laser cutting use techniques of particle capture and analysis that are not ideal nor informative enough. In order for a real-time particle analysis system to be successfully implemented, the method of capture and the selection of the optimum size band have been thoroughly investigated.

Additionally, the particle formation during concrete scabbling was investigated. Concrete was scabbled using a 1kW CO₂ laser and the particles ejected from the surface were investigated for particle size and morphology. Scabbling produces particles which are airborne and hence potential health hazards. The morphology of the airborne particulate showed that the components of the concrete are released from the parent matrix. Some components have particle morphologies that may pose health risks if inhaled (dendritic and needle shaped structures).
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Publications arising from this work


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1 Introduction

Welding, cutting and ablation processes are established laser material processes, generating particles as by-products. The mechanism of formation of these solid by-products and the material phase reached during processing differs between the processes. Ablation processes and welding cause the material to vaporise and recondense to form particulate. Laser cutting of metallic/inorganic materials requires the removal of the liquid phase which subsequently solidifies to particulate. Cutting of organic materials (plastics, wood) follow the recondensation route – vaporisation, condensation and solidification. Thermally induced stresses can cause the ejection of substrate material without phase changes, eg. laser scabbling of concrete.

Depending on the material and the process, as well as process parameters, the surface morphology, chemical composition, shape, density and size of the particulate can change. This change in particle characteristics with process parameters is not only important from a health and safety aspect but can also be used to understand the underlying process, which enables system control, and in turn leads to higher throughputs and quality of product.

1.1 Contributions of this work

The laser cutting of mild steel and the scabbling of concrete has been undertaken. The particulate generated during the laser material
removal process has been characterised for size, shape, surface morphology and degree of agglomeration. An in depth study has been made of the cutting of mild steel and the effect of process parameters on the particulate formed. The relationship between the parameters that quantify product quality and the particulate characteristics are analysed. The effect process parameters have on particle formation are discussed. Additionally, misconceptions regarding particle morphology and density (many of the particles have been found to be thin-walled hollow spheres) have been clarified.

The mechanisms of particle formation (Kelvin-Helmholtz instability, shear driven flow and pressure driven flow) during laser cutting of mild steel have been discussed. Mathematical models explaining these mechanisms have been used to understand the particle formation during laser cutting of mild steel sheet. These models are shown to agree with experimental evidence.

Extensive system characterisation and process monitoring has been carried out to ensure validity of the results. Additionally, feedback loops have been implemented to ensure that process parameters that are affected by the process remain constant. Process control methodology, utilising particle characteristics as the feedback mechanism, has been discussed.

An on-line, real time particle sizing instrument has been developed to fill in the deficiencies of commercial instrumentation. This sizer has been built specifically for applications where an on-line system is
required with physical space constraints. The instrument components are inexpensive and available off the shelf. 95% of the mathematical processing required is performed offline, prior to usage, allowing real time operation.

1.2 Thesis Overview

Chapter 2 provides an insight into the work that has been carried out in the field prior to the submission of this thesis. A review of laser material removal processes and their mechanisms are discussed. The acknowledgement of process by-products and their hazards introduces the need for particle characterisation. The methods of particle size characterisation are introduced along with their merits. Finally, the numerous techniques of system control related to laser material processing are discussed.

Chapter 3 describes the laser system and the particle capture system and discusses the reasons for using particular capture techniques. The particle sizing system is described and its sources of error explained. Finally the monitoring and control system methodology is discussed.

Chapter 4 concentrates on system characterisation. The particle sizing system has been investigated for stability over time and repeatability and has been shown to be compliant with traceable standards. The nozzle stand-off controller incorporates a laser height sensor and has been tested with different material surfaces.
Chapter 5 investigates laser scabbling of concrete.

Chapter 6 discusses the relationship between cut quality parameters (e.g., kerf width, striation frequency) and process parameters (e.g., power, velocity).

Chapter 7 discusses the numerous mechanisms of particle formation (during laser cutting steel) and the regions (operating parameters) within which a particular mechanism operates.

Chapter 8 provides an in-depth discussion of the effect of the laser process parameters on the particulate generated during cutting. The particulate have been investigated for size (distribution), concentration, shape, morphology and surface structure. The mean particle diameter and concentration of the particle formed relate to cut quality parameters. This enables a process control methodology to be created with feedback from the quality of the product rather than process parameters. Implications on health and safety are also presented.

Chapter 9 details the design of the particle sizer. This instrument takes advantage of the dynamic range of CMOS chips. The main aim of designing and building the sizer was to enable real-time (25Hz or thereabouts) sizing. This was achievable by pre-processing information offline in Mathematica and then using the information at run-time in LabVIEW.

Chapter 10 summarises the key contributions of this thesis.

Chapter 11 discusses work planned for the future.
2 Literature Survey

The development of industrial high power laser systems has enabled the application of advanced manufacturing techniques. Processes that were previously mechanical in nature (milling, drilling, flame cutting) have, where feasible, been replaced by laser based processes which are thermal in nature. By-products such as swarf and heavy dust from the mechanical processes were considered to have been eliminated when the process was transferred to laser-based systems. The laser allowed a 'clean' process.

This is not the case. The laser material removal process produces particulate and/or gases that can at best be irritants and at worst, highly carcinogenic. The particulate can range in size from millimetres across down to nanometres. The smaller the particulate, the higher the likelihood that they are airborne and hence inhalable (nasal passages and upper respiratory tract). As they get smaller, they become respirable (lungs). The plots in Figure 2.1 provide an indication of the depository characteristics of aerosols in the human lung \(^1\). Depending on the morphology of the particle and chemical content, it could pose a very serious health hazard.
This chapter discusses the work carried out by other authors with regard to laser cutting, concrete scabbling and the particles produced during laser processing (in general). System design for particle capture and analysis is investigated. Additionally, the methods of control that have been historically applied to laser systems are discussed.

2.1 Laser material processing

The powers attainable by lasers today, combined with low divergences make them ideal for material processing. The monochromatic nature and coherence of the beam allows it to be focussed to a very small spot size (whose size is dependant on the
laser mode) limited by diffraction at the lens. Material processing is entirely non-contact, minimising the need for expensive jigging. Like many mechanical processes in industry, CNC tables are used for workpiece translation. Processing by laser is thus also very accurate and repeatable.

2.1.1 Beam requirements for distributed and localized heating

Depending on the process, the laser beam is either used as a raw beam or focussed to a spot. In the case of surface material removal (concrete scabbling), the raw beam processes large areas of the workpiece. For laser cutting, where material removal is to be minimised, small spot sizes lead to narrow cut widths. Although laser cutting is a thermal process, it is localised and affects only a very small area around the cut.

2.1.2 Beam mode and focussability

The intensity distribution of a laser is essentially Gaussian (TEM$_{00}$). However, when oscillations arise within the cavity, higher order transverse electromagnetic modes (TEM) are setup. The equation of these transverse electromagnetic modes is as follows:

$$E(r, \phi) = E_0 \left( \frac{r \sqrt{2}}{w} \right)^n L_n^p \left( \frac{2r^2}{w^2} \right) e^{-\left( \frac{r^2}{w^2} \right)} \cos(n\phi)$$  \[equ 2.1\]

where: $E(r, \phi)$ is the amplitude at point $(r, \phi)$

$L_n^p(x)$ is a Laguerre polynomial
\( r, \phi \) are the radial and angular coordinates respectively

\( w \) is the beam radius

\( n, p \) are integers (mode numbers for \( r \) and \( \phi \))

In the case of laser cutting, the beam is focussed onto the surface of the material. Depending on the raw beam diameter, the focal length of the lens and the wavelength of the laser, a spot diameter is calculated as follows (assuming TEM\(_{00}\)):

\[
d_{\text{min}} = \frac{2.44f \lambda}{D}
\]  \hspace{1cm} \text{[equ 2.2]}

where \( f \) is the focal length (63.5mm) of the lens, \( \lambda \) is the wavelength (10.6\( \mu \)m) of the laser and \( D \) is the raw beam diameter (15mm).

Figure 2.2: Surface showing change in focussed spot diameter with changes in focal length of the lens and raw beam diameter (varies with power) for CO\(_2\) laser at \( \lambda = 10.6 \mu m \) and TEM\(_{00}\).
2.1.3 Depth of focus

The depth of focus (distance over which the focussed beam has similar intensity) is an important issue when modelling. If the material thickness is greater than the depth of focus, the beam will be defocussed in parts of the beam-material interaction zone. The depth of focus is calculated as follows (assuming TEM\(_{00}\)):

\[
 z_r = 2.56F^2\lambda 
\]  
[eqn 2.3]

where \(F = f/D\) is the F number of the lens (dimensionless).

![Figure 2.3: Surface showing depth of focus changing with focal length of the lens and raw beam diameter for CO\(_2\) laser at \(\lambda = 10.6\mu\text{m}\)](image)

Both the spot size and the depth of focus calculations are valid only for TEM\(_{00}\) modes. The average power density (in Wm\(^{-2}\)) on the surface of the material is then calculated:
\[
\text{powerdensity} = \frac{4P}{\pi d_{\text{min}}^2} \text{Wm}^{-2} \quad \text{[equ 2.4]}
\]

where \(P\) is the power (W) and \(d_{\text{min}}\) is the spot diameter (m).

2.2 Workpiece materials

Although both non-metals and metals can be easily processed by lasers, the mechanisms by which a particular process takes place tends to differ between the two. This is due to differing material properties.

2.2.1 Laser beam absorption

The absorption of laser radiation by the material is dependant on a number of factors:

a. material (electric conductivity)

b. wavelength

c. surface roughness
d. polarization
e. angle of incidence

f. temperature of material surface

The absorption coefficient \(\alpha\) (cm\(^{-1}\)) of the material at the laser wavelength is given by:

\[
\alpha = \frac{4\pi k}{\lambda} \text{m}^{-1} \quad \text{[equ 2.5]}
\]
where $k$ is the complex part of the material refractive index (dimensionless).

$\alpha$ varies with temperature, surface roughness.

**Non-metals**

Insulators have few free electrons (and are hence not electrically conductive). The incident electric field is free to penetrate into the material. Hence, non-metals are usually non-reflective. At low wavelengths, the photon energy is high enough to cause atomic oscillations, and hence increased absorption. This high absorption drops off sharply just before the visible range of wavelengths. As the wavelength of the incident light increases to the mid-infrared range ($5\mu m$), the absorption increases again to high levels.

**Metals**

Metals on the other hand have free electrons. These electrons vibrate and reradiate on interaction with an incident electric field. This leads to reflection of the incident beam at the same angle of incidence but with a $\pi$ phase shift. The absorption by metals to an incident electric field is high at low wavelengths ($<500nm$) and subsequently drops off sharply at higher wavelengths (Figure 2.4).
Figure 2.4: The variation of reflectivity with wavelength for copper, aluminium and carbon steel

2.3 Material removal

Depending on the material and the laser process, the mechanism of material removal varies. Laser cutting of plastics (low density) involves removal of material in the cut zone by vaporization. Cutting metals (high density), however, involves melting the material in the cut zone and ejecting it using a high pressure gas. Concrete scabbling causes stresses in the matrix causing ejection of material; no phase change occurs.
2.3.1 Removal by phase change - Cutting of mild steel

**Beam polarisation and angle of incidence**

The percentage of the laser power absorbed by the material also depends on the angle of incidence of the beam to the cut front and the polarization of the beam with respect to the direction of cutting (x direction) \(^5\). Maximum absorption (≈80\%) occurs when the incidence angle is 80° and a polarization perpendicular (p polarisation) to the cut front. This is the Brewster's angle (Figure 2.5) at which the perpendicular polarization state travels along the material surface while the parallel wave is reflected. Most laser systems, however, are built with a circular polarizer in the optical train, which although reducing the absorption of the beam (as compared to perpendicular to the cut front), maintains a constant absorption in all cut directions.
Figure 2.5: The variation in absorptivity of steel with angle of incidence of the CO₂ laser beam on the cut front, for s (∥), p (⊥) polarised and unpolarised states.

Oxidation cutting
In the case of laser cutting steels with oxygen as the assist gas, an exothermic reaction takes place in the cut zone between the gas and the melt. It has been calculated ⁶, ⁷ that the exothermic oxidation process provides up to 40% of the energy required for melting, the laser beam providing the other 60%. The equations for the given reactions are as follows:

\[ \text{Fe} + \frac{1}{2} \text{O}_2 \rightarrow \text{FeO} \ldots \Delta H = -257.58\text{kJ} / \text{mol} @ 2000K \]

\[ 2\text{Fe} + \frac{3}{2} \text{O}_2 \rightarrow \text{Fe}_2\text{O}_3 \ldots \Delta H = -826.72\text{kJ} / \text{mol} @ 2000K \]
Surface tension effects

The surface tension of a liquid is dependent on its composition and temperature. In the case of laser cutting of steel with oxygen as the assist gas, the oxidation of the melt film causes an increase in temperature (exothermic reaction) which also changes its surface tension. Although other components (Ni, Cr, C, etc.) may be present in the mild steel prior to melting, their concentration would not change very much. The surface tension of the molten parent metal and the oxidised melt vary independently with temperature. The graphs in Keene’s paper\(^8\) show these trends.

Most materials have a surface tension that decreases with temperature \( \frac{d\gamma}{dT} \) is –ve) but in the case where impurities are introduced, as for Fe-O or Fe-S systems, \( \gamma \) could increase with temperature. The trends in Keene’s paper are linear and have equations:

\[
\gamma_{Fe} = 2408 - 0.35T; \quad \text{[equ 2.6]}
\]

\[
\gamma_{Fe-O} = \gamma_{Fe} - 7490(at\%[O]); \quad \text{[equ 2.7]}
\]

\[
\gamma_{Fe} \text{ at } 1700K = 1862 \text{ mN}^{-1}; \quad \text{[equ 2.8]}
\]

where \( \gamma_{Fe} \) and \( \gamma_{Fe-O} \) are the surface tensions of the parent metal and the oxidised metal respectively, at\%[O] is the % composition by atomic number of oxygen. The equations are displayed graphically in Figure 2.6.
Figure 2.6: Surface showing the effect of oxygen content and temperature on the surface tension of mild steel.

**Striation formation**

Striation formation is a dynamic phenomenon of the cutting process (Figure 2.7). It is important from the aspect of product quality as the cut edge roughness is directly related to striation parameters (wavelength, frequency and amplitude).
Figure 2.7: Typical cut edge showing striations. The material is 2mm thick mild steel sheet, cut with a CO\textsubscript{2} laser using oxygen as an assist gas.

Arata \textit{et al.}\textsuperscript{9} proposed that the striations are produced due to an ignition and extinguishing process whereby the oxidation front moves faster than the cutting front (i.e. the oxidation front velocity is more than the cutting velocity). It was found that the oxidation front velocity is approximately 2m/min. At cut velocities lower than this, burning tends to occur. This is where the oxidation front expands radially to some distance prior to extinguishing. At cut velocities larger than 2m/min, the beam is the predominant energy source (although the oxidation reaction still occurs). Ivarson \textit{et al.}\textsuperscript{10} extended this theory to investigate striation formation from the aspect of oxidation dynamics.

Schuocker\textsuperscript{11} maintains that the striations are formed due to oscillations in the beam absorption, power and gas flow rate. These factors cause the temperature of the cut zone to oscillate thereby creating fluctuations in the molten liquid layer.
An alternate theory was formulated by Kai Chen et al.\textsuperscript{12} They explain the formation of striations by the periodical removal of the oxide layer. As the oxide layer grows in thickness, the oxidation reaction gets severely hindered. This reduces the temperature. As the oxide layer reaches a certain thickness, it is removed by the gas jet, and starts to grow again.

2.3.2 Stress induced material removal - Laser scabbling of concrete

Scabbling is the removal of surface material. Heat sources such as a high power laser beam can be used for scabbling and is a non-contact method of material removal. Scanning a high power laser beam across the surface of a concrete block produces thermal stresses in the concrete causing material to be ejected from the surface. The ejected particulate has a wide size distribution, ranging from airborne and inhalable particles to large millimetre sized aggregate.

Composition of Concrete

The basic structure of concrete comprises of a binding material within which are embedded particles or fragments of aggregate. Common aggregates are sand, gravel, crushed stone and iron blast furnace slag. Coarse aggregates like gravel have sizes larger than 4.75\(\mu\)m (No. 4 sieve) while fine aggregates like sand lie between 0.75\(\mu\)m (No. 200 sieve) and 4.75\(\mu\)m (No. 4 sieve) in size. Pozzolans (e.g. fly ash) are admixtures than contain reactive silica and are used to
reduce thermal cracking. Components were identified by SEM analysis in reference to 13.

**Laser scabbling**

Johnston *et al* 14 evaluated the scabbling efficiencies of the Nd:YAG and CO₂ laser. Results showed that both wavelengths provided similar scabbling efficiencies and that increasing beam diameters required lower power densities in order to maintain removal rates.

Savina *et al* 15 investigated the ablation (scabbling) of concrete in order to ascertain the nature of the by-products. A fibre delivered Nd:YAG laser was used to scabble samples of concrete that had been doped with non-radioactive isotopes of caesium and strontium. The ablation by-products were then analysed for these isotopes, in order to track the efficiency of removal and capture of these isotopes. The by-products were not analysed for particle size distribution or concrete components that have de-aggregated.

### 2.4 Nature of removed material

Depending on the material being processed (steel, plastics, wood, etc), the phase composition (gas, solid, liquid) of the fume differs. Mild steel produces particulate comprising non-oxidised metal as well as particles containing metal oxide. Plastics produce not only particulate but also gases due to thermal degradation of the material. Scabbling concrete causes the components of the base material to be released.
The mechanism of material removal during mild steel cutting is one of melting, oxidation and ejection. Minimal vaporisation takes place, as the temperature at the cut-zone is not high enough to vaporise the steel. The temperature is approximately $2000\text{K}$\textsuperscript{7}. The molten metal at the cut-zone is ejected by high pressure gas. The particulate formed attain a spherical shape due to the disruption of the molten zone by the gas flow.

The emissions from the cut-zone can be classified into three main categories:

Respirable particulate – metal/metal oxide sub $10\mu\text{m}$.

Non-respirable particulate – metal/metal oxide $>10\mu\text{m}$.

Gases – in the case of mild steel, none.

The respirable particulate and gases are of major importance in toxicity studies. The non-respirable material although not hazardous in nature, must be collected and extracted efficiently\textsuperscript{16}. 


Sampling techniques

Filtration techniques can be categorised into:

<table>
<thead>
<tr>
<th>Technique</th>
<th>Type</th>
<th>Advantages</th>
<th>Examples</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical separation</td>
<td>Sieves</td>
<td>Fabric filters, Glass fibre filters</td>
<td></td>
<td>16, 18</td>
</tr>
<tr>
<td>Impactors</td>
<td></td>
<td>combines sampling with size fractionation</td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>Cyclones</td>
<td></td>
<td>Centrifugal separation, not very efficient for the capture of respirable particulate (&lt;10μm)</td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>Diffusion devices</td>
<td>Brownian</td>
<td>motion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrostatic separation</td>
<td></td>
<td>Can capture down to 0.01μm</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Magnetic separation</td>
<td></td>
<td>Only for magnetic particles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wet separation</td>
<td></td>
<td>Condensation technique. Can cause agglomeration or chemical reaction</td>
<td>steam, atomiser</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1: Commonly used filtration techniques.
All of these devices are remote capture units. The fume must, however, be collected and transported to these devices. This is where the apparatus has been tailored to specific laser processes and installations. The capturing of fume at the laser head can be split into essentially two different types based on the position of the extraction device with respect to the material being processed. Again this is process-dependant; cutting tends to produce most of the fume below the workpiece, whereas in ablation or concrete scabbling, all of the fume is ejected from the surface of the material.

Capturing fume produced above the workpiece has been achieved in a variety of ways from using simple probes to devices boasting 100% collection efficiency. Arrowsmith and Hughes\(^{20}\), used an annular gas-sheath entrainment cell around the laser nozzle, which proved to be very efficient.

Sampling methods using probes in the exhaust ducting have been widely used\(^{21, 22}\). Iso-kinetic probes are used for sampling dense fume or gases especially when real-time analysis is to be carried out on the fume. These are probes introduced into the duct through which the particle laden flow is carried. The principle is that by maintaining the same velocity at the entrance to the probe nozzle as the velocity in the duct, representative sampling will be possible. If, however, the concentration of fume produced is too low, the sample volume may not be sufficient for most analytical instruments.

An alternative to the iso-kinetic probe is the totally enclosed workpiece. This type of entrainment system completely encloses the
material being processed, except for a cutout for the laser nozzle. The fume is extracted using either a vacuum or is blown through by an external gas or the assist gas and is usually captured on filters. 

A variant of this system is the one used by Ivarson and Powell where a tank filled with a glycol-water mixture is placed below the material to be cut.

2.4.1 Measurement methods

**Meaning of particle size**

The only geometrically consistent object is a sphere which can be described using a single measurement – its diameter. A length specified for a cube could be either the length of one of its sides or its diagonal. Derived diameters are used where the size of the particle affects some property of the particle, eg. aerodynamic diameter and particle settling. Different particle characterisation techniques measure different attributes of size –

Sieving measures the second smallest dimension of the particle. Sedimentation measures the Stokes diameter (ratio of inertia of the particle to its drag as the particle falls through a liquid). Microscopy and image analysis measure diameter based on the particle's projected area or individual dimensions. Laser diffraction measures the particle diameter, which is equivalent to that of a sphere of the same volume. Table 2.2 displays the various mean diameter representations and the sizing techniques that are based on them.
<table>
<thead>
<tr>
<th>Mean</th>
<th>Description</th>
<th>Equation</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>D[1,0]</td>
<td>Number-length mean</td>
<td>$\frac{\sum d}{n}$</td>
<td>Electron Microscopy</td>
</tr>
<tr>
<td>D[2,0]</td>
<td>Surface area number mean</td>
<td>$\sqrt{\frac{\sum d^2}{n}}$</td>
<td>Image analysis</td>
</tr>
<tr>
<td>D[3,0]</td>
<td>Volume-number mean</td>
<td>$\sqrt[3]{\frac{\sum d^3}{n}}$</td>
<td>Electrozone sensing</td>
</tr>
<tr>
<td>D[4,3]</td>
<td>Equivalent volume mean</td>
<td>$\frac{\sum d^4}{\sum d^3}$</td>
<td>Laser diffraction</td>
</tr>
</tbody>
</table>

Table 2.2: Mean diameter representation
### Industrial sizing techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Resolution</th>
<th>Accuracy</th>
<th>Reproducibility</th>
<th>Range</th>
<th>Speed</th>
<th>Destructive</th>
<th>Representative sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser diffraction</td>
<td>High</td>
<td>high</td>
<td>High (&lt;2%)</td>
<td>50000:1</td>
<td>Fast</td>
<td>Non-destructive and non-intrusive</td>
<td>Yes</td>
</tr>
<tr>
<td>Optical Microscopy</td>
<td>High</td>
<td>high</td>
<td>High</td>
<td>3µm -1mm</td>
<td>Slow</td>
<td>Non-destructive</td>
<td>No</td>
</tr>
<tr>
<td>Electron Microscopy</td>
<td>v. high</td>
<td>high</td>
<td>High</td>
<td>20nm-1mm</td>
<td>Slow</td>
<td>Non-destructive</td>
<td>No</td>
</tr>
<tr>
<td>PCS</td>
<td>Low</td>
<td></td>
<td></td>
<td>nm to a few microns</td>
<td>Slow</td>
<td>Non-destructive</td>
<td>Yes</td>
</tr>
<tr>
<td>Electrozone sensing</td>
<td>v. high</td>
<td></td>
<td>Highly accurate between 0.4-1200µm</td>
<td>Low (30:1)</td>
<td>Fast</td>
<td>Requires electrolyte as a dispersant</td>
<td></td>
</tr>
<tr>
<td>Sedimentation</td>
<td></td>
<td></td>
<td></td>
<td>Lower limit of 2µm</td>
<td></td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Centrifugation</td>
<td></td>
<td></td>
<td></td>
<td>down to 0.05µm</td>
<td></td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Sieving</td>
<td>Low</td>
<td></td>
<td></td>
<td>Lower limit of mesh openings, is 1µm.</td>
<td></td>
<td></td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 2.3: Industrial sizing techniques - their advantages and limitations.
Laser diffraction
The particle sizer works on the principle that small particles scatter light with larger solid angles than larger particles. A huge advantage that laser diffraction holds over other techniques is that it is a non-contact method. Additionally, due to its Fourier configuration (the detector is in the back focal plane of the imaging lens), the velocity of the particles traveling through the sample cell does not shift the resultant light intensity at the focal plane.

The more accurate Mie theory (as opposed to Fraunhofer) is implemented in the software. This theory accounts for particles being able to not only scatter light as completely opaque spheres but also as transparent ones. A completely opaque particle diffracts light incident on its surface in a way that is characteristic of only its shape. The particle also absorbs (depending on the material absorption coefficient) a certain amount of this light. A transparent or semi-transparent particle allows some of the incident light to pass through it. Refraction thus takes place. This incomplete attenuation of the incident light also takes place when the particle size drops below 4μm (for λ=633μm laser).

The Mie theory requires that the operator input the optical properties (relative refractive index, absorption coefficient) of the material to be analysed.
Origin of laser diffraction instruments
The instruments used today originate from those devised by Swithenbank and Cornillaut \(^{28, 29}\). Cornillaut used a spinning disc (with photodetectors arranged on its surface in a spiral) as a detector. Swithenbank used a conventional camera and photographed the diffraction pattern. Both system designs were based on a laser (HeNe) as the light source and a Fourier lens with the detector in its focal plane.

Improvements in laser diffraction particle sizing
Although improvements have been made in the areas of multiple scattering, statistical optics \(^{30}\) and deconvolution methods \(^{31}\), a major area of research is that of particle shape. To a certain extent, standard laser diffraction instruments can be extended to provide some measure of shape.

Witt & Rothele \(^{32}\) investigated the development of laser diffraction. The limits of the measurable size range are dependant on the wavelength of the laser, the transmission limits of the medium and the measurement of angular scattering. Extending the lower end of the size range is possible by reducing the wavelength of the laser. The limit of this extension is 0.05\(\mu\)m by the use of a CW HeCd laser at 325nm. The Ar-F (193nm) could be used, but is only available in a pulsed form. Any wavelength lower than 180nm is limited by the transmission in air and requires a vacuum for transmission. Alternatively, measuring scattering angles at large angles (including backscattered radiation) or using two lasers of different wavelengths.
(Malvern Mastersizer2000) \(^{33}\) enables the measurement of sub 0.05\(\mu\)m particles. At the large end, infrared and semiconductor lasers can extend the range beyond 10mm due to their longer wavelengths.

The authors also investigated adaptable beam expansion in order to minimise vignetting (clipping of the lens) due to small particles (small diameter beam). For large particles it is essential that the \(1/e^2\) diameter of the beam is much larger than the largest particle as much of the scattered intensity is at small angles. Hence a large diameter beam is necessary for large particle measurement.

Zhenhua \textit{et al} \(^{34}\) describe the deficiencies in the technology and the research being carried out to satisfy these needs. The authors have presented a statistical approach which corrects for insensitivity due to a few large particles in the measurement sample. The application of high dynamic range CMOS detectors was also described. The Fuga15d sensor manufactured by C-CAM Technologies of Belgium was implemented with success. These sensors have a 140dB dynamic range (as opposed to 40dB for CCDs). This is a major advantage for this application as accurate measurements can be made over the entire angular range (low angles – high intensities). These sensors can be purchased either as linescan systems (upto 1024 pixels) or area scan (511x511 pixels). The area scan systems could be used to investigate particle shape.
Particle shape
The detectors used in most laser diffraction particle sizers are based on measurement of the angular scattering of laser light and are insensitive to variations in azimuthal scattering. This forces the system to assume that the particles presented to it are spherical. One reason for this configuration is that scattering theory for spheres is much simpler than the mathematics involved in calculating scattering patterns for non-spherical particulate. Maintaining the spherical assumption (and retaining the simple theory) and introducing a new detector configuration, which measures azimuthal scattering, allows some shape measurement to be made.

Zhenhua and Heffels \(^{34, 35}\) investigated the use a wedge detector (64 wedges) to analyse particle shape from azimuthal scattering fluctuations. In both cases, a matrix was created which correlated the signal on a particular wedge with the signal on each of the other wedges. The detector used by Heffels et al.\(^{36}\) to measure both shape and size of the particles has a construction based on a disc on whose surface is a pixel array arranged radially.

In-line/on-line particle sizing for control
Laser diffraction instruments are ideal for control systems, providing real-time feedback of particle size distribution. In the case of air as a dispersant, no sample preparation is required and since the technique is non-contact, in situ sizing is possible with minimal intrusion into the particle transport system. In-line particle sizing is the technique where the measurement takes place without the need
for sampling. On-line sizing, however, requires that a sample be taken albeit automatically. Both types measure the size distribution quicker than the time of changes in the process. The EPCS (Ensemble Particle Concentration and Size) sizer by Insitec (now part of Malvern Instruments) is a in-line sizer. It measures distributions at the rate of one every two seconds and at concentrations as low as 1% by volume of particulate over a range of 0.5-1500μm. For high concentrations it is possible to sample the flow (on-line configuration with iso-kinetic probe) and dilute. Accuracy of the results has been shown to be better than 3%. Another such in-line instrument is the Lasentec focal beam reflectance measurement (FBRM) system. A laser beam is focussed using rotating optics on the particles as they flow by. The backscattered pulses from individual particles are used to determine the particle's chord length.

Another in-line system is that proposed by Scott and Boxman. The system is based on the frequency-dependant attenuation or velocity of ultrasound waves as they pass through the sample. Early systems measured the mean diameter and concentration of the particles using two pairs of fixed frequency transducers whereas this instrument measures the attenuation spectrum over 1-100MHz. The size distribution is obtained either from empirical data or theoretical calculations.
2.5 Control

Laser cutting systems usually have built-in closed loop control based around the operating parameters eg. power, velocity, standoff distance. As a processing system this controller is essentially open loop as cut quality is not monitored. In the case of laser cutting, surface roughness of the cut, striation frequency, heat affected zone, kerf width, and dross formation are the most commonly used quality measurement parameters. A quality parameter has to be monitored in-process and used as feedback into a control system.

![Block diagram of typical closed loop process control for an industrial laser cutting system showing locked variables and overall quality control.](image)

Older laser systems have manual control. Achieving a product of acceptable quality depends on the experience of the operator. Additionally, any changes to the process parameters are carried out off-line by examining a product sample. A lot of work has been done on defining the parameters of a laser process but there aren't many cases where these parameters have been related to each
other. Even in the cases where equations have been developed relating processing parameters, they are usually installation and material specific and cannot be carried over to another system.

2.5.1 Variable locking

This is essentially open-loop process control whereby the parameters of the process (power, velocity, etc.) are closed loop controlled to prevent drift and to achieve given setpoints.

**Power**

Different levels of closed-loop power control are possible. Simple systems have the power variable controlled at the section of circuitry that adjusts the laser power. Other systems measure the power at the beam/shutter dumps when the shutters are closed and feed that signal back into the circuitry to control the power off-line. This prevents drift but does not account for losses occurring in the optical system nor is it online. Li et al used a laser beam analyser (LBA) to control the power and monitor mode structure of the beam\(^2\). A laser power controller was developed which enables power to be stabilised within +/-0.2 percent. This reduces start-up time to < 1 minute and allows for online power profiling. Although this is a closed loop control system which maintains power setting, as an overall process, it is open loop. This is because the quality of the end product is not taken into account when the power parameter is changed.
Real-time monitoring systems are available which monitor the power at the workpiece by the reflected power off the material surface. A typical example is the diffractive turning mirror. Some systems use a turning mirror with a small hole, measuring the laser power using a pyroelectric detector whereas others use a zinc-selenide beam splitter.

**Velocity**
This parameter is usually entirely controlled by the CNC machine. No feedback from the cutting process is included. CNC controllers do, usually have ramp up/down settings for corners, ensuring cut accuracy. This, however, needs to be coupled with the laser power to prevent excessive burning of corners.

Many modern systems have been implemented where the laser power (and mode – CW/pulsed) is varied depending on the cutting velocity maintaining P/V ratios on curved paths. Moriyasu et al. used adaptive control to alter the laser’s power and output mode to compensate for the change in velocity at corners during laser cutting. Significant reductions in burning at corners was reported. Because of the velocity dropping to zero or near zero at corners, it was found beneficial to use pulsed operation rather than CW.

**Focus position\Spot size\Depth of focus\Nozzle stand-off**
These four parameters are inter-related in the case of conventional cutting systems. The depth of focus is entirely dependant on the wavelength of the laser, the raw beam diameter and the focal length.
of the lens. Of these, the wavelength of the laser and the focal length of the length are fixed; the raw beam diameter tends to increase with laser power, decreasing the depth of focus. Usually this is not controlled although in applications where the process window is very narrow it is essential. The fixed focal length lens is positioned relative to the nozzle prior to the cutting process (in most cases). Hence, adjusting the nozzle stand-off position affects the focus position and spot size. Ideally, the focus position should be controlled independent of the nozzle to minimize variations in gas pressure at the material surface due to raising or lowering the nozzle.

Several researchers have devised techniques to control focus position/nozzle standoff \(^{42, 46-50}\). Focus position control is important when the workpiece is not perfectly flat or if the sheet tends to distort due to excessive heat absorption. The distance of the nozzle tip from the workpiece provides the focal position datum. Various sensors are available on the market for measuring this distance - capacitive, mechanical skids, optical, inductive and complex imaging systems.

Capacitive sensors can only be used on conductive materials as the workpiece is one of the electrodes \(^{46}\). Additionally, they can be used on-line only on pulsed lasers, the sensor being read between pulses. This is because any sputter or plasma causes a lot of noise in the signal.

Mechanical skids are in contact with the material and thus any surface feature (e.g., previously cut area) that catches on the skid will
cause damage to the skid and possible mis-alignment of the laser head.

Optical techniques consist mostly of laser triangulation sensors. These sensors tend to work very well with most materials except the very transparent ones. A shield protecting the detector from sparks prevents damage. Imaging systems are much more advanced and require considerable processing power to determine the distance. They have the advantage, however, that other process parameters, such as heat affected zone, weld pool size and kerf width can be determined at the same time without additional sensors. A focus control system for YAG laser welding was designed by Haran et al based on an optical sensor included in the fibre system detecting visible and infrared light from a welding process \(^49, 51\). The high frequency components in the signals were removed using low pass filters with a cut-off frequency of 100 Hertz. The difference in the infrared and visible signals indicated the focused error.

**Assist gas/Assist gas pressure**

The assist gas used for cutting a particular material is usually fixed and is not changed during the cutting process. The gas pressure, however, needs to be controlled in order to maintain a specified cut quality (also dependant on other processing parameters). Most users specify gas pressure using a pressure gauge just before the cutting nozzle. This is an open-loop system. Better systems utilize mass flow controllers that control the volume of gas through the nozzle. Gas
pressure control systems where the backpressure at the nozzle is monitored provide an ideal solution.

**CW/Pulsed mode of operation\Pulse width\Repetition rate**
In most cases it is not necessary to switch between continuous mode operation and pulsed mode. Pulsed mode is preferred for precise power input into the material as it can be controlled by varying peak/average pulse powers, pulse shape (in some cases) and repetition rate (as well as duty cycle). This has been investigated by Moriyasu et al.\(^4\)\(^5\) where the mode of operation was switched between CW and pulsed mode at corners during two-dimensional laser profiling.

2.5.2 Control Techniques
The most common controller implemented, especially for focus positioning and power stabilizing is the Proportional Integral Derivative (PID) controller.\(^5\)\(^2\) This type of controller works by minimising the error between the setpoint (specified) and the process variable (measured) and is ideal for single-input single-output systems. Multivariable control tends to be more complicated. Databases and knowledge-based systems were applied with success.\(^4\)\(^1\), \(^5\)\(^3\), \(^5\)\(^4\)
Inputs
The first aspect of a successful control system design is one of input selection. Laser processing systems have numerous input parameters—

- Power, cutting speed, assist gas, assist gas pressure, focus position, spot size, depth of focus, nozzle stand-off, cw/pulsed mode of operation, pulse width and repetition rate

Incorporating all of the above in the control system is not easy especially if no factors relating the various parameters are available. By implementing a knowledge-based system created from an experimental database, multivariable control is possible and has been applied. This type of controller is installation specific. Many control systems have been applied successfully but they are usually single-input single-output systems, e.g. power controllers, and focus position control.

Feedback
Sensor design and application play a major part in a control process. Sensor modules from simple photodiodes to highly complex imaging systems have been implemented. The most common quality parameters for cutting are as follows:

- Surface roughness (striations)
- Kerf width
- Cut edge squareness
Heat affected zone

Extent of dross formation

Striation frequency

Shower of sparks\particulate

Emissions – acoustic and optical

![Diagram of cut quality measurement parameters and the appropriate methods of measurement.](image)

Figure 2.9: Cut quality measurement parameters and the appropriate methods of measurement.
Surface roughness (striations) \ Striation frequency

The edge of the laser cut contains striations, which are periodic structures that cause the cut edge to have an overall roughness. Being periodic, a striation frequency can be calculated from the striation wavelength and the cutting velocity.

\[
f = \frac{\lambda}{v}
\]  \hspace{1cm} \text{[equ 2.9]}

Striations have usually been monitored optically using photodetectors \cite{57}. Olsen \textit{et al} \cite{44} measured the striation frequency by calculating the fast Fourier transforms of the optical signature from a photodiode. As the surface roughness increases the intensity of the emitted light decreases. As dross formation increases the angle of striation is increased thereby increasing the light intensity.

Striation angle

As the cutting velocity is increased for a particular laser power, the cutting front angle increases, to a point where a through cut is not produced. The simplest method of monitoring the angle is by monitoring the shower of sparks produced below the workpiece. A camera mounted at a convenient location below the workpiece feeds an image processor to output a signal proportional to the striation angle.

Kerf width

The kerf width is the width of the cut and is measured using a camera and image processor. Filtering out the radiation emitted from
the cut is a necessity unless the measurement is conducted downstream from the cut (poses a directionality issue).

Cut edge squareness
Essentially, two cameras are required – measuring the top and bottom kerf to deduce the cut squareness.

Heat affected zone
This parameter requires similar equipment and processing power as the measurement of the kerf width.

Extent of dross formation
Yilbas used two fast response photodetectors in a differential configuration, with an illuminating helium neon laser incident on one of them, to monitor the dross formation. The differential setup removes the signal due to the thermal radiation from the cut and allows measurement of the transient absorption of the HeNe due to obstructing dross.

Shower of sparks/particulate
The shower of sparks have been measured using a photodetector. Signal fluctuations are at a minimum during stable cutting but increase as the cut worsens (fluctuating particle sizes).

2.6 Conclusions
The overview of other researchers work in the field of laser material processing and particle sizing has been discussed. This provided a
base from which the work published in this thesis has been carried out. Although the laser has been characterized thoroughly, the knowledge of its effects on various processes is still being enhanced. Additionally, the formation of by-products of laser material processes is still an aspect that is not thoroughly understood.

2.7 References


7. A. Ivarson, J. Powell, and C. Magnusson, *Laser cutting of steels: A physical and chemical analysis of the particles ejected*


14. E. P. Johnston, G. Shannon, W. M. Steen, D. R. Jones, and J. T. Spencer, Evaluation of high-powered lasers for a commercial laser concrete scabbling (large-scale ablation) system,


17. A. Jonasson and A. Nederman, Methods for separating welding fumes and examples of applied techniques.


22. C. Picini, G. Galuppi, and C. Lombardi, Main design parameters of the Italian experimental facility for fume sampling and


33. [www.malvern.co.uk](http://www.malvern.co.uk), *Malvern Instruments website* (Malvern Instruments), retrieved [www.malvern.co.uk](http://www.malvern.co.uk).


3 Experimental Methodology

This chapter describes the laser cutting and scabbling systems. The configurations of the lasers are significantly different. This is due to the localised and distributed beam delivery required for cutting and scabbling respectively. The particle capture and sizing systems for each process are described and their sources of error explained. Finally the monitoring and control system methodology is described.

3.1 Cutting System

3.1.1 Laser

A Coherent CO₂ (10.6μm) laser, rated at 500W, was used for laser cutting. Cutting was carried out in CW mode with a raw beam diameter (100% not 1/e²) of 15mm. The beam was Gaussian in distribution. The optical train consisted of (Figure 3.1):

a. Circular polariser - converts the plane-polarised beam to circular polarisation. This is necessary for maintaining equal absorption of the beam by the steel sheet in all processing directions.

b. Turning mirror - bends the beam through 90°. The water-cooled mirror used was a diamond turned diffraction grating sampling the forward and reflected (off the material) beams onto two pyroelectric detectors.
c. Diffractive power monitor – The pyroelectric detectors allow real-time monitoring of the incident and reflected laser powers.

d. Focussing lens – the 63.5mm focal length zinc selenide lens focussed the raw beam onto the workpiece.

e. Nozzle – a brass converging nozzle, coaxial with the beam, with a 1mm exit aperture was used to direct the pressurised assist gas at the cut zone.

Figure 3.1: 3D model showing a standard CO₂ laser optical train used for cutting. The forward and backscattered detectors are also visible at the bending mirror. Key - a. circular polarizer, b. turning mirror, c. diffractive power monitor, d. focusing lens, e. nozzle

3.1.2 CNC setup

A Fanuc OM series controller, interfaced to a PC running Licom’s AlphaLaser ¹, was used to control the 2-axis processing table.
Shutter control was synchronised with the assist gas solenoid valves and was controlled by the CNC cutting program.

3.1.3 Development of the particle capture system

Most of the fume produced during the laser cutting of materials is ejected below the cut-zone (below the workpiece) due to the effects of the assist gas jet. The characterisation experiments were carried out offline but methods for online capture and analysis were investigated (Figure 3.2).

Choice of particle capture medium

The medium used for particle capture must not, in any way influence the size distribution or morphology of the particulate. Microorganisms and dust can cause irregular results. Air is the medium of choice as it contains a low percentage of solid impurities.

Online capture and analysis of mild steel particulate

Requirements of real-time particle capture:

1. Minimum lag

A factor that is very important for real-time control is the delay between particle production by the laser process and the analysis by the particle sizer should be as small as possible for a control system to be viable. Two options are available -

- Reduce the physical distance between the point of capture and analysis.
Increase the flow rate of the transport medium.

The instrument was moved to a position and orientation where it would provide the minimum delay in analysis of the fume.

**Effect of particle capture system**

1. **Alteration of particle characteristics**

   For the purpose of particle sizing, it is very important that the particles that are collected are not affected by the transport system or medium. The medium should not change the particle characteristics either physically (de-agglomeration and breaking up of particles) or chemically (oxidation, de-agglomeration, dissolution).

2. **Effect of high flow rates**

   The main problem associated with high flow rates is one of particle break-up. Large, weak particles may disintegrate on collision with the transport system walls or with other particles. Changes in direction of the transport system cause dropout to occur.

3. **Sample dilution**

   Another problem associated with high flow rates is one of fume dilution. It was found that by using the vacuum system on full power, the concentration of the particles was too low for detection.
4. Effect of low flow rates

A high flow rate in the transport system is needed to minimise delay times. If the flow rate is too low, large particulate tend to drop out, particularly when there are bends or climbs in the transport system.

5. Representative sampling

Iso-kinetic tubes allow representative sampling from extraction ducts. They work by maintaining (by design) equal air flow rates inside the iso kinetic tube and the extraction duct, thereby sampling the flowing particulate in a size-independent fashion. They were not used due to the concentration not being high enough for ideal diffraction analysis.
Figure 3.2: Particle capture techniques considered during development for mild steel cutting.
Off-line capture and analysis of mild steel particulate

Collecting the fume for offline analysis enables verification of the results through repeat analysis on independent instruments and allows chemical analysis, particle shape, colour and surface texture analysis.

An Edwards 1.5 vacuum pump was used to capture the airborne fume on a 0.8μm membrane filter at a measured flowrate of 0.95m³hr⁻¹. Although the pore size of these membranes is 0.8μm, they can capture smaller particulate. This was the preferred method of capture. Fibre filters capture using depth filtration (Figure 3.3). The particles are entrained at some depth below the surface of the filter. This makes dispersing the particulate for offline analysis difficult. Membrane filters capture particulate on the surface, making dispersion easier.
Figure 3.3: Fibre (a) and membrane (b) filters. The fibre filter shows depth filtration.

Particulate that were not airborne settled to the bottom of the tank and were collected in sample bags for subsequent sieve analysis.
Choice of particle dispersant

Iso-propanol (Propan-2-ol) was used to disperse the particles in order to analyse them in the particle sizer. Ultrasonic action was applied for 30 seconds to aid dispersion of the particulate off the filter media. No agglomeration was seen before dispersion. Iso-propanol provides better wetting characteristics than distilled water, thereby reducing flocculation (clumping together of particles).

Glycerol-water mixture is not a very desirable dispersant when used for particle sizing by a laser-diffraction instrument. This is because a
two-phase (non-homogeneous) liquid is formed producing erroneous scatter. Air was not used as the dispersant because particle concentrations proved to be too low for accurate analysis.

Settling of the particle during size analysis was minimised by using sufficiently high stirring speeds on the sample presentation unit. Dispersants with high relative densities are desirable to minimise the effect of settling.

3.2 Concrete scabbling system

3.2.1 Laser

A 1.5kW CO$_2$ laser was used to provide a 850W, 20mm diameter, multimode raw laser beam, delivered to the concrete at an incident angle of $45^\circ$. The final beam turning mirror was protected from ejected particulate by a 5mm thick KCl window (Figure 3.5).
Figure 3.5: Schematic showing the concrete scabbling and particle entrapment set-up.

3.2.2 Extraction system

Extraction of the particulate was carried out just below the KCl window near the scabbling zone. The vacuum system (Nilfisk industrial vacuum cleaner) was sufficient to draw through all but the heaviest particulate, which were collected from the work area for subsequent sieve analysis.
3.2.3 Particle capture system

Laser scabbling of concrete causes the particulate to be ejected violently up to a meter above the surface of the concrete slab. A wide size distribution of particles is produced (ranging from subμm to millimeters). The entire capture and analysis system was characterized for representative sampling (Chapter 4).

Choice of particle capture medium

The material could either be captured and analysed in the dry powder form or dispersed in a liquid and then analysed. Capturing and analysing the particles in their dry form is preferred as real-time sizing can be carried out using the Malvern MastersizerX. Additionally, there is no unwanted interaction with wet dispersive media. However, efficient material removal of large particles requires a high flowrate to reduce drop out. This caused a sample concentration below the acceptable level required for laser diffraction sizing.

Capture system

The filtration system to collect the particles used a small chamber filled with a distilled water mist produced by an atomizer. The particulate-loaded airflow is drawn through this chamber. The particles attached themselves to the water droplets and then settled out on the walls of the chamber. A baffle is used to maximise the particle-water interaction time. After a run is complete the chamber is opened and the slurry collected for analysis.
Choice of particle dispersant

Distilled water was chosen as the dispersant since it was also utilised during particle capture.

Size Analysis

Large particles were analysed by sieving because they tend to drop out of the water suspension. Smaller particles, especially those that remained in suspension were sized using the laser diffraction particle sizer (see 3.4).

Concrete consists of a number of components. Each of these has a refractive index and absorption coefficient. Since the MastersizerX accepts only a single value for the complex refractive index (R.I. and absorption coefficient), it is not possible to cater for every component of the samples collected. The main component (by % volume/mass) of the concrete analysed using the MastersizerX was made representative of the entire sample. The most common constituents below 150µm were carbonates (limestone) which have a refractive index of 1.70 and absorption coefficient of 0.1 at 632nm.

3.3 SEM analysis

A LEO 440 scanning electron microscope was used to analyse particulate captured from different materials. Electron microscopy enables high magnifications to be used allowing imaging of objects down to nanometres in size. Additionally, the depth of focus is much larger than that allowed by optical microscopy creating three-
dimensional images. It is a useful tool in characterising particle shape, morphology, degree of agglomeration, size and variability of components. It was not used to produce particle size distributions as only a small sample can be analysed.

3.3.1 Sample preparation

Being conductive, the particulate generated during steel cutting require minimal preparation prior to analysis. Non-conductive materials and biological samples such as scabbled concrete, however, must be vacuum-coated with a few nanometres of gold prior to analysis to prevent electrostatic charging effects that cause flaring. The samples must be dry and grease-free to prevent contamination of the vacuum chamber. Particulate are randomly dispersed onto sticky carbon discs that are mounted on aluminium stubs.

3.4 The particle sizer

Sizing of the particulate captured during mild steel cutting and laser scabbling of concrete was achieved using a Malvern MastersizerX laser diffraction sizing instrument.

3.4.1 Construction

The particle sizer comprises an enclosed optical bench on which the laser and detector are mounted, and a PC which controls all operations and analyses the data. It can measure 0.1 to 2000μm
diameter particles over a series of ranges. Measurement in each range requires the lens to be swapped for the appropriate focal length. The 5mW HeNe laser beam passes through the sample cell and the range lens (Figure 3.6), after being expanded and collimated ($\phi=10\text{mm}$).

![Figure 3.6: Laser diffraction instrument construction](image)

The detector comprises 31 annular rings (Figure 9.1) arranged in a semi-circular configuration. The ring surface areas increase logarithmically from the centre outward (so that the largest rings are at the largest scattering angles). The centre of the detector has a 120$\mu$m hole behind which is a photodetector that measures the intensity of the incident beam and is used to calculate particle concentrations. The annular detector is mounted on a xyz stage, which is used to automatically align the detector so that the focused spot is within the 120$\mu$m hole and at focal position.

For each set of data the background reading, the actual sample data and the final result were printed. Since one ring in the detector was not functioning, simple interpolation between the data values was
carried out and the approximate light intensity reading for the ring fed in manually. This does not introduce significant errors because the summation of the diffraction curves for a range of particle sizes is a smooth curve (see Chapter 9).

Dispersed particulate was analysed using the smallest sizing range (0.1 – 80μm) available on the particle sizer.

3.4.2 Sources of error in sizing

Concentration

The concentration of the particulate in the medium must be monitored and be made to stay as constant as possible. The concentration is derived from the obscuration and must be between 10% and 30% (amount of light scattered or absorbed).

If the concentration is too high (>30%), multiple scattering takes place. Multiple scattering is the secondary scattering of light by neighbouring particles. This problem, however, is reduced by the software, which automatically corrects the sample data for multiple scattering, if the obscuration is over 50%. If the obscuration falls below 10%, the signal-to-noise ratio decreases thereby reducing accuracy. The noise includes the variation in the background over time and electronic noise.

In the case of laser-generated steel or concrete fume, it was found out that dispersing the particles in air produced obscuration levels that are too low (less than 5%). This could be due to high flow rates
diluting the fume or that not enough particles were getting to the sample cell (~1.5m away from the laser nozzle).

3.5 Process Monitoring/Control System for laser cutting

National Instruments LabVIEW is used for monitoring and controlling the various parameters of the laser cutting system. LabVIEW provides an intuitive graphical man-machine interface. Data flow execution as opposed to the sequential execution of text-based programming allows parallel execution of tasks to be performed. Multithreading in LabVIEW allows multiple tasks (control, monitoring, data logging) to be time prioritised, enabling control threads to run in real time whilst system monitoring is carried out at intervals. An ATMI016E-2 multifunction board (16 analog inputs, 2 analog outputs, 2 counters, and 8 digital input/outputs) and a PCDIO24 digital input/output board from National Instruments were used for data acquisition.
A focal position controller has been implemented (Figure 3.7) which monitors the height of the nozzle (and hence the focal position) with a laser-based triangulation sensor, and utilises a dc motor to adjust the height above the workpiece (discussed later in the chapter). The laser power is monitored using a Precision Optical Engineering diffractive system (Figure 3.1). The final bending mirror is a diffraction grating, the first order (0.001% of the intensity of the main beam) being incident on a pyrometer. The same mirror produces a first order in the reverse direction due to reflection of beam from workpiece and is incident on another pyrometer. The signal from this...
detector is useful in determining when the beam has broken through the material (eg. drilling or cutting). This is observed on the LabVIEW interface (Figure 3.8) as a sudden drop in backscattered power indicating no more reflection is taking place (Figure 3.10). It is also useful, to a certain extent, in providing an indication of process quality. An unstable back-scattered power indicates an unstable process. The assist gas flow is also controlled using a mass flow controller. Additionally, all laser supplies are monitored in the LabVIEW environment.

Figure 3.8: Laser cutting control system interface. The interface provides information on system state (gas pressures, water temperatures, etc.) as well as process parameters (power, assist gas pressure, etc.). Additionally, the nozzle stand-off control state is displayed.
Figure 3.9: The software environment is implemented in National Instruments LabVIEW. Coding is entirely graphical, and dataflow orientated.
3.6 Nozzle Stand-off control

The nozzle stand-off adjusts the distance between the tip of the nozzle and the workpiece. This affects the spot size on the material surface; and hence the power density. Processes affected include drilling (hole diameter) and cutting (kerf width); affecting the quality of the final product (dross formation, etc.).

The nozzle stand-off distance was altered using a dc motor with a laser based displacement sensor providing the feedback signal. Laser-based displacement sensors are based on the triangulation principle whereby a laser beam illuminates the target, which due to

![Figure 3.10: Typical process parameter trace showing peak in gas flow-rate and indication of material breakthrough.](attachment:3.10.png)
its surface scatters this light (Figure 3.11). This scattered light passes through imaging optics and is projected as a spot onto position sensitive detector (PSD). A PSD is basically a photo-detector with two current outputs. The ratio of the currents determines the distance of the target from the detector. This ratio depends on the position of the spot on the PSD.

Laser-based distance sensors typically have a resolution of the order of tens of microns. A trade-off has to be made between its resolution, range and stand-off (initial distance from target). This is because if large ranges were possible, the PSD would have to be proportionally large to allow similar resolution.

![Figure 3.11: Laser-based displacement sensor - principle of operation](image)

Spurious signals due to secondary radiation (sparks) during material cutting are created due to the optical nature of the measurement. The sensor has bandpass filters that allow the laser wavelength (red) through. A problem arises when flying debris (molten metal and
particulate matter) hits the sensor window. This could cause failure. A sacrificial glass window attached to the sensor in front of the window (Figure 3.12) protects the sensor. Due to the sensor position being offset to the main CO$_2$ laser beam axis, a lag/lead will be present depending on the direction of cutting. This was minimised by setting the displacement sensor at an angle to the beam axis.

![Displacement sensor setup showing angled mounting to reduce lead/lag.](image)

3.6.1 PID (Proportional Integral Derivative) control

The nozzle standoff distance was controlled using PID control. This is the simplest form of controller after on/off control. PID control tends to decrease the rise time, reduce the overshoot and eliminate the steady state error.

The proportional controller reduces the rise time and reduces, but never eliminates the steady-state error. The overshoot also increases. The integral controller, on the other hand, eliminates the steady-state error but tends to make the transient response worse.
The integral controller also increases overshoot and decreases rise time further. The derivative controller increased the stability of the system, reducing the overshoot and improving transient response. These controllers are entirely dependent on each other and changing any one will affect the other two.

A Proportional Integral Derivative controller has a general equation in the continuous time domain as shown below:

\[ u(t) = K_p e(t) + K_i \int_0^t e(t) \, dt + K_d \frac{de(t)}{dt} \]  \[ \text{[equ 3.1]} \]

or

\[ u(t) = G \left[ e(t) + R \int_0^t e(t) \, dt + D \frac{de(t)}{dt} \right] \]  \[ \text{[equ 3.2]} \]

where: \( K_p \), \( K_i \), and \( K_d \) are the proportional, integral and derivative gains respectively.

\( u(t) \) is the controller output.

\( G \) is the system gain.

\( R \) is the reset (repeats per minute)

\( D \) is the derivative (min.)

\( e(t) = \text{measured value of position} - \text{set-point} \)

The system used here, however, is not continuous in the time domain but is a sampled digital system. Hence the equation for the
PID controller has to be modified. The equivalent digital controller is shown below (Figure 3.13):

\[ u(k) = K_p e(k) + K_i \sum_{j=1}^{k} e(j)dt + K_d \frac{(e(k) - e(k-1))}{dt} \]  [equ 3.3]

![PID control schematic](image)

Figure 3.13: PID control schematic

The summation essentially keeps a running sum of the error which is measured every sample period \( dt \). The derivative part of the controller calculates the rate of change in the error.

3.7 Conclusions

The experimental setups for the laser cutting and concrete scabbling experiments have been detailed. The requirements for efficient and representative particle capture and analysis are discussed and the possible sources of error analysed. Finally, the basic aspects of the monitoring and control system have been explained.

3.8 References


4 System characterisation

The particle sizer has been characterised for particle concentration and drift in the background reading over time. Being denser than air, the particles settle during capture. The settling characteristics of the particles are discussed.

The laser-based displacement sensor has been tested with different materials in order to check its response to surface finish and reflectivity. The CO$_2$ laser used for cutting was calibrated for power using a Coherent power meter and beam analyser.

4.1 Characterisation of the Malvern MastersizerX

4.1.1 QAS2001 Standard

The particle sizer was characterised for accuracy and repeatability using NIST traceable particle standards (Malvern Quality Audit Standard QAS2001). Maximum permissible errors are reported which the equipment must not exceed in order to be ISO13320 compliant (particle sizing standard detailing recommended practices).

The QAS2001 standard documentation does not provide data as a size distribution; instead the cumulative figures are provided at the percentiles. Figure 4.1 and Figure 4.2 show the documented size distribution of the standard and that measured by the Malvern MastersizerX. The errors between the standard and measured distribution are within that stipulated by the literature provided with
the QAS2001 except for the error measured at the 99% percentile. The MastersizerX produces a size distribution based on the volume of the particles. Hence a single large particle would skew the volume size distribution toward the larger sizes. This could be caused by foreign particles entering the system during analysis or by agglomeration of the QAS2001 particles.

<table>
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<th>%</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>90</th>
<th>95</th>
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<td>62.44</td>
<td>79.06</td>
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<tr>
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<td>0.26</td>
<td>0.30</td>
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<td>0.54</td>
<td>0.70</td>
<td>0.80</td>
<td>0.48</td>
</tr>
</tbody>
</table>

Table 4.1: The reported size distribution of the QAS2001 standard at the percentiles.

Figure 4.1: The reported and measured size distributions of the QAS2001 particle standard at a 3 month interval. The plots are shown as cumulative distributions in order to aid visualisation of the error in measurement.
4.1.2 Investigation of the variation in background data with time

Prior to any sample being analysed by the Malvern MastersizerX, a background reading is required. This background reading indicates the spurious light scattered by scratches, smears or particles attached to the sample cell windows or lenses. The reading is subtracted from future sample data thereby eliminating background noise. These tests were carried out using air as the medium.

The background was observed over a 10 second time period (Figure 4.3). The results show that there is almost no change in the background. Over a longer period, however, the background tends to
increase Figure 4.4. This is due to particles being dislodged off the transport piping walls.

Figure 4.3: Results of the background stability test over a short period of time ($t_{\text{int}}=10\text{s}$)
4.1.3 Concentration effects on the particle size distribution

The effect of concentration on the particle size distribution was investigated using readily available opaque hollow glass spheres. These spheres range in size from 5 to 40μm with a median size of 6μm (Figure 4.5).
Figure 4.5: Glass beads used to test for concentration effects.

Three sets of data were collected:

Low concentration (<10% obscuration)

Ideal concentration (10-30% obscuration)

High concentration (>30% obscuration) \(^2\)

The overall shape of the distribution remained the same irrespective of the concentration. Possible multiple scattering effects are seen when the concentration is too high. A shoulder is seen on the distribution Figure 4.6.
4.2 Particle Settling

Settling causes unrepresentative sampling to occur as large particles settle out. This skews the particle size distributions toward the smaller sizes. However, by knowing the characteristics of the sampling system, this systematic error can be compensated for and reduced to a minimum.

SEM micrographs of the fume produced during mild steel cutting indicate that the particles are both hollow and spherical. The hollow sphere wall thickness is \(\approx 10\%\) or less of the physical diameter of the spheres, thus producing an effective density that is much lower than
expected for a solid sphere, thereby reducing settling velocity (see Chapter 8).

![3D surface of settling velocity (ms⁻¹) of mild steel particles for sizes up to 60μm and for wall thicknesses up to 100% of the radius.](image)

The settling velocity for a sphere in still air is given by the equation below and is illustrated in Figure 4.7:

\[
V_{\text{sett}} = \frac{\rho_p d^2 g}{18 \eta}
\]  

[equ 4.1]

for \(d>1\mu m\) and \(Reynolds\ number < 1\)

where \(\rho_p\) is the density of the particle (kgm⁻³),

\(d\) is the physical diameter (μm),

\(g\) is gravitational acceleration (ms⁻²),

\(\eta\) is the viscosity of the fluid (air) (Nsm⁻²).
Figure 4.8: Distribution of particles that will settle (in still air) to the bottom of the tank (0.3m) within 5 seconds of cutting. Turbulence due to the assist gas jet is not considered.

From Figure 4.8 it is apparent that within 5 seconds of cutting in a still air environment, the 40μm particles will have settled to the bottom of the tank. This is a worst-case scenario as the particle cut-off would realistically be higher because of the residual stirring effect of the assist gas jet even though it is turned off after cutting. The airflow around the mouth of the sampling probe would cause stirring, keeping the larger particulate in suspension. The airborne fraction contains significant information regarding the mechanism of material removal during cutting.
4.3 Laser Displacement Sensor

The laser displacement sensor was tested on various materials in order to check its accuracy when used with different surface finishes and reflectivities. Materials used included mild steel and stainless steel.

Sheets of test materials were placed below the laser nozzle (laser turned off) and the datum set by touching the nozzle to the surface. The displacement sensor signal was then zeroed. Increasing the nozzle standoff (in steps of 1mm using a manual micrometer adjustment having a resolution of ±0.01mm), the distance displayed on-screen was noted.

![Graph of error and displacement](image)

Figure 4.9: The error produced by the laser displacement sensor between the measured and actual displacement.
Rough surface finishes such as the mild steel plate produced good results (±0.02mm). The stainless steel plate (mirror finish) showed the best accuracy.

4.4 Laser Power Calibration

The graph (Figure 4.10) shows the power measured by the diffractive power meter and the Coherent Model 204 calorimeter-based power meter which is fitted as standard to the laser before the beam delivery system. The power was allowed to stabilise prior to the power meters being read and the values recorded. Readings were compared against a calibrated Coherent LabMaster laser power meter\(^5\).

![Figure 4.10: Power calibration of the Model 204 laser power meter and the diffractive power meter.](image-url)
The Model 204 power meter shows good accuracy. The diffractive meter, however, reads low (≈20% at higher powers). The calibrated LabMaster was used before every experimental run.

4.5 Conclusions

The results of the particle sizer characterization prove that the system is stable over time and yields repeatable and accurate results. The effect of particle settling during capture has been investigated. Although settling does occur, the capture system proves efficient up to 40 μm diameter mild steel particulate, assuming wall thickness of 10% of particle diameter. Finally, tests on the nozzle standoff control system and laser power prove system accuracy and stability.

4.6 References


5 CO₂ laser scabbling of concrete

Laser scabbling of concrete is a recently developed process by which a de-focussed beam scans across the surface of a concrete slab removing the surface layer by thermally induced stresses. This process takes place essentially in the solid phase, although some melting can occur. The particulate produced by this process is one of de-agglomeration or breakup. It is the constituents of the concrete that are released.

The material that has been removed from the main body of the slab is collected for further analysis in order to determine the quantity of airborne material and help specify filtration requirements. The sub-10μm region of the size distribution is of particular interest because commercially available filtration systems are not efficient at collecting these particles, especially the sub-μm range.

The concrete slabs that were scabbled consisted of a mixture of Portland cement, sand and aggregate. Slabs with cast and cut surfaces were scabbled. The effect of different aggregate sizes (mean sizes of 6mm and 10mm) for each of the above was also studied. The particulate and aggregate is analysed using a Malvern MastersizerX, which produces a particle size distribution. The heavier particulate and aggregate are separated out using a sieving technique. Furthermore, a scanning electron microscope is used to analyse particle shape, aggregation potential and identification of the composition of the particulate.
5.1 Results

5.1.1 Particle Size Distributions

The volume distributions of the samples had mean diameters ranging from 20\( \mu m \) to 50\( \mu m \) (Figure 5.1). This is not indicative of the number of airborne particles, due to the masking effect by the volume of the large particles. Assuming the particles are homogeneous spheres, conversion to number fraction is possible. On conversion to number distributions, the resulting histograms show that a large percentage of particulate have sizes in the sub-\( \mu m \) region (Figure 5.1).

Figure 5.1: Typical volume and number size distributions for laser scabbled concrete. The number distribution is derived from the volume distribution.

Particulate having sizes below 80\( \mu m \) were analysed using laser diffraction. Those above 150\( \mu m \) were collected and sieved. The combined diffraction sizing and sieving data for a 10mm aggregate
concrete sample is shown in Figure 5.2. The raw data is displayed in Table 12.2 in Appendix A.

![Particle size distribution of 10mm aggregate (combined sieved and sized data)](image)

**Figure 5.2: Particle size distribution of 10mm aggregate (combined sieved and sized data)**

5.1.2 Composition of Concrete

Concrete comprises of a binding material which is embedded with aggregate. Common fine aggregates are sand, pulverized fuel ash and iron blast furnace slag. Coarse aggregates like gravel have sizes larger than 4.75μm (No. 4 sieve) while fine aggregates like sand lie between 0.75μm (No. 200 sieve) and 4.75μm (No. 4 sieve) in size. It was found that the particulate in concrete are not spherical (assumption of Mie scattering), most of them are cube-shaped and rounded. Very few are acicular (needle-shaped). Admixtures are usually added to concrete to enhance some property of the bulk material. Pozzolans (e.g. fly ash) are admixtures than contain
reactive silica and are used to reduce thermal cracking. Components were identified by SEM analysis in reference to ¹.
Figure 5.3: Micrographs showing the variety of particle shapes in concrete -

a. limestone, b. ettringite, c. fly ash, d. calcium hydroxide.
5.2 Discussion

5.2.1 Particle Size

In order to determine whether the particulate are airborne, the diameters of the particles are converted to aerodynamic diameters based on the mass fractions and densities of the constituent components of concrete (Table 12.1 in Appendix A). The aerodynamic diameter of a particle is the diameter of a sphere having density 1000kgm⁻³ and the same settling velocity as the particle.

\[ d_{\text{aero}} = d_{\text{Stokes}} \sqrt{\frac{\rho_{\text{part}}}{1000 \cdot \chi}} \]  \hspace{1cm} \text{[equ 4.2]}

where

- \( d_{\text{aero}} \) is the aerodynamic diameter of the particle (μm)
- \( d_{\text{Stokes}} \) is the Stokes diameter of the particle (μm)
- \( = \) diameter of the particle if the particle is a sphere.
- \( \rho_{\text{part}} \) is the density of the particle (kgm⁻³)
- \( \chi \) is the shape correction factor

=1 for a sphere

The particles produced during scabbling have been shown to range in shape from spheres to acicular particles. This would influence the settling characteristics of the particles. Ettringite shows agglomerations of acicular particles (Figure 5.3b). This would cause lower settling velocities than a sphere of equivalent diameter, due to drag forces. Pulverised fuel ash consists of hollow spheres (Figure
5.3c). The density is thus far lower than the equivalent solid sphere, lowering settling velocity and hence aerodynamic diameter. The laser diffraction sizer displays particle sizes based on the diameters of spheres having the same volume/mass as the particle. This, for example, converts an acicular particle into a sphere having the same volume and reports the diameter of the sphere. The shape correction factor can be set to unity. The hollow spheres of pulverised fuel ash (fly ash), however, are not taken into account. The laser diffraction instrument cannot detect the hollow nature of the particles. Table 12.1 indicates that the mass fraction of fuel ash is approximately 6% compared to 46% for limestone. The shape correction factor was set at unity.

![Aerodynamic diameters calculated using 2441kgm$^3$ as the average density based on the mass fraction of each component in the concrete.](image)

Figure 5.4: Aerodynamic diameters calculated using 2441kgm$^3$ as the average density based on the mass fraction of each component in the concrete.
The mapping function to convert between distributions is plotted in Figure 5.4. The average density was calculated to be 2441 kgm$^3$. The volume and aerodynamic size distributions of the sub-80\(\mu\)m particulate are shown in Figure 5.5.

![Graph showing volume and aerodynamic size distributions](image)

**Figure 5.5: Conversion of the diameters based on volume into aerodynamic diameters yields a distribution that is shifted toward larger sizes. The cumulative aerodynamic diameter is also plotted.**

The American Conference of Governmental Industrial Hygienists define the depository characteristics of aerosols as shown in Figure 5.6$^2$. These are split into inhalable, thoracic and respirable fractions. Using the median diameters of these distributions, inhalable particulate is <100\(\mu\)m, thoracic <10\(\mu\)m and respirable <4\(\mu\)m. These
values are for aerodynamic diameters and hence are independent of material density.

Figure 5.6: ACGIH definition of respiratory tract deposition of aerosols.

Referring back to Figure 5.5, the plot for aerodynamic diameter indicates that the entire size fraction is inhalable, 10% is thoracic and approximately 3% is respirable.

5.2.2 Effect of shape

Laser diffraction particle sizing is based on the assumption that the particles to be analysed are homogenous spheres. In the case of arbitrarily shaped materials, the sizer produces a size distribution based on particle volume. The results are diameters of spheres having the same volume as the particles being analysed.
The micrographs (Figure 5.3) show that a large range of shapes are present within a sample of the ablated material. Regular shapes such as spheres and cuboids as well as irregular flakes and large aggregates are shown to be present. Some of the particulate present in the various SEM images were identified as certain key components of concrete. Solid or hollow spheres larger than 1\( \mu m \) are pulverized fuel ash, also called fly ash (Figure 5.3c). Some of the hollow spheres maybe empty (cenospheres) or may contain smaller spheres (plerospheres). Silica fume tends to be comprised of solid spheres smaller than 0.1\( \mu m \). The vaporisation and recondensing of the cement matrix also produces small solid spheres. Certain rounded cuboid aggregates were also found. These aggregates are primarily composed of limestone (Figure 5.3a). The primary particles were approximately 1\( \mu m \) in size\(^1,5^8\).

Calcium sulfoaluminates, also known as ettringite show up (Figure 5.3b) as acicular (needle-like) crystals with large aspect ratios (10 x 0.5\( \mu m \)). Calcium hydroxide crystals (Figure 5.3d) are large hexagonal crystals which are usually around 10\( \mu m \). Their shapes can vary between flat plates and thin, elongated structures. CSH is another component of concrete and is composed of fibrous growths which are less than 1\( \mu m \) in diameter\(^1,9\).

In the case of the respirable fraction, the shape is an important factor. Spherical particles can be easily ejected from the respiratory
tract as opposed to acicular (needle-shaped) and dendritic formations.

5.3 Conclusion

Laser scabbling concrete produces a range of particle sizes, ranging from sub-μm to millimeters in size. The phase of the parent material does not change during scabbling. Instead the components comprising the parent material are ejected. This ejected material consists of primary particles as well as agglomerates of the components, each component having unique shapes and aggregation potentials. SEM analysis proves this and provides a means of identification of components.

Some of the particulate and aggregate is airborne. The entire airborne fraction can be inhalable. Approximately 10% is thoracic and 3% respirable. This has significant implications for filter design and health issues.

5.4 References


6  Quality parameters and reactive cutting steel

During oxidation cutting of steel, the cut edge shows striations, which are periodic concave indentations. Laser cut quality was characterised quantitatively by the surface roughness of the cut edge, the striation frequency, the striation angle and the kerf width of the cut; and qualitatively by the dross formation and the heat affected zone (HAZ). This chapter identifies the trends in cut quality parameters with laser power and cut velocity.

Figure 6.1: Cut edge showing striations and dross formation. A Talysurf trace is displayed.
Figure 6.2: Image of the cut zone, indicating the heat affected zone and cut kerf. \( w_{\text{kerf}} \) and \( w_{\text{haiz}} \) are the widths of the kerf and heat affected zone respectively.

The experimental setup for the laser is detailed in Chapter 3. The assist gas pressure was kept constant during these tests at 1.5bar of \( \text{O}_2 \). The workpiece was 2mm thick mild steel sheet. Surface roughness was measured using a Rank Taylor Hobson Talysurf profilometer. The roughness parameter measured is the \( R_a \) (average roughness) value.

The striation wavelength is measured at the same instance as the roughness by the Talysurf profilometer. This is a function of length and is independent of the cutting velocity. To convert this value to striation frequency, it is necessary to introduce the cutting velocity:

\[
f = \frac{1000v}{60\lambda} \text{ Hz} \quad [\text{equ 5.1}]
\]
Images of the cut kerfs and edges were captured using an optical microscope. Kerf widths and striation angles were measured using graticule and UTHSCSA Imagetool, which is a freeware image processing software package.

Figure 6.3: Typical cut edge produced in mild steel during oxidation cutting. The striations are concave in shape and tend to bend away from the normal as the cut velocity is increased.
6.1 Striation angle

6.1.1 Results

![Striation angle](image)

**Figure 6.4:** Striation angle of the cut during the processing of 2mm thick mild steel using 1.5bar of $O_2$. The raw data is shown as points. The curve is fitted.

Striation angles are measured from the vertical and range from 0° to 70° (Figure 6.1). No through cut takes place beyond 80°. The striation angle is highly dependant on cutting velocity. The striations tend to start to bend away from the vertical at a specific depth below the top surface of the metal sheet, depending on the operating parameters.

6.1.2 Discussion

At high P/v ratios, the temperature at the bottom of the cut is higher than at other P/v ratios, reducing melt viscosities and facilitating melt removal. The striation angle is at a minimum. As the cut velocity
increases for a constant laser power, the cut front tends to curve at the bottom of the cut (Figure 6.4). This is due to reduced temperatures at the bottom of the cut as the velocity is increased. The melt viscosity increases, reducing mass removal rates. This angle keeps increasing as the velocity is increased to a point where there is no longer a through cut (Figure 6.5). This causes high workpiece temperatures and warping due to the entrained heat. As this limit of cutting is approached, the melt viscosity increases to the point where the melt cannot be easily ejected from the bottom of the cut. Dross formation thus occurs.
Figure 6.5: Images showing the cut created at 220W and 1900mm/min in 2mm thick mild steel using O₂ at 1.5bar. The cut edge shows striations with striation angle approaching the critical 'no-cut' value. The image of the bottom of the cut shows that no through cut occurs. It is not obvious from the kerf at the top of the cut.
6.2 Surface roughness

6.2.1 Results

Figure 6.6: Average roughness values of the top edge of the cut (processed using 1.5bar of \( \text{O}_2 \), 2mm mild steel).

Figure 6.7: Average roughness values of the bottom edge of the cut (processed using 1.5bar of \( \text{O}_2 \), 2mm mild steel).
High powers and velocities show lower surface roughnesses, whereas low powers and velocities show higher roughnesses. At the top of the cut the $R_a$ value ranges from 2 to 5\(\mu\)m (Figure 6.6) while at the bottom the range is 3 to 8\(\mu\)m (Figure 6.7). The roughness values at the bottom half of the cut edges are higher than that of the top.

Figure 6.8: Micrograph of the cut edge for the 200W, 1000mm/min sample

Figure 6.9: Talysurf plot of top edge. $Ra=4.644\mu m$

(x - 10\(\mu\)m/div, y - 0.5mm/div)

Figure 6.10: Talysurf plot of bottom edge. $Ra=4.875\mu m$

(x - 10\(\mu\)m/div, y - 0.5mm/div)
6.2.2 Discussion

Surface roughness decreases rapidly at velocities greater than 1.8m/min as the laser beam becomes the predominant energy source. At cut velocities below 1.8m/min, the oxidation front moves faster than the cutting front, causing lateral burning to take place, increasing surface roughness. As the cut velocities are increased beyond that value, the laser beam becomes the primary energy input to the cut zone, thereby lowering temperatures and surface roughness because of reduced burning.

Figure 6.11: Both cuts were produced at 250W. The cut on the left was produced at a cutting velocity of 1m/min and the other at 2.2m/min. The velocity significantly affects the roughness and regularity of the cut edge.

High P/v ratios enable the beam to penetrate vertically into the material to a greater depth. This effect is seen in Figure 6.11. The vertical, regular striations produced at low velocities indicate that the energy input is enough to lower melt viscosities, easing material removal. The roughness is higher at the bottom of the cut due to heat conduction into the substrate. This can be seen in the Talysurf traces in Figure 6.13. The striations produced at the bottom are more
pronounced than at the top (Figure 6.12). They are, however, regular unlike those produced at low P/v ratios.

Figure 6.12: The images above are of 2mm thick mild steel processed at 250W, 1m/min and 1.5bar O2. The striations are near vertical. The striations at the bottom of the cut zone (lower image) are more pronounced than those at the top sharing increased lateral burning.

As the velocity is increased, the cut front starts to curve. The striations at the bottom of the cut zone get less defined and less energy is available to produce deep striations. The $R_a$ values decrease.
Figure 6.13: Talysurf traces showing the profile of the cut edge for the top and bottom edges of the cut. Top edges display more uniform variations. The bottom part of the cut experiences variations in gas pressure, absorbed power amongst other instabilities.
6.3 Striation frequency

6.3.1 Results

Figure 6.14: Striation frequencies of the top edge of the cut (processed using 1.5 bar of O$_2$, 2mm mild steel).

Figure 6.15: Striation frequencies of the bottom edge of the cut (processed using 1.5 bar of O$_2$, 2mm mild steel).
The striation frequencies range from 50Hz at low powers and velocities to around 300Hz at high powers and velocities (Figure 6.14). The values for the bottom half of the cut edge increase more rapidly with cutting velocity than those of the top of the cut edge.

The striation frequency is more dependant on the cutting velocity rather than the laser power, as can be seen in Figure 6.14 and Figure 6.15. As the velocity increases for a constant laser power, the striation frequency increases. A dependance on laser power is, however, visible. Increasing laser power increases the frequency.

6.3.2 Discussion

The striation frequencies at the bottom of the cut edge increase rapidly with velocity. This is because the striation angle increases as the cut zone is more unstable.

![Relationship between Ra and striation frequency](image)

*Figure 6.16: The relationship between roughness and striation frequency in the case of laser cutting 2mm thick mild steel at 1.5bar O₂.*
The Ra value is related to the depth of the striations, while the frequency is a measure of its periodicity. At high P/v ratios, with cutting velocities below 1.8m/min, lateral burning occurs, increasing the depth of the striations. Conversely at low P/v ratios, especially cutting velocities above 1.8m/min, burning is reduced, lowering roughness. These trends are displayed in Figure 6.16.

6.4 Kerf width

6.4.1 Results

![Figure 6.17: Kerf width of the top of the cut (processed using 1.5bar of O₂, 2mm mild steel).](image-url)
Kerf widths range from 0.15mm to 0.5mm. The kerf width at the top of the cut is very dependant on laser power and is not significantly affected by cutting velocity (Figure 6.17). The kerf width of the bottom of the cut is, however, dependant on both power and velocity (Figure 6.18).

6.4.2 Discussion

Kerf widths at the top of the cut increase significantly with laser power due to the increasing energy input and due to heat conduction into the body of the material. As mentioned previously, the depth to which the striations remain vertical is dependant on the cut velocity, the top few hundred microns usually being vertical except in extreme cases. This indicates that the temperatures of the top of the cut are dependant mainly on the incident laser power.
At the bottom of the cut, the kerf width is dependant on power and velocity. As the velocity is increased for a constant laser power, the striation angle increases. The angle continues to increase to a point where no through cut is produced. The kerfwidth at the bottom thus decreases with cut velocity.

As the kerfwidth increases, the law of conservation of mass dictates that more material is removed from the cut zone in the form of particulate and/or dross. This trend is visible in the sieve analysis discussed in Chapter 8.

6.5 Conclusions
The effects of laser power and cutting velocity on cut quality parameters have been discussed. The striation angle increases with cut velocity to a point where no through cut occurs. The surface roughness of the cut edge differs significantly at the top and bottom of the cut, and tends to decrease with power and velocity while striation frequency increases. Kerf widths at the top of the cut are dependant on laser power and increase with an increase in laser power. At the bottom of the cut, both power and velocity dictate the kerf width.

6.6 References
1. C. D. Wilcox, S. B. Dove, W. D. McDavid, and D. B. Greer, UTHSCSA Imagetool (University of Texas Health Science
Quality parameters and reactive cutting steel

Center, San Antonio, 2001), retrieved from
http://ddsdx.uthscsa.edu/dig/itdesc.html.

7 Theoretical investigations of particle formation

An understanding of the mechanisms involved during laser cutting is useful as a tool for optimising the process as well as predicting and minimising by-products. The various mechanisms of particle formation are explained along with a simple model relating laser power, cutting velocity, gas pressure, and material thickness to particle diameter.

The mechanisms of melt removal and particle formation are investigated for the CO₂ laser cutting of mild steel sheet using oxygen as an assist gas. Melt removal mechanisms include pressure gradient and shear stress driven flows. These standard models have been extended to include particle formation. Additionally, the Kelvin-Helmholtz instability theory, which is a type of shear driven droplet formation mechanism, has been detailed. These mechanisms provide an understanding of the sphere formation over the complete range of particle sizes as observed experimentally. The mechanisms are categorised based on different laser processing parameters such as laser power, cutting velocity and gas pressure.

7.1 The mechanisms of melt removal and particle formation

There are three regimes of melt ejection and particle formation during laser cutting - droplet formation by pressure driven flow, droplet formation by melt shear and fine particles produced by the Kelvin-
Helmholtz instability (Figure 7.1). Secondary breakup can occur due to gas jet/droplet interaction and droplet vibration.

Figure 7.1: The regimes of particle formation. At low power to velocity ratios, the cut front is at an angle to the gas jet causing pressure gradients and shear to occur. At high ratios, the cutting front is at a glancing incidence enabling the Kelvin Helmholtz instability.

7.1.1 Surface tension

The surface tension of a liquid is dependent on its composition and temperature \(^1\). In the case of laser cutting of steel with oxygen as the assist gas, the oxidation of the melt film causes a change to its surface tension as well as its temperature (exothermic reaction). Although other components (Ni, Cr, C, etc.) may be present in the
parent material prior to melting, their concentration would not change very much. The surface tension of the molten parent metal and the oxidised melt vary independently with temperature. The graphs in Keene's paper show these trends.

Most materials have a surface tension that decreases with temperature \( \left( \frac{d\sigma}{dT} \right) \) is –ve) but in the case where impurities are introduced, as for Fe-O or Fe-S systems, \( \gamma \) would increase with temperature [Figure 7.2]. The liquid material properties in Keene's paper are linear, and are given by:

\[
\sigma_{Fe} = 2408 - 0.35T; \quad \text{[equ 7.1]}
\]

\[
\sigma_{Fe-O} = \sigma_{Fe} - 7490(\text{at}%[O]); \quad \text{[equ 7.2]}
\]

\[
\sigma_{Fe} \text{at } 1700K = 1862 \text{ mNm}^{-1}; \quad \text{[equ 7.3]}
\]

\[
\eta_{Fe} \text{ at } 1700K = 4.6 \times 10^3 \text{ kgm}^{-1}\text{s}^{-1}; \quad \text{[equ 7.4]}
\]

\[
\rho_{Fe} \text{ at } 1700K = 7 \times 10^3 \text{ kgm}^{-3}; \quad \text{[equ 7.5]}
\]

\[
C_{pFe} \text{ at } 1700K = 4.9 \times 10^4 \text{ Jmol}^{-1}\text{K}^{-1}; \quad \text{[equ 7.6]}
\]

where \( \sigma_{Fe} \) and \( \sigma_{Fe-O} \) are the surface tensions of the parent metal and the oxidised metal respectively.

\( \text{at}%[O] \) is the atomic % of oxygen.
Theoretical investigations of particle formation

Figure 7.2: Surface showing the variation in surface tension of molten iron with changes in its oxygen content (% by atomic no. 0-0.8%) and with temperature (1500-3000°C)

7.1.2 Pressure driven flow

Momentum is transferred from the gas to the melt by a pressure gradient. When the striation angle is high, the gas jet is not parallel to the melt film and is incident on it at an angle. The impulse of the gas jet on the melt transfers momentum to the bulk of the melt film. The melt is transported to the bottom of the cut and ejected forming large particles as it leaves the cut zone. This is the dominant particle formation process for non-airborne particles and larger airborne particles. It is the breakdown of this as a detachment mechanism that results in dross adherence at the bottom of the cut.
7.1.3 Kelvin-Helmholtz instability

Robin and Nordin's model examines the formation of particles caused by a transverse gas jet across a molten surface. The laser radiation is absorbed by the cutting front, creating a melt film. The gas jet-melt shear that is produced creates ripples on the surface, which break up according to the Kelvin-Helmholtz instability mechanism to form molten globules that are entrained in the gas flow and solidify to form spherical particles.

These combined effects have been modelled for subsonic gas velocities assuming the gas is compressible and inviscid while the melt is incompressible and viscous. The gas flow over the melt surface amplifies certain components of the initial disturbances hence driving capillary waves. At high enough gas velocities, the waves grow exponentially with time [Figure 7.3]. Although a spectrum of wave numbers is unstable, only the fastest growing mode is considered. The wavelength of this fastest growing mode is:

\[
l_m = \frac{4\pi \sigma (1 - M^2)^{1/2}}{\rho_g v^2}
\]  

[equ 7.7]

and \( \lambda_r \) is:

\[
\lambda_r = \frac{1}{2} \pi \lambda_m
\]  

[equ 7.8]

where \( \sigma \) is the melt surface tension (Nm\(^{-1}\))

\( M \) is the Mach number of the gas (dimensionless)

\( \rho_g \) is the density of the gas (kgm\(^{-3}\))
\( v \) is the viscosity of the melt (Nsm\(^2\))

\( \lambda_m \) is the wavelength of the fastest growing mode (m)

\( \lambda_r \) is the wavelength of oscillations on the ligament (m)

The globules break off in the shape of ellipsoids having a major axis diameter of \( \frac{1}{2} \lambda_r \), and a minor axis diameter of \( \frac{1}{2} \lambda_m \). As the molten globule solidifies, it forms a sphere of a volume equivalent to that of the ellipsoid.

**Figure 7.3: Particle formation by Kelvin Helmholtz instabilities**

When the cut front is nearly vertical, the gas jet interacts with the melt through shearing. These are the conditions for the Kelvin-Helmholtz instability mechanism. This occurs on the interface of two fluids in shear, in this case the gas flow over the melt. This introduces surface waves which amplify to form finger-like projections that grow exponentially in time and eventually break off forming
droplets, which solidify to spheres. The depth of the melt affected is of the order of the wavelength of the surface disturbance, which is of the order of the particle size produced.

7.2 Production of hollow particulate

During laser cutting the mechanism of particle production is similar to that of gas atomization of melts (Figure 7.4). In this case a gas jet blows across the molten metal causing ligaments to be formed at the bottom of the cut zone. These ligaments separate from the bulk melt. This is termed 'primary breakup' ⁴.

The particles formed during the process of laser cutting mild steel are spherical in shape and tend to be hollow and thin walled (as will be seen in the following chapter). The spherical form is easily accounted for by the action of surface tension forces on the ejected molten droplet. Any liquid (or solid) possesses an attractive force between its atoms. Each atom pulls its neighbouring atoms toward it. At the surface of the liquid, however, a deficiency of atoms causes a net force toward the body of the liquid. This creates a skin effect on the surface. For a free falling liquid, the state of minimum energy equates to the surface being continuous and infinite, the result being the formation of a sphere. The porosity of the particles can be caused by two different mechanisms – entrapment and gas diffusion.
Figure 7.4: Schematic showing particle formation from the point of ligament breakup to solidification. It applies to particles produced by pressure driven melt ejection and that due to the Kelvin Helmholtz instability. The dotted lines indicate that the mechanism does not occur for the entire population.

7.2.1 Entrapment

The melt is confined on 3 sides in the cut zone. When the ligament breaks away from the bulk melt, the molten globule can encapsulate a volume of gas that was trapped during ligament separation (Figure 7.5). Non-vertical cut fronts would favour this mechanism of gas entrapment as pressure driven flow dominates.
7.2.2 Gas diffusion

The temperatures of the melt and the oxygen-rich atmosphere in the cut zone promotes the diffusion of oxygen into the melt. As molten droplets are separated from the melt, the droplets solidify to form spheres. The gas diffusion rates and solubilities of high temperature melts are much higher than those of the solid. For example, FeO melts at 1700°C can dissolve 0.34% by mass of oxygen. Solid FeO, however, can diffuse <0.009% by mass of oxygen. As the temperature drops, the solubility of the oxygen in the iron oxide decreases. The escaping oxygen reacts with the carbon in the steel forming carbon monoxide, causing porosity as the droplet solidifies.
7.3 Secondary breakup of droplets

7.3.1 Gas effects

The velocity of the gas and material properties of the molten droplet can cause secondary breakup creating droplets an order of magnitude smaller than the parent droplet. The aerodynamic forces on the droplet depend on the gas velocity and its density. Droplet surface tension, viscosity and density affect whether secondary breakup takes place.

The Weber number, which relates the gas velocity to melt surface tension, density and droplet diameter, is used to specify whether this occurs.

\[
We_s = \frac{\rho_g \Delta U^2 D}{\sigma}
\]  

[equ 7.9]

where \( \rho_g \) is the gas density

\( \Delta U \) is the gas velocity relative to the melt velocity (dimensionless)

\( D \) is the parent droplet diameter (m)

\( \sigma \) is the melt surface tension (Nm\(^{-1}\))

\[
We_L = \frac{\rho_L \Delta U^2 D}{\sigma}
\]  

[equ 7.10]

\[
Re_L = \frac{\rho_L \Delta U^2 D}{\mu_L}
\]  

[equ 7.11]
where $\rho_L$ is the melt density

$\Delta U$ is the variation in velocity across the liquid phase

$D$ is the parent droplet diameter

$\mu_L$ is the dynamic viscosity of the melt

The Ohnesorge number (dimensionless) is used to specify whether the critical Weber number is valid:

$$Z = \frac{\sqrt{We_L}}{Re_L} = \frac{\mu_L}{\sqrt{\rho_L \sigma D}}$$  \[\text{equ 7.12}\]

where $Z$ is the Ohnesorge number (dimensionless)

$We_L$ is the Weber number of the liquid phase (dimensionless)

$Re_L$ is the Reynold number of the liquid phase (dimensionless)

$\rho_L$ is the density of the melt (kgm$^{-3}$)

$\sigma_L$ is the surface tension of the melt (Nm$^{-1}$)

$\mu_L$ is the dynamic viscosity of the melt (Nsm$^{-2}$)

$D$ is the parent droplet diameter

Low Weber numbers cause a *bag formation* to occur (Figure 7.6). The molten droplet entraps the gas creating a balloon that breaks up into small droplets leaving a toroidal ligament that itself breaks up into relatively larger droplets. At high Weber numbers the molten
droplet does not entrain the gas but deforms at the edges to form ligaments that break down to form smaller droplets. There is a critical $W_{es}$ that is dependant on the Ohnesorge number, below which the droplet is stable. This Weber number is given in $^4$ as 13 for a $Z^2$ value <0.1. For a steel or iron oxide melt, the $Z^2$ value never rises above this value of 0.1.

![Secondary breakup occurring](image.png)

**Figure 7.6: An instance of secondary breakup due to bag formation.**

From [Figure 7.7] it is apparent that in the case of mild steel cutting with a gas jet having a velocity of 200m/sec, the gas Weber number is above the critical value for droplets larger than about 400μm, and hence secondary breakup can occur. The surfaces shown assume that the relative velocity between the droplets ejected from the bottom of the cut zone and the gas is the gas velocity at the nozzle. The actual value is lower as some momentum is transferred to the melt by the gas and the gas velocity below the cut zone is lower than at the nozzle.
Figure 7.7: Gas Weber numbers for particles ranging from 1 to 1000\(\mu\)m and at%[O] of 0.2% with a \(Z^2\) less than 0.1. Plots a, b and c show different gas velocities (100, 200 and 300m\(s^{-1}\)). b and c show the critical Weber number (13) being exceeded, hence causing particle formation by secondary breakup.

7.3.2 Breakup due to droplet vibration

Molten droplets have a natural frequency at which the droplet changes shape between being spherical and ellipsoidal\(^4\). Surface tension and dynamic viscosity tend to stabilise this oscillation. If, however, the amplitude of oscillation overcomes the surface tension
forces, secondary breakup will occur. Figure 7.8 shows particles frozen during oscillation.

Figure 7.8: Micrograph of a droplet that has frozen and broken during droplet oscillation.

The natural frequency of oscillation is given as:

$$\omega = \frac{4}{\pi D^{1.5}} \sqrt{\frac{\sigma}{\rho_L}}$$  \[\text{equ 7.13}\]

where

- $\omega$ is the natural frequency of oscillation (Hz)
- $\sigma$ is the surface tension of the droplet (Nm$^{-1}$)
- $\rho_L$ is the density of the droplet (kgm$^3$)
- $D$ is the diameter of the droplet (m)
This equation has been plotted and is shown in Figure 7.9, which indicates that the natural frequencies of droplets are of the order of MHz for small droplets down to kHz for larger droplets. If the resonant frequencies in the kerf match any frequency in this range, there is a high likelihood that secondary breakup will occur. Vicanek et al. calculated melt flow instabilities to occur at frequencies of the order of 2.5 kHz. This indicates that droplet vibration can occur leading to secondary breakup for droplets larger than 400μm.

![Figure 7.9: Natural frequencies of molten steel droplets with surface tension 2500 mN/m](image)

7.4 Conclusions

The mechanisms of particle formation are dependant on the characteristics of the melt flow, which in turn is dependant on the cutting parameters.
Primary particulate production can occur at the bottom of the cut zone, where the melt is ejected forming droplets; or on the melt surface itself. Ejection of the melt at the bottom of the cut zone is caused by pressure driven flow and shear between the gas jet and the bulk melt.

Ejection of particulate from the melt surface occurs when the gas jet is nearly at a glancing angle of incidence to the melt surface. The Kelvin Helmholtz hydrodynamical instability causes droplets to break off from the melt surface.

The hollow nature of the particles formed during cutting is caused by gas encapsulation during melt ejection as well the expanding gas within the particle as it solidifies.

As the particles are formed, they can break up to form smaller droplets due to processes like bag formation, where the gas jet causes breakup; and by droplet vibration due to melt flow instabilities.

7.5 References


8 Analysis of particulate generated during cutting

This chapter discusses the results of laser cutting 2mm thick mild steel sheet and its effects on the particles formed during the process. The laser processing parameters that were varied are the laser power, the cutting velocity and the assist gas pressure. For each combination of parameters, the ejected particles were collected and analysed for size distribution, airborne concentration and morphology.

8.1 Introduction

The ejected particulate range in diameter from sub-μm to millimeters. Analysing the entire size range as a single unit can cause undetected biases. This has been previously explained in Chapter 2. The particulate have been segmented into two size bands – airborne and non-airborne. These ranges have been analysed for size by laser diffraction and by sieving respectively.

Selecting the mean particle diameter and analysing its trend with the process parameters have reduced the airborne particulate size distributions. The particle concentration has been analysed similarly. Particle morphology is investigated by electron microscopy.
8.2 SEM analysis of the particulate generated during laser cutting mild steel

The scanning electron microscope was used to identify particle shape and agglomeration potential.

8.2.1 Results

Size

The particles formed during the laser cutting of mild steel have a broad size distribution ranging from sub-μm to millimeter-sized particles (Figure 8.1, Figure 8.2).

The diffraction-based particle sizer was used for size analysis, the results of which are discussed in 8.3.1. The particulate size was not analysed using the electron microscope because only a small sample of the population can be investigated.
Figure 8.1: A general view of particulate produced during laser cutting of mild steel. The large range of sizes makes sizing the entire range impractical by laser diffraction.

Figure 8.2: The large spheres tend to have smooth surfaces.
Shape

The particles were found to be spherical and hollow. Some particles were elongated and some were found to be broken (Figure 8.3).

Figure 8.3: Elliptical particle. This is not an instance of secondary breakup by ligament formation. Secondary breakup could have occurred by melt oscillation. The molten droplet solidified during oscillation.

Morphology

The spheres tend to be hollow and thin-walled with wall thicknesses <10% of the particle diameter (Figure 8.4). Some particles contain smaller spheres (Figure 8.5). These are usually termed plerospheres. These are formed after solidification, when the larger sphere cracks and collects smaller spheres.
Figure 8.4: The wall thicknesses are typically less than 10% of the diameter of the sphere. Wall thickness = 2.24\mu m, diameter 90\mu m. Wall thickness 2.5% of the diameter.

Figure 8.5: Particle produced during CO$_2$ laser cutting of 2mm thick mild steel sheet. The plerosphere is hollow with a thin wall and contains smaller spheres.
Agglomeration

Agglomeration has not been seen during laser cutting. Prior to solidification some molten droplets can coalesce. This is seen in Figure 8.6.

![Figure 8.6: Micrograph showing particles coalescing prior to solidification.](image)

8.2.2 Discussion

The spherical nature of the particulate is due to the melt surface tension causing the molten droplet to assume a shape of minimum surface energy – a sphere. The secondary breakup of larger droplets occurs by the process of bag formation. Some instances of have been frozen during formation and can be seen as elongated spheres, with one broken end.

The hollow, thin-walled nature of the particulate is consistent with the theory behind particle formation by atomisation as discussed in
Chapter 7. Due to the hollow nature of the particulate, larger spheres will be airborne, and hence inhalable. The size fraction that will remain airborne can be seen in Figure 4.8.

The significance of hollow particles for health and safety

The American Conference of Governmental Industrial Hygienists define the depository characteristics of aerosols as shown in Figure 8.7. These are split into inhalable, thoracic and respirable fractions.

![Figure 8.7: ACGIH definition of respiratory tract deposition of aerosols.](image)

The particle diameters are expressed as aerodynamic diameter, which is the diameter of a sphere having density 1000kgm$^{-3}$ and the same settling velocity as the particle. The particle diameters measured using the light diffraction particle sizer are volume mean
diameters. Figure 8.8 shows the equivalent aerodynamic diameters for hollow mild steel particulate.

![Graph showing the relationship between volume mean diameters and aerodynamic diameters for mild steel particulate, with varying wall thicknesses.]

Figure 8.8: Surface showing the relationship between volume mean diameters and aerodynamic diameters for mild steel particulate, with varying wall thicknesses.

Being cumulative distributions in Figure 8.7, the 50% percentiles of the distributions indicate the medians of the size distributions. The aerodynamic diameter of the peaks can be used to specify depository thresholds in the human respiratory tract. All particulates having aerodynamic diameters below 4\(\mu\)m are respirable, those below 10\(\mu\)m can be deposited in the thorax and those below 100\(\mu\)m are inhalable through the mouth or nose. Relating these values to the surface in Figure 8.8, indicate that mild steel particulate (wall thicknesses <10% diameter) with physical diameters below approximately 60\(\mu\)m are airborne and inhalable. Those below 5\(\mu\)m
are thoracic and those below 1 μm are respirable. The effect of wall thickness on aerodynamic diameter diminishes as the particles get smaller. This is because as the particles get smaller, the wall thickness values are of the same order as those of particle diameter.

Figure 8.9: Deposition characteristics of mild steel particulate in the human respiratory tract. The particle diameters are based on volume and not aerodynamic diameters, assuming wall thickness is 10%.

8.3 Mean particle diameter of the airborne particulate

The size distributions and mean diameter of the airborne particles are presented and the trends discussed.

8.3.1 Laser diffraction sizing results

A typical size distribution of airborne particles was found to be close to monomodal and log-normal (normal distribution on a log scale). An example is shown in Figure 8.10. Depending on the laser operating parameters, the size distribution shifts to higher particle diameters by
becoming bimodal and then monomodal again at the larger particle size (Figure 8.11). The results of mean diameter measurements with processing parameters are shown in Figure 8.12 and the raw data in Table 13.1 in Appendix B.

Figure 8.10: Typical volume size distribution of the airborne fume produced during mild steel cutting of 2mm thick sheet at 200W and 1000mm/min. The cumulative distribution is also shown.
Figure 8.11: Size distributions of particles produced during mild steel cutting of 2mm thick sheet at 175W and at 1000mm/min and 1700mm/min, using 1.5 bar O₂ as an assist gas.

The mean particle diameter results (Figure 8.12) indicate that for a constant velocity, smaller particles are formed at high laser powers. At higher powers (300W), the mean particle diameter shows a minimum of ≈4μm at a 1000mm/min ranging to ≈6μm at both lower (500mm/min) and higher velocities (2500mm/min). At lower powers (150W), this effect is more dramatic with a minimum mean particle diameter of ≈12μm at 1000mm/min, rising to ≈25μm at 500mm/min and over 30μm at around 2000mm/min.
Figure 8.12: 3D surface showing the effect of laser power (W) and cutting velocity (mm/min) on the mean particle diameter of the fume produced during the cutting of mild steel.

8.3.2 Discussion

**Formation of particles at high powers**

High power inputs cause elevated melt temperatures which allow faster melt removal by pressure driven flow as the melt is more fluid. This is indicated as the reduction in striation angle with increased power (Figure 8.13). A reduction in the wavelength of the Kelvin-Helmholtz disturbance (discussed in Chapter 7) also takes place. This can be seen as a reduction in mean diameter of the airborne particles with laser power.
Figure 8.13: 3D surface showing the effect of laser power (W) and cutting velocity (mm/min) on the angle of the striations (2mm mild steel cut using 1.5bar O₂).

Formation of particles at low powers
At low powers, the mean diameter changes by up to 100% depending on the cutting velocity. The power to velocity ratio is not high enough to lower melt viscosities sufficiently in order to facilitate the production of small particles by the Kelvin Helmholtz instability. As the velocity is increased, a minima is observed. The cut front and oxidation front velocities are comparable (1.8m/min)², creating a more stable cut zone. The energy absorption and melt removal effects superimpose to produce this minima. As the velocity is increased further, melt viscosities are increased causing the mean particle diameter to increase. Particle formation takes place by the Kelvin-Helmholtz mechanism but it is dominated by the pressure driven mechanism. Here the molten metal is blown out of the cut
zone, not by surface shear forces, but by shear forces acting on the bulk of the melt. Larger globules are hence produced, solidifying to form larger particulate as seen in Figure 8.12.

The effect of cut velocity on particle size
Smaller diameter particles tend to form at low velocities as the cut front is nearly vertical and the gas jet tangential to it. This causes airborne particulate formation to take place primarily by the Kelvin-Helmholtz mechanism. At low powers, however, the increase in melt viscosities due to the low energy input inhibits the formation of small particles.

![3D surface showing the effect of laser power (W) and cutting velocity (mm/min) on the kerf width of the cut edge at the top of the cut (2mm mild steel cut using 1.5bar O2).](image)

Low velocities also allow time for heat conduction into the workpiece causing lateral burning. This results in increased kerf widths (Figure
8.14) and hence a wide temperature distribution with a range of melt viscosities and a wide particle distribution leading to increased mean particle diameter. The size distribution shifts toward larger sizes forming a bimodal distribution (Figure 8.15). This increase also takes place in the non-airborne fraction. This increase in large particle volume at low velocities is seen in Figure 8.18.

![Figure 8.15: Size distribution of particles produced during laser cutting of 2mm thick mild steel sheet at 175W, 1.5 bar O₂.](image)

8.4 Sieve analysis of non-airborne particulate

Endecotts test sieves (compliant with BS410) were used (mesh #170 (90µm) and #300 (53µm)) to separate the particulate into 3 bins –

- <53µm
The aim of this study is to provide information on the overall particle by-products of the process. Although, only 3 bins are used; combined with the airborne particle size distribution, they provide an insight into the cutting process.

8.4.1 Results

![Sieve analysis <53μm](image)

Figure 8.16: Surface showing mass of sub-53μm particulate for 1.5 bar O₂
The smallest size bin contains some sub-53\(\mu\)m particulate. The 53 to 90\(\mu\)m contains between 0.1 and 0.4g of particulate depending on the operating parameter. The mass of particulate in this bin tends to increase with an increase in laser power and a decrease in cutting.
velocity. The results are noisy causing a poor surface fit. The 90μm+ bin, however, shows a much stronger relationship with the operating parameters. The mass of particulate increases with an increase in power and a decrease in velocity. Similar results were achieved when the assist gas pressure was incremented. The results of these pressure tests are shown in Appendix C.

8.4.2 Discussion

The capture technique used to collect the airborne particulate essentially captures a representative sample of the airborne fume. Some of the airborne particulate will settle to the bottom of the tank. The settling characteristics of mild steel fume are shown in Figure 8.19. This does not affect the airborne concentration results as all experiments were carried out using the same sampling times and capture apparatus. Hence the presence of some particulate in the sub-53μm sieving range (Figure 8.16).
Figure 8.19: Distribution of particles that will settle (in still air) to the bottom of the tank (0.3m) within 5 seconds of cutting. Turbulence due to the assist gas jet is not considered.

As the laser power is increased for a constant cutting velocity, the kerf width will increase. This is because the energy absorbed by the material per unit time increases thereby producing higher melt temperatures in the cut zone. Similarly increasing the cut velocity for a given laser power reduces the kerf width. The correlation between the mass of the 90μm+ particulate (Figure 8.20) and the kerf width complies with the law of conservation of mass.
Figure 8.20: Scatter plots showing the correlation between the kerf widths of the cuts and the mass of the large (>90μm) particulate produced using 1.5 bar O2.

The particulate in the sieved range were hollow with thin walls (Figure 8.21). Ivarson et al. ⁴ found that the large particulate were solid and showed degrees of oxidation from the surface to the core. They analysed particulate larger than 100μm.
8.5 Airborne particle concentration

The airborne particle concentration is measured by the particle sizer by calculating the ratio of the light intensity incident on the obscuration detector before and during sizing.

8.5.1 Results

The airborne particle concentration increases with increasing power and velocity (Figure 8.22). Regarding the change in concentration with cutting velocity, the trend at lower laser powers indicates a small influence of the velocity on the particle concentration. As the power
increases to higher values, however, the rate of increase in the concentration with velocity becomes more significant.

![3D surface showing the effect of laser power and cutting velocity on the concentration of airborne particles for 1.5 bar O₂ and a 2mm thick mild steel sheet. The concentration of airborne particulate increases with laser power and cutting velocity.](image)

**Figure 8.22:** 3D surface showing the effect of laser power and cutting velocity on the concentration of airborne particles for 1.5 bar O₂ and a 2mm thick mild steel sheet. The concentration of airborne particulate increases with laser power and cutting velocity.

### 8.5.2 Discussion

For a constant laser power, as the cutting velocity is increased, the maximum temperature achieved lowers. The width of the temperature distribution also narrows across the cutting front.

As the laser power is increased for a particular cutting velocity, the concentration increases (Figure 8.22). This would be expected as the temperatures in the melt increase, and over a wider area, thereby causing lower melt viscosities. Hence, a greater proportion of the
airborne particles generated would follow the formation mechanism of the Kelvin-Helmholtz instability.

8.5.3 Influence of kerf width on airborne particle concentration

![3D surface showing the effect of power and velocity on the kerf width of the bottom of the cut (1.5 bar O2, 2mm thick mild steel). The kerf width increases with an increase in laser power and a reduction in cutting velocity.](image)

The kerf width at the bottom of the cut zone increases with an increase in laser power and a reduction of the cutting velocity (Figure 8.23). From this it would be expected that the concentration of particles (airborne and non-airborne) would increase in order to satisfy the law of mass conservation. The results of the sieving data discussed in 8.4 shows that the mass of the non-airborne (>90μm) particles have a significant correlation with the kerf width. This trend is not followed with regard to the airborne particulate (Figure 8.22).
The airborne particle concentration increases with laser power as well as cutting velocity.

8.5.4 Interdependence of striation frequency and airborne particle concentration

The concentration of airborne particles increases with an increase in striation frequency, especially with the striation frequency of the bottom of the cut zone. The bottom of the cut is a key area in the formation of particulate because this is the region where melt separation from the parent material occurs. The striations at the top of the cut are usually very uniform. At the bottom of the cut zone, however, the striations tend to be more irregular due to instabilities in the melt flow.

Figure 8.24: Striation frequencies of the bottom edge of the cut (processed using 1.6bar of O₂, 2mm mild steel).
The relationship between the airborne particle concentration with the striation frequency at the bottom of the cut zone (Figure 8.24) is better than with the striation frequencies at the top (Figure 8.25). This indicates that the concentration of the airborne particulate is dependant on the mechanisms taking place at the bottom of the cut during its formation. It thus provides an important measurement parameter of the 'health' of the process.

![Figure 8.25: Striation frequencies of the top edge of the cut (processed using 1.5bar of O₂, 2mm mild steel).](image)

An important observation is that although the striation frequency is very dependant on cut velocity, the concentration of airborne particulate is more dependent on laser power. To a certain extent this is due to the conservation of mass – as the power increases with a constant velocity, the kerf width increases; thereby causing a greater volume of particulate to be formed.
8.5.5 Effect of assist gas pressure on airborne particle concentration

Figure 8.26: 3D surface showing the effect of laser power and cutting velocity on the concentration of airborne particles for 1 bar O₂ and a 2mm thick mild steel sheet. The concentration of airborne particulate increases with laser power and cutting velocity.

At an assist gas pressure of 1 bar O₂, the concentration of airborne particulate produced (Figure 8.26) during cutting follows a similar trend to the 1.5 bar experiments. The change in concentration with power and velocity is more pronounced. Again, the concentration increases faster with laser power than with the cutting velocity.
Figure 8.27: 3D surface showing the effect of laser power and cutting velocity on the concentration of airborne particles for 2 bar O₂ and a 2mm thick mild steel sheet. The concentration of airborne particulate increases with laser power and cutting velocity.

The airborne particulate concentration tends to increase with an increase in laser power and velocity. A major difference between the results of the 1.5 bar (Figure 8.22) and 1 bar (Figure 8.26), and the 2 bar is that a diagonal maxima is observed. This single maxima on the diagonal supports the evidence that a particular power to velocity ratio provides the optimum cut (assuming all other parameters are constant). This power to velocity relation is essentially linear.

Black⁵ defines severance energy for laser cutting as:

\[ \Phi = \frac{P}{V_s} \]  

[equ 7.14]

where: \( \Phi \) is the severance energy (Jmm⁻²)
P is the laser power (W)

V is the cutting velocity (mm/s)

s is the material thickness (mm)

This ratio is calculated from experimental data and is based on the operating parameters yielding the best quality cuts. The range of reported severance energies is $6.0 \text{Jmm}^{-2} < \Phi < 13.0 \text{Jmm}^{-2}$.

The measured severance energy of the airborne concentration in Figure 8.27 is $6.0 \text{Jmm}^{-2}$ at all points on the maxima except one, which is $7.2 \text{Jmm}^{-2}$. These values indicate that the maxima follows a line of constant severance energy.

![3D surface showing the effect of laser power and cutting velocity on the concentration of airborne particles for 3 bar O$_2$ and a 2mm thick mild steel sheet.](image)

Figure 8.28: 3D surface showing the effect of laser power and cutting velocity on the concentration of airborne particles for 3 bar O$_2$ and a 2mm thick mild steel sheet.
Figure 8.28 shows the effect of power and velocity on the airborne particle concentration during 3 bar oxygen cutting. The surface fit is poor due to noise.

8.6 Conclusions

The analysis of the airborne and non-airborne solid-phase by-products of laser cutting allow an understanding of the underlying process. Laser cutting of mild steel produces particles that are spherical in shape. The spheres are hollow with thin walls with thicknesses <10% of the diameter. The thinner the wall, the lower the overall density of the particle, increasing its ability to remain airborne and inhalable.

The airborne fraction is important from a health and safety aspect in order to ascertain the possibility of inhalation of the particulate. At wall thicknesses <10% of the particle diameter, the 60μm particulate is inhalable. Particles less than 5μm can be deposited in the thorax; and particles below 1μm in diameter are respirable and can penetrate the smallest passages of the human respiratory tract.

Airborne concentrations have been found to increase with laser power and velocity and tend to be at a maximum when cutting is at its most efficient. Although being a detriment to health and safety controls in the workplace, it has significant positive implications for process control.
Laser diffraction particle sizing is an ideal method of size analysis for spherical particles. No shape correction factors need to be used reducing the possibility of errors. From a health and safety point of view, spheres are easier for the respiratory tract to reject as compared to acicular (needle-shaped) or dendritic particles.

8.7 References


9 CMOS Particle Sizer

The Malvern MastersizerX used during the experimental work is only suitable for off-line analysis of particle size. The physical size of the instrument (1.5m long) prevents it from being placed sufficiently close to the point of particle production in order to sample in real time without a significant lag. Additionally, the analysis of the raw data takes seconds (>10s) to complete. No provision is available for data output as a feedback signal to a control system.

The main aim of designing a system from basic principles is to create a system-specific instrument capable of real time (25Hz) sizing in situ. The diffraction instrument utilizes CMOS camera technology. The low cost (<$10) linescan chip has a large dynamic range thereby negating the need for proprietary sensors (such as those used in commercial instrumentation). The design norm of commercial instrument detectors is based on annular rings, with ring area increasing with radius (in order to detect relatively low intensities at large solid angles). An example is shown in Figure 9.1.
Figure 9.1: Commercial laser diffraction particle sizer detector. The semicircular rings increase in area with radius. This particular detector does not have a central hole and photodiode. The 3 sectors in the centre are used to align the system.
9.1 Optical geometry of the CMOS particle sizer construction

Figure 9.2: The CMOS sizer comprises of a helium neon laser, beam expansion optics, a Fourier lens and the CMOS linescan detector at the lens focal plane.

9.2 Diffraction of light due to a particle

Fraunhofer diffraction occurs when the light incident on the particle is parallel and monochromatic. Diffraction takes place in the far field (i.e., the image plane is at a distance several times the size of the diffracting aperture/particle). The irradiance due to a monochromatic collimated beam incident on a circular aperture/particle, at the plane of observation is given by $^1$:

$$I(\theta) = I_0 \left[ \frac{2J_1(ka \cdot \sin \theta)}{ka \cdot \sin \theta} \right]^2 = I_0 \left[ \frac{2J_1(\alpha \sin \theta)}{\alpha \sin \theta} \right]^2$$  \[equ 9.1\]

where $k = \frac{2\pi}{\lambda}$ is the wave number

$I(\theta)$ is the intensity of the diffracted light

$I_0$ is the intensity of the incident beam
a is the diameter of the aperture/particle

$\theta$ is the diffraction angle

$J_1$ is the Bessel function of the first order.

Figure 9.3: Intensity distribution due to Fraunhofer diffraction (5\(\mu\)m)

The Fraunhofer diffraction due to a 5\(\mu\)m particle is shown in Figure 9.3. The intensity is a function of only size of the aperture/particle and the angle. As the particle size reduces to the order of the wavelength of the laser (\(\approx 1\mu m\)), reflection and refraction also take place (Figure 9.4). Their contribution is especially important after the first minima of the diffraction pattern where their effects are of the order of the diffracted intensity (Figure 9.5).
Mie scattering theory provides a solution to the scattering of light by spherical particles that have a size of the order of the incident light wavelength. An approximation to the Mie solution is used here. 

$$I(d, \eta, \theta) = \frac{\pi d^2}{4} I_{F+RR}(d, \eta, \theta)$$  \hspace{1cm} [equ 9.2]  

$$I_{F+RR}(d, \eta, \theta) = [I_F(d, \theta) + I_{rfl}(\eta, \theta) + I_{rfl}(\eta, \theta)]$$  \hspace{1cm} [equ 9.3]  

where $I_{F+RR}(d, \eta, \theta)$ is the total intensity of diffracted light.
$I_p$ is the intensity of light by Fraunhofer diffraction

$I_{ref}$ is the reflected intensity

$I_{refr}$ is the refracted intensity

$\eta$ is the complex refractive index of the particle

$$I_p(d, \theta) = \frac{I_1^2 (ka \cdot \sin \theta)}{\pi \sin^2 \theta} \tag{equ 9.4}$$

$$I_{ref}(\eta, \theta) = \frac{1}{8\pi} \left[ \frac{\sin(\frac{\eta}{2})}{\sin(\frac{\eta}{2})} + \eta^2 \sin(\frac{\eta}{2}) - \left[ \eta^2 - 1 + \sin(\frac{\eta}{2}) \right]^{\frac{1}{2}} \right] + \eta^2 \sin(\frac{\eta}{2}) + \left[ \eta^2 - 1 + \sin(\frac{\eta}{2}) \right]^{\frac{1}{2}} \tag{equ 9.5}$$

$$I_{refr}(\eta, \theta) = \frac{2}{\pi (\eta^2 - 1)} \left( \frac{\eta \cos(\frac{\eta}{2}) - 1}{\cos(\frac{\eta}{2})} \right) \left( \frac{\eta - \cos(\frac{\eta}{2})}{\eta^2 + 1 - 2\eta \cos(\frac{\eta}{2})} \right)^2 \left( 1 + \sec^4(\frac{\eta}{2}) \right) \tag{equ 9.6}$$

### 9.3 Retrieval of size information

The interaction of light with particles is a form of the Fredholm equation of the first kind $^{3-5}$:

$$g(x) = \int_a^b K(x, y) f(y) dy \tag{equ 9.7}$$

where $g(x)$ is the measured quantity (in this case the light intensity on the linescan camera), $K(x, y)$ is the kernel of the integral equation (scattering matrix)
f(y) is function to be determined (size distribution).

If the sizes are placed into \( m \) size bins, the recorded intensity pattern can be described linearly as a set of equations:

\[
L = Aq + \epsilon
\]  

[Equation 9.8]

\[
\begin{bmatrix}
L_1 \\
L_2 \\
\vdots \\
L_m
\end{bmatrix}
= \begin{bmatrix}
a_{11} & a_{12} & \ldots & a_{1m} \\
a_{21} & \ldots & \ldots & \ldots \\
\vdots & \ldots & \ldots & \ldots \\
a_{m1} & \ldots & \ldots & a_{mm}
\end{bmatrix}
\begin{bmatrix}
q_1 \\
q_2 \\
\vdots \\
q_m
\end{bmatrix}
+ \begin{bmatrix}
\epsilon_1 \\
\epsilon_2 \\
\vdots \\
\epsilon_m
\end{bmatrix}
\]  

[Equation 9.9]

Figure 9.6: The matrix manipulation required to retrieve the size distribution involves the inversion of the forward scattering matrix.

where

- \( L \) is the integrated light intensity (due to all the particles) on a particular pixel (angle)

- \( A \) is the scattering matrix containing scattering patterns for each size bin based on either Fraunhofer or Mie theory

- \( q \) is the weighting for a particular size bin (size distribution)

- \( \epsilon \) is a constant dependant on the measurement errors of the optical system.
In order to recover size information from the integrated scattering pattern, matrix $A$ needs to be inverted, i.e.:

$$q = A^{-1}(L - \varepsilon)$$  \[\text{equ} 9.10\]

This is straightforward if $A$ is square and non-singular, in which case the inverse exists. Matrix $A$, however, is not square. The Moore-Penrose pseudo-inverse is used\(^2,6,7\).

9.4 Moore-Penrose pseudo-inverse

Given $n \times m$ matrix $A$, its pseudo-inverse is $m \times n$ matrix $A^\dagger$ which satisfies
\[ A A^+ A = A \]
\[ A^+ A A^+ = A^+ \]
\[ (AA^+)^T = AA^+ \]
\[ (A^+ A)^T = A^+ A \]  
\[ \text{[equ 9.11]} \]

The derivation for the pseudo-inverse matrix is as follows:

\[
Aq = L \\
A^T Aq = A^T L \\
q = (A^T A)^{-1} A^T L \\
q = A^+ L 
\]
\[ \text{[equ 9.12]} \]

9.5 Phillips-Twomey Algorithm

The inversion of matrix \( A \) is not usually stable. This is largely due to measurement errors in matrix \( L \) and systematic errors due to the inversion. The Phillips-Twomey algorithm \[^4,^5\] improve the solution by introducing a smoothing factor.

\[
q = (A^T A + \gamma H)^{-1} A^T L 
\]
\[ \text{[equ 9.13]} \]

where \( \gamma \) is the smoothing factor (\( \gamma = 0 \) yields the Moore-Penrose solution)

\( H \) is the smoothing matrix of the second degree of the form:

\[
H = \begin{bmatrix}
0 & 0 & 0 & 0 & \cdots & \cdots & 0 \\
-1 & 2 & -1 & 0 & \cdots & \cdots & 0 \\
0 & -1 & 2 & -1 & \cdots & \cdots & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
0 & \cdots & 0 & -1 & 2 & -1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix} 
\]
\[ \text{[equ 9.14]} \]
\( \gamma \) is usually determined empirically by trial and error; too low a value causes instability and too large a value causes too much smoothing, a loss in size information. The matrix \( H \) used varies between researchers \(^2,7\) but it essentially adds weighting to the diagonal in order to stabilise the inversion (Figure 9.8).

\[ \begin{pmatrix} X & \gamma \end{pmatrix}^{-1} X \]

\[ \text{pixel no.} \]

\[ \text{intensity} \]

\[ \text{dim} \]

\[ 50 \]

\[ 100 \]

\[ -50000 \]

\[ 50000 \]

\[ 0 \]

\[ \text{Figure 9.8: Smoothed inverse matrix} \]

9.6 Resolution of detector

Particles scatter light to all angles irrespective of their size, the only difference being the relative intensities at a particular angle. The integrated scattering pattern falling on the linescan array is essentially a sinc function in 1D. The zero order of the diffraction pattern, comprising the undiffracted and small scattering angles, has an intensity that is many orders of magnitude larger (intensity of this...
order increases as particle size increases) than the higher orders (which are at larger angles). This is the reason why commercial instruments have detectors that have a logarithmic increase in detector area as the angle increases.

The pixels are 125\(\mu\)m by 7.8\(\mu\)m with a 7.8\(\mu\)m spacing between pixel centers. The maximum irradiance (saturation) is 45\(\mu\)Wcm\(^{-2}\) (45\(\times\)10\(^{-10}\) Wm\(^{-2}\)) at an integration time (time over which charge is accumulated) of 2ms. Using a 12-bit ADC with a 2.5V CCD output range provides a resolution of 0.61mV. It is very important to exclude all but the laser wavelength from reaching the detector in order to improve signal to noise ratios at the tail ends of the diffraction pattern. Interference filters were not be used because their transmission is a function of incident angle. Instead the optical train was covered to reduce ambient light from affecting the system.

The dynamic range and the resolution of the CMOS linescan camera both affect the reproduction of the integrated diffraction pattern. The dynamic range of each pixel affects the reproduction to a greater extent. It is important that the CMOS array is capable of capturing the entire range of light intensities, including both the tails of the pattern as well as the zero order (light intensity being many orders of magnitude larger than at the tails of the pattern). Using a detector having a high spatial resolution reduces the signal to noise ratio at larger angles. Less charge is accumulated per pixel, as proportionally (to pixel area) less light falls on the pixels.
The detector captures the 'integrated' scattering patterns over the entire particle size distribution. The sum of all these individual patterns does not contain minima as do the individual scattering patterns. Hence the detector spatial resolution need not be very high. Individual patterns and their sum are displayed below (Figure 9.9):

```
a.

intensity

\[ \begin{array}{c}
50. \\
20. \\
10. \\
5. \\
2. \\
1. \\
\end{array} \]

angle

\[ \begin{array}{c}
0 \\
0.1 \\
0.2 \\
0.3 \\
0.4 \\
0.5 \\
\end{array} \]

b.

intensity

\[ \begin{array}{c}
200. \\
100. \\
50. \\
20. \\
10. \\
5. \\
2. \\
1. \\
\end{array} \]

angle

\[ \begin{array}{c}
0 \\
0.1 \\
0.2 \\
0.3 \\
0.4 \\
0.5 \\
\end{array} \]

c.

intensity

\[ \begin{array}{c}
1000. \\
100. \\
10. \\
1. \\
\end{array} \]

angle

\[ \begin{array}{c}
0 \\
0.1 \\
0.2 \\
0.3 \\
0.4 \\
0.5 \\
\end{array} \]
```
9.7 Solving the problem of limited dynamic range

Using a neutral density filter (or decreasing the integration time of the CCD) will only prevent saturation. The signal to noise ratios of the pixels measuring the tail of the pattern will decrease.

A rotary system with different density filters could be used consecutively for different parts of the diffraction pattern. Particles leaving the interrogation region (in the laser beam) between filter changes is a problem.

Zhenhua et al. used a Fuga 15d logarithmic CCD camera manufactured by C-CAM Technologies, Belgium. It is a 511x511 pixel sensor with a 7.3x7.3mm^2 sensor area.

**Figure 9.9:** 5µm (a), 10µm (b) and 50µm (c) particle scattering patterns and their sum (d).
9.8 Optical system

Lens equation

\[ \frac{1}{S} + \frac{1}{S'} = \frac{1}{f} \]  \hspace{1cm} [equ 9.15]

\[ \frac{1}{S} = \frac{S' - f}{fS'} \]  \hspace{1cm} [equ 9.16]

From similar triangles:

\[ \frac{r}{S' - f} = \frac{h}{S'} \]  \hspace{1cm} [equ 9.17]

\[ \frac{r}{h} = \frac{S' - f}{S'} \]  \hspace{1cm} [equ 9.18]

\[ \therefore \frac{f}{S} = \frac{r}{h} \]  \hspace{1cm} [equ 9.19]

\[ \frac{h}{S} = \frac{r}{f} = \tan \theta \approx \theta \]  \hspace{1cm} [equ 9.20]

for small \( \theta \) in radians

\[ \therefore \theta = \frac{r}{f} \]  \hspace{1cm} [equ 9.21]
for particles suspended in air\textsuperscript{9}

\[ \theta = \frac{r}{f\eta_m} \]  

[equ 9.22]

for particles suspended in a medium of refractive index \( \eta_m \)

9.9 Optical system calculations

![Diagram of LIS-1024 CMOS linescan camera geometry]

Each pixel has been taken to be a sector with angle \( 2\phi_n \) where \( n \) is the pixel index, pixel 1 being at a distance offset from the optical axis. Each pixel is bounded by an inner and outer radius. The angle \( \phi \) decreases as the pixel index increases (further away from the optical axis). Thus the error due to the pixel shape decreases as the pixel index increases (shape tends to a rectangle). For lower radii (toward optical axis) the value of intensity is high, reducing the effect of the error.
For pixel 1:

\[ I(1) = \int_{\text{offset}}^{r_1+7.8 \mu m} \int_{0}^{2\phi} I r dr d\phi \]  
[equ 9.23]

For pixel 2:

\[ I(2) = \int_{r_2=\text{offset}+125}^{r_2+7.8 \mu m} \int_{0}^{2\phi} I r dr d\phi \]  
[equ 9.24]

For pixel n:

\[ I(n) = \int_{r_n=\text{offset}+(n-1)125 \mu m}^{r_n+7.8 \mu m} \int_{0}^{2\phi} I r dr d\phi \]  
[equ 9.25]

\[ \phi_n = \tan^{-1}\left( \frac{125/2}{\frac{7.8}{2} + \text{offset} + (n-1)7.8} \right) \]  
[equ 9.26]

Light on pixel \( \Delta r_j \):

\[ I(\Delta r_j) = \int_{d_{\text{min}}}^{d_{\text{max}}} N q_0(d) \cdot I(\Delta r_j, d) \cdot d \]  
[equ 9.27]

where \( N \) is the total number of particles

\( q_0(d) \) is the size distribution

\( d_{\text{min}} \) and \( d_{\text{max}} \) are the minimum and maximum particle diameters respectively

\( I(\Delta r_j, d) \) is the intensity as a function of pixel no. and particle diameter.

\[ I(\Delta r_j, d) = \int_{r}^{r+7.8 \mu m} \int_{0}^{2\phi} I(r, d, \eta) \cdot r \cdot dr \cdot d\phi \]  
[equ 9.28]
\[
I(\Delta r) = \int_{d_{\text{min}}}^{d_{\text{max}}} Nq_0(d) \cdot \frac{\mu}{\eta} \cdot \phi(r,d,\eta) \cdot r \cdot dr \cdot dd \quad \text{[equ 9.29]}
\]

\[
r = f\theta \quad \text{[equ 9.30]}
\]

\[
dr = f \cdot d\theta
\]

\[
I(\Delta \theta_j) = \frac{\pi N \phi_n f^2}{4} \int_{d_{\text{min}}}^{d_{\text{max}}} \int_{\theta_1}^{\theta_2} d^2 \cdot q_0(d) \cdot I_{F+RR}(\theta,d,\eta) \cdot \theta^2 \cdot d\theta \cdot dd \quad \text{[equ 9.31]}
\]

This equation can't be solved analytically for \(q_0(d)\). Hence we split the size range into \(M\) intervals.

\[
I(\Delta \theta_j) = \frac{\pi N \phi_n f^2}{4} \sum_{i=1}^{M} q_0(d_{\text{av}}) \int_{d_i}^{d_{i+1}} \int_{\theta_1}^{\theta_2} d^2 \cdot I_{F+RR}(\theta,d,\eta) \cdot \theta^2 \cdot d\theta \cdot dd
\quad \text{[equ 9.32]}
\]

where \(d_{\text{av}}\) is the average diameter from \(d_i\) to \(d_{i+1}\).

\(q_0(d)\) is the number distribution.

Converting it into a volume distribution \(^{11}\) increases the stability of the matrix inversion process.

\[
q_0(d) = \frac{d^{-3} q_3(d)}{\int_{d_{\text{min}}}^{d_{\text{max}}} d^{-3} q_3(d) \cdot dd} \quad \text{[equ 9.33]}
\]

\[
A_{ji} = C \phi \int_{d_i}^{d_{i+1}} \int_{\theta_1}^{\theta_2} d^{-1} \cdot I_{F+RR}(\theta,d,\eta) \cdot \theta^2 \cdot d\theta \cdot dd \quad \text{[equ 9.34]}
\]

where \(A_{ji}\) are the matrix coefficients, \(C\) is a constant which can be dropped.
9.10 Data acquisition and matrix multiplication

The pseudo-inverse matrix is calculated for a specific refractive index of particle. The calculation is performed in Wolfram’s Mathematica. The calculation of a 1024x1024 matrix takes approximately 2 days on a 1GHz Pentium III computer. Hence, a 128x128 matrix was used whereby the intensity of light over every 8 pixels was integrated. This reduces the computation time down to a few hours.

The data from the linescan detector is captured using a National Instruments data acquisition card and LabVIEW. The multiplication of the inverse matrix with the vector captured from the detector is calculated at approximately 25Hz.

9.11 Conclusions

The principle of operation and the design of the CMOS particle sizer have been discussed. The use of simple optics and ‘off the shelf’ sensors allows a compact system to be constructed. By performing all processor intensive calculations off-line, a real-time sizing system is achieved.

9.12 References


10 Conclusions

Laser cutting and ablation of materials have enabled an enhancement in product quality. This enhancement brings with it the production of undesirable by-products. The analysis of the solid-phase by-products of laser material processes contributes toward the enrichment of process knowledge by providing information on the mechanisms of particle formation and the relationship between the by-products and the process parameters.

An experimental study of the quality of the product of laser cutting mild steel sheet was undertaken to identify the relationship between product quality and the cutting by-products. This study provides an insight into the relationship between product quality and measured parameters of the by-product.

A theoretical study of the mechanisms of particle formation during steel cutting was carried out to enhance the understanding of the cutting process.

Similarly, the laser scabbling of concrete was investigated in order to determine the composition of the ejected material produced during the process. This allows the efficient design of extraction and filtration systems to contain concrete particulate.

The findings from the analysis of the particulate produced during mild steel cutting have scope for the implementation of a process control strategy. The requirements for real-time particle sizing and the
specific size ranges that must be monitored have been discussed. The limitation of commercial particle sizing instrumentation has led to the development of a low-cost, small footprint, real-time sizing solution.

The main findings are summarized in the following sections:

10.1 Mild steel cutting

The quality of the product is essential to any industrial process. It was found that striation angles of the cut edge increase with cut velocity to a point where no through cut occurs. The surface roughness of the cut edge differs significantly at the top and bottom of the cut, and tends to decrease with power and velocity while striation frequency increases. Kerf widths at the top of the cut are dependant on laser power and increase with an increase in laser power. At the bottom of the cut, both power and velocity dictate the kerf width. This lays down a foundation defining the relationship between cut quality and the process parameters.

The particles produced during mild steel cutting tend to be spherical and hollow. They are thin-walled, having wall thicknesses typically less than 10% of the particle diameter. The thinner the wall, the lower the overall density of the particle, increasing its ability to remain airborne and inhalable. Particle sizes below 60\(\mu\)m are inhalable and can be deposited in the nose and mouth. Those having sizes below 5\(\mu\)m are thoracic and are deposited in the upper airways. Sizes
below 1\(\mu\)m are respirable causing them to be deposited in the smallest chambers of the lungs. This has significant implications for health and safety as well as filtration strategies.

The volume mean diameter of the airborne particles ranges from <4\(\mu\)m to 30\(\mu\)m depending on process parameters. The concentration of the airborne particulate tends to increase with an increase in laser power and velocity and has been shown to be an indication of process efficiency.

Non-airborne particulate provide less information regarding the health of the process. The only significant parameter is the mass of ejected particulate. This tends to increase with an increase in laser power and a decrease in cut velocity. This is a direct consequence of the law of conservation of mass.

The formation of hollow spheres during laser cutting occurs by a combination of several mechanisms. The operating regions of these mechanisms tend to overlap depending on process parameters. Large spheres are formed by pressure driven flow and by shear of the bulk melt when the power to velocity ratio is low. This is due to high melt viscosities. At high ratios, smaller particles are formed by the Kelvin Helmholtz instability. Additionally, secondary breakup of the molten droplets can occur by bag formation or by droplet vibration.
10.2 Concrete scabbling

The scabbling of concrete using high powered lasers causes material to be ejected off the surface of the parent material. The ejected matter is composed of the components of concrete. No phase change occurs. The particulate may be released as primary particles of the particular concrete component or as agglomerates of the same.

Analysis of the size distributions indicate that some of the particulate and aggregate is airborne. The entire airborne fraction can be inhalable. Approximately 10% is thoracic and 3% respirable. The shapes of the ejected particulate range from spherical to acicular, depending on the concrete component released. Again, this has significant implications for filter design and health issues as certain shapes inhibit foreign body rejection by the respiratory system.

10.3 Particle sizing for real-time analysis

A sizing instrument has been developed incorporating low cost detection with simple optical geometry. This enables the system to have a footprint that is a fraction of the size of commercial instruments. By establishing key processor-intensive areas and performing these tasks off-line, a real-time sizing solution was facilitated.
11 Further Work

The influence of processing parameters on the particles produced shows that process efficiency can be monitored and controlled using the process by-products. In particular the airborne particle concentration shows promise as feedback into a process control system. A simple proportional integral derivative controller, as used for the nozzle stand-off control system, could track this position of maximum airborne concentration. Quantitative data is not essential. A process parameter could be varied till a concentration maxima is reached. As contours are being cut, the velocity changes, thereby moving away from the optimum. This would be detected by a reduction in concentration, and the velocity would be increased. Similarly, other parameters could be adjusted to maintain this optimum.

The detection system for the airborne concentration is based on the knowledge of the particle size distribution. Thus, the system can be tailored to detect only the concentration of a specific size band.
12 Appendix A

12.1 Constituents of concrete

<table>
<thead>
<tr>
<th>Material</th>
<th>Common name</th>
<th>kgm⁻³ concrete</th>
<th>Mass fraction</th>
<th>Density x10³ kgm⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland cement</td>
<td>Blue Circle BS12</td>
<td>228</td>
<td>0.10</td>
<td>60%CaO²=3.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>40% SiO₂=2.4</td>
</tr>
<tr>
<td>Pulverised fuel ash</td>
<td>Pozzolan BS3892</td>
<td>152</td>
<td>0.06</td>
<td>SiO₂=2.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Al₂O₃=4.0</td>
</tr>
<tr>
<td>20mm coarse aggregate</td>
<td>Limestone</td>
<td>735</td>
<td>0.46</td>
<td>2.8</td>
</tr>
<tr>
<td>10mm coarse aggregate</td>
<td>Limestone</td>
<td>350</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural pit sand</td>
<td></td>
<td>722</td>
<td>0.31</td>
<td>SiO₂=2.4</td>
</tr>
<tr>
<td>H₂O</td>
<td></td>
<td>170</td>
<td>0.07</td>
<td>1</td>
</tr>
<tr>
<td>Superplasticiser</td>
<td>FEB SP3</td>
<td>3</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

Table 12.1: Components of concrete including mass fraction and density of each component. This was used to calculate the average density in order to convert volume size distributions to aerodynamic size distributions.
### 12.2 Size distribution for laser scabbled concrete

<table>
<thead>
<tr>
<th>Size (μm)</th>
<th>0.05</th>
<th>0.12</th>
<th>0.15</th>
<th>0.19</th>
<th>0.23</th>
<th>0.28</th>
<th>0.35</th>
<th>0.43</th>
<th>0.53</th>
<th>0.66</th>
<th>0.81</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>% by vol</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.000796</td>
<td>0.001137</td>
<td>0.001492</td>
<td>0.001592</td>
<td>0.00153</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Laser diffraction data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (μm)</td>
</tr>
<tr>
<td>% by vol</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Laser diffraction data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (μm)</td>
</tr>
<tr>
<td>% by vol</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sieved data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (μm)</td>
</tr>
<tr>
<td>% by vol</td>
</tr>
</tbody>
</table>

Table 12.2: Combined laser diffraction and sieving size distribution for the particulate generated during laser scabbling of a 10mm aggregate sample.
13 Appendix B

13.1 Volume size distribution of mild steel particulate

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>0.48</td>
<td>0</td>
</tr>
<tr>
<td>0.59</td>
<td>0</td>
</tr>
<tr>
<td>0.71</td>
<td>0</td>
</tr>
<tr>
<td>0.86</td>
<td>0</td>
</tr>
<tr>
<td>1.04</td>
<td>0</td>
</tr>
<tr>
<td>1.26</td>
<td>0</td>
</tr>
<tr>
<td>1.52</td>
<td>0</td>
</tr>
<tr>
<td>1.84</td>
<td>0</td>
</tr>
<tr>
<td>2.23</td>
<td>0</td>
</tr>
<tr>
<td>2.7</td>
<td>0</td>
</tr>
<tr>
<td>3.27</td>
<td>0</td>
</tr>
<tr>
<td>3.95</td>
<td>0</td>
</tr>
<tr>
<td>4.79</td>
<td>0</td>
</tr>
<tr>
<td>5.79</td>
<td>0</td>
</tr>
<tr>
<td>7.01</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.48</td>
<td>1.84</td>
</tr>
<tr>
<td>10.27</td>
<td>0.84</td>
</tr>
<tr>
<td>12.43</td>
<td>0.33</td>
</tr>
<tr>
<td>15.05</td>
<td>0.11</td>
</tr>
<tr>
<td>18.21</td>
<td>0.03</td>
</tr>
<tr>
<td>22.04</td>
<td>0.01</td>
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<tr>
<td>26.68</td>
<td>0</td>
</tr>
<tr>
<td>32.29</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>39.08</td>
<td>0</td>
</tr>
<tr>
<td>47.3</td>
<td>0</td>
</tr>
<tr>
<td>57.25</td>
<td>0</td>
</tr>
<tr>
<td>69.3</td>
<td>0</td>
</tr>
<tr>
<td>83.87</td>
<td>0</td>
</tr>
<tr>
<td>101.52</td>
<td>0</td>
</tr>
<tr>
<td>122.87</td>
<td>0</td>
</tr>
<tr>
<td>148.72</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 13.1: Size distribution of mild steel particulate produced during the laser cutting of 2mm thick sheet at 200W and 1000mm/min.

13.2 Particle mean diameters and quality parameters for mild steel cutting

<table>
<thead>
<tr>
<th>Power</th>
<th>Velocity</th>
<th>Mean diameter</th>
<th>Kerf width (top)</th>
<th>Kerf width (bottom)</th>
<th>Ra (top)</th>
<th>Ra (bottom)</th>
<th>Striation frequency (top)</th>
<th>Striation frequency (bottom)</th>
<th>Striation angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>mm/min</td>
<td>µm</td>
<td>mm</td>
<td>mm</td>
<td>µm</td>
<td>µm</td>
<td>Hz</td>
<td>Hz</td>
<td>deg</td>
</tr>
<tr>
<td>130.00</td>
<td>300.00</td>
<td>6.20</td>
<td>0.26</td>
<td>0.09</td>
<td>7.62</td>
<td>5.65</td>
<td>16.45</td>
<td>19.01</td>
<td>4.56</td>
</tr>
<tr>
<td>130.00</td>
<td>500.00</td>
<td>16.89</td>
<td>0.29</td>
<td>0.13</td>
<td>4.32</td>
<td>4.85</td>
<td>54.15</td>
<td>29.64</td>
<td>16.56</td>
</tr>
<tr>
<td>130.00</td>
<td>700.00</td>
<td>8.49</td>
<td>0.26</td>
<td>0.12</td>
<td>8.77</td>
<td>6.87</td>
<td>29.06</td>
<td>32.14</td>
<td>18.90</td>
</tr>
<tr>
<td>153.00</td>
<td>800.00</td>
<td>11.74</td>
<td>0.25</td>
<td>0.10</td>
<td>2.79</td>
<td>5.08</td>
<td>110.10</td>
<td>43.70</td>
<td>13.64</td>
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14 Appendix C

14.1 Sieving data

1 bar O₂

Sieve analysis <53μm

Sieve analysis 53μm<x<90μm
Figure 14.1: Sieving results of particulate produced during the cutting of 2mm thick mild steel using 1 bar O₂.
2 bar O$_2$

Sieve analysis <53μm

Sieve analysis 53μm<x<90μm
Figure 14.2: Sieving results of particulate produced during the cutting of 2mm thick mild steel using 2 bar $O_2$
3 bar O₂

Sieve analysis <53 µm

Sieve analysis 53 µm < x < 90 µm
Figure 14.3: Sieving results of particulate produced during the cutting of 2mm thick mild steel using 3 bar O₂