NOTE TO USERS

The original manuscript received by UMI contains pages with indistinct and/or slanted print. Pages were microfilmed as received.

This reproduction is the best copy available

UMI
COATING REMOVAL FROM ALUMINUM USING WHEAT STARCH BLAST CLEANING

BY

ÉTIENNE JEAN

A thesis submitted in conformity with the requirements for the degree of Master of Applied Science (M.A.Sc.)
Graduate Department of Mechanical and Industrial Engineering
University of Toronto

© Copyright by Étienne Jean, 1997
The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L’auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

L’auteur conserve la propriété du droit d’auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

0-612-29427-7
Abstract

Coating Removal from Aluminum using Wheat Starch Blast Cleaning

M.A.Sc. Thesis
by
Étienne Jean
Graduate Department of Mechanical and Industrial Engineering
University of Toronto
1997

Wheat starch blast cleaning is increasingly used to remove organic coatings from aircraft. The aim of this work was to maximize the productivity of the process by gaining a better understanding of the mechanism of coating removal, and by studying how various process parameters affect it. The impact sites left by individual wheat starch particles on the coating were examined, the size and shape of the particles were studied, and particle velocities were measured. The relationship between particle size and velocity was also explored using a mathematical model. Finally, the results of these experiments were correlated with paint removal rates, which were found to depend strongly on nozzle angle and particle velocity, but also depended on particle size and shape. The best paint removal rates were achieved at a nozzle angle of 45°, and it was shown that the topcoat was removed in a cumulative fashion by chipping (ductile erosion). Lastly, a selective stripping “window” was observed for the coating system studied: i.e. it was possible to remove the topcoat while leaving the underlying primer intact.
Acknowledgments

I would like to express my appreciation for the guidance and support of my supervisor Dr. Jan K. Spelt during the course of this thesis. I would also like to thank my colleagues for their help and friendship during these two years: Marcello Papini and Borislav Djurovic for their collaboration on my project and James Wylde for his continual technical assistance.

This work has been made possible by the financial and material support of the Natural Sciences and Engineering Research Council of Canada and of CAE Electronics. I would especially like to thank André Cantin and Denis Monette from CAE Electronics for their help (and for a few great lunches).

I would also like to thank all my friends who made these two years in Toronto more enjoyable. I learned a lot through the conversations I had with them, even though it was more often than not completely unrelated to my thesis work. Thanks to them. I will bring back much more from Toronto than just a diploma.
# Contents

Abstract

Acknowledgments

1 Introduction
   1.1 Background ......................................................... 1
   1.2 Wheat starch depainting ........................................... 2
   1.3 Literature review .................................................. 2
   1.4 Thesis objectives .................................................. 3
   1.5 Thesis outline ..................................................... 4

2 Wheat starch blast cleaning
   2.1 Equipment .......................................................... 5
   2.2 Blasting parameters ................................................ 6
      2.2.1 Abrasive media ................................................. 6
      2.2.2 Media mass flowrate ......................................... 8
      2.2.3 Pressure .......................................................... 8
      2.2.4 Angle of attack and standoff distance ....................... 9
   2.3 Samples ............................................................ 9
   2.4 Blast cleaning experimental procedures ......................... 11
      2.4.1 Paint stripping rates ........................................ 11
      2.4.2 Substrate damage ............................................... 12
      2.4.3 Media consumption ............................................. 12
   2.5 Empirical observations ........................................... 12
CONTENTS

6.1.3 Aero Almen strip tests ........................................ 88
6.2 Results ............................................................. 90
6.3 Discussion ......................................................... 97

7 Discussion and conclusions ............................... 100
7.1 Recommendations for future work ..................... 102

Appendices ............................................................ 109

A Wheat starch water content ................................. 109
A.1 Recycled wheat starch ........................................ 109
A.1.1 Water content determination .......................... 109
A.1.2 Results .......................................................... 110
A.2 Wheat starch storage .......................................... 111
A.2.1 Results .......................................................... 112

B Computer programs ............................................. 114
B.1 Size and shape analysis program ....................... 114
B.1.1 Caveats .......................................................... 115
B.2 Velocity measurement program .......................... 116
B.2.1 Source code .................................................... 116

C Improved particle velocity measurement setup .......... 118
## List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Quality control checks for the sample panels</td>
<td>10</td>
</tr>
<tr>
<td>3.1</td>
<td>Blasting parameters used for the micrograph study</td>
<td>16</td>
</tr>
<tr>
<td>4.1</td>
<td>Standard US mesh sizes</td>
<td>43</td>
</tr>
<tr>
<td>4.2</td>
<td>Comparison of size distributions obtained by sieving and optically for Envirostrip 12/30</td>
<td>49</td>
</tr>
<tr>
<td>4.3</td>
<td>Comparison of size distributions obtained by sieving and optically for Envirostrip 30/50</td>
<td>49</td>
</tr>
<tr>
<td>4.4</td>
<td>Comparison of size distributions obtained by sieving and optically for Envirostrip 30/100</td>
<td>50</td>
</tr>
<tr>
<td>4.5</td>
<td>Comparison of size distributions obtained by sieving and optically for production mix</td>
<td>50</td>
</tr>
<tr>
<td>4.6</td>
<td>Envirostrip wheat starch size specifications</td>
<td>54</td>
</tr>
<tr>
<td>5.1</td>
<td>Wheat starch average particle velocities measured optically with the round nozzle</td>
<td>63</td>
</tr>
<tr>
<td>5.2</td>
<td>Wheat starch particle velocities measured optically with the flat nozzle</td>
<td>64</td>
</tr>
<tr>
<td>5.3</td>
<td>Values of the parameters of the velocity model</td>
<td>71</td>
</tr>
<tr>
<td>5.4</td>
<td>Size distribution of the mixes used in the experiments</td>
<td>75</td>
</tr>
<tr>
<td>5.5</td>
<td>Average particle diameter, average particle mass, calculated average particle velocity and total kinetic energy transferred to different mixes</td>
<td>78</td>
</tr>
<tr>
<td>5.6</td>
<td>Wheat starch average particle velocities measured with the rotating disk, with the round nozzle</td>
<td>80</td>
</tr>
</tbody>
</table>
5.7 Wheat starch average particle velocities measured with the rotating disk.
   with the flat nozzle .................................................. 83

6.1 Comparison of the paint stripping obtained with the round and the flat
   nozzle ........................................................................ 88
6.2 Deflection of the Aero Almen strips .................................. 89
6.3 Paint stripping rates with the flat nozzle at 5.44 kg/min and 207 kPa .. 90

A.1 Equilibrium water content of Envirostrip 30/50 .................... 112
List of Figures

2.1 Blast cabinet .............................................. 6
2.2 Blast machine ............................................. 7
2.3 Needle pressure gage ...................................... 9
2.4 Angle of attack and standoff distance .................... 10

3.1 Shutter used to interrupt the abrasive flow at the outlet of the nozzle ........ 15
3.2 Transition between undamaged topcoat and complete topcoat removal down to the primer ........................................... 17
3.3 Transition between regions of low and high damage to the topcoat .......... 18
3.4 Transition between the topcoat and the primer ........................... 20
3.5 Topcoat removal down to the primer .................................. 21
3.6 Partial primer removal ......................................... 22
3.7 Transition between regions of low and high damage to the topcoat .......... 23
3.8 Transition between topcoat and primer .................................. 24
3.9 Partial topcoat removal at 20° .................................... 25
3.10 Impact site viewed at high magnification ............................. 26
3.11 Area between the impact sites, in the zone of transition from low to high topcoat damage ............................................. 27
3.12 Primer removal .................................................. 28
3.13 Airgun experimental setup ....................................... 30
3.14 Multiple exposure picture of the impact of a wheat starch particle against a target .............................................. 31
3.15 Impact site left by one Envirostrip 12/30 particle at normal angle of attack $\alpha = 90^\circ$ and $v \approx 130$ m/s. .......................... 32
LIST OF FIGURES

3.16 Enlargement of the region of Figure 3.15 pointed to by the arrow number one. ........................................... 33
3.17 Impact site caused by an Envirostrip 12.30 particle at an intermediate angle of attack \( \alpha = 45^\circ \), and \( v \approx 130 \text{ m/s} \) ............................................. 34
3.18 V-shaped mark left in the topcoat by an Envirostrip 12.30 particle. \( \alpha = 45^\circ \) and \( v \approx 130 \text{ m/s} \) ............................................. 35
3.19 Converging marks left in the topcoat by a single Envirostrip 12.30 particle. \( \alpha = 45^\circ \) and \( v \approx 130 \text{ m/s} \) ............................................. 36
3.20 Crater left by the impact of a single Envirostrip 12.30 particle .......... 37
3.21 Damage caused by an Envirostrip 30.50 particle .......................... 38

4.1 Experimental setup used for the size, shape distribution .................. 42
4.2 Radius ratio and roundness coefficients of four different shapes ........ 44
4.3 Average minimum diameter of wheat starch particles: comparison of repetitions with the same media ........................................... 46
4.4 Size distribution of different wheat starch mixes obtained optically .... 51
4.5 Size distribution of different wheat starch mixes obtained by sieving . 52
4.6 Average diameter of different media: optical measurements ............ 53
4.7 Comparison of the radius ratio of different wheat starch mixes .......... 55
4.8 Comparison of the roundness coefficient of different wheat starch mixes 56

5.1 Setup used for velocity measurement ......................................... 60
5.2 Multiple exposure picture obtained with Envirostrip 12.30 ............... 61
5.3 Wheat starch particles average velocities measured with the round nozzle 65
5.4 Power of the abrasive stream measured with the round nozzle ........... 67
5.5 Calculated particle velocity as a function of particle diameter .......... 72
5.6 Kinetic energy of a particle of given diameter ............................. 73
5.7 Kinetic energy of 1 kg of particles of given diameter ...................... 74
5.8 Kinetic energy of 1 kg of particles of a given mesh size ................... 76
5.9 Kinetic energy distribution per kilogram of different mixes ............... 77
5.10 Wheat starch particles average velocities measured with the rotating disk (round nozzle) ........................... 81
LIST OF FIGURES

5.11 Power of the abrasive stream measured with the rotating disk round nozzle: 82
6.1 Sliding table setup ................................................. 85
6.2 Layout of the traces on the sample panels .......................... 86
6.3 Normal and tangential components of work exposure for all the paint stripping experiments ................................. 91
6.4 Paint thickness removed using Envirostrip 30.50 .................. 92
6.5 Error in the paint thickness removed induced by the paint thickness gage 93
6.6 Paint thickness removed using production mix ....................... 95
6.7 Comparisons of mass exposures. 5.5 kg, min '12 lb. min', 205 kPa '30 psi', 150 mm '6''' ........................................... 96
6.8 Comparison of work exposures ....................................... 98
A.1 Water content of recycled wheat starch ............................. 110
A.2 Containers used to expose the wheat starch samples to controlled relative humidity conditions ............................... 111
A.3 Equilibrium water content of Envirostrip 30.50 as a function of relative humidity, at 35°C. ................................. 113
B.1 Use of the digital I O lines for the velocity measurements ........ 117
C.1 Improved particle velocity measurement setup ....................... 119
Chapter 1

Introduction

1.1 Background

For reasons related to corrosion prevention, non-destructive evaluation and aesthetics, an aircraft is repainted many times during its lifespan [1]. Because the weight of a layer of paint over an entire aircraft is significant and because the adherence of paint on top of an old layer of paint is poor, aircraft must be depainted prior to applying new paint. Until quite recently, this was done using methylene chloride and phenol-based solvents.

These solvents have many disadvantages. They are flammable and highly toxic, which endangers the security of the workers responsible for the depainting. Moreover, their use generates a large quantity of toxic waste, which poses environmental problems, and is difficult and expensive to dispose of safely.

To address the environmental problems generated by the use of benzene-based solvents, the Environment Protection Agency (E.P.A., in the United States) has greatly restricted their use. As well, several other countries including Canada are in the process of setting up similar legislation.

Because of these new rules, the aerospace industry has started to seek other means of depainting aircraft. The alternatives that are studied are less hazardous solvents, high intensity flashes, lasers, water jets and blast cleaning using plastic, wheat starch or CO₂ pellets as the abrasive. Foster [2] and Forth [3] give good summaries of these developments in paint removal.
1.2 Wheat starch depainting

One of the most promising depainting methods is wheat starch blast cleaning. A significant advantage over other methods is that wheat starch blasting can do selective stripping: that is, it can remove only the top layer of a paint system, leaving the primer intact, thus reducing the amount of waste generated and the cost of repainting. Wheat starch blast cleaning can also safely remove a wide variety of coatings from a number of substrates, including delicate composite materials. Finally, since the abrasive itself is nontoxic, the only hazardous components of the waste come from the paint that has been removed, and the waste can often be classified as nontoxic [4]. The amount of waste can be further reduced by biodegradation [5, 6].

1.3 Literature review

Wheat starch coating removal appeared around 1990 and, so far, all the research that has been done in that field has focused on industrial aspects of the process. Although ADM/Ogilvie and CAE Electronics, the two companies that own the technology, have done a great deal of research to improve the process (see [7, 8, 9, 10, 11]), the mechanics that govern organic coating removal using wheat starch dry stripping are still unknown and, although a large number of qualitative observations have been made, no quantitative information is available on how the blasting parameters affect the paint stripping process.

In the wider field of solid particle erosion, much more fundamental work has been done. However, most of that work has focused on the wear of metallic surfaces, and little effort has been devoted to the erosion of organic coatings. The results of most of that work have, therefore, little direct application to the present research.

Finnie and McFadden [12, 13] have developed a model for the cutting erosion of ductile metals at low angles of attack. According to that model, the volume, \( V \), of material removed by a mass \( M \) of eroding particles striking the surface with a velocity \( U' \) obeys a relationship of the form \( V \sim MU^n \), where the value of \( n \) is between 2 and 3.

Brach [14, 15] has derived a comprehensive set of equations governing the impact dynamics of a particle against a substrate. His theory is based on the equations of
impulse and momentum, and can predict the energy loss of the particles and whether rolling or sliding exists when the particle leaves the surface.

Sundararaj小店 [16, 17] extended the models of Finnie and Brachs, to explain the erosion of metal substrates for all impact angles, and both ductile and brittle erosion. His analysis was based on the material properties of the particles and the target, which are extremely difficult to obtain for organic coatings and irregular wheat starch particles.

Another important contribution to the field of solid particle erosion was made by Hutchings et al. [18], who are among the very few authors who have published results on the wear of organic coatings. Their approach was based on the use of a gas blast erosion apparatus which is very similar to the blast cabinet used for the present research. Their analysis accounted for the size and composition of the particles. Hutchings [19], also studied systematically the influence of various blasting parameters on the velocity of the particles.

Some work has also been done to evaluate the durability of a coating by subjecting it to precisely controlled erosive conditions. Although the conditions used were very different from those investigated by the present research. Hutchings et al. [18], Chui et al. [20], Dioh et al. [21] and Schmitt et al. [22] helped define the methods used for this research. Some normalized tests to evaluate the abrasion resistance of coatings also exist, but they are generally characterized by a poor reproducibility (see [23]).

Finally, although the field of shot-peening has some similarity with blast cleaning, very little effort have been devoted to understanding the process itself. There has been much more concern about the effects of shot-peening and their quantification than about the equipment used to blast the surfaces with high-velocity beads. In most studies, the intensity of shot-peening is evaluated by Almen strip tests [24] (i.e. by measuring the deflection of thin metal strips after shot peening), but the way in which a change in blasting parameters affects the Almen arc height is not well documented.

1.4 Thesis objectives

The goals of the thesis research were to establish the mechanism of paint removal and the relative roles of various particle and blasting parameters for a specific aerospace paint
system on aluminium. More specifically, the effects of the following parameters were studied: shape, size and velocity of the particles, mass flowrate of media and angle between the nozzle and the surface to be depainted. The paint system chosen was MIL-P-23377 epoxy polyamide primer (25 µm [1 mil] thick) with MIL-C-83286 polyurethane topcoat (50–75 µm [2–3 mils] thick) on pretreated (chemical conversion treatment) AA 2024-T3 clad aluminium.

1.5 Thesis outline

The work has been divided into six chapters. Firstly, Chapter 2 presents the equipment that was used in this research, and the parameters used to control the process.

In Chapter 3, the impact sites left by the impact of wheat starch particles on the paint are studied in order to gain a better understanding of the paint removal process. The methods used are explained, micrographs are analysed and the qualitative conclusions are presented. The impact sites obtained with a stream of particles and the results of single particle impacts are studied.

Chapter 4 describes the experiments that were done in order to measure the size distribution and to quantify the shape of the wheat starch particles. The methods used are presented, and the implications of the results are discussed.

Chapter 5 presents the results of two different methods for measuring the velocity of the wheat starch particles as they exit the nozzle. A theoretical model is also developed to predict the velocity of the particles.

Next, in Chapter 6, experiments on the paint striping rates are presented. A new approach to characterize the paint striping rates is introduced, along with new parameters to quantify the exposure of the depainted surface to the abrasive stream. Theories are developed to explain the observations.

Finally, Chapter 7 summarises the conclusions obtained, and formulates recommendations for future work.
Chapter 2

Wheat starch blast cleaning

2.1 Equipment

The equipment used for wheat starch blast cleaning is similar to that used for sand-blasting. Figure 2.1 illustrates the main components of the blast cabinet used in the present research.

The abrasive media is stocked in the blast machine. The media valve controls the mass flowrate of media, which is fed into the compressed air stream at the bottom of the blasting machine. The air-abrasive stream is brought to the blast cabinet in a flexible rubber hose at the end of which a nozzle accelerates the abrasive particles. All the blasting is done inside the cabinet enclosure to prevent the dispersion of potentially harmful dust and to allow the media to be recycled. The used media is collected at the bottom of the cabinet and is carried to the reclaimer, where the fine particles are separated from the large ones. The large particles fall into the blast machine to be reused and the fine ones are sent to the dust collector, where they are discarded.

It should be noted that this type of blast cabinet cannot operate continuously; the blast machine is pressurised during operation, and an automatic valve seals it from the reclaimer. As long as the blast machine is pressurised, the recycled media stays in the reclaimer. When the blasting stops, the blast machine depressurizes, and the recycled media falls into it.

The cabinet used for the present research was manufactured by Clemco (model PCN
Figure 2.1: Blast cabinet

and was used with two different nozzles: a standard 6.35mm [1/4"] double-venturi nozzle and an experimental flat nozzle provided by CAE Electronics with an opening of 48 mm by 8 mm. The compressed air used by the blast cabinet was supplied by a compressor (Broomwade model V750, 200 hp) and dried to a dewpoint of 4.4°C [40°F] by an air drier (Atlas Copco model FD80).

2.2 Blasting parameters

The blast cleaning process can be controlled via five parameters: the abrasive media, the media mass flowrate, the pressure, the angle of attack and the standoff distance.

2.2.1 Abrasive media

The abrasive particles can be classified by their size distribution, their shape and their moisture content. Chapter 4 will present the analysis of the shape and size of the particles, and Appendix A will present the work that was done with respect to the moisture content of the wheat starch.

In this study, the only abrasive media used was Envirostrip wheat starch supplied by ADM/Ogilvie. All the experiments were performed with media of different mesh sizes.
Compressed air

Compressed air

Blast machine

Inspection door

Blast hose coupler

Figure 2.2: Blast machine

obtained from ADM/Ogilvie or with production mix, which was obtained from the CAE Envirostrip Test Center in Montréal. The production mix is obtained by continuously adding Envirostrip 12/30 to the recycled media to replace the fine particles that are eliminated by the reclaimer. It is the media used in all the tests done at the Envirostrip Test Center and the one that provides the highest paint stripping rates. In the rest of this work, it will be referred to as pmix.

Since Monette [25] showed that the wheat starch aggressivity varies greatly as it is recycled, it was decided to pay considerable attention to the state of the abrasive media used. Therefore, in order to eliminate the uncertainties associated with the history of the media used, only new media was used except for pmix, which was assumed to represent an equilibrium state between new and recycled media. In other words, a single charge of media was only used once.
To make sure that no old media was present in the blast machine before the experiments, the blast machine was emptied with a vacuum cleaner through the inspection door (see Figure 2.2), and any remaining particles in the media valve or in the blast hose were also removed with a vacuum cleaner through the blast hose connector.

### 2.2.2 Media mass flowrate

The mass flowrate of abrasive particles was adjusted with the media valve and was calculated as follows:

\[ \dot{m} = \frac{M}{\Delta t} \]  

where \( \dot{m} \) is the mass flowrate, \( M \) the mass of media in the blast machine and \( \Delta t \) the time it takes to empty the blast machine. To measure the flowrate, the blast machine was first emptied according to the procedure explained in Section 2.2.1. A sufficient quantity of media to perform the experiment was then precisely weighed and put in the blast machine through the inspection door. A timer was then used to record the duration of the abrasive jet. The blast machine made an easily identifiable sound when the abrasive media was exhausted, and it was possible to record \( \Delta t \) within ±1 second. The mass flowrate and pressure were very unstable during the first few and last seconds of blasting, so care was taken not to perform experiments during that period. The flow was left to stabilize for at least 10 seconds before starting the experiments, and nothing was done during the last 5 seconds of blasting.

Early experiments showed that the control of the mass flowrate obtained with the media valve was not very good, and that any change in the type of media or in the pressure led to large changes in the mass flowrate. so the actual mass flowrate was recorded for all the experiments.

### 2.2.3 Pressure

The blasting pressure was measured as specified by the Department of National Defence [26] using a needle pressure gauge as shown in Figure 2.3. The pressure at the blast machine was kept constant by a pressure regulator, but it had to be adjusted with reference to the nozzle pressure to take in account the pressure losses in the blast hose.
2.2.4 Angle of attack and standoff distance

The angle of attack was measured as the smallest angle between the axis of the nozzle and the surface to be depainted. To distinguish between the case when the stream of particles goes in the direction of travel of the sample and the case when the stream of particles goes in the direction opposite to the direction of the sample, it was decided that the angle of attack would be positive when the sample travels in the direction opposite to the stream, as illustrated in Figure 2.4, and negative otherwise.

The standoff distance was measured along the axis of the nozzle, from its end to the surface. The uncertainty in the standoff distance was about ±6 mm at an angle of attack of 45 degrees, but increased at lower angles. Fortunately, previous experimenters reported that the standoff distance did not have a very large effect on the blasting process.

2.3 Samples

The paint system used throughout this research were, as indicated in Section 1.4, MIL-P-23377 epoxy polyamide primer (25 μm [1 mil] thick) with a MIL-C-83286 Tempo matte grey polyurethane topcoat for a maximum total thickness of 100 μm [4 mils]. The substrate was AA 2024-T3 clad aluminium pretreated with chemical conversion treatment as per CFTO C-12-010-010/TP-000 Part 4 Section 2. The panels were painted on both sides and measured 30 cm x 30 cm x 3.2 mm thick. They were provided by the Canadian Department of National Defence.
The panels were delivered in batches of 10, and three panels in every batch were chosen at random for quality control checks. These were subjected to the ASTM tape paint adhesion test [27] and to the ASTM pencil hardness test [28]. The paint thickness was measured using an eddy-current paint thickness gauge on these panels and on all the panels that were used for the paint stripping rate experiments. All the panels tested were within acceptable limits. Table 2.1 summarises the results of these quality-control tests.

Table 2.1: Quality control checks for the sample panels

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range of measured values</th>
<th>Range of acceptable values</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paint adhesion</td>
<td>4B–5B</td>
<td>4B–5B</td>
<td>[27]</td>
</tr>
<tr>
<td>Paint hardness</td>
<td>F</td>
<td>-</td>
<td>[28]</td>
</tr>
<tr>
<td>Paint thickness</td>
<td>$87 \mu m–96 \mu m$</td>
<td>$75 \mu m–100 \mu m$</td>
<td>ISO 2808-1974 - 5</td>
</tr>
</tbody>
</table>
2.4 Blast cleaning experimental procedures

Wheat starch blast cleaning performance is evaluated by three parameters: the paint stripping rate, the damage done to the substrate and the media consumption. Both the paint stripping rate and the media consumption are economic factors: they determine the cost of stripping an airplane. On the other side, the damage done to the substrate determines if the process is acceptable: i.e. if an airplane can be depainted without unacceptable loss of safety or performance. These three parameters are linked, since increasing the paint stripping rates will usually only be possible at the cost of an increased potential for substrate damage and an increased media consumption.

Because of the complexity of the problem, it was decided to concentrate only on the optimization of the paint stripping rates.

2.4.1 Paint stripping rates

The paint stripping rates were determined as the maximum speed of the nozzle relative to the surface that can remove a paint system down to a specified layer: i.e. to the primer or to the substrate. The threshold for topcoat removal is reached when no topcoat is visible on the top of the primer, and the threshold for complete stripping is reached when no primer is visible on the substrate. For the paint system chosen for the present research, the topcoat was grey and the primer was yellow, which made it very easy to determine which degree of stripping was achieved.

The paint stripping rates were calculated as the area of paint removed divided by the amount of time needed to remove that area. When using an automated testing method, the paint stripping rates (psr) are calculated as follows:

\[ \text{psr} = \frac{u \times u}{w} \]

where \( u \) is the speed of the nozzle relative to the surface and \( w \) is the width of the trace left by the abrasive stream on the sample. The paint stripping rates are expressed in \( \text{m}^2/\text{h} \).
CHAPTER 2. WHEAT STARCH BLAST CLEANING

2.4.2 Substrate damage

The substrate damage is, for metallic substrates, the amount of plastic work that the substrate has sustained. It is measured by the surface roughness of the substrate after blasting and by the Aero Almen Arc height [29], i.e., by the deflection of thin aluminium strips after they have been exposed to the abrasive stream.

For composite substrates, the damage is qualitatively assessed by visual observation, using a microscope.

2.4.3 Media consumption

As the wheat starch particles strike the coating they break and get smaller. When they are too small, they must be removed from the blast cleaning system because wheat starch dust smaller than 125 μm is explosive, and because it is too aggressive, and can easily damage the substrate. The media consumption is, therefore, the mass of media that must be added to the system per unit time to maintain a constant size distribution.

2.5 Empirical observations

Probably the most important source of information for this research came from the unpublished observations of Denis Monette of CAE Electronics' Envirostrip Test Facility in Montréal. Over several years, he has used wheat starch paint stripping on a wide variety of substrates and paint systems, and has done a large number of experiments in order to maximize the paint stripping efficiency by varying the blasting parameters. The author met him on several occasions in 1995–1997, and collected the following observations.

Firstly, recycling the wheat starch has a considerable effect on the paint stripping efficiency. New media is not very aggressive but, as it is recycled and as the particles break, the media becomes more and more aggressive. This increased efficiency was attributed by Monette to a wider size distribution of the wheat starch particles, and to a change in the shape of the particles as they break.

Secondly, the water content of the wheat starch influences the paint stripping efficiency and the consumption of wheat starch. When the media is very dry, high paint
stripping rates can be achieved, but the media consumption is also very high, because the wheat starch particles break very quickly.

Thirdly, paint stripping rates go up with blasting pressure, but so does the potential for damaging the substrate. It is also possible to obtain high paint stripping rates at relatively low pressures (207 kPa [30 psi]) when using high media mass flowrates (>6.80 kg/min [15 lb/min]). In that case, the potential for damaging the substrate does not increase.

For some multi-layer coatings, including the MIL-P-23377/MIL-C-83286 coating system used in the present research, there is a selective stripping window, that is a range of speeds at which the nozzle can travel across the sample while removing the topcoat and not removing the primer. Some primers can tolerate overexposure to the abrasive stream without apparently suffering any damage.

Paint stripping is very sensitive to the angle between the nozzle and the surface to be depainted. Generally, the best paint stripping rates are achieved at intermediate angles, that is 45°-50°. Normal and low angles (20°) yield lower paint stripping rates. However, low angles enlarge the selective stripping window and decrease the potential for damaging the substrate, which makes their use suitable in some cases. High angles increase the potential for damaging the substrate, and reduce the selective stripping window, often making it impossible to perform selective stripping. Monette also reported that the direction of movement of the nozzle with respect to the flow direction of the abrasive stream has little or no impact on the paint stripping rates.

The standoff distance does not have a significant effect on the paint stripping rates. Generally, smaller standoff distances yield better paint stripping rates, but the difference is small: going from a standoff distance of 20.3 cm [8"] to 22.9 cm [9"] will not have any noticeable effect on paint stripping rates.

Lastly, the paint stripping process depends heavily on the coating system and on the substrate. For instance, selective stripping is not possible with all multi-layer coating systems, and identical coating systems can exhibit completely different behaviour on composite materials than on aluminium.
Chapter 3

Qualitative description of impact sites

In order to gain a better understanding of the paint removal process, a qualitative study was made of single wheat starch particle impact sites. The goal was to determine the mechanism of paint removal: i.e. whether the paint was removed by cutting, plowing, brittle erosion or delamination. These experiments also provided an estimate of the amount of damage caused by the impact of a single particle.

The work was divided in two parts: firstly, experiments were carried with the blast cabinet by exposing samples to the abrasive jet for short periods. Secondly, to confirm the results obtained with the blast cabinet, an airgun was used to launch single wheat starch particles against coated panels.

3.1 Impact sites with the blast cabinet

3.1.1 Methodology

To expose the samples to controlled amounts of media, a shutter was built (see Figure 3.1). It rotated about the nozzle, and could interrupt the jet of abrasive by blocking it with a metal plate. The shutter was operated manually, and allowed control of the exposure times to approximately 1 second, which was the exposure used for all the tests.
Figure 3.1: Shutter used to interrupt the abrasive flow at the outlet of the nozzle

The efficiency of the shutter was validated by blocking the stream of wheat starch for several minutes, and then checking the damage done to a sample. It was found that the shutter was able to quickly and reliably interrupt the abrasive stream.

During the experiments, only the coating directly under the abrasive stream was left exposed, and the rest of the sample panels was masked with thin aluminium plates to prevent interference between the tests. There were 9 tests on each sample panel, leaving a distance of 7.6 cm [3 in] between adjacent tests. Each exposure produced a range of impact site densities, depending on the distance from the centre-line of the nozzle. Individual impact sites were best observed at the edges of the flow.

After the tests, specimens of 25 mm by 25 mm were cut from the sample panels. The specimens were cleaned with ethanol. They were then inspected using an optical microscope, and several color pictures were taken. A few samples were also inspected using a scanning electron microscope.

Table 3.1 summarizes the range of parameters used to perform this experiment. The notation "*1" means that the media was recycled once, and "*2" means that the media was recycled twice.
Table 3.1: Blasting parameters used for the micrograph study

<table>
<thead>
<tr>
<th>Media</th>
<th>Mass flowrate [kg/min]</th>
<th>Pressure [kPa]</th>
<th>Angle [°]</th>
<th>Standoff distance [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>30/50</td>
<td>5.0</td>
<td>207</td>
<td>45</td>
<td>15</td>
</tr>
<tr>
<td>30/50*1</td>
<td>5.0</td>
<td>207</td>
<td>45</td>
<td>15</td>
</tr>
<tr>
<td>30/50*2</td>
<td>5.0</td>
<td>207</td>
<td>45</td>
<td>15</td>
</tr>
<tr>
<td>12/30</td>
<td>5.0</td>
<td>207</td>
<td>45</td>
<td>15</td>
</tr>
<tr>
<td>12/30*1</td>
<td>5.0</td>
<td>207</td>
<td>45</td>
<td>15</td>
</tr>
<tr>
<td>12/30*2</td>
<td>5.0</td>
<td>207</td>
<td>45</td>
<td>15</td>
</tr>
<tr>
<td>pmix</td>
<td>5.0</td>
<td>207</td>
<td>45</td>
<td>15</td>
</tr>
<tr>
<td>30/50</td>
<td>5.0</td>
<td>207</td>
<td>90</td>
<td>15</td>
</tr>
<tr>
<td>30/50*1</td>
<td>5.0</td>
<td>207</td>
<td>90</td>
<td>15</td>
</tr>
<tr>
<td>30/50*2</td>
<td>5.0</td>
<td>207</td>
<td>90</td>
<td>15</td>
</tr>
<tr>
<td>30/50</td>
<td>5.0</td>
<td>207</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>30/50*1</td>
<td>5.0</td>
<td>207</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>30/50*2</td>
<td>5.0</td>
<td>207</td>
<td>20</td>
<td>15</td>
</tr>
</tbody>
</table>
Figure 3.2: Transition between undamaged topcoat and complete topcoat removal down to the primer. Envirostrip 30/50, 5.0 kg/min [11 lb/min], 207 kPa [30 psi], 45°, 15 cm [6”]

3.1.2 Optical micrographs

In Figure 3.2, the effect of a wide range of local exposure conditions can be observed. At the far left of the picture (marker number one), no paint has been removed at all and very little damage is visible. At the far right of the picture (marker number three), the topcoat has been removed completely, and the primer is exposed. In the first third of the picture from the left, a few impact sites can be seen (marker number two), and it is evident that the size of the impact sites varies widely. It should also be noted that the shape of the impact sites does not seem to reflect the fact that the stream of particles was flowing from left to right.

Figure 3.3 shows the detail of the transition between the undamaged topcoat and the
Figure 3.3: Transition between regions of low and high damage to the topcoat. Envirostrip 30/50, 5.0 kg/min [11 lb/min], 207 kPa [30 psi], 45°, 15 cm [6"]
heavily damaged topcoat for the same sample as Figure 3.2. Although a large number of impacts are apparently superimposed at the far right of the picture (marker number two) and some topcoat appears to have been removed, the primer is not exposed anywhere. This indicates that no delamination occurred, and that the topcoat was removed in a cumulative fashion: i.e. each impact removed a small amount of coating, and multiple impacts were needed to remove the topcoat completely.

To the left of the same picture (marker number one), one can note that the topcoat is perfectly intact between the craters. This is a good indication that most craters in that area are the result of single impacts. If, on the contrary, most craters were the result of multiple impacts, one would not expect the paint to be intact between the craters, for there is no reason why two particles would strike at the same spot when the density of impacts is so low.

Next, Figure 3.4 shows the detail of the transition between the topcoat and the primer, again for the same sample. At the far left of the picture (marker number one), the heavily damaged topcoat is visible, and at the far right (marker number three), the primer is completely exposed. The transition from the topcoat to the primer is very irregular, and some islands of topcoat can be seen in the middle of the picture (marker number two). It should be noted that the primer does not seem to be damaged, even at the far right of the picture, where the exposure to the abrasive stream was the highest. This is corroborated by the presence a residual film of grey topcoat over the entire surface of the yellow primer which, unfortunately, cannot be seen easily on the black and white picture.

The transition between the topcoat and the primer when using a larger media size (Envirostrip 12/30 instead of Envirostrip 30/50) is illustrated in Figure 3.5. It can be seen that the transition is more irregular and that the size of the islands of topcoat is much larger than that observed on Figure 3.4. As well, the height of the islands of topcoat seems greater, implying that bigger wheat starch particles removed more paint per impact than do smaller ones.

In Figure 3.6, primer removal can be observed. It seems that the primer is removed in relatively large chunks and quite abruptly, since the primer around the spots where it has been removed shows no sign of damage. Moreover, the zones where the primer has been removed are very clean, and the rolling lines of the substrate are clearly visible.
Figure 3.4: Transition between the topcoat and the primer. Envirostrip 30/50. 5.0 kg/min [11 lb/min], 207 kPa [30 psi], 45°, 15 cm [6"]
Figure 3.5: Topcoat removal down to the primer. Envirostrip 12/30, 5.0 kg/min [11 lb/min], 207 kPa [30 psi], 45°, 15 cm [6"]
Figure 3.6: Partial primer removal. Production mix, 5.0 kg/min [11 lb/min], 207 kPa [30 psi], 45°, 15 cm [6"]
Figure 3.7: Transition between regions of low and high damage to the topcoat. Production mix. 5.0 kg/min [11 lb/min]. 207 kPa [30 psi]. 45°. 15 cm [6”]

Thus, some delamination may occur between the primer and the substrate.

Figure 3.7 shows the effect of production mix on the topcoat. The topcoat was removed in a fashion similar to that observed with Envirostrip 30/50 (see Figure 3.3). except that there are more impact sites and they are smaller. This was expected, since the average particle size of production mix is less than that of Envirostrip 30/50.

The effect of high angles of attack are depicted in Figure 3.8. At the far left (marker number one), the topcoat is completely removed and at the far right, the partially damaged topcoat can be seen (marker number three). The transition between the topcoat and the primer (marker number two) is much more clearly defined and less irregular than in Figure 3.4. The depth of the impact sites also seems greater than that observed at an angle of attack of 45°.
Figure 3.8: Transition between topcoat and primer. Envirostrip 30/50. 5.0 kg/min [11 lb/min], 207 kPa [30 psi], 90°, 15 cm[6"]
Figure 3.9: Partial topcoat removal. Envirostrip 30/50. 5.0 kg/min [11 lb/min]. 207 kPa [30 psi]. 20°. 15 cm [6”]. (Picture taken in the region of the sample that was the most damaged.)
Figure 3.10: Impact site viewed at high magnification. Envirostrip 30/50. 5.0 kg/min. 207 kPa. $45^\circ$. 15 cm

Figure 3.9 illustrates the effect of low angles of attack. The impact sites are very shallow and the abrasive stream was unable to completely remove the topcoat. From this, one might be tempted to jump to the conclusion that higher angles yield better paint stripping rates. However, Chapter 6 will show that this is wrong.

3.1.3 Scanning electron micrographs

Figure 3.10 shows an impact site located in a zone that had a light exposure to the abrasive stream, ensuring that the damage was caused by a single particle. The paint around the crater is intact and walls of the crater are very rough, indicating that the
paint was not removed in a purely brittle fashion. The fact that no cracks radiate from the impact site further support the hypothesis that the paint removal mechanism is not brittle. It should also be noted that, although the particle removed some paint, it did not go very deeply into the topcoat, and the primer was unaffected by the impact.

From the same sample, Figure 3.11 shows an enlargement of a zone located approximately at the right of Figure 3.3. It is interesting to note that, although the picture was taken in a heavily damaged zone, the area between the impact sites is still intact, as can be seen on the plateau at the top left corner of the picture. The same kind of impact sites seen in Figure 3.10 can be observed here.

Finally, Figure 3.12 illustrates primer removal. One can note that the area of primer
Figure 3.12: Primer removal. Envirostrip 12/30*1, 4.54 kg/min, 172 kPa, 45°, 15 cm. exposure time 4 s. The particle in the crater is dust.
removed is significantly larger than the impact sites observed on the topcoat (c.f. Figure 3.10). and that, as was observed in Figure 3.6, the surface of the aluminum in the center of the crater is perfectly clean. Although it is not possible to draw a conclusion about the mechanism of primer removal at this point, this would be consistent with a delamination of the primer from the substrate.

3.2 Impact sites with the airgun

To confirm the observations made with the blast cabinet, experiments were made using an airgun which allowed precise control over the number, size, velocity and angle of attack of the particles. In addition, the setup allowed the measurement of the velocity of the particle before and after the impact, which made it possible to calculate the kinetic energy lost during the collision, and to study particle fragmentation.

The airgun setup is illustrated in Figure 3.13. The wheat starch particle(s) was placed in a polyurethane sabot that was introduced into the breech of the barrel. When triggered, a solenoid valve allowed compressed air to accelerate the sabot and the particle. At the end of the barrel, the sabot was stopped, allowing the particle to continue on its own. The passage of the particle was detected by an infrared trigger, which activated the flash delay controller. As the particle flew towards the sample, hit it and rebounded, the flash delay controller triggered the four high-speed flashes in sequence. The image captured by the two cameras was hence the superposition of four images taken at different times. Once the sequence of flashes was completed, the pictures were acquired by a computer, which was used to store and analyse them.

Figure 3.14 shows a typical multiple exposure picture of a wheat starch particle colliding with a sample. The incident particle can be seen at two different times. Upon impact, the particle shattered, and its fragments can be seen after the impact.

All the experiments with the airgun were made using a particle velocity of approximately 130 m/s, which corresponds approximately to the highest velocities measured in the blast cabinet (see Section 5.1). The airgun experiments were performed using Envirostrip 12/30 (1071 μm average particle diameter) and Envirostrip 30/50 (664 μm average particle diameter) at angles of attack of 45° and 90°.
Figure 3.13: Airgun experimental setup
3.2.1 Scanning electron micrographs

The zone indicated by the arrows in Figure 3.15 illustrates the damage done by large particles at normal angle of attack. Curiously, the topcoat has not been penetrated, and all that is left on it is a mere dimple. The paint was not even scratched, as one can see in Figure 3.16.

As can be seen in Figure 3.17, lower angles of attack produce more damage. The surface of the paint was penetrated, and some topcoat was removed. Although much smaller in size, this impact site is similar to the one illustrated in Figure 3.10.

Figure 3.18 shows two scratches apparently caused by particle fragmentation. The wheat starch particle seems to have hit the sample at the bottom of the picture and broken into two main fragments, each of which left a scratch in the paint, forming the V-shaped mark. It is interesting to note that a significant amount of topcoat was damaged and removed after the incoming particle shattered.

The shattering of wheat starch particles on a larger scale is illustrated in Figure 3.19. Here, several divergent scratches were left in the topcoat as a wheat starch particle
Figure 3.15: Impact site left by one Envirostrip 12/30 particle at normal angle of attack $\alpha = 90^\circ$ and $v \approx 130$ m/s.
Figure 3.16: Enlargement of the region of Figure 3.15 pointed to by the arrow number one.
Figure 3.17: Impact site caused by an Envirostrip 12/30 particle at an intermediate angle of attack ($\alpha \approx 45^\circ$) and $v \approx 130$ m/s.
Figure 3.18: V-shaped mark left in the topcoat by an Envirostrip 12/30 particle. $\alpha = 45^\circ$ and $v \approx 130 \text{ m/s}$.
Figure 3.19: Converging marks left in the topcoat by a single Envirostrip 12/30 particle. 
$\alpha = 45^\circ$ and $v \approx 130$ m/s
Figure 3.20: Crater left by the impact of a single Envirostrip 12/30 particle. $\alpha = 45^\circ$ and $v \approx 130$ m/s. (Several Envirostrip 12/30 particles were launched at the same time: this picture shows only one of the many impacts left on the sample).

shattered in the top left corner of the picture, and its fragments apparently slid on the sample. The V-shaped marked of Figure 3.18 can also be seen at the end of arrow number one, but it was made during a separate collision.

Figure 3.20 shows one of the impacts left after launching several particles at a time with the airgun. As one can see, the particle plowed the topcoat in the direction indicated by arrow number one, causing it to tear open at the bottom of the crater (arrow number three). The marker number two shows the ridge of topcoat that was displaced by the particle. One can note that, although the topcoat was damaged, very little, if any was
Figure 3.21: Damage caused by an Envirostrip 30/50 particle. $\alpha = 45^\circ$ and $v \approx 90$ m/s. (Several Envirostrip 30/50 particles were launched at the same time; this picture shows only one of the many impacts left on the sample).

removed. It is plausible that subsequent impacts on the same zone would remove the paint more easily after this initial damage. This type of damage is different from what was observed in Figure 3.3, in which all the impacts seem to have removed some paint, and where it appeared that there was no initiation period before the topcoat started to be removed.

Finally, Figure 3.21 illustrates the damaged caused by Envirostrip 30/50 particles at smaller velocities. As one can see, the topcoat was displaced by the particle (arrow number one), which left several small scratches and cracks in the paint, some of which
are indicated by the arrows around marker number two. As in Figure 3.20, very little paint was removed by the impact, but the topcoat was damaged, perhaps leaving it more vulnerable to subsequent impacts.

3.3 Qualitative observations

Firstly, the topcoat was removed in cumulative way and, to remove it completely, several impacts were needed on the same spot. Depending on the conditions of the tests, different mechanisms of topcoat removal were observed. On the samples obtained with the blast cabinet, as in Figure 3.10, every impact seemed to remove some topcoat. While some of the impact sites obtained with the airgun were similar to those obtained with the blast cabinet, in some others the topcoat was damaged by the impacts but not removed, as seen in Figure 3.20 and in Figure 3.31.

The first topcoat removal behaviour observed suggests that there was no initiation period before the topcoat started to be removed and the second suggests that, on the contrary, the first impacts damaged the topcoat without removing it, and then the subsequent impacts actually removed the damaged topcoat. This apparent contradiction will be explained in Chapter 6, where it will be shown that there was indeed an initiation period that varied with the angle of attack, the size and the velocity of the particles.

In the cases where some topcoat was removed by individual impacts, a relatively large amount of damage was caused by a single wheat starch particle. For instance, the average diameter of the impact sites left by Envirostrip 30/50 particles (664 μm average diameter) when using blast cabinet was about 70 μm, that is about 1/10 the particle diameter.

Secondly, the impact sites did not show any indication of the direction of the abrasive stream. Since one would expect the shape of the impact sites to reflect the direction of the incoming particles if the tangential component of their velocity played an important role in the paint removal process, this could imply that the tangential component of the particle velocity did not play a significant role in the topcoat removal process.

Thirdly, delamination could be ruled out as the process of topcoat removal. The topcoat was removed gradually by a cutting process. However, delamination could have
played some role in the removal of primer, since it was removed rather abruptly.

Fourthly, it was observed that the primer can resist some exposure to the abrasive stream without showing any apparent damage. That *initiation time* before the primer started to be damaged is consistent with the selective stripping window reported in Section 2.5. With respect to the topcoat, there was no such initiation time, as some topcoat was removed even after extremely light exposures to the abrasive stream.

Finally, the impact sites obtained with the airgun showed that, when particle fragmentation occurred, some coating damage and removal took place after the particle broke.
Chapter 4

Particle size and shape distribution

Earlier work by Oestreich and Monette [25], as well as the empirical observations mentioned in Section 2.5 showed that paint stripping rates increased sharply as the size of the wheat starch particles decreased. In these experiments, the best paint stripping rates were achieved when using recycled media.

More specifically, the best paint stripping rates were achieved when using production mix, which was a mix of new and recycled media (see Section 2.2.1). It is interesting to note that, although the size distribution of production mix was similar to that of Envirostrip 30/100, the paint stripping rates obtained with production mix were significantly higher than those obtained with Envirostrip 30/100.

One hypothesis to explain this last result is that the shape of recycled particles is different and removes the paint more efficiently. A second possibility is that the higher paint stripping rates observed with production mix could be due to the presence of very small wheat starch particles that are not correctly detected by the conventional sieving methods used to obtain the size distribution. It was therefore decided to study the size and shape distribution of the wheat starch media by using a new approach.

4.1 Experimental procedure

Powder materials are often characterised by their size distribution obtained by sieving; that is by putting a known mass of material on top of a stack of sieves, with the largest
mesh at the top of the stack and the finest at the bottom. The stack of sieves is then shaken for a period of time, after which the powder left on every sieve is weighed. The size distribution is reported as the ratio of the mass of material on a certain sieve over the total mass of material. The size distribution of wheat starch particles is normally obtained using the guidelines outlined in [30].

The main weaknesses of this procedure are that it does not give any information on the shape of the particles, and the size distribution is influenced by the way in which the sieves are shaken. For instance, relatively fragile particles like wheat starch will break if they are shaken too vigorously or for too long.

The size distribution method devised for the present study is illustrated in Figure 4.1. A small quantity of particles were poured on a piece of matte black cardboard and a microscope (Leica Wild M3B) was used to observe them. A picture of the particles was taken by a video camera installed on the microscope, and the particles were measured by image analysis software (Image-Pro version 1.2, by Media Cybernetics). The microscope was set to a magnification of 6.4X, so that an 10 mm long object filled the width of the
screen (resolution of 64 pixels/mm).

Only about 10 particles were analysed on each picture. and since only a small area of the cardboard was covered by single a picture. the cardboard was moved under the microscope until its entire area was analysed. The particles on the cardboard were then discarded, and new particles (from the same sample) were poured on the cardboard. These steps were repeated until a least 500 particles were analysed.

For every particle on the picture. the image analysis software measured the minimum \(d_{\text{min}}\), maximum \(d_{\text{max}}\) and average \(d_{\text{avg}}\) diameters. the area \(A\) and the perimeter \(P\). To eliminate the particles that were too small to be accurately measured. the image analysis program was configured to discard particles with a minimum diameter smaller than 50 \(\mu\text{m}\). That data was later post-processed using a worksheet program. and the particles were classified according to their minimum diameter. which was assumed to be similar to the classification done by sieving. That classification was based on the mesh sizes listed in Table 4.1, which were the same mesh sizes as the ones used in [25].
Two different shape parameters were also calculated. The radius ratio \((Rr)\) measures the elongation of a particle and is calculated as follows:

\[
Rr = \frac{r_{max}}{r_{min}} = \frac{d_{max}}{d_{min}}
\]

where \(d_{min}\) and \(d_{max}\) are respectively the maximum and minimum diameters of a particle. The radius ratio is always greater than 1, which is the value associated with a circle.

The roundness coefficient \((Rd)\) measures how irregular the contour of a particle is. It is calculated as follows:

\[
Rd = \frac{P^2}{4\pi A}
\]

where \(P\) is the perimeter of the particle and \(A\) is its area. A circle has a roundness of 1, which is the smallest possible value. Very irregular particles have high values of \(Rd\). It should be noted that both the roundness coefficient and the radius ratio have no units and are independent of the size of the particle for which they are measured. Figure 4.2 illustrates the radius ratios and roundness coefficients of a few shapes.

Finally, the volume \((V)\) of the particles was calculated as:

\[
V = \frac{4}{3}\pi \frac{d_{avg}^3}{8}
\]

where \(d_{avg}\) is the average diameter of the particles. The size distribution of the particles was calculated as the volume of particles in a certain size range divided by the total volume of particles. Assuming that all particles had the same density, that “volume distribution” was equivalent to the size distribution measured by sieving.

The measurements obtained from the particles were based on a two-dimensional projection of the tri-dimensional wheat starch particles. Each wheat starch particle could
assume many different orientations when resting on a flat surface. So, since the particles were irregular, several different sets of 2-D measurements could be obtained for the same particle depending on its orientation. However, qualitative observations showed that the particles were not flat or flake-like and could rest on any of their numerous sides. Since a large number of particles were measured, it was assumed that the variability induced by using 2-D measurements to characterize 3-D particles was negligible.

Lastly, the shape measurements were only used to compare the wheat starch mixes and to establish if there were differences between them. If there was a systematic bias induced in the results by the experimental method, it was the same for all the experiments. Therefore, a systematic bias would not have affected the conclusions of this chapter, since they were based on a comparison of the shape and size parameters, and not on their absolute values.

4.1.1 Sampling procedure

Many books on powders [30] stress the importance of the sampling procedure. When powders are transported and stored, small particles tend to gather at the bottom of the heap and large ones tend to go to the top. Therefore, care must be taken to collect a representative sample.

For the present study, the sampling procedure was as follows. Firstly, a large sample (about 2 kg) was scooped from a new barrel of wheat starch. The sample was taken as deep as possible in the barrel. Secondly, that sample was divided by coning and quartering until a small sample (about 2 g) was obtained. Coning and quartering consists of pouring the material on a flat surface, and then dividing the cone of material into four quarters. Two opposite quarters are discarded and the two others are mixed together, and the process is repeated until a sufficiently small sample is obtained.

That sample was then poured, a small amount at a time, on the piece of black cardboard that was used as a background for the image analysis. Each time some of the small sample was poured on the black cardboard, it was first mixed thoroughly to minimize segregation.

Even with all the precautions taken to ensure that the samples were representative,
Figure 4.3: Average minimum diameter of wheat starch particles: comparison of repetitions with the same media.

The total mass of wheat starch analysed was only of the order of 0.15 g, which is extremely small and thus sensitive to biased sampling. To minimize this sampling error, 10 independent samples were taken for each wheat starch type and analysed separately.

Figure 4.3 illustrates the spread of the measured average minimum diameter among several experiments performed with the same media. That spread was due to the sampling procedure and to the fact that two-dimensional measurements were used to characterize three-dimensional particles (repeatability error). Because of the very small size of the particles and because of the experimental setup used, it was impossible to measure the spread associated with the repeatability error by, for instance, analysing the same particles twice. However, for the reasons outlined earlier, it was assumed that this variability was small compared to that due to the sampling procedure.

Although the average minimum diameter varied between repetitions with the same media, that variability was small compared to the difference between the average min-
imum diameter of different types of media. and it was concluded that the sampling procedure was valid.

4.1.2 Statistical analysis

To eliminate the bias induced by the sampling procedure. the statistical analysis was carried out on the averages obtained for each experiment rather than on all the data points collected. The following provides the details of the analysis.

Let $x$ be some measured quantity, $a$ be the number of replications of an experiment, and $b_i$ the number of data points recorded during experiment $i$. The average over one experiment is:

$$
\bar{x}_i = \frac{1}{b_i} \sum_{j=1}^{b_i} x_{ij}
$$

The average and standard deviation over all the replications of an experiment are:

$$
\bar{x} = \frac{1}{a} \sum_{i=1}^{a} \bar{x}_i
$$

$$
S_x^2 = \frac{1}{a-1} \sum_{i=1}^{a} (\bar{x}_i - \bar{x})^2
$$

Before carrying the analysis any further. the outliers were eliminated according to the $2S_x$ criterion. that is, the experiments for which $|\bar{x} - \bar{x}_i| > 2S_x$ were eliminated. and $\bar{x}$ and $S_x$ were recalculated. The confidence limits for the averages were calculated as follows:

$$
\mu_{\text{min}} = \bar{x} - \frac{S_x t_{\alpha/2; \nu}}{\sqrt{\alpha}}
$$

$$
\mu_{\text{max}} = \bar{x} + \frac{S_x t_{\alpha/2; \nu}}{\sqrt{\alpha}}
$$

where $t$ is the Student statistical distribution function. $\alpha$ is the significance level of the test and $\nu$ is the number of degrees of freedom of the statistical distribution function.

For the present research. the highest confidence level $P_\alpha$ at which it was possible to draw a statistically significant conclusion was 90%. and 10 replications of each experiment were made, so:

$$
\alpha = 1 - P_\alpha = 0.1
$$
$\nu = n - 1 = 9$

$t_{0.05,9} = 1.833$

$\mu_{\min} = \overline{x} - \frac{1.833S_x}{\sqrt{9}}$

$\mu_{\max} = \overline{x} + 0.611S_x$  \hspace{1cm} (4.9)

$\mu_{\max} = \overline{x} + 0.611S_x$  \hspace{1cm} (4.10)

4.2 Results

4.2.1 Size distribution

The size distribution obtained optically was found to be in reasonable agreement with the size distribution obtained by meshing. The size distributions obtained optically are compared to the size distributions obtained by sieving (data from [25] and from [31]) in Table 4.2, in Table 4.3 and in Table 4.4. It should be noted that the specification for Envirostrip starch media (see Table 4.6) allows for some variation, and both the size distributions obtained optically and the size distributions obtained by meshing are reasonably close to these specifications. The size distribution of production mix is tabulated in Table 4.5.

optically for four different media, and Figure 4.5 compares the size distributions obtained by sieving for the same four media. Production mix has the widest size distribution, and also contains the most fine particles (mesh size less than 60). Envirostrip 12/30 media has the narrowest size distribution and Envirostrip 30/50 and Envirostrip 30/100 are between these two extremes. It is interesting to note that the center of the production mix size distribution coincides with the center of the Envirostrip 30/50 size distribution.

However, in terms of average particle size, one can clearly see from Figure 4.6 that the average particle size of production mix is much smaller than that of Envirostrip 30/50. One can note that, while there is a difference in aggressiveness between production mix and of Envirostrip 30/100, the difference between their average particle size is insignificant, which implies that the paint removal rates are not uniquely controlled by the
Table 4.2: Comparison of size distributions obtained by sieving and optically for Envirostrip 12/30

<table>
<thead>
<tr>
<th>Mesh size (as % retained on mesh)</th>
<th>Sieving</th>
<th>Optical</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 60</td>
<td>0.3</td>
<td>0.0</td>
</tr>
<tr>
<td>60</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>50</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>40</td>
<td>2.8</td>
<td>3.6</td>
</tr>
<tr>
<td>30</td>
<td>16.4</td>
<td>22.5</td>
</tr>
<tr>
<td>20</td>
<td>73.1</td>
<td>73.0</td>
</tr>
<tr>
<td>12</td>
<td>7.2</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Table 4.3: Comparison of size distributions obtained by sieving and optically for Envirostrip 30/50

<table>
<thead>
<tr>
<th>Mesh size (as % retained on mesh)</th>
<th>Sieving</th>
<th>Optical</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 100</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>100</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>80</td>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>60</td>
<td>2.1</td>
<td>2.5</td>
</tr>
<tr>
<td>50</td>
<td>28.6</td>
<td>27.5</td>
</tr>
<tr>
<td>40</td>
<td>65.9</td>
<td>54.3</td>
</tr>
<tr>
<td>30</td>
<td>2.6</td>
<td>14.8</td>
</tr>
</tbody>
</table>
Table 4.4: Comparison of size distributions obtained by sieving and optically for Envirostrip 30/100

<table>
<thead>
<tr>
<th>Mesh size (as % retained on mesh)</th>
<th>Sieving</th>
<th>Optical</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>4.7</td>
<td>0.7</td>
</tr>
<tr>
<td>100</td>
<td>6.6</td>
<td>1.2</td>
</tr>
<tr>
<td>80</td>
<td>15.4</td>
<td>9.8</td>
</tr>
<tr>
<td>60</td>
<td>33.9</td>
<td>17.8</td>
</tr>
<tr>
<td>50</td>
<td>31.1</td>
<td>66.2</td>
</tr>
<tr>
<td>40</td>
<td>8.4</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Table 4.5: Comparison of size distributions obtained by sieving and optically for production mix

<table>
<thead>
<tr>
<th>Mesh size (as % retained on mesh)</th>
<th>Sieving</th>
<th>Optical</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;100</td>
<td>9</td>
<td>1.3</td>
</tr>
<tr>
<td>100</td>
<td>7</td>
<td>1.4</td>
</tr>
<tr>
<td>90</td>
<td>13</td>
<td>-</td>
</tr>
<tr>
<td>80</td>
<td>16</td>
<td>6.8</td>
</tr>
<tr>
<td>70</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>60</td>
<td>14</td>
<td>6.3</td>
</tr>
<tr>
<td>50</td>
<td>10</td>
<td>20.1</td>
</tr>
<tr>
<td>40</td>
<td>6</td>
<td>26.0</td>
</tr>
<tr>
<td>30</td>
<td>4</td>
<td>23.9</td>
</tr>
<tr>
<td>20</td>
<td>6</td>
<td>14.2</td>
</tr>
</tbody>
</table>
Figure 4.4: Size distribution of different wheat starch mixes obtained optically. □ Production mix, ■ Envirostrip 30/100. ■ Envirostrip 30/50. ■ Envirostrip 12/30.
Figure 4.5: Size distribution of different wheat starch mixes obtained by sieving. □ Production mix. ■ Envirostrip 30/100, ■ Envirostrip 30/50. ■ Envirostrip 12/30.
Figure 4.6: Average diameter of different media (optical measurements)
Table 4.6: Envirostrip wheat starch size specifications (from [32])

<table>
<thead>
<tr>
<th>Mesh size</th>
<th>Size distribution (as % retained on mesh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Envirostrip 12/30</td>
</tr>
<tr>
<td>12</td>
<td>max. 5%</td>
</tr>
<tr>
<td>20</td>
<td>min. 65%</td>
</tr>
<tr>
<td>30</td>
<td>max. through 5% a</td>
</tr>
<tr>
<td>40</td>
<td>-</td>
</tr>
<tr>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>60</td>
<td>min. 50%</td>
</tr>
<tr>
<td>80</td>
<td>min. 10%</td>
</tr>
<tr>
<td>100</td>
<td>max. through 10%</td>
</tr>
</tbody>
</table>

*aIn other words, at most 5% of the media is smaller than mesh 30, i.e. would go through mesh 30.

average particle size. Finally, it is worth mentioning that when the media are ranked in order of increasing average diameter, they are also in order of decreasing aggressiveness, as will be seen in Chapter 6.

4.2.2 Shape of wheat starch particles

The analysis of the radius ratio data for Envirostrip 12/30, Envirostrip 30/50, Envirostrip 30/100 and production mix reveals that production mix particles are rounder than new particles. As can be seen on Figure 4.7, the radius ratio of Envirostrip 12/30 and Envirostrip 30/50 particles are in the same range, and the radius ratio of production mix particles is significantly lower. The radius ratio of Envirostrip 30/100 is between that of production mix and of the two larger types of Envirostrip media, and the difference in radius ratio between Envirostrip 30/100 and production mix is insignificant. Thus, smaller particles, as found in Envirostrip 30/100 and in production mix, have a different shape from larger particles.

It might be intuitively expected that elongated particles (i.e. particles with a high
Figure 4.7: Comparison of the radius ratio of different wheat starch mixes. The error bars correspond to the 90% confidence interval.
radius ratio) cut into the paint the most easily. However Figure 4.7 shows that, on the contrary, the particles with the lowest radius ratio are the most aggressive (neglecting the effect of different size distributions). This surprising result implies that the kinetic energy of round particles is somehow better used to remove the paint.

![Figure 4.8: Comparison of the roundness coefficient of different wheat starch mixes. The error bars correspond to the 90% confidence interval.](image)

Contrary to the interesting results obtained from the analysis of the radius ratio, the analysis of the roundness coefficients does not allow any clear conclusion to be made. As can be see in Figure 4.8, at the 90% confidence level, neither the difference between production mix and Envirostrip 30/50 nor the difference between Envirostrip 30/50 and Envirostrip 12/30 are significant. However, one can note that an increasing roundness coefficient (more irregular perimeter) generally corresponds to decreasing aggressiveness (again, neglecting size distribution effects). This supports the previous result, that the more aggressive media have particles that tend to be more spherical.
4.3 Discussion

The analysis of the size and shape data for Envirostrip 12/30, Envirostrip 30/50, Envirostrip 30/100 and production mix revealed several trends. Although it was not possible to definitively link cause and effect in all cases because size and shape changed simultaneously.

Firstly, the aggressiveness of a mix decreased as the average size of the particles increased. This will be explained in Chapter 5, where it will be shown that smaller particles reach a higher velocity. However, it was shown that the difference in particle size between Envirostrip 30/100 and production mix is insignificant, so the paint removal rates must also be controlled by other factors.

Secondly, it was observed that media with higher aggressiveness also had wide size distributions. Two hypotheses could possibly explain this observation. Firstly, a balance of large and small particles may be needed in order to remove the paint most efficiently. For instance, the large particles could remove the hard, glossy finish of the topcoat, and small particles could then more easily remove relatively the rest of the paint. Or, alternatively, the width of the size distribution itself could have no importance at all, and only the content in small particles (smaller than mesh 60) of a mix could be significant, since media with wide size distribution also had a significant proportion of small particles. The median of the size distribution, for instance, did not mean anything, since Envirostrip 30/50 and production mix had the same median size, but very different aggressiveness.

Thirdly, smaller mixes had a lower average radius ratio (i.e. were less elongated) than larger mixes, and were much more aggressive. A proposed explanation is that elongated particles fracture more easily upon impact than round particles, perhaps resulting in a less efficient use of their kinetic energy.

It was impossible to draw a statistically significant conclusion regarding the differences in roundness coefficients of different media. In other words, it was not possible to prove that the different wheat starch mixes had different roundness coefficients.

The most revealing comparisons are between production mix and Envirostrip 30/100. These two mixes have almost identical average particle diameters, roundness ratios and
roundness coefficients, but it is known that production mix is more aggressive (see paint stripping rates in Chapter 6). The only significant difference between production mix and Envirostrip 30/100 was the shape of the size distribution: i.e. Figure 4.4 shows that production mix has a broader distribution. Perhaps this contributes to the added aggressiveness of production mix.

It is also interesting to note that the shape parameters of the particles varied simultaneously with their size, and that Envirostrip 30/100 and production mix had the same average diameter and the same shape parameters. This could imply that the shape of wheat starch particles is physically related to their size. A possible explanation is that, as the particles get smaller (either through a manufacturing process or through recycling), they approach the natural size (or grain size) of wheat starch crystals, so that their shape gets closer to the natural shape of these crystals.
Chapter 5

Velocity of wheat starch particles

As mentioned in Section 2.2, the blasting conditions are readily characterized in industry by various operating parameters such as nozzle pressure, media mass flowrate and standoff distance. However, the effect of these parameters on paint removal depends heavily on the type of equipment used. It was, therefore, decided to use the velocity of the particles as an independent means of characterizing the blasting conditions.

Moreover, the velocity of the particles was suspected to be one of the main parameters governing the paint stripping process. A knowledge of the velocity of the particles was needed to verify if either the normal or tangential component of the velocity controlled the paint stripping process, and velocity data were also necessary to calculate the work exposure, a new parameter proposed in Chapter 6 to quantify the blasting conditions.

Wheat starch particle velocities were studied using two different approaches. Firstly, the velocity of the particles at the exit of the nozzle were measured by high-speed photography and, secondly, a mathematical model was built to qualitatively study the velocity distribution of the particles as a function of their size. Finally, the results of these two approaches were compared with the velocities measured by another experimental method (see [33]).
5.1 Velocity measurements

5.1.1 Experimental setup

Wheat starch particle velocities were measured inside the blast cabinet with the setup illustrated in Figure 5.1. Four high-speed flashes (Strobotac, model Stroboslave 1539 A) and a black and white video camera (Hitachi KP-M1U) were put in front of the blast cabinet window. A flash delay controller, adjustable in increments of 1 μs, triggered the four flashes in sequence, and a frame grabber transferred the multiple exposure picture to a computer, where it was stored. An interface board also allowed the computer to start the flash sequence, and a small program was written to trigger the flashes, capture the video picture and save it on disk. The end of the nozzle was included in the pictures.
Figure 5.2: Multiple exposure picture obtained with Envirostrip 12/30, 207 kPa, 2.72 kg/min. 25 μs between the flashes. The nozzle is visible at the left of the picture.

to serve as a reference length (the nozzle external diameter was 33.63 mm) when the analysis was done.

The nozzle was held in front of the camera by a clamp (not shown in Figure 5.1) and, to minimize the dust in the blast cabinet, a deflector was used to direct the wheat starch stream towards the bottom of the blast cabinet, where it was recovered by the media recycling unit.

Once the experiment was completed, the pictures were analysed using image analysis software (Image-Pro version 1.2, by Media Cybernetics). Each group of four equally spaced dots in a row were considered to be a single particle, at four different times. The velocity of the particles was calculated as follows:

\[ v = \frac{l}{3\Delta t} \]  

(5.1)

where \( v \) is the velocity of the particles, \( l \) the distance between the center of the first and last particles of the row and \( \Delta t \) the delay between each flash. A sample picture obtained with the experimental setup is shown in Figure 5.2. To select the best flash delay, and to ensure that no particle was going so fast that it was not correctly identified, an experiment was conducted using decreasing flash delays. It was found that a flash delay of 25 μs gave the best results, and that no particle was going significantly faster than 250 m/s.

The effect of the out-of-plane velocity components was neglectible, since the divergence of the abrasive stream at the exit of the nozzle was small. On the multiple-exposure
pictures. the vertical distance (i.e. normal the the abrasive stream) between the first and last image of a particle was never larger than 1 mm.

Because it was possible to positively identify only a few particles on each picture, the program written to control the acquisition of pictures was configured to take 40 pictures at an interval of 1 second. The quality of the pictures varied considerably depending on the blasting conditions and, due a high dust level inside the blast cabinet, it was impossible to measure the velocity of production mix particles. Similarly, the velocity measured with Envirostrip 30/100 at 4.54 kg/min [10 lb/min] should be taken with caution.

Other methods used to measure the velocity of the particles

Three other methods have also been used to measure the velocity of the particles. Firstly, an attempt was made to use the electronic shutter of a video camera to get very short exposure times. During the exposure time, the wheat starch particles travelled over a certain distance, leaving a streak on the pictures. By dividing the length of the streaks by the exposure time, the velocity was obtained. However, it was found that an extremely intense illumination was needed in order to clearly see the streaks on the video images, and the method was abandoned.

In an attempt to solve the illumination problem encountered with the previous method, a photographic flash was used as the light source when the video camera shutter was left open. The length of the streaks was therefore controlled by the velocity of the particles and the duration of the flash. This did not work either because it was difficult to determine the duration the light pulse emitted by the flash, since the pulse began and ended very gradually.

Lastly, a rotating disk device similar to the one described by Ruff and Ives [34] was built and successfully used by Djurovic [33] to measure the velocity of Envirostrip 12/30, Envirostrip 30/50 and Envirostrip 30/100. The average velocities measured with the rotating disk are compared with the ones obtained with the multiple flash technique in Section 5.3
Table 5.1: Wheat starch average particle velocities measured optically with the round nozzle

<table>
<thead>
<tr>
<th>Media</th>
<th>Pressure [kPa]</th>
<th>Mass flowrate [kg/min]</th>
<th>Average velocity [m/s]</th>
<th>Number of particles (n)</th>
<th>95% confidence limits [m/s]</th>
<th>Power [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/30</td>
<td>241</td>
<td>4.54</td>
<td>116.9</td>
<td>133</td>
<td>113.8 - 120.0</td>
<td>597</td>
</tr>
<tr>
<td>30/50</td>
<td>241</td>
<td>4.54</td>
<td>111.1</td>
<td>123</td>
<td>106.7 - 115.4</td>
<td>615</td>
</tr>
<tr>
<td>30/100</td>
<td>241</td>
<td>4.54</td>
<td>106.8</td>
<td>78</td>
<td>102.1 - 111.5</td>
<td>527</td>
</tr>
<tr>
<td>12/30</td>
<td>207</td>
<td>4.54</td>
<td>112.4</td>
<td>191</td>
<td>106.3 - 118.4</td>
<td>488</td>
</tr>
<tr>
<td>30/50</td>
<td>207</td>
<td>4.54</td>
<td>107.3</td>
<td>86</td>
<td>101.2 - 113.4</td>
<td>503</td>
</tr>
<tr>
<td>30/100</td>
<td>207</td>
<td>4.54</td>
<td>94.5</td>
<td>90</td>
<td>90.6 - 98.3</td>
<td>411</td>
</tr>
<tr>
<td>12/30</td>
<td>172</td>
<td>4.54</td>
<td>109.0</td>
<td>167</td>
<td>107.3 - 110.7</td>
<td>420</td>
</tr>
<tr>
<td>30/50</td>
<td>172</td>
<td>4.54</td>
<td>98.2</td>
<td>233</td>
<td>95.6 - 100.7</td>
<td>414</td>
</tr>
<tr>
<td>30/100</td>
<td>172</td>
<td>4.54</td>
<td>96.8</td>
<td>94</td>
<td>92.4 - 101.2</td>
<td>465</td>
</tr>
<tr>
<td>12/30</td>
<td>241</td>
<td>2.72</td>
<td>135.3</td>
<td>165</td>
<td>132.8 - 137.8</td>
<td>405</td>
</tr>
<tr>
<td>30/50</td>
<td>241</td>
<td>2.72</td>
<td>132.0</td>
<td>85</td>
<td>126.9 - 137.1</td>
<td>417</td>
</tr>
<tr>
<td>12/30</td>
<td>207</td>
<td>2.72</td>
<td>124.6</td>
<td>235</td>
<td>122.9 - 126.2</td>
<td>342</td>
</tr>
<tr>
<td>30/50</td>
<td>207</td>
<td>2.72</td>
<td>123.6</td>
<td>72</td>
<td>118.2 - 129.0</td>
<td>346</td>
</tr>
<tr>
<td>30/100</td>
<td>207</td>
<td>2.72</td>
<td>134.5</td>
<td>108</td>
<td>129.7 - 139.3</td>
<td>434</td>
</tr>
<tr>
<td>12/30</td>
<td>172</td>
<td>2.72</td>
<td>122.4</td>
<td>288</td>
<td>121.0 - 123.9</td>
<td>301</td>
</tr>
<tr>
<td>30/50</td>
<td>172</td>
<td>2.72</td>
<td>126.5</td>
<td>92</td>
<td>122.6 - 130.4</td>
<td>360</td>
</tr>
<tr>
<td>12/30</td>
<td>241</td>
<td>1.81</td>
<td>144.6</td>
<td>114</td>
<td>141.9 - 147.3</td>
<td>320</td>
</tr>
<tr>
<td>30/50</td>
<td>241</td>
<td>1.81</td>
<td>167.9</td>
<td>79</td>
<td>156.3 - 179.6</td>
<td>514</td>
</tr>
</tbody>
</table>
Table 5.2: Wheat starch particle velocities measured optically with the flat nozzle

<table>
<thead>
<tr>
<th>Media</th>
<th>Pressure [kPa]</th>
<th>Mass flowrate [kg/min]</th>
<th>Average velocity [m/s]</th>
<th>Number of particles (n)</th>
<th>95% confidence limits [m/s]</th>
<th>Power [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/30</td>
<td>207</td>
<td>4.54</td>
<td>146.2</td>
<td>152</td>
<td>142.2 150.3</td>
<td>959</td>
</tr>
<tr>
<td>30/50</td>
<td>207</td>
<td>4.54</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

5.1.2 Results

The velocities measured with the round nozzle are tabulated in Table 5.1, and the velocities measured with the flat nozzle are tabulated in Table 5.2. Due to high levels of dust inside the blast cabinet, it was only possible to measure particle velocities when using Envirostrip 12/30 with the flat nozzle. The only velocity measurement obtained with the flat nozzle showed that, under similar operating parameters, the particles were accelerated to higher speeds than with the round nozzle.

As can be seen in Figure 5.3, the mass flowrate was the parameter that had the largest impact on particle velocity. As the mass flowrate increased, the particle velocity decreased. An increase in pressure also yielded a velocity increase, but that effect was small compared to the effect of the mass flowrate. The small influence of pressure on the average particle velocity is somewhat in contradiction to the qualitative observations reported in Section 2.5; i.e., that an increase in pressure yielded a significant increase in productivity. However, Figure 5.4 will show that the stream power increased sharply with the pressure, which reconciles the measurements with the qualitative observations.

One can note that the average velocities measured with Envirostrip 30/100 at 4.54 kg/min did not vary with pressure in the same fashion as Envirostrip 12/30 and Envirostrip 30/50. This confirms that the velocities measured with Envirostrip 30/100 at 4.54 kg/min are not reliable.

Finally, particle velocity did not show any clear trend with respect to particle size. For instance, the average velocity of Envirostrip 30/50 and Envirostrip 12/30 were about the same at 2.72 kg/min, but the velocity of Envirostrip 30/50 was lower than that of
CHAPTER 5. VELOCITY OF WHEAT STARCH PARTICLES

Figure 5.3: Wheat starch particles average velocities measured with the round nozzle. ◆ Envirostrip 12/30 at 1.81 kg/min. ○ Envirostrip 12/30 at 2.72 kg/min, □ Envirostrip 12/30 at 4.54 kg/min. ◆ Envirostrip 30/50 at 1.81 kg/min. ● Envirostrip 30/50 at 2.72 kg/min. ■ Envirostrip 30/50 at 4.54 kg/min. ● Envirostrip 30/100 at 2.72 kg/min. □ Envirostrip 30/100 at 4.54 kg/min.
Envirostrip 12/30 at 4.54 kg/min and higher at 1.81 kg/min.

The power of the stream of particles was calculated as follows. The kinetic energy, $K$, of a single particle is:

$$K = \frac{1}{2}mv^2$$  \hspace{1cm} (5.2)

Here, the mass, $m$, and the velocity, $v$, of the individual particles is unknown, but the mass flowrate, $\dot{m}$, and the average velocity, $\bar{v}$, are. The power $P$ of the stream is hence:

$$P = \frac{1}{2}\dot{m}\bar{v}^2$$  \hspace{1cm} (5.3)

The total stream power in illustrated in Figure 5.4. It is interesting to note that, while an increase in mass flowrate resulted in a decreased particle velocity, the total power of the stream increased. This is due to the fact that the decrease in particle velocity was more than offset by the increase in mass flowrate. In addition, pressure had a much greater effect on stream power than on velocity, since it is a function of the square of velocity.

To summarize, the velocity measurements showed that the power of the flow increased both with the pressure and with the mass flowrate. In addition, the particle velocity increased with the pressure but decreased with the mass flowrate. This is consistent with the empirical observations reported in Section 2.5, namely that higher blasting pressures yielded higher paint stripping rates but at the cost of an increased potential for substrate damage, and that higher mass flowrates yielded higher paint stripping rates without increasing the potential for substrate damage. Moreover, this indicates that the paint stripping rates depended on the stream power and that the potential for substrate damage depended on particle velocity.

### 5.2 Velocity model

The velocity model was based on the following assumptions:

- All the particles have the same density.
- The particles are round and have all the same drag coefficient.
- All the particles arrive at the nozzle with the same velocity.
Figure 5.4: Power of the abrasive stream measured with the round nozzle. ◇ Envirostrip 12/30 at 1.81 kg/min, ◆ Envirostrip 12/30 at 2.72 kg/min, □ Envirostrip 12/30 at 4.54 kg/min, ● Envirostrip 30/50 at 1.81 kg/min, ○ Envirostrip 30/50 at 2.72 kg/min, ■ Envirostrip 30/50 at 4.54 kg/min. ◆ Envirostrip 30/100 at 2.72 kg/min. □ Envirostrip 30/100 at 4.54 kg/min
• All the particles are exposed to the same air speed in the nozzle.
• The distance over which the particles accelerate is the same for all particles.
• The velocity of the air stream is uniform in the nozzle.
• The flow conditions in the nozzle are independent of the mass flowrate of particles.
• There are no interparticle effects (i.e. collisions).
• The density of the air is constant as it passes through the throat of the nozzle and exits.

It should be noted that the assumption that there are no interparticle effects is somewhat problematic since the velocity measurements showed that, under the same pressure, the average velocities varied widely with the mass flowrate and the type of media used. The velocity model is thus only valid for very small mass flowrates, when interparticle effects are negligible. However, the model allows the variations of particle velocity and kinetic energy to be qualitatively analysed with respect to particle size.

The following symbols were used:

$c_d$  Drag coefficient of the particles
$v_a$  Speed of the air in the expansion portion of the nozzle
$v_i$  Initial velocity of a particle (i.e. before it enters the nozzle)
$v_o$  Velocity of a particle at the exit of the nozzle
$v$  Instantaneous velocity of a particle
$a$  Instantaneous acceleration of a particle
$\rho_a$  Density of the air
$\rho$  Particle density
$d$  Particle diameter
$A$  Frontal area of a particle
$m$  Particle mass
$x_a$  Acceleration distance
$\Delta t$  Duration of the acceleration
5.2.1 Velocity distribution

The mass of an idealized (spherical) particle is:

\[ m = \rho \frac{4}{3} \pi r^3 = \frac{\pi \rho}{6} d^3 \tag{5.4} \]

And its frontal surface:

\[ A = \pi r^2 = \pi \frac{d^2}{4} \tag{5.5} \]

The drag on a particle is:

\[ D = \frac{1}{2} \rho_a \ast (v_v - v)^2 \ast C_d \ast A \tag{5.6} \]

Thus, the acceleration a particle is:

\[ a = \frac{D}{m} = \frac{3 c_d \rho_a (v_v - v)^2}{4 \rho d} \tag{5.7} \]

To obtain the velocity of the particles, the following differential equation must be solved:

\[ \frac{\delta v}{\delta t} = \frac{3 c_d \rho_a}{4 \rho d} \left( v_v^2 - 2 v_v v + v^2 \right) \tag{5.8} \]

\[ \frac{\delta v}{v_v^2 - 2 v_v v + v^2} = \frac{3 c_d \rho_a}{4 \rho d} \delta t \]

\[ \frac{1}{v_v - v} = \frac{3 c_d \rho_a t}{4 \rho d} + C_1 \]

\[ v = v_v - \frac{4 \rho d}{3 c_d \rho_a t + 4 \rho d C_1} \tag{5.9} \]

And, since the first boundary condition is \( v(t = 0) = v_i \),

\[ v_i = v_v - \frac{4 \rho d}{4 \rho d C_1} \]

\[ C_1 = \frac{1}{v_v - v_i} \tag{5.10} \]

To shorten the expression, the following constant is defined:

\[ \alpha = \frac{3 c_d \rho_a}{4 \rho d} \tag{5.11} \]
And the final expression for \( v \) is:

\[
v(t) = v_v - \frac{1}{\alpha t + \frac{1}{v_v - v_i}}
\]  

That expression is solved for \( x(t) \):

\[
v(t) = \frac{\delta x}{\delta t} = v_v - \frac{v_v - v_i}{\alpha(v_v - v_i)t + 1}
\]

\[
\delta x = \left[ v_v - \frac{v_v - v_i}{\alpha(v_v - v_i)t + 1} \right] \delta t
\]

\[
x + C_2 = v_v t - \frac{v_v - v_i}{\alpha(v_v - v_i)} \ln \left[ \alpha(v_v - v_i)t + 1 \right] + C_2
\]

\[
x + C_2 = v_v t - \frac{1}{\alpha} \ln \left[ \alpha(v_v - v_i) + 1 \right]
\]  

The second boundary condition being \( x(t = 0) = 0 \), the solution for \( C_2 \) is:

\[
x(t = 0) + C_2 = 0 + C_2
\]

\[
C_2 = -\frac{1}{\alpha} \ln [1]
\]

\[
C_2 = 0
\]  

The last boundary condition is \( x(t = \Delta t) = x_a \), so:

\[
x(\Delta t) = x_a
\]

\[
x_a = v_v \Delta t - \frac{1}{\alpha} \ln \left[ \alpha (v_v - v_i) + 1 \right]
\]

and the value of \( v_o \) is calculated from:

\[
v_o = v_v - \frac{1}{\alpha \Delta t + \frac{1}{v_o - v_i}}
\]  

To obtain the value of \( v_o \), the value of \( \Delta t \) must be obtained from Equation 5.15. It is, however, impossible to solve analytically and must be solved using a numerical technique, which requires values for \( c_d \), \( \rho_a \), \( \rho \), \( v_v \), \( v_i \) and \( x_a \). The values of \( \rho_a \) and \( \rho \) were known, and the values of \( v_v \), \( v_i \) and \( x_a \) were adjusted so the velocities calculated with the model were comparable to those measured with the round nozzle at 4.54 kg/min and
CHAPTER 5. VELOCITY OF WHEAT STARCH PARTICLES

Table 5.3: Values of the parameters of the velocity model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_d$</td>
<td>0.75</td>
<td>Close to the drag coefficient of a sphere</td>
</tr>
<tr>
<td>$\rho_a$</td>
<td>1.23 kg/m$^3$</td>
<td>Density of the air at standard conditions</td>
</tr>
<tr>
<td>$\rho$</td>
<td>1400 kg/m$^3$</td>
<td>Density of wheat starch</td>
</tr>
<tr>
<td>$v_u$</td>
<td>500 m/s</td>
<td>A supersonic velocity is expected in the expansion portion of the nozzle</td>
</tr>
<tr>
<td>$x_a$</td>
<td>0.03 m</td>
<td>The throat of the nozzle is very short</td>
</tr>
<tr>
<td>$v_i$</td>
<td>30 m/s</td>
<td>The initial velocity of the particles is very small compared to their final velocity</td>
</tr>
</tbody>
</table>
207 kPa. It should be stressed that, although the set of values chosen is realistic, they may not correspond exactly to the flow conditions inside the nozzle. The results of the velocity model are therefore only valid for comparison purposes. The chosen values are summarized in Table 5.3.

Figure 5.5 illustrates the velocity of the particles as a function of their diameter. One can note that the velocity increases sharply as the size of the particles decreases. Dust, i.e. particles smaller than mesh 100 (150 μm), reach especially high velocities, around 180 m/s. This could explain the high aggressiveness and high potential for substrate damage observed with small media mixes. On the contrary, large particles such as the ones present in Envirostrip 12/30 are not accelerated to speeds much faster than about 80 m/s.
5.2.2 Kinetic energy distribution

As seen previously, the mass of an idealized particle is:

\[ m = \frac{1}{6} \rho \pi d^3 \]

and its kinetic energy is:

\[ K = \frac{mv_o^2}{2} = \frac{\rho \pi d^3 v_o^2}{6} \]

The kinetic energy of 1 kg of particles of a given diameter is thus

\[ K' = \frac{v_o^2}{2} \]  \hspace{1cm} (5.18)

Assuming the model obtained earlier is valid, the relationship between the kinetic energy of a particle and its diameter is shown in Figure 5.6. One can note that, although large particles are much slower than small ones, their large weight offsets their low velocity, so individual large particles carry more kinetic energy than small ones. This is
Figure 5.7: Kinetic energy of 1 kg of particles of given diameter
Table 5.4: Size distribution of the mixes used in the experiments (as measured in Chapter 4)

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Envirostrip 12/30 [%]</th>
<th>Envirostrip 30/50 [%]</th>
<th>Envirostrip 30/100 [%]</th>
<th>Production mix [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>0.7</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>20</td>
<td>73.0</td>
<td>0.3</td>
<td>0.0</td>
<td>14.1</td>
</tr>
<tr>
<td>30</td>
<td>22.5</td>
<td>14.6</td>
<td>0.1</td>
<td>23.9</td>
</tr>
<tr>
<td>40</td>
<td>3.6</td>
<td>54.3</td>
<td>4.2</td>
<td>26.1</td>
</tr>
<tr>
<td>50</td>
<td>0.2</td>
<td>27.5</td>
<td>66.2</td>
<td>20.1</td>
</tr>
<tr>
<td>60</td>
<td>0.0</td>
<td>2.5</td>
<td>17.8</td>
<td>6.3</td>
</tr>
<tr>
<td>80</td>
<td>0.0</td>
<td>0.7</td>
<td>9.8</td>
<td>6.8</td>
</tr>
<tr>
<td>100</td>
<td>0.0</td>
<td>0.1</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td>120</td>
<td>0.0</td>
<td>0.0</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>140</td>
<td>0.0</td>
<td>0.0</td>
<td>0.3</td>
<td>0.6</td>
</tr>
</tbody>
</table>

consistent with the observation that large particles do more damage at a time than small ones (see Chapter 3).

The kinetic energy of 1 kg of particles of a given diameter is illustrated in Figure 5.7. One can note that, while the kinetic energy per individual particle is higher for large particles, the total kinetic energy per kg of particles of given size is much higher for small particles. This could support the hypothesis that a balance of large and small particles, i.e. a wide size distribution, is needed in order to remove the paint the most efficiently.

### 5.2.3 Size distribution of the particles

To calculate the total kinetic energy of the particles of a given mix, the size distribution needs to be taken into account. This information is available as the percentage of the weight of the mix that will stay on different meshes. Table 5.4 presents the size distributions for the different mixes used in the experiments, and Table 4.1 lists the particle sizes corresponding to the mesh sizes.
### Figure 5.8: Kinetic energy of 1 kg of particles of a given mesh size

The average kinetic energy per particle in a certain range of diameters is calculated as follows:

\[
K' = \frac{1}{d_2 - d_1} \int_{d_1}^{d_2} K(d) \, dd = \frac{1}{d_2 - d_1} \int_{d_1}^{d_2} \frac{1}{2} m(d) v_o^2(d) \, dd
\]  

(5.19)

And the average mass of a single particle is.

\[
\bar{m} = \frac{1}{d_2 - d_1} \int_{d_1}^{d_2} m(d) \, dd
\]  

(5.20)

Assuming that particle diameters are evenly distributed, the kinetic energy of 1 kg of particles in a given range of diameters is thus:

\[
\bar{K}' = \int_{d_1}^{d_2} \frac{v_o^2(d)}{2}
\]  

(5.21)

The kinetic energy of 1 kg of media of a given mesh size is plotted in Figure 5.8. As was observed in Figure 5.7, the kinetic energy per kilogram of particles rises quickly as the particles get smaller. For instance, 1 kg of mesh 60 particles will have more than two time as much kinetic energy as 1 kg of mesh 30 particles.
Figure 5.9: Kinetic energy distribution per kilogram of different mixes. □ Envirostrip 12/30, □ Envirostrip 30/50, □ Envirostrip 30/100, ■ Production mix
Table 5.5: Average particle diameter, average particle mass, calculated average particle velocity and total kinetic energy transferred to different mixes

<table>
<thead>
<tr>
<th>Media</th>
<th>Average diameter [μm]</th>
<th>Average mass [μg]</th>
<th>Average velocity [m/s]</th>
<th>Kinetic Energy [kJ/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Envirostrip 12/30</td>
<td>971</td>
<td>673</td>
<td>78.7</td>
<td>3.10</td>
</tr>
<tr>
<td>Envirostrip 30/50</td>
<td>446</td>
<td>65.1</td>
<td>110.0</td>
<td>6.04</td>
</tr>
<tr>
<td>Production mix</td>
<td>355</td>
<td>32.8</td>
<td>110.1</td>
<td>6.06</td>
</tr>
<tr>
<td>Envirostrip 30/100</td>
<td>309</td>
<td>21.7</td>
<td>127.2</td>
<td>8.09</td>
</tr>
</tbody>
</table>

The kinetic energy distribution per kilogram of a given mix is illustrated in Figure 5.9. As one can see, the kinetic energy distribution of production mix is very wide compared to that of Envirostrip 12/30 and Envirostrip 30/50, for which the kinetic energy is concentrated into a narrow size range.

Finally, the average particle diameter, average particle mass, average particle velocity and total kinetic energy per kilogram of media are tabulated in Table 5.5. As one can see, both the calculated average particle velocity and the total kinetic energy per kilogram of media increase when the average particle diameter decreases. Although this was not shown by the velocity measurements, it is consistent with the empirical observation that smaller particles yield higher paint stripping rates (see Section 2.5).

One can note, in Table 5.5, that Envirostrip 30/100 has, according to the calculations, a smaller average particle size and a higher kinetic energy than production mix. This is due to the assumption that particle diameters are evenly distributed in a given mesh size (see Section 5.2.3). Actually, the average particle diameter that was measured for Envirostrip 30/100 is slightly larger than that of production mix (see Figure 4.6).

The fact that the velocity measurements did not reveal any trend with respect to particle size may be due to a lack of sensitivity to small particles. The small particles did not show very well on the pictures taken to determine their velocity and it was impossible to reliably establish the average velocity of mixes such as Envirostrip 30/100 and production mix.
5.3 Comparison with rotating disk results

The average particle velocities measured with the rotating disk device for the round nozzle are tabulated in Table 5.6, and those measured for the flat nozzle are tabulated in Table 5.7. As one can see, the velocities measured with the rotating disk were higher than those obtained with the multiple flash technique (see Table 5.1). This can be partly attributed to the lack of sensitivity of the optical method to small particles, as discussed earlier. In addition, Ponnaganti [35] showed that the rotation of the disks creates a disturbance in the air flow pattern which can introduce a systematic error in the measurements of particle velocity. This was estimated to be 18\% for the rotating disk and to 10\% for the multiple flash method [35, 36]. Both values correspond approximately to the uncertainty in the velocities measured in the present study, respectively with the rotating disk and with the multiple flash method.

Nevertheless, as one can see from Figure 5.10, the velocities measured for the round nozzle with the rotating disk were much more consistent than those measured with the multiple flash technique (see Figure 5.3). All the velocities measured showed a clear trend with pressure. In addition, the velocities increased with decreasing average particle size, as predicted by the theoretical model developed in Section 5.2 and, finally, the velocity decreased with increasing mass flowrates (similar to that measured with the multiple flash technique).

The total stream power for round nozzle, calculated from Equation 5.3, is illustrated in Figure 5.11. The same sharp increase of stream power with pressure observed with the multiple flash technique was observed for the rotating disk velocity measurements. Moreover, the rotating disk velocity measurements confirmed that, while the velocity decreased with increasing mass flowrates, the total stream power increased.

Finally, one can note that the velocities measured with the rotating disk for the flat nozzle are much higher than those measured for the round nozzle. This is due to the fact that the flat nozzle was optimized for wheat starch paint removal and that, under the same blasting conditions, the double-venturi round nozzle is relatively inefficient [37]. The higher efficiency of the flat nozzle was confirmed by comparing the paint removal obtained with the round and flat nozzles (see Table 6.1).
Table 5.6: Wheat starch average particle velocities measured with the rotating disk, with the round nozzle

<table>
<thead>
<tr>
<th>Media</th>
<th>Pressure [kPa]</th>
<th>Mass flowrate [kg/min]</th>
<th>Average velocity [m/s]</th>
<th>Power [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/30</td>
<td>207</td>
<td>5.44</td>
<td>120.4</td>
<td>657</td>
</tr>
<tr>
<td>30/50</td>
<td>207</td>
<td>5.44</td>
<td>128.5</td>
<td>789</td>
</tr>
<tr>
<td>30/100</td>
<td>207</td>
<td>5.44</td>
<td>136.5</td>
<td>845</td>
</tr>
<tr>
<td>30/50</td>
<td>172</td>
<td>5.44</td>
<td>116.4</td>
<td>614</td>
</tr>
<tr>
<td>30/100</td>
<td>172</td>
<td>5.44</td>
<td>121.3</td>
<td>667</td>
</tr>
<tr>
<td>12/30</td>
<td>138</td>
<td>5.44</td>
<td>98.9</td>
<td>443</td>
</tr>
<tr>
<td>30/50</td>
<td>138</td>
<td>5.44</td>
<td>102.4</td>
<td>475</td>
</tr>
<tr>
<td>30/100</td>
<td>138</td>
<td>5.44</td>
<td>99.3</td>
<td>447</td>
</tr>
<tr>
<td>12/30</td>
<td>207</td>
<td>4.08</td>
<td>133.5</td>
<td>606</td>
</tr>
<tr>
<td>30/50</td>
<td>207</td>
<td>4.08</td>
<td>136.6</td>
<td>634</td>
</tr>
<tr>
<td>30/100</td>
<td>207</td>
<td>4.08</td>
<td>142.6</td>
<td>691</td>
</tr>
<tr>
<td>30/50</td>
<td>172</td>
<td>4.08</td>
<td>130.1</td>
<td>575</td>
</tr>
<tr>
<td>30/100</td>
<td>172</td>
<td>4.08</td>
<td>132.8</td>
<td>600</td>
</tr>
<tr>
<td>12/30</td>
<td>138</td>
<td>4.08</td>
<td>112.1</td>
<td>427</td>
</tr>
<tr>
<td>30/50</td>
<td>138</td>
<td>4.08</td>
<td>113.6</td>
<td>439</td>
</tr>
<tr>
<td>30/100</td>
<td>138</td>
<td>4.08</td>
<td>118.0</td>
<td>473</td>
</tr>
<tr>
<td>30/50</td>
<td>207</td>
<td>2.72</td>
<td>147.1</td>
<td>490</td>
</tr>
<tr>
<td>30/50</td>
<td>138</td>
<td>2.72</td>
<td>118.9</td>
<td>320</td>
</tr>
</tbody>
</table>
Figure 5.10: Wheat starch particles average velocities measured with the rotating disk (round nozzle).diamondEnvirostrip 12/30 at 4.08 kg/min. CircleEnvirostrip 12/30 at 5.44 kg/min. DiamondEnvirostrip 30/50 at 4.08 kg/min. CircleEnvirostrip 30/50 at 5.44 kg/min. TriangleEnvirostrip 30/100 at 4.08 kg/min. CircleEnvirostrip 30/100 at 5.44 kg/min.
CHAPTER 5. VELOCITY OF WHEAT STARCH PARTICLES

Figure 5.11: Power of the abrasive stream measured with the rotating disk (round nozzle). ◇ Envirostrip 12/30 at 4.08 kg/min. ○ Envirostrip 12/30 at 5.44 kg/min. ◆ Envirostrip 30/50 at 4.08 kg/min. ● Envirostrip 30/50 at 5.44 kg/min. ★ Envirostrip 30/100 at 4.08 kg/min. ★ Envirostrip 30/100 at 5.44 kg/min
While the multiple flash technique could allow precise, unbiased velocities measurements to be made, and could eventually allow simultaneous measurement of the size and velocity of the particles, the limitations of the experimental setup used in the present research prevented reliable velocity measurements to be made. These limitations are: the low resolution of the pictures which made it difficult to see small particles, the low picture quality due to high dust levels in the blast cabinet and the poor repeatability inherent to the manual analysis of the pictures. These shortcomings are analysed in detail Appendix C, and solutions to improve the experimental setup are proposed.

Despite the fact that the velocities measured with the rotating disk are prone to a systematic bias, they seem, at least for now, more reliable than those obtained with the multiple flash technique. The velocities measured for the flat nozzle with the rotating disk will, therefore, be the ones used in the calculations of work exposure, in Chapter 6.
Chapter 6

Paint stripping rates

The experimental work described in this chapter was aimed at answering several questions raised by the previous chapters.

Firstly, a new parameter, the *work exposure*, was developed to quantify the blasting conditions and to verify if the paint stripping rates were only a function of the abrasive stream power, independent of particle shape and size.

Similarly, the work exposure could separate the effects due to the normal and tangential components of the velocity of the particles. Since brittle erosion is controlled by the tangential component of the particle velocity [15], it could be determined if this was the removal mechanism.

Finally, the paint thickness removed was measured with respect to the exposure of the samples to the abrasive stream. This was used to verify if the topcoat was removed in a cumulative fashion and if there was an initiation period before it started to be removed. In addition, these measurements were used to establish if there was a selective stripping window, as suggested in Sections 2.5 and in Chapter 3.

6.1 Experimental procedure

To vary the exposure of the samples to the abrasive stream, a sliding table was built. The flat nozzle was held rigidly in position by an adjustable clamp, and the sample moved under it (see Figure 6.1). The sliding table was driven by a DC motor which allowed
precise control of the speed from about 5 mm/s [1 ft/min] up to 115 mm/s [22.5 ft/min].

For each set of selected blasting parameters, at least five traces were made, each using a different sliding table speed. The threshold for topcoat removal was determined to the nearest 5 mm/s, as specified in Section 2.4. The paint stripping rates, \( psr \), were calculated according to Equation 2.2, i.e. \( psr = w \times u \). where \( u \) is the table speed and the width of the trace \( w \) used in all the calculations was calculated as the average width of all traces made using the same operating parameters. It was argued that, when the mass flowrate, nozzle pressure, nozzle angle and standoff distance were kept constant, the area that was exposed to the abrasive stream should be constant as well.

Similarly, the mass flowrates, \( \bar{m} \). used in the calculations were calculated as the average of the mass flowrates measured during all the experiments for which the position of the media valve, the pressure and the media were unchanged.

Up to a maximum of eight traces were made on each face of the panel (see Figure 6.2). Each trace was 15 cm long and covered half the length of the panel. When doing experiments on one half of the panel, the other half was masked with an aluminium plate to prevent interference between the tests. The lateral distance between the center of
6.1.1 Paint thickness

Before the experiments were done, the paint thickness was measured every 1.3 cm along the intended centerline of every trace, for a total of 11 measures using an eddy-current paint thickness gage (DeFelsko Corp., Positector model 6000), which had a resolution of ±2 μm. After the experiments were completed, the paint thickness was measured again at the same points and the thickness of paint removed was calculated as follows: let \( h_{0,i} \) be the \( i^{th} \) paint thickness measured before the test and \( h_{1,i} \) the \( i^{th} \) paint thickness measured after the test. The paint thickness \( h_i \) removed on every point was therefore:

\[
h_i = h_{0,i} - h_{1,i}
\]

The average paint thickness removed was thus

\[
\bar{h} = \frac{1}{n} \sum h_i
\]

and the standard deviation of the thickness removed:

\[
s^2 = \frac{1}{n-1} \sum (h_i - \bar{h})^2
\]

The confidence interval for the paint thickness removed was:

\[
\Delta h = \frac{t_{\alpha/2,n}}{\sqrt{n}}
\]
\[ h_{\text{min}} = \bar{h} - \frac{t_{\alpha/2}\nu}{\sqrt{n}} \quad (6.4) \]
\[ h_{\text{min}} = \bar{h} + \frac{t_{\alpha/2}\nu}{\sqrt{n}} \quad (6.5) \]

where \( t \) is the Student statistical distribution function, \( \alpha \) is the significance level of the test and \( \nu \) is the number of degrees of freedom of the statistical distribution function. A confidence level of 95% was used and the data had \( \nu = n - 1 = 10 \) degrees of freedom, so the equations were:

\[ h_{\text{min}} = \bar{h} - 0.6718\bar{s} \quad (6.6) \]
\[ h_{\text{min}} = \bar{h} + 0.6718\bar{s} \quad (6.7) \]

### 6.1.2 Work exposure

The *work exposure* was proposed as a new parameter to quantify the blasting conditions. It expressed the amount of energy a unit area of coating was exposed to and encompassed the effects of media type, mass flowrate, pressure and relative nozzle speed. It was calculated as follows:

\[ W_{\text{exp}} = \frac{1}{uw} \frac{\bar{m}\bar{v}^2}{2} \quad (6.8) \]

where \( \bar{m} \) was the mass flowrate and \( \bar{v} \) was the average particle velocity.

To establish on which component of particle velocity the paint removal depended, the components of work exposure due to normal and tangential velocity components were calculated as follows:

\[ W_{\text{exp}_n} = W_{\text{exp}} \sin^2 \alpha \quad (6.9) \]
\[ W_{\text{exp}_t} = W_{\text{exp}} \cos^2 \alpha \quad (6.10) \]

The expression of the paint thickness removed as a function of work exposure allows the effect of kinetic energy on the paint removal process to be separated from the effect of the other parameters (particle size and shape, etc.). Therefore, if the paint removal mechanism depends only on the kinetic energy of the particles, the thicknesses of coating removed when using two different conditions (e.g. two different media) that yield the same work exposure should be identical. On the other hand, if the paint removal is not
Table 6.1: Comparison of the paint stripping obtained with the round and the flat nozzle. Sliding table speed: 30.5 mm/s. Envirostrip 30/50. 2.27 kg/min. 207 kPa. 45°. 15 cm standoff.

<table>
<thead>
<tr>
<th>Nozzle type</th>
<th>Paint thickness removed [μm]</th>
<th>Trace width [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round nozzle</td>
<td>13</td>
<td>26</td>
</tr>
<tr>
<td>Flat nozzle</td>
<td>53</td>
<td>46</td>
</tr>
</tbody>
</table>

controlled solely by the kinetic energy of the particles. the paint thicknesses removed will not be the same, and it will be possible to determine how other parameters influence the paint removal process.

The main weakness of the work exposure was that its calculation required the average velocity of the particles to be known. As explained in Chapter 5, it was impossible to obtain reliable optical measures of the particle velocity when using the flat nozzle, which was the nozzle used for all the paint stripping rate experiments. Thus, the velocities used in the calculations were the ones measured with the rotating disk, with the round nozzle.

The difference in the aggressiveness of the round and flat nozzle was determined by measuring the paint thickness removed with both nozzles under the same conditions. The paint thickness removed with the flat nozzle was much greater than with the round nozzle, as can be seen in Table 6.1.

Finally, another parameter, the mass exposure, was used to quantify the effectiveness of the blast cleaning conditions. It is similar to the work exposure except that it does not take into account the velocity of the particles. The mass exposure was defined as,

$$M_{exp} = \frac{m}{uw}$$

and represents the mass of media blasted at a unit area of coating.

6.1.3 Aero Almen strip tests

Aero Almen tests assess the aggressiveness of the blasting conditions by measuring the deflection of thin aluminum strips after they have been exposed to the abrasive stream.
Table 6.2: Deflection of the Aero Almen strips

<table>
<thead>
<tr>
<th>Media</th>
<th>30/50</th>
<th>12/30</th>
<th>30/50</th>
<th>30/50</th>
<th>30/100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure [kPa]</td>
<td>207</td>
<td>207</td>
<td>241</td>
<td>172</td>
<td>207</td>
</tr>
<tr>
<td>Deflection [µm]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>after 1 cycle</td>
<td>45</td>
<td>3</td>
<td>2</td>
<td>41</td>
<td>23</td>
</tr>
<tr>
<td>after 5 cycles</td>
<td>56</td>
<td>30</td>
<td>48</td>
<td>60</td>
<td>48</td>
</tr>
<tr>
<td>after 10 cycles</td>
<td>95</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

on one side. The impact of the particles causes plastic deformations on the surface the aluminium strips, and the deflection of the strips is related to the amount of plastic deformation caused by the particles.

Aero Almen tests were done to assess the overall "power" that the equipment was able to provide. This verified that the aggressiveness obtained with the blast cabinet used in the present research was similar to that obtained in industry with different equipment. The tests were performed as specified in [29], using the round nozzle.

The Almen strips were prepared from bare AA 2024-T3 aluminium 813 µm thick [0.032 inch]. The dimensions of the strips were 74.7-77.7 mm by 18.9-19.1 mm. The initial deflection of each specimen was measured using an Almen gage and the specimens with an initial deflection greater than 25 µm were discarded.

A total of five tests under different conditions were performed, and five Almen strips were used for each test. The mass flowrate was 4.54 kg/min, the standoff distance was approximately 15 cm and the nozzle angle was 45° for all the tests. The results are summarized in Table 6.2. The highest deflections obtained were within 10% of the ones measured by Oestreich and Monette in [25], which confirmed that the equipment used in the present research yielded similar aggressiveness to that of the equipment used in industry.
CHAPTER 6. PAINT STRIPPING RATES

Table 6.3: Paint stripping rates with the flat nozzle at 5.44 kg/min and 207 kPa

<table>
<thead>
<tr>
<th>Media</th>
<th>30/50</th>
<th>30/50</th>
<th>30/50</th>
<th>30/50</th>
<th>30/100</th>
<th>p_{mix}</th>
<th>p_{mix}</th>
<th>p_{mix}</th>
<th>p_{mix}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle [°]</td>
<td>20</td>
<td>45</td>
<td>70</td>
<td>90</td>
<td>45</td>
<td>20</td>
<td>45</td>
<td>70</td>
<td>90</td>
</tr>
<tr>
<td>Trace width [mm]</td>
<td>47.2</td>
<td>51.4</td>
<td>47.8</td>
<td>45.3</td>
<td>46.0</td>
<td>51.3</td>
<td>52.4</td>
<td>45.8</td>
<td>45.2</td>
</tr>
<tr>
<td>Mass exposure [kg/m²]</td>
<td>149</td>
<td>56.7</td>
<td>106</td>
<td>144</td>
<td>54.9</td>
<td>78.2</td>
<td>48.0</td>
<td>48.6</td>
<td>74.0</td>
</tr>
<tr>
<td>Average Velocity [m/s]</td>
<td>172</td>
<td>172</td>
<td>172</td>
<td>172</td>
<td>197</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Work exposure [kJ/m²]</td>
<td>2010</td>
<td>873</td>
<td>1410</td>
<td>1930</td>
<td>957</td>
<td>1410</td>
<td>990</td>
<td>880</td>
<td>1340</td>
</tr>
<tr>
<td>Paint stripping rate [m²/h]</td>
<td>2.41</td>
<td>5.56</td>
<td>3.44</td>
<td>2.52</td>
<td>6.62</td>
<td>4.62</td>
<td>6.60</td>
<td>6.07</td>
<td>4.88</td>
</tr>
</tbody>
</table>

6.2 Results

The paint stripping rates for topcoat removal were measured under nine different conditions, using the flat nozzle, a mass flowrate of 5.44 kg/min, a pressure of 207 kPa and a standoff distance of 15 cm. The results are summarized in Table 6.3. As one can see, the highest paint stripping rates were obtained with production mix. For each media used, the paint stripping rates were maximum at an angle of attack of 45°, which implied that paint removal was not a sole function of the normal component of particle velocity.

The dependence of the paint removal process on the work exposure components due to normal and tangential components of velocity can be seen in Figure 6.3. The paint thickness removed showed no trend with respect to either the normal or tangential components of velocity.
Figure 6.3: Normal and tangential components of work exposure for all the paint stripping experiments. ○ Normal component. ♦ Tangential component.
Figure 6.4: Paint thickness removed using Envirostrip 30/50. 5.5 kg/min [12 lb/min], 205 kPa [30 psi], 150 mm [6”]. The error bars correspond to the 95% confidence limits on the paint thickness removed. □ 20°. ◇ 45°. ○ 70°. △ 90°.
The thickness of paint removed with respect to mass exposure for Envirostrip 30/50 is illustrated in Figure 6.4. As in Table 6.3, the best paint stripping rates were obtained at 45°. The rate at which the paint was removed at 70° is lower and, surprisingly, the curves for stripping at 20° and 90° are almost identical.

In addition, one can notice that the curves for depainting at 20°, 45° and 90° exhibit an abrupt change of slope around 50 μm of paint removal, corresponding to the thickness of the topcoat. Moreover, the curves for stripping at 20° and 45° clearly exhibit a plateau for a large exposure range, which indicates that no primer was removed for increasing exposures, up to a certain point where the curve for stripping at 45° starts to rise again (at about 125 kg/m²), indicating that the primer began to be removed.

Also, the fact that all the curves have a linear portion before the selective stripping plateau confirms that the topcoat was removed in an essentially cumulative fashion. In other words, during topcoat removal, the thickness of coating removed was a linear function of the exposure.

![Figure 6.5: Error in the paint thickness removed induced by the paint thickness gage](image)

Finally, the existence of a short initiation period, before the topcoat starts to be removed, can be noted at 20°, 70° and 90°. Although the paint thickness gage did not measure any significant loss of coating thickness, some coating was visibly removed at very low exposures. This was partly attributable to the fact that the size of the tip of the paint thickness gage was large compared to the size of the impact sites on the topcoat, so the paint thickness gage only measured the thickness defined by the peaks around
CHAPTER 6. PAINT STRIPPING RATES

the craters. As illustrated in Figure 6.5, for relatively low densities of impacts, it was impossible to measure paint removal, even though some paint was actually removed.

Nevertheless, this alone could not explain the relatively large shift to the right of all the paint removal curves, i.e. they do not pass through the origin. For instance, in Figure 6.4, the linear portion of the curve for Envirostrip 30/50 at 45°, corresponding to the removal of topcoat, intersects the horizontal axis at about 25 kg/m². This means that the paint thickness gage did not measure any coating removal at an exposure of 25 kg/m². There are two possible explanations: firstly, there were enough undamaged peaks to support the tip of the paint thickness gage or, secondly, there was an initiation time before the onset of cumulative topcoat removal.

One can assume that the maximum peak height is proportional to the paint thickness removed, and it was established (c.f. Chapter 3) that several impacts were required at a single site for complete removal of the topcoat. Thus, as the mass exposure went from 25 kg/m² to 50 kg/m², 50 μm of paint were removed. As so 25 kg/m² must correspond to multiple saturation coverage: i.e. every point of the surface has been hit by several particles. This implies that the initial mass exposure of 25 kg/m² must also correspond to multiple saturation coverage, but without any change in the maximum peak height. Therefore, there must be an initiation period before the topcoat starts to be removed at a steady rate. As one can see from Figure 6.4, that initiation time was very short at 45°, and was longer at 20°, 70° and 90°.

To sum up, the topcoat started to be removed very slowly until some threshold was passed, and then was removed much more quickly, the thickness of topcoat removed varying linearly with mass exposure. Then, once all the topcoat was removed, the primer was not removed over a certain range of mass exposures. When the mass exposure reached another threshold, the primer then started to be removed in turn.

The same behavior was observed with production mix, whose removal is illustrated in Figure 6.6. However, the selective stripping "window" was much smaller than with Envirostrip 30/50 at 45°, and completely vanished at 90°.

A comparison of the aggressiveness of Envirostrip 30/50, Envirostrip 30/100 and production mix at the same angle of attack (45°) revealed great differences in the quantity of media that had to be used to reach the same degree of stripping. As can be seen in
Figure 6.6: Paint thickness removed using production mix. 5.5 kg/min [12 lb/min], 205 kPa [30 psi], 150 mm [6"]. The error bars correspond to the 95% confidence limits on the paint thickness removed. □ 20°. ◇ 45°. ◇ 70°. △ 90°.
Figure 6.7: Comparisons of mass exposures. 5.5 kg/min [12 lb/min], 205 kPa [30 psi], 150 mm [6"]. □ Envirostrip 30/50 at 45°, ○ Envirostrip 30/100 at 45°, ◇ Production mix at 45°.
Figure 6.7. topcoat removal was achieved with much smaller mass exposures when using production mix than new Envirostrip media. In fact, the amount of media required to perform selective stripping varied inversely with the average particle size of the media used. One can also note that the selective stripping window decreased considerably with the more aggressive media.

When the work exposure was calculated, to take into account the average velocity of the particles, it appeared that the kinetic energy of the particles was not the only parameter that controlled the paint removal process. As one can see in Figure 6.8, less work was needed at 45° to remove the same thickness of paint with Envirostrip 30/100 than with Envirostrip 30/50, and even less work was needed with production mix. Somehow, the kinetic energy of production mix and Envirostrip 30/100 particles was more efficiently used to remove the paint.

This could be attributed to the smaller average particle size of Envirostrip 30/100 and of production mix or to a difference in particle shape. Another possibility, which was not explored, was that there was a difference in particle hardness due to a difference in the moisture content of the starch media. For example, there may have been less water (harder particles) in production mix because of its smaller average particle size, and because the moisture content of the particles decrease as they are recycled (see Section A.1. While no work was undertaken with respect to particle hardness, it was shown in Chapter 4 that there were particle size and shape differences between the media, so it is proposed that the higher efficiency of production mix and of Envirostrip 30/100 over Envirostrip 30/50 is due, at least partly, to a smaller particle size.

6.3 Discussion

The paint stripping rate experiments confirmed several of the empirical results presented in Section 2.5. Firstly, the existence of a selective stripping window was confirmed for the paint system used. The width of that selective stripping was large at shallow angles of attack, decreased at high angles and even sometimes completely vanished at 90°. The selective stripping window was also larger with less aggressive media than with very aggressive ones.
Figure 6.8: Comparison of work exposures. 5.5 kg/min [12 lb/min]. 205 kPa [30 psi], 150 mm [6”]. □ Envirostrip 30/50 at 45°, ○ Envirostrip 30/100 at 45°, ◦ Production mix at 45°.
Secondly, it was shown that the paint stripping rates were not controlled by the normal or tangential components of the velocity of the particles. In fact, the best paint stripping rates with all the media used were obtained at an angle of attack of 45°.

Thirdly, it was demonstrated that the topcoat was removed in a cumulative fashion but that there was a short initiation time before the topcoat started to be removed. It is proposed that, although every impact on the topcoat removed some paint, individual wheat starch particles removed much more coating once the glossy finish of the topcoat was removed, presumably because they had more “grip” on the coating.

And, finally, it was shown that the paint stripping was not only controlled by the particle kinetic energy (or stream power), but that other parameters influenced the paint stripping process.

For instance, although production mix and Envirostrip 30/100 had identical average particle diameter, average roundness coefficient and average radius ratio, production mix was significantly more aggressive than Envirostrip 30/100. The only difference between the two media was their shape distribution, which was wider for production mix. This implies that wide size distributions are more aggressive than narrow ones.

It was, however, impossible to isolate the difference in aggressiveness between Envirostrip 30/50 and production mix (or Envirostrip 30/100) due to average particle diameter, to particle shape or to size distribution because they all varied simultaneously. The difference in aggressiveness could therefore be due to all these factors.
Chapter 7

Discussion and conclusions

Wheat starch removal of an aerospace paint system (MIL-C-83286 topcoat with MIL-P-23377 primer on AA 2024-T3 aluminum panels) was studied with respect to particle velocity, angle of attack, particle size and particle shape. The paint removal rates were found to be dependent on particle velocity, angle of attack, particle size distribution, and may also depend on particle shape.

The qualitative study of the impact sites revealed that the topcoat was not removed by delamination from the primer nor by pure brittle erosion, but in a cumulative fashion, as several impacts were needed to remove it completely. Before the topcoat started to be removed, there was a short initiation period (see Figures 6.4 and 6.6) which varied with the blasting conditions. That initiation period was longer at low particle velocities, and with large particles.

Before the primer started to be removed, there was a long initiation period, or selective stripping window during which the primer was exposed to the abrasive stream without apparently suffering any damage (c.f. Figures 6.4 and 6.6). That window increased at low angles of attack and vanished at high angles. It also depended on the wheat starch mix used, and larger media had a larger selective stripping window. When the samples were exposed to the abrasive stream for a long enough time, the primer was removed rather abruptly from the aluminum substrate, possibly by delamination.

For each set of blasting conditions tested, the paint removal rates were maximum at an angle of attack of 45° and decreased at higher and lower angles of attack. The
paint was removed in an almost identical fashion at 20° and 90° (c.f. Figure 6.4). and the paint removal rates did not show any correlation with either the normal or the tangential component of the particle velocity (c.f. Figure 6.3).

Of the four different wheat starch mixes studied. the best paint removal rates were achieved with production mix. a recycled wheat starch mix with a broad distribution of particle sizes.

The comparison of the paint stripping rates obtained with production mix and Envirostrip 30/100 showed that the width of the size distribution has an influence on the paint removal process. since the only measurable difference between these two mixes was the wider size distribution of production mix (c.f. Figure 4.4).

On the other hand. the comparison of the paint stripping rates obtained with Envirostrip 30/50 and with production mix (or with Envirostrip 30/100) did not allow to decouple the possible effects of particle shape from those of size distribution. since they varied simultaneously. One can only conclude that particle shape may influence the paint removal process.

The shape of wheat starch particles seems to be physically related to their size, since both the shape parameters and the average particle size vary simultaneously (c.f. Figures 4.6 and 4.8). It is especially revealing that. although Envirostrip 30/100 is directly manufactured to a specified size and production mix is obtained by recycling initially larger particles. they both have the same shape parameters.

It was shown in Section 5.2 that. while small particles are accelerated to higher velocities. larger ones carry individually much more kinetic energy (c.f. Figure 5.6). so they presumably do more damage when the hit the paint. It is thus proposed that large particles remove more easily the hard. glossy finish of the topcoat with their high individual kinetic energy than smaller particles which, individually. do not have enough kinetic energy to damage the finish of the topcoat. On the other hand. smaller particles would remove more easily the rest of the topcoat. since they have globally more kinetic energy. A balance of small and large particles (wide size distribution). as found in production mix (c.f. Figure 4.4). would thus result in higher paint removal rates.

The velocity of wheat starch particles was studied with respect to three blasting parameters: media. pressure and mass flowrate. The velocity was found to increase
with the blasting pressure and to decrease with the mass flowrate. The average particle velocity also increased with decreasing average particle size.

The total power transferred to the flow increased with the mass flowrate, even if the average particle velocity decreased. This is especially interesting since it appears (c.f. Section 2.5) that the potential for damaging the substrate is closely linked to the velocity of the particles, while the paint stripping rates depended largely on the total flow power (c.f. Figure 6.8). It is thus possible obtain high productivity with a low potential for damaging the substrate by using a high media mass flowrate.

To summarize, the best paint removal rates can be obtained with small, recycled media (production mix) at a high mass flowrate and at an angle of attack of 45°. The selective stripping window can be enlarged by using lower angles of attack and larger particle size (e.g. Envirostrip 30/50 mix). When delicate structures need to be depainted and substrate damage is an issue, high mass flowrates and larger average particle size will yield the best paint removal rates while minimizing the potential for substrate damage.

7.1 Recommendations for future work

Wheat starch depainting is a relatively new process, and the mechanics that govern it are still largely unknown. While a better understanding of it was gained by the present research, further work should be done in order to deepen our knowledge of the fundamental mechanisms by which coatings are removed. Some recommendations for further research are as follows:

1. Improve the accuracy of the particle velocity measurements, including a means of simultaneously measuring particle size and speed (see Appendix C for an improved setup for measuring particle velocity).

2. Compare the paint stripping rates obtained with production mix and another recycled mix with the same average particle size, but a narrower size distribution. This would show if the width of the size distribution really influences the paint stripping rates.
3. Compare the paint stripping rates obtained with new and recycled media of the same mesh size. This would show if the higher paint stripping rates obtained with production mix are due to a difference in particle shape, or to a difference in size distribution.

4. Compare the paint thickness removed versus the exposure for a sample lightly sanded (to degloss the topcoat) and a regular sample. This would show if the initiation period observed with topcoat is due to the smooth initial surface of the topcoat.

5. Study how the hardness of wheat starch particles is related to their water content, and how that hardness affects the paint stripping rates (see Appendix A for some work that was done on wheat starch water content).

6. Measure the paint stripping rates and thickness of paint removed at a larger number of angles of attack between 20° and 90°, to establish precisely how the paint stripping rates evolve with respect to the angle.
References


REFERENCES


REFERENCES


[22] Joseph Zahavi and George F. Jr. Schmitt. Solid particle erosion of polymeric coat-

resistance of organic coatings by falling abrasive. Testing method D 968-81. Philadel-


coating removal from 2024-T3 aluminium alloys. In Batelle memorial institute.


[27] American Society for Testing and Materials. Measuring adhesion by tape test. Test-


Appendix A

Wheat starch water content

Qualitative observations reported in Section 2.5 revealed that the blasting aggressivity and the media consumption rate both depended on the wheat starch water content. Two experiments were conducted to measure wheat starch water content. Firstly, wheat starch water content was monitored as the media was recycled in the blast cabinet and, secondly, the equilibrium wheat starch water content was measured under different relative humidity and temperature conditions in order to establish the sensitivity of the water content to the storage conditions.

A.1 Recycled wheat starch

Envirostrip 12/30 wheat starch was blasted at 207 kPa [30 psi] and was recycled several times. The dewpoint of the compressed air used by the blast cabinet was lowered to 4.4°C [40°F] by an air dried (Atlas Copco model FD80). A sample of the recycled wheat starch was taken after every cycle, and its water content was determined as follows:

A.1.1 Water content determination

Firstly, the oven (VWR 1410D) was preheated to 105°C. Small aluminum cups were dried in the oven for 5 minutes and weighed to ±0.0001 g. Their weight was recorded as “A”.

Next, about 2 grams of wheat starch were put in the cups, and the cups were weighed
Figure A.1: Water content of recycled wheat starch

again. That weight was recorded as “B”. The cups with the wheat starch samples were then left in the oven for 24 hour. after what they were left to cool for 2-3 minutes and their final weight was measured and recorded as “C”.

The moisture content was calculated as per [38]:

\[
\% \text{ Moisture contents} = \frac{B - C}{B - A} \times 100
\]  (A.1)

A.1.2 Results

The evolution of the water content of recycled wheat starch is illustrated in Figure A.1. The wheat starch lost almost the same quantity of water every time it was recycled, that is about 0.5%. Hence, to maintain the water content of the wheat starch medium, one would need to add water at a rate of 0.5% of the mass of starch every time the media is recycled. i.e.,

\[
\dot{m}_{H_2O} = 0.005 \times \dot{m}
\]  (A.2)
Airtight cover

Wheat starch samples

NaOH solution

Figure A.2: Containers used to expose the wheat starch samples to controlled relative humidity conditions

where $\dot{m}_{\text{H}_2\text{O}}$ is the rate at which water must be added to the system (in kilograms per minute), and $\dot{m}$ is the mass flowrate of wheat starch, as defined in Section 2.2.

A.2 Wheat starch storage

To determine the equilibrium water content of wheat starch, several wheat starch samples were subjected to controlled relative humidity and temperature conditions (B.A.Sc. thesis of C. Yung, see [39]). Several containers, similar to the one illustrated in Figure A.2, were built to hold the wheat starch samples, and were placed in an environmental chamber with a precisely controlled temperature. A solution of water and sodium hydroxide (NaOH) was poured into the containers to maintain the correct relative humidity level.

The relative humidity was calculated as:

$$\%RH = \frac{pp_{\text{H}_2\text{O}}}{pp_{\text{sat}}}$$  \hspace{1cm} (A.3)

where $\%RH$ is the relative humidity, $pp_{\text{H}_2\text{O}}$ is the partial pressure of water in the air and $pp_{\text{sat}}$ is the partial pressure of water in the air at saturation.

The partial pressure of the water-NaOH solution was adjusted by varying the concentration of NaOH in the solution. The concentrations of NaOH required to obtain a specific partial pressure were obtained from [40]. The relative humidity in the containers was monitored using a relative humidity/temperature probe (Omega HX11), and the
NaOH concentrations were adjusted as needed before placing the wheat starch samples in the containers.

The water content of the wheat starch samples was determined as explained in Section A.1.1 at least once a week, until the variation between successive water content determinations was less than 1%; the equilibrium water content was said to be reached at this point. The time that the wheat starch samples took to reach equilibrium was also recorded.

**A.2.1 Results**

The equilibrium water contents are tabulated in Table A.1. All the samples reached equilibrium within two weeks. The experiment done at a temperature of 70°C showed that the equilibrium water content was at most a weak function of the temperature when the relative humidity was kept constant, but that the time taken by the samples to reach equilibrium was much shorter than at lower temperatures.

As illustrated in Figure A.3, the equilibrium water content of wheat starch rose almost

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>Relative humidity [%]</th>
<th>Number of days to stabilize</th>
<th>Equilibrium water content [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>30</td>
<td>5</td>
<td>9.47</td>
</tr>
<tr>
<td>35</td>
<td>40</td>
<td>5</td>
<td>10.38</td>
</tr>
<tr>
<td>35</td>
<td>45</td>
<td>10</td>
<td>11.59</td>
</tr>
<tr>
<td>35</td>
<td>50</td>
<td>7</td>
<td>11.84</td>
</tr>
<tr>
<td>35</td>
<td>55</td>
<td>7</td>
<td>12.77</td>
</tr>
<tr>
<td>35</td>
<td>60</td>
<td>8</td>
<td>13.36</td>
</tr>
<tr>
<td>35</td>
<td>70</td>
<td>9</td>
<td>15.09</td>
</tr>
<tr>
<td>35</td>
<td>85</td>
<td>8</td>
<td>18.99</td>
</tr>
<tr>
<td>70</td>
<td>45</td>
<td>3</td>
<td>11.16</td>
</tr>
</tbody>
</table>
linearly with the relative humidity. It should be noted that the starch particles exposed to a relative humidity higher than 60% stuck together and formed a flaky pellet. Even after drying, these samples would have not been usable as a blasting medium, so storing the wheat starch blasting medium in environments with more than 60% of relative humidity should be avoided.

Figure A.3: Equilibrium water content of Envirostrip 30/50 as a function of relative humidity, at 35°C.
Appendix B

Computer programs

Two computer programs were written for the present research. The first one was used to automate the size and shape analysis of wheat starch particles, and the second was used to control the flashes and the video camera during the velocity experiments.

B.1 Size and shape analysis program

The size and shape analysis program was made of two different parts. The first one controls Image-Pro (version 1.2) during the data acquisition and saves a binary file that contains all the data gathered during the session. This first program resides in the directory c:\etienne\sizedist\src and is named autodis.exe. It is written in plain C language, and the source code is located in the same directory as the executable.

To use autodis.exe, simply start it from a DOS session or directly from within Windows. The program automatically launches Image-Pro and asks the user what setting to use. The name of the settings correspond to the name of a directory in c:\etienne\sizedist were autodis will save all the parameters used to make Image-Pro recognize and measure the particles correctly, in addition to the binary and ascii files associated with the particles analysed. So, the next time autodis is run using the same settings, it will automatically configure Image-Pro the same way it was the last time these settings were used. There is thus no need to re-configure Image-Pro every time a new batch of media is analysed, as long as the same lighting, magnification, etc.
are used.

When the setting names is entered, the autodis displays a list of all the things that must be adjusted before starting to analyse the particles. Follow the instruction on the screen. and once everything is set properly, the analysis of the data can begin.

To take a frame and analyse it, type <return>. Once all the data is processed, type <q> to quit autodis. The data will be saved in a binary file whose name is in the format mmddhhmm.bin, where mm is the current month, dd the date, and hhmm the hour at which the data acquisition began.

Although the program has been extremely stable during all the experiments, the integrity of the data already analysed should be preserved in the binary file if it crashes.

Once the experiments are done, the data can be extracted from the binary files using the program postproc.exe located in the directory c:\etienne\autodis\srclite. The C++ source code is also in the same directory. The post-processing program only extracts the binary data and writes it to a text file, along with a log file that describes any problem encountered during the processing. Another version of the post-processing program can be found in the directory c:\etienne\autodis\src. That version was supposed to do the entire statistical analysis, but it never worked properly so, unless somebody is willing to debug the C++ source, its use is not advised.

Rather, the post-processing itself should be done using Excel, which can import the ascii files created by postproc. There is also a set of Excel 4.0 macros called postproc.xlm in the directory c:\etienne\autodis that makes the post-processing semi-automatic.

B.1.1 Caveats

- While postproc.exe will translate binary data files containing any combination of measurements and save the corresponding data file correctly, this is not the case for autodis.exe. The current version of autodis.exe is configured to get from Image-Pro and to save to the binary file only the minimum diameter, maximum diameter, average diameter, area and perimeter of the particles. The code would need only minor modifications handle other measurements.
• For some reason, the window in which autodis.exe is run needs to be reactivated each time an image is analysed by Image-Pro. Otherwise, the program will not respond to the keyboard entries. To reactivate the window, just activate another window and reactivate autodis’s window. or more simply, just click on autodis.exe in the task bar.

B.2 Velocity measurement program

The program used to control the frame grabber (Coreco Oculus TCX) and the flashes is called autograb.exe, and is located in the directory c:\etienne\vel\src. Its C++ source code is in the same directory and, unless there is a really serious reason to add functionality to the program, it is strongly advised to use it as is.

The program should be run from a DOS session, and its use is pretty straightforward: simply follow the menus. Only two things should be kept in mind: firstly, the contrast and brightness have to be adjusted, otherwise the particles may be not visible at on the pictures and, secondly, the area that will be saved to disk should be as small as possible. The computer is not fast enough to save full-screen pictures to disk every second and, besides, these pictures take up a lot of hard disk space.

The digital I/O lines are used as indicated in Figure B.1. Just keep in mind that the inputs and outputs have a polarity: if one input or output does not seems to work, inverse the connections and try again. (The white I/O modules are outputs and the red ones are inputs).

B.2.1 Source code

The program is divided in the following classes:

• The class opto22 provides an interface to the Opto22 digital I/O board. The flash delay controller is controlled through this class.

• The class frameGrabber provides an interface to the Coreco Oculus TCX frame grabber. It comprise the routines that save the pictures to disk (tiffSave).
Figure B.1: Use of the digital I/O lines for the velocity measurements

- The class `textMenu` displays a menu and provides an user interface for the program.

All the classes have been thoroughly debugged and tested, and it is easy to expand the program on them or to develop a new program that would use them.
Appendix C

Improved particle velocity measurement setup

The proposed improved velocity measurement setup is illustrated in Figure C.1. By using a different lens with the camera, the picture could be enlarged to focus on a smaller area (10 mm wide), making it possible to identify smaller particles and to measure particle velocities in different regions of the abrasive stream. In addition, it would be possible to determine the size of the particles as well as their velocity, since the resolution of the pictures would be comparable to what was obtained with the size and shape distribution setup (c.f. Section 4.1). The flash delays would be lowered to 5 μs so that the four images of the particles would fit on the pictures.

To further improve the image quality, the camera would view the stream of particles through a long tube which would prevent rebounding particles from appearing in the pictures. Air would be allowed to enter the tube from the camera opening (outside the cabinet), and the small negative pressure inside the blast cabinet (provided by the media reclamer fan) would create an air stream that would prevent dust media from entering the tube.

In addition, the dust level in the blast cabinet could be decreased by using a larger deflector with the flat nozzle.

Finally, the analysis of the pictures could be done automatically, therefore reducing the variability inherent to the manual analysis. The multiple exposure pictures obtained
APPENDIX C. IMPROVED PARTICLE VELOCITY MEASUREMENT SETUP

Figure C.1: Improved particle velocity measurement setup

with the blast cabinet (c.f. Figure 5.2) are very similar to those obtained in fluid mechanics experiments by placing markers in a flow (usually neutrally buoyant spheres). and there exist programs that calculate the velocity field of a flow based on these pictures. These programs could probably be used to calculate the velocity of the wheat starch particles.
IMAGE EVALUATION
TEST TARGET (QA-3)

1.0
1.1
1.25
1.4
1.6

1.0
1.1
1.25
1.4
1.6

150mm

6"

APPLIED IMAGE, Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/452-0300
Fax: 716/288-5969

© 1993. Applied Image, Inc. All Rights Reserved