EXPERIMENTAL INVESTIGATION OF THE MECHANICS OF VIBRATORY FINISHING

by

Shuwen Wang

A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
Department of Mechanical and Industrial Engineering
University of Toronto

© Copyright by Shuwen Wang 1999
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.
Abstract

EXPERIMENTAL INVESTIGATION OF THE MECHANICS OF VIBRATORY FINISHING

Shuwen Wang

M. A. Sc. Thesis 1999
Department of Mechanical and Industrial Engineering
University of Toronto

Vibratory finishing involves a large number of parameters which may affect the quality of the finished surface and the speed of finishing. To improve the quality and efficiency of surface finishing it is useful to better understand the fundamental mechanisms involved with vibratory surface finishing. This was the overall objective of the thesis.

To achieve the main goal of the thesis, a normal force sensor was designed and successfully built to measure the normal contact force between the media and the part. The measured force signals were processed by means of a Matlab program developed by the author.

The effects of media size, shape, surface roughness and lubrication on the surface hardness and roughness changes of aluminum workpieces were studied in this thesis. The interactions between the media and the part were also investigated by means of videotaping and scanning electron microscopy.
# Table of Contents

Abstract .........................................................................................................................i

Table of Contents ..........................................................................................................iii

List of Figures ..................................................................................................................vi

List of Tables ...................................................................................................................xiii

Nomenclature ................................................................................................................xv

Acknowledgements .......................................................................................................xviii

1.0 Introduction .............................................................................................................1

1.1 Review of Literature and Mechanics of Wear .........................................................1

1.2 Motivation ...............................................................................................................3

1.3 Thesis Objectives ...................................................................................................4

1.4 Thesis Outline .........................................................................................................4

2.0 Experimental Apparatus and Procedures ..............................................................6

2.1 Vibratory Surface Finishing Equipment ................................................................6

2.1.1 Vibratory Finisher .............................................................................................6

2.1.2 Model of Part ....................................................................................................10

2.1.3 Finishing Media and Lubrication .....................................................................14

2.2 Surface Analysis and Videotaping Equipment ......................................................26

2.3 Experimental Procedures .....................................................................................32

3.0 Normal Contact Force Sensor ...............................................................................33

3.1 Design of Normal Contact Force Sensor ............................................................33

3.2 Calibration of the Force Sensor ............................................................................40
4.0 Measurement of Normal Contact Forces ............................................. 50
  4.1 Experimental Setup ........................................................................ 50
  4.2 Force Signal Processing ................................................................... 52

5.0 Surface Analysis ........................................................................... 67
  5.1 Procedure ..................................................................................... 67
  5.2 Results and Discussion .................................................................. 68
    5.2.1 Hardness ................................................................................ 68
    5.2.2 Roughness ............................................................................ 70
    5.2.3 Effects of Media Roughness on HV and R_a ............................... 72
    5.2.4 Effects of Media Shape on HV and Ra ...................................... 73
    5.2.5 Repeatability ......................................................................... 74
    5.2.6 Topographies of Finished Workpiece and Media Surfaces ........ 74
    5.2.7 Summary ............................................................................. 74

6.0 Videotaping the Media Contact .................................................... 98
  6.1 Procedure ..................................................................................... 98
  6.2 Results and Discussion .................................................................. 98

7.0 Discussion and Conclusions .......................................................... 100
  7.1 Discussion .................................................................................... 100
    7.1.1 Effect of Media Size .................................................................. 100
    7.1.2 Effect of Media Roughness ....................................................... 101
    7.1.3 Effect of Lubrication ................................................................ 101
    7.1.4 Effect of Initial Hardness and Roughness of the Workpieces .... 103
    7.1.5 Effect of Interaction Between the Media and the Part ............... 103
  7.2 Conclusions .................................................................................. 104
    7.2.1 Experimental Setup ................................................................. 104
### 7.2.2 Normal Contact Force Between the Media and the Part ..........................104

### 7.2.3 Surface Analysis of the Media and the Finished Workpieces ..................105

### 7.2.4 Videotaping of the Contact Between the Media and the Part ..................106

### 7.3 Future Work ..........................................................................................106

### Appendices

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>SEM-EDX of Cylindrical Media</td>
<td>A1</td>
</tr>
<tr>
<td>B</td>
<td>Vibration Analysis of the Sensor</td>
<td>B1</td>
</tr>
<tr>
<td>C</td>
<td>Comparison of Normal Contact Forces for Different Media</td>
<td>C1</td>
</tr>
<tr>
<td>D</td>
<td>Matlab Program for Contact Force Processing</td>
<td>D1</td>
</tr>
<tr>
<td>E</td>
<td>Surface of AA1100-O in Dry Finishing for 1 min Using 9 mm Media</td>
<td>E1</td>
</tr>
<tr>
<td>F</td>
<td>Surface of AA1100-O in Dry Finishing for 5 min Using 9 mm Media</td>
<td>F1</td>
</tr>
<tr>
<td>G</td>
<td>Surface of AA1100-O in Dry Finishing for 10 min Using 9 mm Media</td>
<td>G1</td>
</tr>
<tr>
<td>H</td>
<td>Surface of AA1100-O in Dry Finishing for 20 min Using 9 mm Media</td>
<td>H1</td>
</tr>
<tr>
<td>I</td>
<td>Surface of AA1100-O in Dry Finishing for 40 min Using 9 mm Media</td>
<td>I1</td>
</tr>
<tr>
<td>J</td>
<td>Surface of AA1100-O in Dry Finishing for 80 min Using 9 mm Media</td>
<td>J1</td>
</tr>
<tr>
<td>K</td>
<td>Motion of Cylindrical Media</td>
<td>K1</td>
</tr>
</tbody>
</table>

### Numbered References ...............................................................................R1
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig. 2.1</td>
<td>Vibratory finisher (a) 3D and (b) 2D model</td>
<td>7</td>
</tr>
<tr>
<td>Fig. 2.2</td>
<td>Force spectrum of vibrating beam attached to the bowl</td>
<td>8</td>
</tr>
<tr>
<td>Fig. 2.3</td>
<td>Motion path in horizontal plane</td>
<td>9</td>
</tr>
<tr>
<td>Fig. 2.4</td>
<td>Motion path in vertical plane</td>
<td>9</td>
</tr>
<tr>
<td>Fig. 2.5</td>
<td>Dimensions (mm) of chosen cylindrical part</td>
<td>12</td>
</tr>
<tr>
<td>Fig. 2.6</td>
<td>Dry finishing showing part at top of bowl</td>
<td>12</td>
</tr>
<tr>
<td>Fig. 2.7</td>
<td>Spherical ceramic media (A-11 mm, B-9 mm, C-7 mm)</td>
<td>17</td>
</tr>
<tr>
<td>Fig. 2.8</td>
<td>Scanning electron micrograph of the fresh 9 mm spherical ceramic media</td>
<td>18</td>
</tr>
<tr>
<td>Fig. 2.9</td>
<td>Scanning electron micrograph of the fresh cylindrical ceramic media</td>
<td>18</td>
</tr>
<tr>
<td>Fig. 2.10</td>
<td>(a) Typical topography (WYKO) of fresh 7 mm spherical media</td>
<td>19</td>
</tr>
<tr>
<td>Fig. 2.10</td>
<td>(b) Typical topography (WYKO) of used 9 mm spherical media</td>
<td>19</td>
</tr>
<tr>
<td>Fig. 2.10</td>
<td>(c) Typical topography (WYKO) of used 11 mm spherical media</td>
<td>20</td>
</tr>
<tr>
<td>Fig. 2.11</td>
<td>Typical topography of used media (9 mm)</td>
<td>20</td>
</tr>
<tr>
<td>Fig. 2.12</td>
<td>(a) SEM-EDX analysis of 7 mm media</td>
<td>21</td>
</tr>
<tr>
<td>Fig. 2.12</td>
<td>(b) SEM-EDX analysis of 9 mm media</td>
<td>22</td>
</tr>
<tr>
<td>Fig. 2.12</td>
<td>(c) SEM-EDX analysis of 11 mm media</td>
<td>23</td>
</tr>
<tr>
<td>Fig. 2.13</td>
<td>Illustration of (a) skewness and (b) Kurtosis</td>
<td>24</td>
</tr>
<tr>
<td>Fig. 2.14</td>
<td>Size changes of media</td>
<td>25</td>
</tr>
<tr>
<td>Fig. 2.15</td>
<td>Surface roughness changes as a function of finishing time</td>
<td>25</td>
</tr>
</tbody>
</table>
Fig. 2.16 The WYKO RST Plus optical profilometer system ........................................... 27

Fig. 2.17 Microhardness tester ...................................................................................... 28

Fig. 2.18 Super-micro CCD color camera ..................................................................... 29

Fig. 2.19 Installation of camera and fiber-optic light ................................................... 30

Fig. 2.20 Videotaping system ....................................................................................... 31

Fig. 3.1 (a) and (b) Illustration of the fixed-fixed beam and strain gauges
(1, 2, 3, and 4 are strain gauges) .................................................................................. 35

Fig. 3.2 Full-bridge circuit .............................................................................................. 35

Fig. 3.3 The design of the sensor (all dimensions in mm) .............................................. 39

Fig. 3.4 Static calibration of force sensor ....................................................................... 41

Fig. 3.5 A schematic of the dynamic calibration ............................................................ 43

Fig. 3.6 Sensor dynamic calibration (no attached load at an acceleration of 30 m/s²) ... 43

Fig. 3.7 Sensor dynamic calibration. (4 grams load at an acceleration of 10 m/s² and 1 gram
load at an acceleration of 20 m/s² at sampling rate 1000 Hz) ........................................ 44

Fig. 3.8 Dynamic noise of the sensor in finisher with sensor covered and in the bowl at
sampling rate 500 Hz ..................................................................................................... 44

Fig. 3.9 Force response of single media impact at sampling rate 4800 Hz ..................... 47

Fig. 3.10 Force spectrum of single media impact ............................................................ 48

Fig. 3.11 First peak of impact signal of Fig. 3.9 (sampling rate 4800 Hz ) ...................... 48

Fig. 3.12 Freely falling body striking a body of finite stiffness ....................................... 49

vii
Fig. 4.1 The system for normal contact force measurement ........................................51

Fig. 4.2 Representative of normal force spectrum for sensor in finisher at sampling frequency
2000 Hz ......................................................................................................................51

Fig. 4.3 Normal contact force in dry finishing with media of diameters (a) 7 mm, (b) 9 mm,
(c) 11 mm ..............................................................................................................53

Fig. 4.4 Force spectra in dry finishing with media of diameters (a) 7 mm, (b) 9 mm,
(c) 11 mm ..............................................................................................................54

Fig. 4.5 Normal contact forces in wet finishing with media of diameters (a) 7 mm, (b) 9 mm,
(c) 11 mm ..............................................................................................................55

Fig. 4.6 Force spectra in wet finishing with media of diameters
(a) 7 mm, (b) 9 mm, (c) 11 mm ..............................................................................56

Fig. 4.7 Comparison of Fast Fourier Transform (FFT) of (a) raw force signal and (b) the
extracted impact events ............................................................................................58

Fig. 4.8 Average max. impact force vs. media size. Error bars represent 95% confidence
intervals .....................................................................................................................62

Fig. 4.9 Average impact force vs. media size. Error bars represent 95% confidence intervals62

Fig. 4.10 Average impulse vs. media size. Error bars represent 95% confidence intervals ...63

Fig. 4.11 Percentage of contact time as a function of media sizes. Error bars represent 95%
confidence intervals ...............................................................................................63
Fig. 5.1 Effect of lubrication on HV changes for AA1100-O (a) 7 mm, $R_a$ 17.5 ± 4.1 μm, (b) 9 mm, $R_a$ 15.4 ± 6.3 μm, and (c) 11 mm, $R_a$ 16.2 ± 4.7 μm. Error bars indicate 95% confidence intervals for 6 measurements on one workpiece

Fig. 5.2 Effect of lubrication on HV changes for AA6061-T6 (a) 7 mm, $R_a$ 17.5 ± 4.1 μm, (b) 9 mm, $R_a$ 15.4 ± 6.3 μm, and (c) 11 mm, $R_a$ 16.2 ± 4.7 μm. Error bars indicate 95% confidence intervals for 6 measurements on one workpiece.

Fig. 5.3 Comparison of HV changes for AA1100-O in washing the media and the part during finishing ($R_a$ 13.8 ± 2.3 μm) with dry, wet, and lubricated finishing ($R_a$ 15.4 ± 6.3 μm). Errors indicate 95% confidence intervals for 6 measurements on one workpiece.

Fig. 5.4 Effects of media size on HV changes for AA1100-O in (a) dry, (b) wet, and (c) lubricated finishing with $R_a$ 17.5 ± 4.1 μm (7 mm), 15.4 ± 6.3 μm (9 mm), and 16.2 ± 4.7 μm (11 mm), error bars indicate the 95% confidence intervals in 6 measurements on one workpiece.

Fig. 5.5 Effects of media size on HV changes for AA6061-T6 in (a) dry, (b) wet, and (c) lubricated finishing with $R_a$ 17.5 ± 4.1 μm (7 mm), 15.4 ± 6.3 μm (9 mm), and 16.2 ± 4.7 μm (11 mm), error bars indicate the 95% confidence intervals in 6 measurements on one workpiece.

Fig. 5.6 Effect of lubrication on $R_a$ changes for AA1100-O (a) 7 mm, $R_a$ 17.5 ± 4.1 μm, (b) 9 mm, $R_a$ 15.4 ± 6.3 μm, and (c) 11 mm, $R_a$ 16.2 ± 4.7 μm. Error bars indicate 95% confidence intervals for 6 measurements on one workpiece.
Fig. 5.7 Effect of lubrication on $R_a$ changes for AA6061-T6 (a) 7 mm, $R_a$ 17.5 ± 4.1 μm, (b) 9 mm, $R_a$ 15.4 ± 6.3 μm, and (c) 11 mm, $R_a$ 16.2 ± 4.7 μm. Error bars indicate 95% confidence intervals for 6 measurements on one workpiece.

Fig. 5.8 Comparison of $R_a$ changes for (a) AA1100-O and (b) AA6061-T6 in washing the media (Ra 13.8 ± 2.3 μm) and the part during finishing with dry, wet, and lubricated finishing (Ra 15.4 ± 6.3 μm). Error bars indicate 95% confidence intervals for 6 measurements on one workpiece.

Fig. 5.9 Effects of media size on $R_a$ changes for AA6061-T6 in (a) dry, (b) wet, and (c) lubricated finishing with $R_a$ 17.5 ± 4.1 μm (7 mm), 15.4 ± 6.3 μm (9 mm), and 16.2 ± 4.7 μm (11 mm), error bars indicate the 95% confidence intervals in 6 measurements on one workpiece.

Fig. 5.10 Effects of media size on $R_a$ changes for AA6061-T6 in (a) dry, (b) wet, and (c) lubricated finishing with $R_a$ 17.5 ± 4.1 μm (7 mm), 15.4 ± 6.3 μm (9 mm), and 16.2 ± 4.7 μm (11 mm), error bars indicate the 95% confidence intervals in 6 measurements on one workpiece.

Fig. 5.11 Effects of 9 mm media roughness ($-x-$ $R_a$ = 15.4 ± 6.3 μm, $R_{uk}$ = -0.43 ± 0.54, -o- $R_a$ = 13.8 ± 2.3 μm, $R_{uk}$ = -0.156 ± 0.35) on HV changes for AA1100-O in (a) dry, (b) wet, and (c) lubricated finishing. Error bars indicate the 95% confidence intervals for 6 measurements on one workpiece.

Fig. 5.12 Effects of 9 mm media roughness ($-x-$ $R_a$ = 15.4 ± 6.3 μm, $R_{uk}$ = -0.43 ± 0.54, -o- $R_a$ = 13.8 ± 2.3 μm, $R_{uk}$ = -0.156 ± 0.35) on $R_a$ changes for AA1100-O in (a) dry, (b)
wet, and (c) lubricated finishing. Error bars indicate the 95% confidence intervals for 6 measurements on one workpiece. ...

Fig. 5.13 Effects of 9 mm media roughness (-x- $R_a = 15.4 \pm 6.3 \mu m$, $R_{pk} = -0.43 \pm 0.54$, -o- $R_a = 13.8 \pm 2.3 \mu m$, $R_{pk} = -0.156 \pm 0.35$) on $R_a$ changes for AA6061-T6 in (a) dry, (b) wet, and (c) lubricated finishing. Error bars indicate the 95% confidence intervals for 6 measurements on one workpiece. ...

Fig. 5.14 Effect of media shape and size on HV changes of (a) AA1100-O and (b) AA6061-T6 in dry finishing. The media roughness $R_a$ were $17.5 \pm 4.1 \mu m$ (7 mm), $15.4 \pm 6.3 \mu m$ (9 mm), and $16.2 \pm 4.7 \mu m$ (11 mm). Error bars indicate 95% confidence intervals for 6 measurements on one workpiece ...

Fig. 5.15 Effect of media shape and size on $R_a$ changes of (a) AA1100-O and (b) AA6061-T6 in dry finishing. The media roughness $R_a$ were $17.5 \pm 4.1 \mu m$ (7 mm), $15.4 \pm 6.3 \mu m$ (9 mm), and $16.2 \pm 4.7 \mu m$ (11 mm). Error bars indicate 95% confidence intervals for 6 measurements on one workpiece ...

Fig. 5.16 Repeatability in dry finishing AA1100-O using 9 mm media of the same roughness ($Ra \ 13.8 \pm 4.7 \mu m$). Error bars indicate 95% confidence intervals for 6 measurements on one workpiece. ...

Fig. 5.17 SEMs of individual impact sites on AA1100-O after dry finishing for 10 s. Scale bars represent: top row -60 and 120 \mu m, bottom row -86 and 86 \mu m ...

Fig. 5.18 SEMs of individual impact sites on AA1100-O after dry finishing for 10 s. Scale bars represent: top row -60 and 100 \mu m, bottom row -86 and 86 \mu m...
Fig. 5.19 SEMs of individual impact sites on AA1100-O after dry finishing for 10 s. Scale bars represent: top row -100 and 86 μm, bottom row -200 and 120 μm .........................94

Fig. 5.20 WYKO of individual impact site on AA1100-O after dry finishing for 10 s (a) 2D and (b) 3D ........................................................................................................95

Fig. 5.21 WYKO of individual impact site on AA1100-O after wet finishing for 10 s (a) 2D and (b) 3D ........................................................................................................96

Fig. 5.22 WYKO of individual impact site on AA1100-O after lubricated finishing for 10 s (a) 2D and (b) 3D ........................................................................................................97

Fig. 6.1 Video frames showing typical large gaps between contacting 9 mm spheres .......99
List of Tables

Table 2.1 Average periods of motion of different aluminum cylindrical parts in dry finishing using fresh 9 mm media, $P_r$: Radial period in second, $P_a$: Axial period in second, $P_c$: Circumferential period in second. The data are average of 10 measurements in each case. ................................................................. 11

Table 2.2 Motion periods of a cylindrical part (68 mm diam. x 80 mm) in different media and lubrication conditions (radial period, axial period, and circumferential period). Averages are for 10 measurements. ................................................................. 13

Table 2.3 Surface roughness of the fresh 7, 9, and 11 mm spherical media ($n = 5$, one measurement on each media). Errors represent 95% confidence intervals. ............ 15

Table 2.4 Roughness mean differences of the three fresh media ($\times$ indicates there are differences between the two population means at the 95% confidence level; $\checkmark$ indicates there are no differences between the two population means at the 95% confidence level) ................................................................. 16

Table 4.1 Statistics for normal contact forces of 7, 9, and 11 mm media in dry finishing over 8 s with sensor facing forward. The data are the average of 10 runs with 8 s for each run. The 95% confidence intervals are also listed ($n = 10$). .................. 59
Table 4.2 Statistics for normal contact forces of 7, 9, and 11 mm media in wet finishing over 8 s with sensor facing forward. The data are the average of 10 runs with 8 seconds for each run. The 95% confidence intervals are listed (n = 10). .............60

Table 4.3 Comparison of normal contact force statistics of 9 mm media in dry and wet finishing with sensor facing forward and backward over 8 s. The data are the average of 10 runs with 8 seconds for each run with a sampling frequency of 500 Hz. The 95% confidence intervals are listed (n = 10). .........................65

Table 4.4 Comparison of normal contact force statistics of 9 mm media in dry finishing with sensor fixed and moving. The data are the average of 10 runs with 8 s for each run with a sampling frequency of 500 Hz. The 95% confidence intervals are listed (n = 10). .................................................................66

Table 5.1 Roughness of two 9 mm media. First means the media was used for 20 h when the experiments were carried out; second means the media was used for 40 h when the experiments were carried out. The data in the Table were the average of 5 measurements. .................................................................72
## Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>English Units</th>
<th>SI Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>constant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>area</td>
<td>in²</td>
<td>m²</td>
</tr>
<tr>
<td>A, A₀, A₁...</td>
<td>constants</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>width</td>
<td>in</td>
<td>m</td>
</tr>
<tr>
<td>B, B₁, B₂...</td>
<td>constants</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c, c₀, c₁...</td>
<td>constants</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C, C₁...</td>
<td>constants</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Young's modulus</td>
<td>lb/in²</td>
<td>Pa</td>
</tr>
<tr>
<td>F</td>
<td>force</td>
<td>lb</td>
<td>N</td>
</tr>
<tr>
<td>F₀</td>
<td>amplitude of force F(t)</td>
<td>lb</td>
<td>N</td>
</tr>
<tr>
<td>H</td>
<td>distance</td>
<td>in.</td>
<td>m</td>
</tr>
<tr>
<td>h</td>
<td>beam thickness</td>
<td>in.</td>
<td>m</td>
</tr>
<tr>
<td>hₘᵢₙ</td>
<td>min. lubricant film thickness</td>
<td>in.</td>
<td>m</td>
</tr>
<tr>
<td>HV</td>
<td>Vickers hardness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Iᵗʰ integer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>area moment of inertia</td>
<td>in⁴</td>
<td>m⁴</td>
</tr>
<tr>
<td>kₑ𝑞</td>
<td>equivalent stiffness</td>
<td>lb/in.</td>
<td>N/m</td>
</tr>
<tr>
<td>l, L</td>
<td>lengths</td>
<td>in.</td>
<td>m</td>
</tr>
<tr>
<td>lₑ</td>
<td>strain gauge length</td>
<td>in.</td>
<td>m</td>
</tr>
<tr>
<td>m, M</td>
<td>mass</td>
<td>lb-sec²/in.</td>
<td>kg</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit 1</td>
<td>Unit 2</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td>m_i</td>
<td>i\textsuperscript{th} integer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>bending moment</td>
<td>lb-in.</td>
<td>N-m</td>
</tr>
<tr>
<td>P_a</td>
<td>axial motion period of part</td>
<td>sec</td>
<td>s</td>
</tr>
<tr>
<td>P_c</td>
<td>circumferential motion period of part</td>
<td>sec</td>
<td>s</td>
</tr>
<tr>
<td>P_{imp}</td>
<td>impact force</td>
<td>lb</td>
<td>N</td>
</tr>
<tr>
<td>P_r</td>
<td>radial motion period of part</td>
<td>sec</td>
<td>s</td>
</tr>
<tr>
<td>Q_j</td>
<td>j\textsuperscript{th} generalized force</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R_a</td>
<td>roughness average</td>
<td>μin.</td>
<td>μm</td>
</tr>
<tr>
<td>R_{ku}</td>
<td>kurtosis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R_q</td>
<td>root-mean-square roughness</td>
<td>μin.</td>
<td>μm</td>
</tr>
<tr>
<td>R_{sk}</td>
<td>skewness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R_t</td>
<td>maximum height of the profile</td>
<td>μin.</td>
<td>μm</td>
</tr>
<tr>
<td>R_z</td>
<td>average max. height of the profile</td>
<td>μin.</td>
<td>μm</td>
</tr>
<tr>
<td>s</td>
<td>exponential coefficient, root of equation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t</td>
<td>time</td>
<td>sec</td>
<td>s</td>
</tr>
<tr>
<td>t_i</td>
<td>i\textsuperscript{th} time station</td>
<td>sec</td>
<td>s</td>
</tr>
<tr>
<td>T</td>
<td>torque</td>
<td>lb-in.</td>
<td>N-m</td>
</tr>
<tr>
<td>T</td>
<td>kinetic energy</td>
<td>in.-lb</td>
<td>J</td>
</tr>
<tr>
<td>V</td>
<td>shear force</td>
<td>lb</td>
<td>N</td>
</tr>
<tr>
<td>w, w_1, w_2...</td>
<td>transverse deflections</td>
<td>in.</td>
<td>m</td>
</tr>
<tr>
<td>w_0</td>
<td>value of w at t = 0</td>
<td>in.</td>
<td>m</td>
</tr>
</tbody>
</table>

xvi
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_0$</td>
<td>value of $W$ at $t = 0$</td>
<td>in./sec</td>
<td>m/s</td>
</tr>
<tr>
<td>$w_m$</td>
<td>$m^{th}$ mode of vibration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W$</td>
<td>weight of mass</td>
<td>lb</td>
<td>N</td>
</tr>
<tr>
<td>$W$</td>
<td>transverse displacement</td>
<td>in.</td>
<td>m</td>
</tr>
<tr>
<td>$x, y, z$</td>
<td>Cartesian coordinates</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$X$</td>
<td>transverse displacement at the middle of the beam</td>
<td>in.</td>
<td>m</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>confidence level</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta, \gamma$</td>
<td>constants</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\lambda$</td>
<td>constant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\lambda_i$</td>
<td>$i^{th}$ constant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td>mass density</td>
<td>lb·sec$^2$/in$^4$</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>strain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma$</td>
<td>stress</td>
<td>psi</td>
<td>Pa</td>
</tr>
<tr>
<td>$\sigma^*$</td>
<td>RMS roughness of two surfaces</td>
<td>$\mu$m</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>$\tau$</td>
<td>period of oscillation,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\omega_i$</td>
<td>$i^{th}$ natural frequency</td>
<td>rad/sec</td>
<td>rad/s</td>
</tr>
<tr>
<td>$\delta_s$</td>
<td>static displacement</td>
<td>in.</td>
<td>m</td>
</tr>
</tbody>
</table>

xvii
Acknowledgments

I would like to thank my supervisor Professor Jan K. Spelt for his guidance, encouragement and kindness during this project. I would also like to thank my colleagues in the Materials and Process Mechanics Lab in the Department of Mechanical and Industrial Engineering at the University of Toronto, in particular, Munir Ahmed, Yijun Tu, Payam Tangestanian, Marcello Papini, and Alan Ruxing Wang for their technical assistance and friendships during this period.

Thanks are due to Manufacturing and Materials Ontario (MMO), AMP of Canada Ltd. and the University of Toronto for their financial support.

I would also like to thank the Research Lab of AMP of Canada Ltd. for providing aluminum samples, abrasive media, assistance in hardness and roughness measurement, and especially for Dr. Roland S. Timsit’s valuable technical advice.
Chapter 1

Introduction

Since the 1950s, vibratory finishing has been widely used in manufacturing. A vibratory finishing system usually consists of a spring-mounted open chamber containing granular media, to which a vibratory motion generator is attached. The motion generator normally consists of one or two rotating shafts with eccentric weights. By adjustment of the eccentric weight or the speed of the drive system, the amplitude and frequency of the finisher can be controlled. The chamber of the finisher can be of a round or oval bowl, or a U-shaped tub.

Vibratory finishing has often been used to improve surface appearance and wear resistance, to increase hardness and smoothness, and to clean and dry surfaces. The process has been used to finish metal, ceramic, and plastic parts using a wide variety of media such as steel balls, rough ceramic spheres and angle-cut cylinders, and even crushed corn cobs.
1.1 Review of Literature and Mechanics of Wear

The process of vibratory surface finishing is a combination of rubbing, ploughing, and cutting processes due to normal impact and two-body or three-body abrasive wear. Abrasive wear occurs when a hard, rough surface slides against a softer surface, digs into it, and plows a series of grooves [1]. For ductile surfaces and hard particles which have sharp-edged faces cutting occurs, which removes chips of material from the surface. Hard particles which have smooth edges or rounded faces will plow the softer surface. During plowing, the surface material is pushed both transversely to the direction of the particle motion and in front of the particle to form a groove with ridges. Some material may be removed during this process, but more material will pile up along the groove edges. After repeated plowing, the piled materials will be removed from its surface due to fatigue and become debris. For brittle material, the groove is formed by crack propagation and subsequent chipping of the surface material [2]. For a ductile material, the surface will be displaced plastically by abrasive wear, while for a hard surface, little plastic displacement will occur. In the latter situation, wear may happen as a result of brittle cracking of the surface material.

In abrasive wear, there is a critical particle size below which the wear rate is strongly dependent on the particle size. Wear becomes independent of the particle size if the latter is above the critical value.

Xie and Williams [3] developed a model to predict the coefficient of friction and the wear rate when a surface slides against a randomly rough harder surface. The model indicated that both the friction and wear rate depend greatly on the roughness characteristics of the
harder surface, the hardness of both surfaces, the nominal contact pressure or load and the state of lubrication.

Yamaguchi and Takakura [4] carried out experiments on the effects of abrasive grain size on surface finishing and abrasion in lubricated abrasive flow finishing of aluminum. Their experimental results indicated that the degree of abrasion of the aluminum specimen increased with increasing particle size of the media (alumina powders), and the roughness of the finished aluminum specimen depended on the combination of the particle size of the abrasive media and the initial surface roughness of the specimen.

Fraas [5] pointed out that the motion of a vibration-fluidized bed was a combination of linear, whirl, oscillation, and rocking motions. He also discussed the motion of a single particle (0.3 ~ 3 mm) in the vibration-fluidized bed, and estimated the duration of the impact for a pellet of SiO₂ striking an aluminum plate (0.42 ms). The impact (vertical) and transport (horizontal) velocity of a particle in a vibration-fluidized bed (vibration frequency of 30 Hz with a double amplitude of 3 mm) was 16.3 cm/s and 15.5 cm/s, respectively.

1.2 Motivation

Vibratory finishing involves a large number of parameters which may affect the quality of the finished surface and the speed of finishing. To improve the quality and efficiency of surface finishing it is useful to better understand the fundamental mechanisms involved with vibratory surface finishing. This may help guide the selection of optimal finishing parameters,
such as the vibration frequency and amplitude, media size, shape and roughness, lubrication, and finishing time.

1.3 Thesis Objectives

The overall objective of the thesis was to investigate the mechanism of vibratory surface finishing by means of the following measurements and analyses:

- design of a suitable sensor to measure the contact forces between the abrasive media and a part
- analysis of the measured contact forces
- measurement and analysis of the surface hardness and roughness of finished aluminum surfaces
- analysis of the relationships between the contact force, workpiece and media hardness and roughness, media size, lubrication, and finishing time
- videotaping the relative motion between the media and the part
- characterizing the motion of the media and part in the vibratory finisher

1.4 Thesis Outline

Chapter 1 introduces the concept of vibratory surface finishing and involves a review of literature and the mechanism of abrasive wear. Chapter 2 describes the setup of experimental apparatus and procedures of experiments. Chapter 3 gives the detailed design and vibrational analysis of the force sensor designed by the author. Chapter 4 describes the
contact force measurements and the force signal processing using MATLAB. Chapter 5 presents the results and analysis of the measurements of hardness and roughness changes of the workpieces. Chapter 6 presents the videotaping results. Chapter 7 gives a discussion of the data and considers the mechanisms of vibratory surface finishing. The conclusion of the thesis and the possible future directions of research are also presented in this chapter.
Chapter 2

Experimental Apparatus and Procedures

The equipment used in this project was in three groups: vibratory surface finishing, surface analysis, and videotaping equipment.

2.1 Vibratory Surface Finishing Equipment

2.1.1 Vibratory Finisher

Vibratory finishing systems usually consist of a spring-mounted open chamber to which a vibratory motion generator is attached. The motion generator normally consists of one or two rotating shafts with eccentric weights. By adjustment of the eccentric weight or the speed of the drive system, the amplitude and frequency of the finisher can be controlled.

The vibratory finisher (Model 150S, Burr King Mfg. Co., Inc., Warsaw, USA) used in this project, was an annular bowl with an outside diameter of 15 in (38.1 cm), an inner diameter of 6 in (15.2 cm), and a depth of 5.75 in (14.6 cm) as shown in Fig. 2.1. It oscillated in an elliptical path at 30 Hz (1800 rpm).
Fig. 2.1 Vibratory finisher (a) 3D model and (b) 2D model
Driving Frequency of Finisher

To check the driving frequency of the finisher, one end of a strain-gauged aluminum beam was attached to the finisher, while the other end was fixed. Figure 2.2 shows the frequency response of the beam strain gauges, and confirmed that the driving frequency of the finisher was 30 Hz.

Fig. 2.2 Force spectrum of vibrating beam attached to the bowl

Motion of Finisher

The vibration double amplitude and the motion paths of the finisher in both the horizontal (X-Y) and vertical (X-Z) planes were obtained by using an image processing technique. The X-Y and X-Z motions of the finisher were videotaped, then digitized frame by frame using the Image-Pro software, to find the X, Y, and Z positions of two marks; one on the top of the bowl, the other on the side. Figures 2.3 and 2.4 show the X-Y and X-Z paths of the finisher, respectively. From Figs. 2.3 and 2.4, it was found that the double amplitude of the finisher in X,Y and Z directions was approximately 0.7, 0.8, and 1.8 mm, respectively.
Fig. 2.3 Motion path in horizontal plane

Fig. 2.4 Motion path in vertical plane
2.1.2 Model of Part

To study the surface hardness and roughness changes of the aluminum workpieces after finishing, a prototype part was needed to carry the workpiece in thefinisher. This same prototype part was instrumented with a contact force sensor and a small video camera. After observing the motions of some parts within the finisher, it was decided to choose a cylindrical part because its motion was quite regular within the finisher.

It was observed that a cylindrical part would move in a spiral around the bowl with its longitudinal axis remaining horizontal. It would travel down into the media at the center of the bowl and up at the outer wall. The part would also rotate about its own longitudinal axis. In addition to moving with its longitudinal axis remaining horizontal, the cylindrical part can be induced to tumble end-over-end around the periphery of the bowl. In this case, only the tumbling and the circumferential frequency are relevant in a bowl of the present size.

Effect of Cylindrical Part Size and Density on Its Motion

To find the maximum dimensions of the cylindrical part which could move freely within the finisher, six cylinders with different dimensions were tested. The dimensions of the cylinders and the periods of motion are shown in Table 2.1. The radial motion period, \( P_r \), refers to the time for the part to move one cycle from the top of the media to the bottom of the bowl and then back to the top of the media (the position shown in Fig. 2.6). The axial motion period, \( P_a \), is the time for the part to revolve one cycle upon its own longitudinal axis. In these experiments, it was found that \( P_r \) was equal to \( P_a \). The circumferential motion period, \( P_c \), was the time for the part to move once around the bowl. The results indicated
that, although the diameter of the part had less effect on the motion than the part length, both the diameter and the length had no significant effect on the motion of the part in the tested range.

The results also indicated that the density of the part had little effect on its motion within the range from 0.58 to 1.13 g/cm³. It is noted that the bulk density of the 9 mm media was 1.3 to 1.49 g/cm³.

Table 2.1 Average periods of motion of different aluminum cylindrical parts in dry finishing using fresh 9 mm media, Pr: Radial period, Pa: Axial period in second, Pc: Circumferential period. The data are average of 10 measurements in each case.

<table>
<thead>
<tr>
<th>Cylinder Length (mm)</th>
<th>Cylinder Diameter (mm)</th>
<th>Density g/cm³</th>
<th>Average P₀, Pₐ (s)</th>
<th>Average Pₑ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>26</td>
<td>1.13</td>
<td>7.5</td>
<td>25.5</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>1.00</td>
<td>7</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>0.58</td>
<td>6.5</td>
<td>28</td>
</tr>
<tr>
<td>70</td>
<td>26</td>
<td>1.08</td>
<td>7.75</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>0.80</td>
<td>8</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>0.81</td>
<td>8.75</td>
<td>30.5</td>
</tr>
</tbody>
</table>

Figure 2.5 shows the dimensions of the chosen cylinder. Different weights could be put into the cylinder so that the density (0.75 g/cm³) and balance could be maintained as the part was fitted to hold the force sensor, video camera or aluminum workpieces.
Fig. 2.5 Dimensions (mm) of chosen aluminum cylinder

Fig. 2.6 Dry finishing showing part at top of bowl
Motion of the Chosen Cylindrical Part

Figure 2.6 shows the motion of the part (0.75 g/cm³) in the finisher in dry finishing, and Table 2.2 gives the radial, axial and circumferential motion periods of the cylinder in the bowl using 7, 9, and 11 mm spherical media in dry, wet and lubricated finishing. Table 2.2 illustrates that lubrication did have an appreciable effect on part motion; movement became progressively slower as lubrication increased.

Table 2.2. Motion periods of a cylindrical part (68 mm diam. × 80 mm) in different media and lubrication conditions (radial period, axial period, and circumferential period). Averages are for 10 measurements

<table>
<thead>
<tr>
<th>Media Dia. (spherical)</th>
<th>Results</th>
<th>Dry</th>
<th>Wet</th>
<th>Lubricated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(P_r), (P_a) (s)</td>
<td>(P_c) (s)</td>
<td>(P_r), (P_a) (s)</td>
</tr>
<tr>
<td>7 mm</td>
<td>Average</td>
<td>10</td>
<td>36</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Stdev</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>9 mm</td>
<td>Average</td>
<td>12</td>
<td>37</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Stdev</td>
<td>1</td>
<td>0.5</td>
<td>2</td>
</tr>
<tr>
<td>11 mm</td>
<td>Average</td>
<td>12</td>
<td>38</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Stdev</td>
<td>1</td>
<td>1</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Effect of Force Sensor and Video Cables on the Motion of the Part

For 9 mm media in dry finishing, \(P_r\) and \(P_a\) were about 12 s and \(P_c\) was about 37 s without any sensor cables. With the force sensor wire, \(P_r\) and \(P_a\) were about 14 s, and \(P_c\) was
about 46 s. In videotaping, the cable (including fiber-optic cable) effect on the motion of the cylinder was almost the same as that in the force sensor (16 s and 48 s). It can be concluded that the force sensor and the video cables had a relatively small effect on the part motion.

2.1.3 Finishing Media and Lubrication

Topography of Media

The media used in the project were three kinds of approximately spherical ceramic media (A, B, and C) (Abrasive Finishing Inc., 11770 Dexter Rd., Chelsea, MI 48118, USA) with average diameters (in measurements on 20 spheres) of 7.1 (SD = 0.35 mm), 8.6 (SD = 0.56 mm), and 11 mm (SD = 0.73 mm) shown in Fig. 2.7.

The typical topography of the spherical and another cylindrical media are shown in Figs. 2.8 and 2.9 (SEMs). Figures 2.10 (a)-(c) and 2.11 show the typical topographies (WYKO, see Section 2.2) of fresh and used spherical media. From SEM-EDX elemental analysis, the spherical media were composed mainly of Si, Al, K, Ca, Ti and Fe as shown in Fig. 2.12 (a), (b), and (c), and the cylindrical ceramic media was mainly composed of Si, Al, Mg, K, Ca, Ti, Mn, and Fe (Appendix A). The surface roughness of the fresh 7, 9, and 11 mm spherical media are shown in Table 2.3.

Here, $R_s$, roughness average, is the mean height as calculated over the entire measured array; $R_z$, average maximum height of the profile, is one fifth the sum of the absolute values of the heights of the five highest profile peaks and the depths of the five deepest profile valleys in one cutoff length of the roughness profile; $R_d$, skewness, is a measure of the asymmetry of the profile about the mean line; $R_k$, kurtosis, is a measure of
the peakedness of the profile about the mean line, it provides information about the "spikiness" of a surface, or of the sharpness of the height distribution function, which does not necessarily mean the sharpness of individual peaks and valleys [6]. Figure 2.13 illustrates the skewness and kurtosis.

<table>
<thead>
<tr>
<th>Media</th>
<th>$R_a$</th>
<th>$R_z$</th>
<th>$R_{ku}$</th>
<th>$R_{ak}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 mm</td>
<td>19.6 ± 3.16</td>
<td>123 ± 46.5</td>
<td>2.89 ± 1.76</td>
<td>-0.320 ± 0.97</td>
</tr>
<tr>
<td>9 mm</td>
<td>21.8 ± 8.60</td>
<td>169 ± 28.7</td>
<td>3.75 ± 3.26</td>
<td>-0.716 ± 0.90</td>
</tr>
<tr>
<td>11 mm</td>
<td>19.2 ± 5.68</td>
<td>119 ± 25.6</td>
<td>2.53 ± 0.35</td>
<td>-0.180 ± 0.32</td>
</tr>
</tbody>
</table>

**Testing the equality of two means of the media roughness**

The following formula was used to compute a $t$ score for the difference between two means [7]:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{s^2 / n_1 + s^2 / n_2}}$$  \hspace{1cm} (2.1)

where, $n_1$, $n_2$ are the data numbers of the two media, $\bar{x}_1$, and $\bar{x}_2$ are the average roughness of the two media, and $s^2$ is a pooled estimate of the population variance ($\sigma^2$), based on the standard deviation $s$ of both samples combined. The formula for computing $s^2$ is
The t statistic in Eq. (2.1) under the null hypothesis \( \mu_1 - \mu_2 = 0 \) with 8 degrees of freedom was used with the two-tailed test, i.e., if \(-t_{a/2,v} \leq t \leq t_{a/2,v}\), accept \( H_0 (\mu_1 - \mu_2 = 0)\); thus, there may be no difference between the two means at 100\%(1-\alpha)\% confidence level; if \( t \leq -t_{a/2,v} \), or \( t \geq t_{a/2,v}\), reject \( H_0 (\mu_1 - \mu_2 = 0)\), i.e., there may be difference between the two means at 100\%(1-\alpha)\% confidence level. The test results for the roughness of the three media are shown in Table 2.4.

Table 2.4 Roughness mean differences of the three fresh media (\( \times \) indicates there are differences between the two population means at the 95% confidence level; \( \checkmark \) indicates there are no differences between the two population means at the 95% confidence level)

<table>
<thead>
<tr>
<th></th>
<th>7 mm</th>
<th></th>
<th>9 mm</th>
<th></th>
<th>11 mm</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( R_a )</td>
<td>( R_z )</td>
<td>( R_{ku} )</td>
<td>( R_{sk} )</td>
<td>( R_a )</td>
<td>( R_z )</td>
</tr>
<tr>
<td>7 mm</td>
<td>( \checkmark )</td>
<td>( \times )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>9 mm</td>
<td>( \checkmark )</td>
<td>( \times )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
</tbody>
</table>

The changes of media size and roughness

In the experiments, the media were used in cycles consisting of 2.5 h dry, 2.5 h wet, and 2.5 h lubricated. The size and roughness changes of 7, 9, and 11 mm media used for up
to 40 hours in these cycles are shown in Figs. 2.14 and 2.15. It can be seen that there were only small size changes of the media in the whole processing. After 10 hours (7 and 11 mm) or 20 hours (9 mm) the roughness of the media decreased slowly.

Lubrication

In order to operate "wet", the media was washed in a container with water, then transferred to the finisher. A small amount of excess water in the bottom of the finisher kept the media wet. To operate "lubricated", the media was first rinsed in a 2% by volume solution of water and detergent (Fantastik, DowBrands Canada Inc.) and then put in the finisher. Again, a small amount water in the bottom of the finisher kept the media from drying during the experiment. In some of the later experiments a fourth condition was also studied; i.e., continuous water spray of the media during the experiment.

Fig. 2.7 Spherical ceramic media (A-11 mm, B-9 mm, C-7 mm)
Fig. 2.8 Scanning electron micrograph of the fresh 9 mm spherical ceramic media

Fig. 2.9 Scanning electron micrograph of the fresh cylindrical ceramic media
Fig. 2.10 (a) Typical topographies of fresh 7 mm spherical media

Fig. 2.10 (b) Typical topographies of fresh 7 mm spherical media
Fig. 2.10 (c) Typical topographies of fresh 7 mm spherical media

Fig. 2.11 Typical topography of used media (9mm)
Fig. 2.12 (a) SEM-EDX of 7 mm media
Fig. 2.12 (b) SEM-EDX of 9 mm media
Fig. 2.12 (c) SEM-EDX of 11 mm media
Fig. 2.13 Illustration of (a) skewness and (b) kurtosis (from WYKO program manual)
Fig. 2.14 Size changes of media. Error bars indicate 95% confidence intervals on 20 measurements.

Fig. 2.15 Surface roughness changes as a function of finishing time in cycles of 2.5 h dry, 2.5 wet, and 2.5 h lubricated. Error bars indicate 95% confidence intervals on 5 measurements.
2.2 Surface Analysis and Videotaping Equipment

The aluminum workpieces and the media surfaces were analyzed for roughness and micro-topography using a 3D optical profilometer (WYKO), and the hardness of the workpiece surfaces was measured using a microhardness tester.

Surface Roughness Analysis Equipment

Figure 2.16 shows the WYKO RST Plus system [6], which includes an optical profiler unit and auto-filter wheel assembly, a video monitor, an interface control box, a PC compatible computer (with Pentium™ processor) supplied with WYKO’s Vision™ software running under Microsoft Windows™, an HP DeskJet printer, and a vibration isolation table. The RST Plus interferometer takes data by combining the path of light reflecting off the test surface with the path of light reflecting off an internal reference surface. When the two paths combine, the light waves interfere to produce a pattern of dark and light bands called fringes. The video monitor allows one to see the appearance of fringes on the sample. Once the fringes were properly adjusted, the measurement could be carried out over the sample surface. The system will give a vertical resolution of up to 3 nm.
Fig. 2.16 The WYKO RST Plus optical profilometer system
**Microhardness Tester**

The hardness of the finished aluminum workpieces was measured using the Micromet II Digital Micro Hardness Tester (Buehler Ltd., USA) as shown in Fig. 2.17. A square-based pyramidal diamond indenter with face angles of 136° (Vickers) was forced into the surface of the test piece with a 10 ~ 100 g (0.1 ~ 1 N) force to give a micro-indentation. The indentation was photographed by a CCD camera, and the image was digitized and processed by a PC computer. The diagonals of the indentation and the resulting Vickers hardness (HV) of the workpieces were given by the computer immediately.

Fig. 2.17 Microhardness tester
Videotaping System

The videotaping system included an IK-SM40A TOSHIBA super-micro CCD color camera, a JVC VCR, and a video digitizer (Snappy).

Figure 2.18 shows the IK-SM40A micro CCD color camera. The miniature color camera used a ¼", 410,000-pixel CCD image sensor with a micro-lens to create more than 470-line horizontal resolution and more than 350-line vertical resolution. The camera head was 42 mm long and 7 mm in diameter.

The micro color camera, and a fiber-optic light (Part No.: A08025.40, Subtechnique Inc., USA) were installed in a cylindrical part. A disk of hard foam was installed in the aluminum part and had three holes in it to hold the camera, the fiber-optic light, and a counterweight to maintain the balance of the part. Figure 2.19 shows the installation of the camera and the fiber-optic light. In front of the camera there was a glass window which was sealed by using WEATHER SHIELD Silicone Seal (Home Hardware Stores Ltd., St. Jacobs, ON., Canada). The whole videotaping system is shown in Fig. 2.20.

Fig. 2.18 Super-micro CCD color camera
Fig. 2.19 Installation of camera and fiber-optic light in the part
Fiber Optic Light

Camera and Part

Controller

Monitor

VCR

Computer

Snappy

Fig. 2.20 Videotaping system
2.3 Experimental Procedure

First, the aluminum sheet (0.8 mm thickness AA1100-O and AA6061-T6 alloys) was cut into circular workpieces of 50 mm diameter. Then, a workpiece was glued to the end (facing forward) of the cylindrical part using a hot melt adhesive. After finishing, the workpiece was removed by melting the glue, rinsed in tap water, and then washed in methanol in an ultrasonic cleaner for 5 to 10 minutes before surface measurement.

The workpieces were finished in dry, wet, and lubricated conditions for 5, 10, 20, 40, and 80 minutes using 7, 9, 11 mm spherical ceramic media, and another proprietary cylindrical media. The two aluminum alloys (AA1100-O and AA6061-T6) were used simultaneously in all the experiments, i.e. two identical parts were used in each experiment.

* See lubrication in Section 2.1.3.
Chapter 3

Normal Contact Force Sensor

Although the vibratory surface finishing technique is widely used in manufacturing, the mechanism of this process is still largely unknown. Understanding the interactions between the finishing media and the part is vital to understanding the mechanism of vibratory surface finishing processes. To study the interaction between the media and the part, a dynamic normal contact force sensor was built to measure the normal contact force between the media and a prototypical part. A list of symbols used in this Chapter is included in the Nomenclature.

3.1 Design of Normal Contact Force Sensor

General Design of the Force Sensor

In dry finishing, the interaction between the media and the part is mostly normal contact although some friction between the media and the part also exists. This was qualitatively supported by videotapes of media-part interactions (see Chapter 6). Therefore, the sensor was designed to measure the normal contact force only.

Since the sensor had to measure dynamic loads with a maximum force of about 2N, it was difficult to find a suitable sensor on the market. After considering the functions,
characteristics and the cost of the required sensor, it was decided to design and build a force sensor.

The design employed a strain gauge technique using a fixed-fixed beam as the spring element. To ensure that the force was transferred instantaneously, the beam material had to be relatively stiff and as light as possible. Although steel is stiffer than aluminum, it is much heavier. On the other hand, magnesium is light but has a smaller modulus than aluminum, and its thermal expansion coefficient is high. Therefore, we chose aluminum as the spring element. From ref. [8], aluminum AA2024-T81 is the best material as a sensor spring element; however, it is difficult to obtain, especially in small quantities. Thus, we chose aluminum AA6061-T6 which is readily available.

The deflections of a fixed-fixed beam caused by normal or tangential forces can be measured by a suitable arrangement of strain gauges. Although, the deflection of a fixed-fixed beam will be smaller than that of a cantilever beam for a given load, the latter cannot distinguish between the deflections caused by normal and tangential forces. There are some other designs which can meet the requirement of distinguishing normal forces from tangential forces, however they are difficult to machine and their deflections are too small. Therefore, a fixed-fixed aluminum beam was chosen as the spring element of the force sensor.
Fig. 3.1 (a) and (b) Illustration of fixed-fixed beam and strain gauges

(1, 2, 3, and 4 are strain gauges)

Fig. 3.2 Full-bridge circuit
By suitable arrangement of the strain gauges on the beam, for example, making a full-bridge as shown in Figs. 3.1 and 3.2, the effect of tangential forces on the overall signal could be eliminated. When a tangential force is applied to the sensing disk, it will cause additional stresses in positions 1, 2, 3, and 4. The values in positions 1 and 3 are equal, but in a opposite direction. Positions 2 and 4 are in the same situation. By means of the full-bridge circuit shown in Fig. 3.2, all these effects caused by the tangential forces were eliminated.

**Design of the Spring Element of the Sensor**

The sensor had to be sensitive enough to detect the small signals produced by the impact of media. Therefore, the strain on the fixed-fixed beam had to be large enough after the application of a small force (0 ~ 2N). The length of the beam was constrained by the size of the part, leaving the thickness and width of the beam to be determined according to the requirement of the sensor’s sensitivity.

From solid mechanics [9], the maximum bending moments of the fixed-fixed beam with a concentrated mid-span load are \( \frac{F \cdot L}{8} \) in both the middle and the ends of the beam. Here, \( F \) is the normal force applied at the middle of the beam, and \( L \) is the length of the beam as shown in Fig. 3.3.

Since \( I = \frac{b \times h^3}{12} \), \( \varepsilon = \frac{\sigma}{E} \), and \( c = \frac{h}{2} \),
where, \( b \) is the width and \( h \) is the thickness of the beam, the elongation of the beam over a distance \( x_1 \) to \( x_2 \) in Fig. 3.1 (b) is

\[
\Delta l = \int_{x_1}^{x_2} \varepsilon \, dx
\]

\[
= \int_{x_1}^{x_2} \frac{Mc}{IE} \, dx
\]

\[
= \int_{x_1}^{x_2} \frac{FL}{8} \left( \frac{Fx}{2} \right) c \, dx
\]

\[
= \frac{Fc}{8IE} (x_2 - x_1) \left( L - 2(x_2 + x_1) \right)
\]

\[
= \frac{3Fl_g}{4bh^2E} \left( L - 2(2x_1 + l_g) \right)
\]

(3.1)

Hence, for a certain resolution of the sensor, the maximum thickness of the beam can be obtained from the following equation:

\[
h_{\text{Max}}^2 = \frac{3Fl_g}{4bE\Delta l} \left( L - 2(x_1 + l_g) \right)
\]

\[
= \frac{3F}{4bE\varepsilon_{\text{Min}}} \left( L - 2(2x_1 + l_g) \right)
\]

(3.2)

where, \( l_g = x_2 - x_1 = 0.003 \) m (the length of the chosen strain gauge); \( x_1 = 0.005 \) m (from the middle of the beam); \( \Delta l_{\text{Min}} = l_g \times \varepsilon_{\text{Min}} \). From ref. [10] we know that the maximum elastic strain
of aluminum is 0.4%. We also know that the sensitivity of the strain gauge is 0.1%, therefore, the sensor sensitivity is $0.4\% \times 0.1\%$, i.e., $\varepsilon_{\text{max}} = 4\mu\varepsilon$.

Under the dimensional constraints of the sensor and the dimension limits of the strain gauges, it was decided that the length $L$ of the beam should be 0.05 m. Since the width of the chosen strain gauge SG-3/120-LY13 (OMEGA) is 0.004 m and its length $l_s$ is 0.003 m, the width $b$ of the beam was set at 0.01 m.

From Eq. (3.2), the following results were obtained: for 0.1% resolution in load, $h_{\text{max}} = 0.136$ mm; for 0.5% resolution in load, $h_{\text{max}} = 0.305$ mm; for 1% resolution in load, $h_{\text{max}} = 0.430$ mm. Here, $E = 69 \times 10^9$ Pa and $F = 2$ N. Considering the value of the normal contact forces and the accuracy requirement of the measurement, the thickness $h$ of the beam was set at 0.40 mm, giving a sensor resolution greater than 1% in rated load (2 N). The detailed design of the sensor is shown in Fig. 3.3. It should be noted that the actual force applied on the beam is not a concentrated force as shown in Fig. 3.1 (b), which resulting a slightly smaller moment on the beam [9], and a slightly lower resolution of the sensor.
Fig. 3.3 The design of the sensor (all dimensions in mm)

Natural Frequency of the Sensor

The parameters of the spring element of the sensor (fixed-fixed beam) were as the follows:

\[ F_0 = 2 \text{ N} \quad L = 0.05 \text{ m} \quad \rho = 2715 \text{ kg/m}^3 \]
\[
A = b \times h \, m^2 \\
I = \frac{b \times h^3}{12} \, m^4 \\
\Omega = 60 \pi \, \text{rad/s}
\]

and \( \lambda_m = \beta_m L \) (\( m = 1, 2, 3 \ldots \)), which were calculated in Appendix B. Substituting the above data into the following equation:

\[
\omega_m = \lambda_m^2 \sqrt{\frac{E \cdot I}{\rho \cdot A \cdot L^4}}
\]

the lowest natural frequency of the sensor was 820 Hz, which was well above the driving frequency of the vibratory finisher (30 Hz).

### 3.2 Calibration of the Force Sensor

#### Static Calibration

For static calibration of the sensor, 5 masses (e.g. 42.3, 67.9, 97.9, 119.3, and 151.6 g) were put on the disk of the sensor incrementally, and each output voltage was recorded in order of increasing mass with a sampling frequency of 500 Hz. The steps were as follows: first, 42.3 g mass was put on the disk and the output voltage was recorded, then 25.6 g was added and the output recorded, then 20 g was added, etc. The unloading calibration was done in the reverse way. Figures 3.4 (a) and (b) show the calibrations of the first and the second sensor which displayed nearly linear load-deflection responses, and their slopes (voltage to load) were 0.0054 V/g (0.551 V/N) and 0.0039 V/g (0.398 V/N). In experiments, the second sensor was used after the first one was broken. Error bars in Figs. 3.4 (a) and (b) indicate the 95% confidence intervals.
**Normal Contact Force Sensor**

![Graph](image)

**Fig. 3.4** Static calibration of force sensors (a) first sensor, (b) second sensor
**Dynamic Calibration**

The dynamic calibration of the sensor was completed by clamping the cylinder and sensor to a SHAKER TABLE Model 400ATE/R/S/T (Unholtz-Dickie Corp.). Figure 3.5 shows the setup of the dynamic calibration. The vibration frequency and amplitude of the SHAKER TABLE could be controlled by a controller both manually and automatically through a computer. The calibration was performed at frequencies of 0, 30, 60, 90, 120 and 150 Hz with a fixed peak acceleration of 30 m/s² without attached load; with a peak acceleration of 20 m/s² with a one-gram load, and with a peak acceleration of 10 m/s² with a four-gram load attached to the sensor with a sampling frequency of 1000 Hz. The calibration data are shown in Figs. 3.6 and 3.7, and reveal that the vibration had no significant effect on the output of the sensor in the range from 30 to 60 Hz; the range spanned by the bowl driving frequency and its first harmonic.

From Fig. 3.6 the mass of the sensing disk can be calculated as about one gram. Figure 3.7 indicates that the predicted loads of 1 and 4 grams at 20 m/s² and 10 m/s² using the static calibration were close to the measured values at 30 and 60 Hz (difference less than 3% and 8% for 1 g and 4 g, respectively), although the differences between the predicted and measured values increased with the increasing vibration frequency.

The dynamic noise of the sensor (operating condition) was obtained by covering the sensing disk of the sensor and run it together with media in the finisher. This noise (peak average ± 0.015 V) was caused by the vibration of the sensor and electronic noise, which was used as the threshold in force signal processing in Chapter 4.
Fig. 3.5 A schematic of the dynamic calibration

Fig. 3.6 Sensor dynamic calibration (no attached load at an acceleration of 30 m/s$^2$)
Fig. 3.7 Sensor dynamic calibration. 4 grams load at an acceleration of 10 m/s² and 1 gram load at an acceleration of 20 m/s² at sampling rate 1000 Hz

Fig. 3.8 Dynamic noise of the sensor in finisher with sensor covered and in the bowl at sampling rate 500 Hz
Impact Response of the Sensor

Although the impact conditions in the finisher, such as relative velocity between media and the part were unknown, it was of interest to explore the response of the sensor to the impact a free-falling mass.

Figure 3.9 is the force response of the sensor when a single spherical media (1 gram and 9 mm diameter) fell freely from 10 mm striking the sensor. The sampling frequency was 4800 Hz. Figure 3.10 is the frequency response of the impact force. In Fig. 3.9, the first peak value is about 2 N caused by the first impact, while the second and subsequent groups of signals were caused by the second and following impacts as the media bounced. Figure 3.10 shows that most of the energy was located at about 700 Hz, which was close to the predicted natural frequency of the sensor (820 Hz). Figure 3.9 also reveals that the “ringing” of the sensor decays rapidly from approximately 0.5 N to half of this in 5 ms. This ringing will contribute to signal noise.

Calculation of the Impact Impulse

From Fig. 3.9 it was found that the interval between the first impact and the second impact (rebound) was 0.04 s. The rebound velocity of the media can thus be calculated as 0.196 m/s, with an initial impact velocity of 0.443 m/s. Hence, the momentum change of the media was:

\[ m \times \Delta v = 0.001 \times (0.443 - (-0.196)) \]
The impulse of the first impact taken from Fig. 3.10 is 1.0×10⁻³ N.s, which is larger than the momentum change of the media. This discrepancy is probably due to errors in the measurement of the drop height, the finite sampling frequency (4800 Hz) and the neglect of media rotation upon rebound.

**Estimation of the Impact Force**

The impact in the above experiment can be simplified as a weight \( W \) (0.01 N) which falls freely through a distance \( H \) (0.01 m) striking the end of a free standing spring as shown in Fig. 3.11. Therefore, the impact force can be estimated as [11]:

\[
P_{\text{imp}} = W(1 + \sqrt{1 + \frac{2H}{\delta_{st}}})
\]

(3.3)

and

\[
\delta_{st} = \frac{W}{k_{eq}}
\]

(3.4)

According to ref. [12], for a fixed-fixed beam:

\[
k_{eq} = \frac{192EI}{l^3}
\]

(3.5)

\[
\delta_{st} = \frac{Wl^3}{192EI}
\]

\[
= 1.77 \times 10^{-6} \text{ (m)}
\]
Chapter 3

Normal Contact Force Sensor

Here, \( W = 0.01 \text{N}, L = 0.05 \text{ m}, E = 69 \times 10^9 \text{ Pa}, \ I = \frac{b \times h^3}{12} \text{ m}^4, b = 0.01 \text{ m and } h = 0.0004 \text{ m}. \)

Thus, the impact force can be estimated from Eq. (3.4) as 1 N, which is smaller than the measured maximum impact force (over 2 N). It is noted, however, that Eq. (3.4) is intended to only give a rough estimation of the impact force because it assumes that the stresses throughout the impacted member reach peak values at the same time and thus, in practice, has an associated uncertainty of 200 - 300% [13].

![Force response of single media impact at sampling rate 4800 Hz](image)

Fig. 3.9 Force response of single media impact at sampling rate 4800 Hz
Fig. 3.10 Force spectrum of single media impact

Fig. 3.11 First peak of impact signal of Fig. 3.9 (sampling rate 4800 Hz)
Fig. 3.12 Freely falling body striking a body of finite stiffness
Chapter 4

Measurement of Normal Contact Forces

4.1 Experimental setup

Figure 4.1 shows the setup used to measure the normal contact forces. The vibratory finisher and the force sensor with its specifications were described in Chapters 2 and 3, respectively.

The output voltage from the sensor was amplified and then digitized by a PCI-20057T-1 high-density analog I/O panel (Burr-Brown Corporation). Finally, the digitized data were input to a computer for processing using Matlab. According to the sampling theorem, if a band-limited signal is sampled at a rate that is twice the highest frequency component in the signal, the sample values exactly describe the original signal [14]. A sampling frequency of 500 Hz was chosen for the experiments because the driving frequency was 30 Hz. Figure 4.2 shows that the harmonics of the forces were under 250 Hz (sampling frequency was 2000 Hz). As well, 500 Hz was high enough to capture approximately 7 data points per impact event while minimizing the required data storage.
Fig. 4.1 The system for normal contact force measurement

Fig. 4.2 Representative of normal force spectrum for sensor in finisher at sampling rate 2000 Hz
4.2 Force Signal Processing

Figures 4.3 and 4.4 present typical normal contact forces and their Fourier Transform spectra for 7, 9 and 11 mm media in dry finishing. The maximum impact force for 7, 9, and 11 mm media in dry finishing was about 0.5, 1, and 2 N, respectively. The spectra in Fig. 4.4 show that the normal impact forces generated harmonic forces with frequencies of 30, 60, 90, and 120 Hz, with the main frequency located at the bowl driving frequency of 30 Hz.

Similarly, Figs. 4.5 and 4.6 show typical normal contact forces and their spectra for 7, 9 and 11 mm media in wet finishing. The maximum impact force for 7, 9, and 11 mm media was about 0.6, 0.8, and 1.15 N, respectively.
Fig. 4.3 Normal contact force in dry finishing with media of diameters (a) 7 mm, (b) 9 mm, (c) 11 mm
Fig. 4.4 Force spectra in dry finishing with media of diameters
(a) 7 mm, (b) 9 mm, (c) 11 mm
Fig. 4.5 Normal contact forces in wet finishing with media of diameters
(a) 7 mm, (b) 9 mm, (c) 11 mm
Fig. 4.6 Force spectra in wet finishing with media of diameters (a) 7 mm, (b) 9 mm, (c) 11 mm)
Since the force signals were highly variable, the maximum force in a short period could not represent the whole impact process. Therefore, a program was developed to process the force signals using Matlab, thereby obtaining the impact parameters, such as the total number of impacts in a certain time (8 s), average maximum impact force, average impact force, average impact duration, average impulse, and the percentage of contact time.

The program identified individual impacts within each 8 s measurement period, and then found the maximum impact force and location, average impact force, impact duration, and impulse in each impact event. Next, it calculated the average of each of these parameters plus the contact percentage in each measurement of 8 s. Finally, the average of all the above parameters in ten 8 s measurement periods were obtained. The Matlab program is shown in Appendix D.

In the program, a threshold (0.015 v) was set up according to the dynamic noise of the sensor. Below this threshold, the data was considered as noise and ignored.

Figure 4.7 shows one check of the program. The Fast Fourier Transform (FFT) of the raw force signal is essentially the same as that of the processed signal containing only extracted impact events.
Fig. 4.7 Comparison of Fast Fourier Transform (FFT) of (a) raw force signal and (b) the extracted impact events.
The statistics for normal contact forces in dry and wet finishing when the part was moving forward are shown in Tables 4.1 and 4.2, respectively.

Table 4.1  Statistics for normal contact forces of 7, 9, and 11 mm media in dry finishing over 8 s with sensor facing forward. The data are the average of 10 runs with 8 s for each run. The 95% confidence intervals are also listed (n = 10).

<table>
<thead>
<tr>
<th>Media</th>
<th>Av. No. of impacts in 8 s</th>
<th>Av. max. impact force (N)</th>
<th>Av. impact force (N)</th>
<th>Av. impact duration (ms)</th>
<th>Av. impulse per impact 10^{-3} (N.s)</th>
<th>Av. contact percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 mm</td>
<td>130</td>
<td>0.183</td>
<td>0.086</td>
<td>20.2</td>
<td>1.6</td>
<td>32</td>
</tr>
<tr>
<td>95 % CI</td>
<td>±52</td>
<td>±0.03</td>
<td>±0.01</td>
<td>±2.3</td>
<td>±0.5</td>
<td>±13</td>
</tr>
<tr>
<td>9 mm</td>
<td>130</td>
<td>0.207</td>
<td>0.100</td>
<td>19.2</td>
<td>2.0</td>
<td>31</td>
</tr>
<tr>
<td>95 % CI</td>
<td>±50</td>
<td>±0.05</td>
<td>±0.02</td>
<td>±3.8</td>
<td>±0.8</td>
<td>±11</td>
</tr>
<tr>
<td>11 mm</td>
<td>136</td>
<td>0.290</td>
<td>0.121</td>
<td>17.7</td>
<td>2.1</td>
<td>29</td>
</tr>
<tr>
<td>95 % CI</td>
<td>±43</td>
<td>±0.07</td>
<td>±0.03</td>
<td>±3.5</td>
<td>±0.8</td>
<td>±11</td>
</tr>
</tbody>
</table>

Here, 95%CI = t_{α/2,v} \times \frac{s}{\sqrt{n}}, s = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n}}, x_i is the i^{th} measured data, \bar{x} is the average of samples, t_{α/2,v} corresponds to the two-sided t test, v = n-1, n = 10, and α = 0.05.
Table 4.2  Statistics for normal contact forces of 7, 9, and 11 mm media in wet finishing over 8 s with sensor facing forward. The data are the average of 10 runs with 8 seconds for each run. The 95% confidence intervals are listed (n = 10).

<table>
<thead>
<tr>
<th>Media</th>
<th>Av. No. of impacts in 8 s</th>
<th>Av. max. impact force (N)</th>
<th>Av. impact force (N)</th>
<th>Av. impact duration (ms)</th>
<th>Av. impulse per impact 10⁻³ (N.s)</th>
<th>Av. contact percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 mm</td>
<td>126</td>
<td>0.200</td>
<td>0.100</td>
<td>20.6</td>
<td>1.80</td>
<td>31</td>
</tr>
<tr>
<td>95 % CI</td>
<td>±53</td>
<td>±0.05</td>
<td>±0.02</td>
<td>±3.4</td>
<td>±0.6</td>
<td>±14</td>
</tr>
<tr>
<td>9 mm</td>
<td>115</td>
<td>0.201</td>
<td>0.100</td>
<td>19.8</td>
<td>1.80</td>
<td>29</td>
</tr>
<tr>
<td>95 % CI</td>
<td>±55</td>
<td>±0.04</td>
<td>±0.02</td>
<td>±2.1</td>
<td>±0.5</td>
<td>±12</td>
</tr>
<tr>
<td>11 mm</td>
<td>110</td>
<td>0.245</td>
<td>0.110</td>
<td>16.9</td>
<td>1.70</td>
<td>23</td>
</tr>
<tr>
<td>95 % CI</td>
<td>±75</td>
<td>±0.06</td>
<td>±0.03</td>
<td>±2.6</td>
<td>±0.6</td>
<td>±15</td>
</tr>
</tbody>
</table>

Figures 4.8 and 4.9 show the effects of media size on the average maximum impact force and the average impact force in dry and wet finishing. The largest average maximum impact force was that of 11 mm media in dry finishing, while the smallest average force was that of 7 mm media in dry finishing.

The t-test at the 95% confidence level (Section 2.1.3) shown that, in dry finishing the average maximum impact force was different between 7 and 11 mm media, and between 9 and 11 mm media, but there was no difference between 7 and 9 mm media. The average impact force was different among 7, 9, and 11 mm media at the 95% confidence level.

Similarly, in wet finishing, the average maximum impact force was different between 7 and 11 mm media and between 9 and 11 mm media at the 95% confidence level, but was
not different between 7 and 9 mm media. The average impact force was not different among 7, 9, and 11 mm media at the 95% confidence level in wet finishing.

It is interesting to see that the average maximum impact force and the average impact force between 9 mm media and the part in dry finishing were very similar to those in wet finishing, and the average maximum impact force and average impact force between the 7 mm media and the part in dry finishing was smaller than in wet finishing. But for 11 mm media, the average maximum impact force and the average impact force in dry finishing were larger than those in wet finishing.

Figure 4.10 shows the relationship between the average impulse and the media size in both dry and wet finishing, and Fig. 4.11 shows the effects of media size on the percentage contact time. It was found that the media size had no significant effect on the average impulse, although the latter increased slowly with the increasing media size in dry finishing. Media size had a small inverse effect on the contact percentages in both dry and wet finishing.
Fig. 4.8 Average max. impact force vs. media size. Error bars represent 95% confidence intervals.

Fig. 4.9 Average impact force vs. media size. Error bars represent 95% confidence intervals.
Fig. 4.10  Average impulse vs. media size. Error bars represent 95% confidence intervals.

Fig. 4.11  Percentage of contact time as a function of media size. Error bars represent 95% confidence intervals.
Effect of Media Motion on Normal Contact Forces

Table 4.3 shows that when the sensor was facing backward (opposite to direction of circumferential velocity) the impact parameters were essentially identical those when the sensor was facing forward in dry and wet finishing. This suggesting that the normal contact forces within the finisher were uniform.

Table 4.4 shows that when the sensor was fixed in the bowl, both the average maximum impact force and the average impact force were larger than when the sensor was moving. It is interesting that when the sensor was fixed and facing backward, both the average maximum impact force and the average impact force were smaller than those when the sensor was fixed and facing forward, but the other parameters were larger.
Table 4.3 Comparison of normal contact force statistics for 9 mm media in dry and wet finishing with sensor facing forward and backward over 8 s. The data are the average of 10 runs with 8 s for each run with a sampling frequency of 500 Hz. The 95% confidence intervals are listed (n =10).

<table>
<thead>
<tr>
<th>Orientation and Finishing Conditions</th>
<th>Av. No. of impacts in 8 s</th>
<th>Av. max. impact force (N)</th>
<th>Av. impact force (N)</th>
<th>Av. impact duration (ms)</th>
<th>Av. impulse per impact $10^{-3}$ (N.s)</th>
<th>Av. contact percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward (dry)</td>
<td>131</td>
<td>0.207</td>
<td>0.100</td>
<td>19.2</td>
<td>2.00</td>
<td>31</td>
</tr>
<tr>
<td>95% CI</td>
<td>±50</td>
<td>±0.074</td>
<td>±0.031</td>
<td>±3.5</td>
<td>±0.8</td>
<td>±11</td>
</tr>
<tr>
<td>Backward (dry)</td>
<td>121</td>
<td>0.203</td>
<td>0.091</td>
<td>17.2</td>
<td>1.40</td>
<td>26</td>
</tr>
<tr>
<td>95% CI</td>
<td>±67</td>
<td>±0.062</td>
<td>±0.028</td>
<td>±5.1</td>
<td>±0.8</td>
<td>±20</td>
</tr>
<tr>
<td>Forward (wet)</td>
<td>115</td>
<td>0.201</td>
<td>0.100</td>
<td>19.8</td>
<td>1.80</td>
<td>29</td>
</tr>
<tr>
<td>95% CI</td>
<td>±50</td>
<td>±0.042</td>
<td>±0.023</td>
<td>±2.1</td>
<td>±0.5</td>
<td>±12</td>
</tr>
<tr>
<td>Backward (wet)</td>
<td>133</td>
<td>0.202</td>
<td>0.091</td>
<td>16.5</td>
<td>1.30</td>
<td>27</td>
</tr>
<tr>
<td>95% CI</td>
<td>±67</td>
<td>±0.062</td>
<td>±0.034</td>
<td>±5.9</td>
<td>±1</td>
<td>±22</td>
</tr>
</tbody>
</table>
Table 4.4 Comparison of normal contact force statistics for 9 mm media in dry finishing with sensor fixed and moving. The data are the average of 10 runs with 8 s for each run with a sampling frequency of 500 Hz. The 95% confidence intervals are listed (n = 10).

<table>
<thead>
<tr>
<th>Orientation and freedom</th>
<th>Av. No. of impacts in 8 s</th>
<th>Av. max. impact force (N)</th>
<th>Av. impact force (N)</th>
<th>Av. impact duration (ms)</th>
<th>Av. impulse per impact $10^{-3}$ (N.s)</th>
<th>Av. contact percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward (moving)</td>
<td>131</td>
<td>0.207</td>
<td>0.099</td>
<td>19.2</td>
<td>2.0</td>
<td>32</td>
</tr>
<tr>
<td>95% CI</td>
<td>±50</td>
<td>±0.074</td>
<td>±0.031</td>
<td>±3.5</td>
<td>±0.8</td>
<td>±11</td>
</tr>
<tr>
<td>Backward (moving)</td>
<td>121</td>
<td>0.203</td>
<td>0.091</td>
<td>17.2</td>
<td>1.4</td>
<td>26</td>
</tr>
<tr>
<td>95% CI</td>
<td>±67</td>
<td>±0.062</td>
<td>±0.028</td>
<td>±5.1</td>
<td>±0.8</td>
<td>±20</td>
</tr>
<tr>
<td>Forward (fixed)</td>
<td>107</td>
<td>0.415</td>
<td>0.139</td>
<td>12.5</td>
<td>1.5</td>
<td>18</td>
</tr>
<tr>
<td>95% CI</td>
<td>±51</td>
<td>±0.111</td>
<td>±0.04</td>
<td>±2.7</td>
<td>±0.5</td>
<td>±9</td>
</tr>
<tr>
<td>Backward (fixed)</td>
<td>130</td>
<td>0.27</td>
<td>0.136</td>
<td>22.4</td>
<td>3.0</td>
<td>36</td>
</tr>
<tr>
<td>95% CI</td>
<td>±86</td>
<td>±0.043</td>
<td>±0.037</td>
<td>±4.6</td>
<td>±1.3</td>
<td>±29</td>
</tr>
</tbody>
</table>
Chapter 5

Surface Analysis

The surface analysis focused on the hardness, roughness and microtopography of the finished workpieces and media. The hardness was measured using a Micromet II Microhardness Tester, which was described in Chapter 2. Roughness was measured using a non-contact optical profilometer (WYKO), which was also described in Chapter 2. The microtopography of the finished aluminum workpiece and media were obtained by means of the scanning electron microscopy (SEM) as well as the optical profilometer (WYKO).

5.1 Procedure

The hardness of the finished workpieces was measured using a micro-hardness tester with 25 - 100 g weights, 15 s measuring time, and a magnification of 40X, while surface roughness was measured using the optical profilometer (WYKO) (described in Chapter 2) with a magnification of 5.1X. At least 5 measurements were made at different locations on each workpiece. More details about the experimental procedure were given in Chapter 2.

By means of t-testing described in Section 2.1.3, the population means of the average roughness, $R_s$, skewness, $R_s$, and kurtosis, $R_{ku}$, of 7, 9, and 11 mm media used in
the experiments (media had been used for at least 10 h before experiments) were not significantly different at the 95% confidence level. Therefore, the media in these experiments differed significantly only in its size.

5.2 Results and Discussion

5.2.1 Hardness

Effect of Lubrication on Hardness

Figures 5.1 (a) to 5.1 (c) show the Vickers hardness (HV) changes in the AA1100-O workpiece in dry, wet, and lubricated finishing using three kinds of spherical media as described in Chapter 2, while Figs. 5.2 (a) to 5.2 (c) show the Vickers hardness (HV) changes in the AA6061-T6 workpiece under the same finishing conditions.

The Vickers hardness (HV) was calculated as $HV = \frac{1854.4 \cdot P}{d^2}$, where, $P$ was the test load in gf, and $d$ was the arithmetic mean of the two diagonals $d_1$ and $d_2$ of the indentation in μm. Therefore, one Vickers hardness number equals 9.807 MPa.

For 9 mm media, the maximum hardness in AA1100-O in dry finishing was 22% greater than in wet finishing and 35% larger than in lubricated finishing. For 11 mm media, the maximum hardness in AA1100-O in dry finishing was 20% and 69% larger than in wet and lubricated finishing, respectively. After finishing for 80 minutes, the hardness of AA1100-O workpieces finished by using 7, 9, and 11 mm media in dry, wet, and lubricated finishing were almost the same. However, for 7 mm media, hardness changes in AA1100-O did not display a maximum, and in wet finishing they were greater than those in dry and lubricated finishing perhaps due to the larger contact force measured in Chapter 4.
For AA6061-T6, lubrication had no significant effect on the hardness changes of the workpiece with the exception of that for 11 mm lubricated, which was smaller than dry or wet. The hardness was more uniform over the surface when finishing with detergent than with the other finishing conditions (the error bars of both the alloys in lubricated finishing were smaller than those in the other two finishing conditions). With dry finishing using 9 and 11 mm media, a local maximum hardness occurred at 20 and 10 min, respectively, although longer times created even higher hardness.

When the media and the workpiece were washed using a continuous water spray during finishing, the hardness changes in the workpiece were much smaller than those in dry, wet, and lubricated finishing as shown in Fig. 5.3. Water spray introduced much more water into the finisher, which may have reduced the contact stresses due to the increasing thickness of the intervening water film. Continuous spray may also have further reduced the friction coefficient and minimized three-body wear by removing fines.

**Effect of Media Size on Hardness**

Figures 5.4(a), (b), and (c) show the effects of media size on the hardness changes in the AA1100-O workpieces in dry, wet, and lubricated finishing, respectively. For AA1100-O in dry finishing, media size was approximately proportional to the hardness changes, but the effect declined after the hardness of the workpiece reached its maximum. The media size had no significant effect on hardness changes of the workpieces in wet and lubricated finishing. The continuous increasing of hardness with 7 mm media in Figs. 5.4 (a) and (b) may be an indication that it is approaching a maximum more slowly than 9 and 11 mm media.
Figures 5.5(a), (b), and (c) show the effects of media size on the hardness changes in AA6061-T6 workpiece in dry, wet, and lubricated finishing, respectively. For AA6061-T6, 11 mm dry media produced the greatest hardness changes. Under lubricated conditions, as with AA1100-O, 7 mm media produced a slightly greater hardness than the larger media.

Effect of Finishing Time on Hardness

For AA1100-O, the hardness changes reached a maximum after finishing for 40 minutes when using 9 or 11 mm media under dry, wet, or lubricated conditions (Figs. 5.1 (b) and (c)), while for AA6061-T6, the hardness increased continuously with increasing finishing time (Fig. 5.2 (a), (b), and (c)). When finishing using 7 mm media, the hardness of both alloys increased with increasing finishing time within the whole experimental period, suggesting that the slower acting 7 mm media was still approaching a maximum at 80 min. It is believed that 7 mm media have a smaller impact energy than 9 and 11 mm media.

The hardness reduction of the workpiece after the maximum may be due to removal of the surface of layer.

5.2.2 Roughness

The trends displayed by the roughness changes in the workpiece were similar to those evident in the hardness changes.
Effect of Lubrication on Roughness

Figures 5.6 (a)-(c) show the average roughness changes in AA1100-O workpieces in dry, wet, and lubricated finishing using 7, 9, and 11 mm spherical media, respectively. For 7 mm media, the maximum roughness of the workpiece in wet finishing was almost double that in dry and lubricated finishing. For 9 mm media, the roughness in dry finishing was much bigger than in other conditions. For 11 mm media, the roughness of the workpiece in dry finishing was more than double that in wet finishing and more than triple that in lubricated finishing. Figures 5.7 (a)-(c) show the average roughness changes in AA6061-T6. The trends in AA6061-T6 were similar to those in AA1100-O except that the roughness were almost the same in dry and wet finishing when using 11 mm media.

As shown in Fig. 5.8, the roughness of the workpiece was almost the same in lubricated finishing and in finishing while continuously washing the media. As in Fig. 5.3, dry finishing produced the greatest changes in the workpiece surface.

In Fig. 5.6, for 7 mm media in wet finishing and for 11 mm media in all the finishing conditions, the roughness of the workpiece declined after reaching its maximum, but the roughness of the workpiece finished using 9 mm media increased continuously in 80 min.

Effect of Media Size on Roughness

Figures 5.9 (a), (b), and (c) show the effects of media size on the roughness changes in the AA1100-O workpiece in dry, wet, and lubricated finishing, respectively. In dry finishing, the roughness of the workpiece increased with increasing size of media. In wet and lubricated finishing, 7 and 11 mm media produced the greatest roughness changes. It is
believed that the greater roughness of the 7 mm media more than compensated for the lower impact energy compared with 11 mm media.

The trends of roughness changes in AA6061-T6 displayed in Figs. 5.10 (a) - (c) were similar to those in Figs. 5.9 (a) - (c).

**Effect of Finishing Time on Roughness**

The trends displayed by the roughness changes were same as those seen in the hardness changes.

5.2.3 Effects of Media Roughness on HV and Ra

Figures 5.11 (a) to (c) show the hardness changes in AA1100-O workpieces in dry, wet, and lubricated finishing using different 9 mm media (used for 20 h and 40 h). The roughness of the two 9 mm media are shown in Table 5.1.

Table 5.1 Roughness of two 9 mm media. First means the media was used for 20 h when the experiments were carried out; second means the media was used for 40 h when the experiments were carried out. The data in the Table were the average of 5 measurements.

<table>
<thead>
<tr>
<th></th>
<th>Av. $R_a$</th>
<th>Av. $R_z$</th>
<th>Av. $R_{ak}$</th>
<th>Av. $R_{ku}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>15.4</td>
<td>129.6</td>
<td>-0.430</td>
<td>3.486</td>
</tr>
<tr>
<td>95% CL</td>
<td>±6.3</td>
<td>±22.8</td>
<td>±0.540</td>
<td>±3.38</td>
</tr>
<tr>
<td>Second</td>
<td>13.8</td>
<td>126.4</td>
<td>-0.156</td>
<td>2.916</td>
</tr>
<tr>
<td>95% CL</td>
<td>±2.3</td>
<td>±79.7</td>
<td>±0.350</td>
<td>±2.192</td>
</tr>
</tbody>
</table>
It was found by means of the t-test that $R_s$ and $R_{ak}$ of the two samples of 9 mm media were different at the 95% confidence level, but that of $R_z$ and $R_{ku}$ were not significantly different.

The maximum surface hardness of the AA1100-O workpieces approximately doubled when it was finished using the rougher media.

Similarly, for both AA1100-O and AA6061-T6, Figs. 5.12 and 5.13 show that the maximum average roughness $R_a$ of the workpieces more than doubled in dry, wet and lubricated finishing when using the rougher media.

5.2.4 Effects of Media Shape on HV and Ra

Figures 5.14 (a) and (b) show the effects of media size and shape on the hardness changes in AA1100-O and AA6061-T6, respectively, after dry finishing for 20 minutes. For AA1100-O, the hardness changes after dry finishing using a cylindrical media were smaller than those seen when using spherical media. The possible reason is that the interaction between the spherical media and the part was dominated by normal impact, while the interaction between the cylindrical media and the part was dominated by sliding. For AA6061-T6, the effect of media shape was less significant perhaps due to greater initial hardness of AA6061-T6.

Figures 5.15 (a) and (b) show the roughness changes in AA1100-O and AA6061-T6 after dry finishing for 20 minutes using cylindrical and the three sizes of spherical media. The effect of the cylindrical media on Ra changes in AA1100-O was between those of 7 mm and
9 mm media, but for AA6061-T6, it was smaller than that of 11 mm media and greater than those of 7 and 9 mm media.

5.2.5 Repeatability

The repeatability of the measurement of roughness of the workpieces was evaluated using the same roughness of 9 mm media in dry finishing; i.e. two separate experiments were done one immediately after the other. The results shown in Fig. 5.16 demonstrated that these measurements were identical within the confidence limits.

5.2.6 Topographies of Finished Workpiece and Media Surfaces

Examples of typical individual impact indentations (SEMs) on the AA1100-O workpieces after dry, wet, and lubricated finishing for 10 seconds using 9 mm media are shown in Figs. 5.17 - 5.19. The corresponding WYKO measurements are shown in Figs. 5.20 - 5.22. In addition, lower magnification micrographs of the AA1100-O after finishing for 1, 5, 10, 20, 40, and 80 minutes are shown in Appendices E - J. The topographies of the finished surfaces are discussed in Chapter 7.

5.2.7 Summary

- Generally, the hardness of workpieces increased with finishing time, but reached a maximum and then declined.
- Dry finishing usually produced greater hardness increases of workpieces than wet or lubricated finishing.
• Usually, the hardness of workpieces increased with increasing media size (equal media Ra).

• For a given media, the hardness and roughness of workpieces increased with increasing media Ra.

• The trends of the hardness change of workpieces can be applied to the trends of roughness change of workpieces.

• Media size and shape had no significant effect on the hardness and roughness changes of the AA6061-T6 workpieces.

• Water spray made smaller hardness and roughness changes of the workpieces than dry, wet, and lubricated finishing.

• The interaction between the media and the part is a combination of impact, rolling, and sliding.
Fig. 5.1 Effect of lubrication on HV changes for AA1100-O (a) 7 mm, $R_a$ 17.5 ± 4.1 μm, (b) 9 mm, $R_a$ 15.4 ± 6.3 μm, and (c) 11 mm, $R_a$ 16.2 ± 4.7 μm. Error bars indicate 95% confidence intervals for 6 measurements on one workpiece.
Fig. 5.2 Effect of lubrication on HV changes for AA6061-T6 (a) 7 mm, $R_s$ 17.5 ± 4.1 μm, 
(b) 9 mm, $R_s$ 15.4 ± 6.3 μm, and (c) 11 mm, $R_s$ 16.2 ± 4.7 μm. Error bars indicate 95% 
confidence intervals for 6 measurements on one workpiece.
Fig. 5.3 Comparison of HV changes for AA1100-O in washing the 9 mm media and the part during finishing (Ra 13.8 ± 2.3 μm) with dry, wet, and lubricated finishing (Ra 15.4 ± 6.3 μm). Errors indicate 95% confidence intervals for 6 measurements on one workpiece.
Fig. 5.4 Effects of media size on HV changes for AA1100-O in (a) dry, (b) wet, and (c) lubricated finishing with $R_a$ 17.5 ± 4.1 μm (7 mm), 15.4 ± 6.3 μm (9 mm), and 16.2 ± 4.7 μm (11 mm). Error bars indicate the 95% confidence intervals for 6 measurements on one workpiece.
Fig. 5.5 Effects of media size on HV changes for AA6061-T6 in (a) dry, (b) wet, and (c) lubricated finishing with $R_a$ 17.5 ± 4.1 μm (7 mm), 15.4 ± 6.3 μm (9 mm), and 16.2 ± 4.7 μm (11 mm), error bars indicate the 95% confidence intervals for 6 measurements on one workpiece.
Fig. 5.6 Effects of lubrication on $R_a$ changes for AA1100-O (a) 7 mm, $R_a$ 17.5 ± 4.1 µm, (b) 9 mm, $R_a$ 15.4 ± 6.3 µm, and (c) 11 mm, $R_a$ 16.2 ± 4.7 µm. Error bars indicate 95% confidence intervals for 6 measurements on one workpiece.
Fig. 5.7 Effects of lubrication on $R_a$ changes for AA6061-T6 (a) 7 mm, $R_a$ 17.5 $\pm$ 4.1 $\mu$m, (b) 9 mm, $R_a$ 15.4 $\pm$ 6.3 $\mu$m, and (c) 11 mm, $R_a$ 16.2 $\pm$ 4.7 $\mu$m. Error bars indicate 95% confidence intervals in 6 measurements on one workpiece.
Fig. 5.8 Comparison of $R_a$ changes for (a) AA1100-O and (b) AA6061-T6 in washing the media ($R_a 13.8 \pm 2.3 \ \mu m$) and the part during finishing with dry, wet, and lubricated finishing (media $R_a 15.4 \pm 6.3 \ \mu m$). Error bars indicate 95% confidence intervals for 6 measurements on one workpiece.
Fig. 5.9 Effects of media size on $R_a$ changes for AA1100-O in (a) dry, (b) wet, and (c) lubricated finishing with $R_a$ 17.5 $\pm$ 4.1 $\mu$m (7 mm), 15.4 $\pm$ 6.3 $\mu$m (9 mm), and 16.2 $\pm$ 4.7 $\mu$m (11 mm). Error bars indicate the 95% confidence intervals for 6 measurements on one workpiece.
Fig. 5.10 Effects of media size on $R_a$ changes for AA6061-T6 in (a) dry, (b) wet, and (c) lubricated finishing with $R_a$ 17.5 ± 4.1 μm (7 mm), 15.4 ± 6.3 μm (9 mm), and 16.2 ± 4.7 μm (11 mm). Error bars indicate the 95% confidence intervals for 6 measurements on one workpiece.
Fig. 5.11 Effects of 9 mm media roughness (\(-\times\) $R_a$ 15.4 $\pm$ 6.3 $\mu$m, $R_{sk}$ -0.43 $\pm$ 0.54, \(-o\) $R_a$ 13.8 $\pm$ 2.3 $\mu$m, $R_{sk}$ -0.156 $\pm$ 0.35) on HV changes for AA1100-O in (a) dry, (b) wet, and (c) lubricated finishing. Error bars indicate the 95% confidence intervals for 6 measurements on one workpiece.
Fig. 5.12 Effects of 9 mm media roughness (-x- $R_a 15.4 \pm 6.3 \, \mu m$, $R_{sk} -0.43 \pm 0.54$, -o- $R_a 13.8 \pm 2.3 \, \mu m$, $R_{sk} -0.156 \pm 0.35$) on $R_a$ changes for AA1100-O in (a) dry, (b) wet, and (c) lubricated finishing. Error bars indicate the 95% confidence intervals for 6 measurements on one workpiece.
Fig. 5.13 Effects of 9 mm media roughness ($-\times-R_a\ 15.4 \pm 6.3\ \mu m$, $R_{sk} -0.43 \pm 0.54$, $-o-R_a\ 13.8 \pm 2.3\ \mu m$, $R_{sk} -0.156 \pm 0.35$) on $R_a$ changes for AA6061-T6 in (a) dry, (b) wet, and (c) lubricated finishing. Error bars indicate the 95% confidence intervals for 6 measurements on one workpiece.
Fig. 5.14 Effects of media shape and size on HV changes of (a) AA1100-O and (b) AA6061-T6 in dry finishing. The media roughness $R_s$ were 17.5 ± 4.1 μm (7 mm), 15.4 ± 6.3 μm (9 mm), and 16.2 ± 4.7 μm (11 mm). Error bars indicate 95% confidence intervals for 6 measurements on one workpiece.
Fig. 5.15 Effects of media shape and size on $R_a$ changes of (a) AA1100-O and (b) AA6061-T6. The media roughness $R_a$ were $17.5 \pm 4.1 \mu m$ (7 mm), $15.4 \pm 6.3 \mu m$ (9 mm), and $16.2 \pm 4.7 \mu m$ (11 mm). Error bars indicate 95% confidence intervals in 6 measurements on one workpiece.
Fig. 5.16 Repeatability in dry finishing AA1100-O using 9 mm media of the same roughness (Ra 13.8 ± 4.7 µm). Error bars indicate 95% confidence intervals for 6 measurements on one workpiece.
Fig. 5.17 SEMs of individual impact sites on AA1100-O after dry finishing for 10 s. Scale bars represent: top row-60 and 120 μm, bottom row - 86 and 86 μm.
Fig. 5.18 SEMs of individual impact sites on AA1100-O after wet finishing for 10 s. Scale bars represent: top row - 60 and 100 µm, bottom row - 86 and 86µm
FIG. 5.19 SEMS of individual impact sites on AAN100-0 after lubricated grinding for 10 s. Scale bars represent: top row - 100 and 200 and bottom row - 86 and 120 µm.

Surface Analysis
Fig. 5.20 WYKO individual impact site on AA1100-O in fry finishing (a) 2D (b) 3D
Fig. 5.21 WYKO individual impact site on AA1100-O in wet finishing (a) 2D (b) 3D
Fig. 5.22 WYKO individual impact site on AA1100-O in lubricated finishing (a) 2D (b) 3D
Chapter 6

Videotaping the Media Contact

6.1 Procedure

The interactions between the 9 mm spherical ceramic media and the part in dry, wet, and lubricated conditions were videotaped using the miniature color video camera and the JVC video recorder. In dry finishing, the interaction was videotaped when the part was both at the top and at the bottom of the finisher. The experimental setup can be seen in Chapter 2 (Fig. 2.20).

The contact percentage was estimated by counting the percentage of time during which media appeared to contact the equivalent of a 10 mm diameter area at the center of the monitor, and the relative speed of the media moving over the surface of the part was estimated by counting the time for a media particle to pass a 10 mm long equivalent distance on the monitor.

6.2 Results and Discussion

The videotape confirmed the conclusion from the normal contact force measurements that the contact between media and the part was not continuous. Figure 6.1 shows that there were large gaps between the spherical media and the part. The percentage
of time during which there was contact between the media and the part was estimated to be about 26% when at the top of the bowl, and approximately 35% at the bottom of the bowl. The average contact percentage in the finisher was estimated from the force sensor to be about 28% with a 95% confidence interval of 11%. Therefore, the videotaping verified the contact percentage calculated from the force signals.

The average relative speeds of the 9 mm media past the surface of the part were 11, 7, and 4 cm/s, with 95% confidence intervals of 10.7, 5.3, and 2.7 cm/s in dry, wet, and lubricated finishing, respectively. The above averages were obtained from 10 measurements.

![Video frames showing typical large gaps between contacting 9 mm spheres](image)

Fig. 6.1 Video frames showing typical large gaps between contacting 9 mm spheres

The videotaping also revealed that the interaction between the spherical media and the part was a combination of normal impact, rolling, and sliding. In wet finishing, more sliding were found than in dry finishing. It was also found that in lubricated finishing there were bubbles around the media, and the relative speed of the media was smaller than in dry and wet finishing. The motion of cylindrical media is described in Appendix K.
Chapter 7

Discussion and Conclusions

7.1 Discussion

7.1.1 Effect of Media Size

In dry finishing, the normal contact forces (average maximum impact force and average impact force) increased with increasing media size from 7 to 11 mm diameter (Figs. 4.8 and 4.9); in wet finishing, media size had no significant effect on the average impact force at 95% confidence level.

It was also observed that the hardness of the workpiece and its maximum hardness increased with the media size in dry finishing for both AA1100-O and AA6061-T6. However, in wet and lubricated finishing, media size had no significant effect on the hardness changes of the workpieces.

In all the three finishing conditions for both AA1100-O and AA6061-T6, media size had little effect on the roughness changes of the workpieces except in dry finishing for AA1100-O.

In dry finishing, since the interaction between the media and the part was dominated by impact, within a certain range of media size, the larger the media the more impact energy will be given to the work surfaces leaving deeper indentations and more residual stresses. This
will then increase the hardness and roughness of the workpiece surfaces. But in wet and lubricated finishing, sliding seems to be more evident and therefore media size was not as important as the topography of the media.

7.1.2 Effect of Media Roughness

Figures 5.11 and 5.12 show that media roughness had a significant effect on both the hardness and roughness changes of the workpieces. It was observed that there were more sharp-edged faces on the surface of the rougher media (Figs. 2.10 (a)-(c)) than on the smoother media (Fig. 2.11). During finishing the sharp-edged faces may cut and remove more material from the surface of the workpieces, leaving deeper indentations, while the smoother edged faces on the surface of the media will slid or plow on the work surface, making longer and smoother scratches.

7.1.3 Effect of Lubrication

Figures 5.1 (b) and (c), and Figs. 5.2 (b) and (c) show that dry finishing caused the largest hardness increases, and lubricated finishing caused the smallest changes. Similarly, Figs. 5.6 (b) and (c), and Figs. 5.7 (b) and (c) show that dry finishing caused the largest roughness increases, and lubricated finishing caused the smallest changes. The controversial values for 7 mm media may be due to its higher surface roughness of the media.

Effective lubrication can lower the incidence of asperity contact, reduce the surface shear force, and decrease the wear rate [15]. In lubricated vibratory finishing, there is a lubricant film between the contacting surfaces, and the thickness of the lubricant film plays an
important role during the interaction between surfaces. When the film breaks down, more asperities interact with each other and the softer surface will be increasingly damaged. The ratio of the minimum lubricant film thickness, \( h_{\text{min}} \), and the root-mean-square roughness of the two surfaces, \( \sigma^* \), determines when the lubricant film begins to break down [15].

\[
\lambda = \frac{h_{\text{min}}}{\sigma^*}
\]

(7.1)

here,

\[
\sigma^{*2} = R_{\text{s1}}^2 + R_{\text{s2}}^2
\]

(7.2)

and, \( R_{\text{s1}} \) and \( R_{\text{s2}} \) are the root-mean-square roughness of each surface. If \( \lambda > 3 \), a full fluid film will separate the two surfaces, and almost no contact will occur between asperities, causing both friction and wear to be very small. If \( 1 < \lambda < 3 \), some contacts between asperities will occur. If \( \lambda < 1 \), severe surface damage will occur. Figures 5.17 to 5.19 show that, in dry finishing (\( \lambda = 0 \)), the surface was most damaged. In wet finishing, \( \lambda \) should be larger than zero and less than that in lubricated finishing because detergent can decrease surface tension and thereby improve the wetting of surfaces, and also increase the lubricity. Figure 5.18 shows that the roughness in wet finishing was therefore between that in dry (Fig. 5.17) and lubricated finishing (Fig. 5.19). The surface roughness in lubricated finishing was the smallest, reflecting the largest \( \lambda \) value.

During finishing, debris will be produced due to wear of the aluminum workpiece surfaces and the fractured ceramic media, which causes three-body abrasive wear. In lubricated finishing, lubricant will remove or submerge the debris and reduce three-body abrasive wear.
7.1.4 Effect of Initial Hardness of the Workpieces

The abrasive wear rate of a surface is inversely proportional to the hardness of the surface [1]. In the test range of this project, it was observed that the hardness of the AA1100-O workpiece increased to a maximum value then declined, but for AA6061-T6, hardness increased continuously within the test range. This may due to the increased wear rate of the softer AA1100-O, since the exposure of a new surface layer would cause a decrease in hardness. However, the trends of surface roughness changes for AA1100-O and AA6061-T6 were very similar.

7.1.5 Effect of Interaction Between the Media and the Part

The videotaping showed that there were significant gaps between the media, qualitatively confirming that the 1 cm diameter sensing area of the part was in contact with the media only about 30% time. It also showed that the interaction between the media and the part was a combination of normal impact (predominant), rolling, and to a lesser extent sliding in dry finishing. Since the friction coefficient is higher in dry finishing than in lubricated finishing, sliding would be less likely than rolling in dry finishing.

In wet and lubricated finishing, more sliding was found because lubrication reduced the coefficient of friction, which made the media slide more readily, producing shallow grooves due to the decrease of the contact forces between the media and the work surface. The detergent solution produced a smaller coefficient of friction than water, therefore the sliding distance was longer and the grooves were shallower than in wet finishing, as shown in
Figs. 5.18 and 5.19. Thus, a more uniform surface hardness and roughness were obtained from lubricated finishing may due to the longer distance of sliding or ploughing.

7.2 Conclusions

7.2.1 Experimental Setup

A videotaping system could capture the interactions between the media and the part in dry, wet, and lubricated finishing.

A force sensor was designed to measure the normal contact force between the media and the part in dry and wet finishing conditions. Its rated force measurement was 2 N with a resolution of approximately 1% of rated load. The first natural frequency of the sensor was 820 Hz.

7.2.2 Normal Contact Force Between the Media and the Part

The average maximum normal impact force, average normal impact force, and average impulse increased with increasing media size in dry finishing, but there were no significant differences in wet finishing at the 95% confidence level. Average percentage of contact time was inversely proportional to increasing media size in both dry and wet finishing, although the differences were small.

The measured normal contact forces between the media and the part were very similar when the sensor was moving facing forward and backward in both dry and wet finishing. This suggests that the contact forces were uniform within the finisher. When the part was fixed on the finisher, its contact forces increased.
7.2.3 Surface Analysis of the Media and the Finished Workpieces

The media roughness decreased slowly after finishing 10 h for 7 and 11 mm media and 20 h for 9 mm media. The size decreased very little when used for 40 h.

The surface hardness and roughness changes of the workpieces had the following trends in the experiments:

- Generally, the hardness of workpieces increased with finishing time, but reached a maximum and then declined.
- Dry finishing usually produced greater hardness increases of workpieces than wet or lubricated finishing.
- Usually, the hardness of workpieces increased with increasing media size (equal media Ra).
- For a given media, the hardness and roughness of workpieces increased with increasing media Ra.
- The trends of the hardness change of workpieces can be applied to the trends of roughness change of workpieces.
- Media size and shape had no significant effect on the hardness and roughness changes of the AA6061-T6 workpieces.
- Water spray made smaller hardness and roughness changes of the workpieces than dry, wet, and lubricated finishing.
- The interaction between the media and the part was a combination of impact, rolling, and sliding.
7.2.4 Videotaping of the Contacts Between the Media and the Part

The videotaping verified that the contact between the media and the part was a combination of normal impact, rolling and sliding, and that there were relatively large contact gaps between the media and the part. Lubrication reduced the speed of the media within the finisher and the relative speed of the media over the surface of the part.

7.3 Future Work

As stated in Chapter 1, vibratory surface finishing is a new research area and its mechanism is largely unknown. This thesis was an initial investigation in this area. To better understand the mechanism of vibratory finishing, the following additional information and equipment would be useful:

1. A more accurate and waterproof sensor should be built to measure the contact forces under lubricated and continuous spray conditions.
2. The sliding, rolling, and normal impact interactions between the media and the part should be investigated further.
3. The effect of vibration amplitude and frequency of the finisher on the surface hardness and roughness changes of the workpieces remains of interest.
4. The dynamics of the media motion within the finisher needs to be further investigated and modeled.
5. The motions of parts of different geometry and their effects on the surface hardness and roughness changes need to be investigated.
(6) Ultimately, a mathematical model needs to be developed to simulate the interactions between various media and a part, and to predict the surface hardness and roughness changes of the workpieces.
Appendix A

SEM-EDX of Cylindrical Media

X-RAY: 0 - 20 keV
Live: 100s Preset: 100s Remaining: 0s

MEM1: AMP MEDEIA
Appendix B

Vibration Analysis of the Sensor

The key element in the sensor is the spring element, modeled as a fixed-fixed beam with a concentrated time-varying transverse force applied at the middle of the beam. The natural frequencies, characteristic modes and the forced response of the beam are calculated below.

Fig. 3.4 Illustration of a forced fixed-fixed beam

Fig. 3.5 Illustration of an element of a bending beam
Development of the Equation of the Vibrating Beam

\[ \sum F_y = 0: \]

\[-(V+dV)+f(x, t)dx+V=\rho A(x)dx \frac{\partial^2 w(x, t)}{\partial t^2} \] (B3.1)

\[ \sum M_0 = 0: \]

\[(M+dM) - (V+dV)dx + f(x, t)dx \frac{dx}{2} - M = 0 \] (B3.2)

\[ \therefore \quad dV=\frac{\partial V}{\partial x} dx, \quad dM=\frac{\partial M}{\partial x} dx \]

\[ \therefore \quad -\frac{\partial V(x, t)}{\partial x} + f(x, t) = \rho A(x) \frac{\partial^2 w(x, t)}{\partial t^2} \] (B3.3)

\[ \frac{\partial M(x, t)}{\partial x} - V(x, t) = 0 \] (B3.4)

Apply \( V = \frac{\partial M}{\partial x} \) from Eq. (B3.4), Eq. (B3.3) becomes

\[ -\frac{\partial^2 M(x, t)}{\partial x^2} + f(x, t) = \rho A(x) \frac{\partial^2 w(x, t)}{\partial t^2} \] (B3.5)

From Euler-Bernoulli theory:

\[ M(x, t) = EI(x) \frac{\partial^2 w(x, t)}{\partial x^2} \] (B3.6)

Inserting Eq. (a3.6) into (a3.5):

\[ \frac{\partial^2}{\partial x^2} \left[ EI(x) \frac{\partial^2 w(x, t)}{\partial x^2} \right] + \rho A(x) \frac{\partial^2 w(x, t)}{\partial t^2} = f(x, t) \] (B3.7)

For a uniform beam, Eq. (B3.7) reduces to:
For free vibration, \( f(x, t) = 0 \) and so the equation of motion becomes:

\[
\frac{\partial^4 w(x, t)}{\partial x^4} + \rho A(x) \frac{\partial^2 w(x, t)}{\partial t^2} = f(x, t)
\]  

(B3.8)

where

\[
c^2 = \frac{EI}{\rho A}
\]

(B3.10)

Letting

\[
w(x, t) = W(x)T(t)
\]

(B3.11)

and substituting Eq. (B3.11) into (B3.9) leads to:

\[
\frac{c^2}{W(x)} \frac{d^4 W(x)}{dx^4} - \frac{1}{T(t)} \frac{d^2 T(t)}{dt^2} = a = \omega^2
\]

(B3.12)

where \( a = \omega^2 \) is a positive constant. Equation (B3.12) can be written as two equations:

\[
\frac{d^4 W(x)}{dx^4} - \beta^4 W(x) = 0
\]  

(B3.13)

\[
\frac{d^2 T(t)}{dt^2} + \omega^2 T(t) = 0
\]  

(B3.14)

where

\[
\beta^4 = \frac{\omega^2}{c^2} = \frac{\rho A \omega^2}{EI}
\]

(B3.15)

The solution of Eq. (B3.14) can be expressed as:

\[
T(t) = A \cos \omega t + B \sin \omega t
\]  

(B3.16)

Where \( A \) and \( B \) are constants that can be found from the initial conditions.

For the solution of Eq. (B3.13), we assume:

\[
W(x) = Ce^x
\]  

(B3.17)

where \( C \) and \( s \) are constants, and derive the auxiliary equation as:
The roots of the equation are:

\[ s_{1,2} = \pm \beta, \quad s_{3,4} = \pm i\beta \]  \hspace{1cm} (B3.19)

Hence the solution of Eq. (B3.15) becomes:

\[ W(x) = C_1 e^{\beta x} + C_2 e^{-\beta x} + C_3 e^{i\beta x} + C_4 e^{-i\beta x} \]  \hspace{1cm} (B3.20)

where \( C_1, C_2, C_3 \) and \( C_4 \) are constants found from boundary conditions. Eq. (B3.20) can also be expressed as:

\[ W(x) = C_1 \cos \beta x + C_2 \sin \beta x + C_3 \cosh \beta x + C_4 \sinh \beta x \]  \hspace{1cm} (B3.21)

or

\[ W(x) = C_1 (\cos \beta x + \cosh \beta x) + C_2 (\cos \beta x - \cosh \beta x) \\
+ C_3 (\sin \beta x + \sinh \beta x) + C_4 (\sin \beta x - \sinh \beta x) \]  \hspace{1cm} (B3.22)

The natural frequencies of the beam can be calculated from Eq. (B3.15) as:

\[ \omega_m = \beta_m^2 \sqrt{\frac{EI}{\rho A}} = (\beta_m l)^2 \sqrt{\frac{EI}{\rho Al^4}} \]  \hspace{1cm} (B3.23)

The function \( W(x) \) is known as the normal mode or characteristic function of the beam and \( \omega_m \) is called the \( m \)th natural frequency of the beam. The unknown constants \( C_1 \) to \( C_4 \) in Eq. (B3.21) or Eq. (B3.22), and the value of \( \beta_m \) in Eq. (B3.23) can be determined from the boundary conditions of the beam.

For a fixed-fixed beam, the boundary conditions are:

\[ W(x) \big|_{x=0} = 0 \]  \hspace{1cm} (B3.24)

\[ \frac{dW}{dx} \big|_{x=0} = 0 \]  \hspace{1cm} (B3.25)

\[ W(x) \big|_{x=L} = 0 \]  \hspace{1cm} (B3.26)
Substituting Eq. (B3.24) and (B3.25) into Eq. (B3.22) gives

\[ C_1 = 0, \quad C_3 = 0 \quad \text{(B3.28)} \]

Substituting Eq. (B3.26) and (B3.25) into Eq. (B3.27) we obtain:

\[ C_2 (\cos \beta_m L - \cosh \beta_m L) + C_4 (\sin \beta_m L - \sinh \beta_m L) = 0 \quad \text{(B3.29)} \]

\[ C_2 (\sin \beta_m L + \sinh \beta_m L) + C_4 (\cos \beta_m L - \cosh \beta_m L) = 0 \]

Equating the determinant of coefficients in Eq. (B3.29) to zero:

\[ [\cos \beta_m L - \cosh \beta_m L]^2 + \sin^2 \beta_m L - \sinh^2 \beta_m L = 0 \quad \text{(B3.30)} \]

or \[ \cos(\beta_m L) \cosh(\beta_m L) = 1 \quad \text{(B3.31)} \]

Solving Eq. (B3.31), the roots can be obtained:

\[
\begin{array}{c|c}
 m & \beta_m L \\
\hline
1 & 4.7300 \\
2 & 7.8532 \\
3 & 10.9956 \\
4 & 14.1372 \\
\vdots & \vdots \\
\end{array}
\]

From Eq. (B3.29), we get:

\[ C_4 = \frac{\cos \beta_m L - \cosh \beta_m L}{\sin \beta_m L - \sinh \beta_m L} C_2 \quad \text{(B3.32)} \]
Hence, the general characteristic function of the fixed-fixed beam is:

\[ W_m(\alpha) = \left[ \cosh \beta_m \alpha - \cos \beta_m \alpha - \frac{\cos \beta_m L}{\sin \beta_m L} \right] \left( \sinh \beta_m \alpha - \sin \beta_m \alpha \right) \]

The free vibration of the beam can be obtained as:

\[ w(x,t) = \sum_{m=1}^{\infty} w_m(x) q_m(t) \]  

and the general or total solution of the fixed-fixed ends beam can be expressed by summation of the normal modes:

\[ w_m(x,t) = \sum_{m=1}^{\infty} w_m(x,t) \quad (m = 1, 2, 3 \ldots \infty) \]

For this forced fixed-fixed beam, assume that a concentrated harmonic force \( F(t) = f_0 \sin(\Omega t) \) applied at the middle of the beam, the deflection of the beam can be written as:

\[ w_m(x, t) = \sum_{m=1}^{\infty} w_m(x) q_m(t) \]

where,

\[ q_m(t) = A_m \cos(\omega_m t) + B_m \sin(\omega_m t) + \frac{1}{\rho A \mu} \int_0^t \Phi_m(\tau) \sin[\omega_m (t - \tau)] d\tau \]

and

\[ \Phi_m(t) = \int_0^1 f(t) W_m(x) dx \]  

\[ \mu = \int_0^L (W_m(x))^2 dx \]
Substituting Eq. (B3.33) and \( F(t) = f_0 \sin(\Omega t) \) into Eq. (B3.37) and then Eq. (B3.36), the general solution of the forced vibration of the fixed-fixed beam can be written as:

\[
w(x, t) = \sum_{m=1}^{\infty} \frac{W_m X_m}{\omega_m} \frac{F_0}{\rho AL} \int_{0}^{t} \sin(\Omega \tau) \sin(t - \tau) d\tau
\]  

(B3.40)
Appendix C

Comparison of Normal Contact Forces for Different Media

Table C1  Statistics of normal contact forces in dry finishing with sensor facing forward. The data are the average of 10 runs with 10 seconds for each run. The 95% confidence intervals are listed (n = 10).

<table>
<thead>
<tr>
<th>Media</th>
<th>Av. No. of impacts in 8 s</th>
<th>Av. max. impact force (N)</th>
<th>Av. impact force (N)</th>
<th>Av. impact duration (ms)</th>
<th>Av. impulse per impact $10^3$ (N.s)</th>
<th>Av. contact percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 mm</td>
<td>128</td>
<td>0.183</td>
<td>0.086</td>
<td>20.2</td>
<td>1.6</td>
<td>32</td>
</tr>
<tr>
<td>95 % CI</td>
<td>±52</td>
<td>±0.03</td>
<td>±0.01</td>
<td>±2.3</td>
<td>±0.5</td>
<td>±13</td>
</tr>
<tr>
<td>9 mm</td>
<td>131</td>
<td>0.207</td>
<td>0.100</td>
<td>19.2</td>
<td>2.0</td>
<td>31</td>
</tr>
<tr>
<td>95 % CI</td>
<td>±50</td>
<td>±0.05</td>
<td>±0.02</td>
<td>±3.8</td>
<td>±0.8</td>
<td>±11</td>
</tr>
<tr>
<td>11 mm</td>
<td>135</td>
<td>0.290</td>
<td>0.121</td>
<td>17.7</td>
<td>2.1</td>
<td>29</td>
</tr>
<tr>
<td>95 % CI</td>
<td>±43</td>
<td>±0.07</td>
<td>±0.03</td>
<td>±3.5</td>
<td>±0.8</td>
<td>±11</td>
</tr>
<tr>
<td>Cylindrical</td>
<td>115</td>
<td>0.265</td>
<td>0.171</td>
<td>17.0</td>
<td>2.6</td>
<td>21</td>
</tr>
<tr>
<td>95 % CI</td>
<td>±47</td>
<td>±0.08</td>
<td>±0.05</td>
<td>±4.8</td>
<td>±0.6</td>
<td>±15</td>
</tr>
</tbody>
</table>
Appendix D

Matlab Program for Contact Force Processing

```matlab
clear all;
load abc;
x=abc;
L = length(x);
SF = 500;
UpperGate = 0.15;
LowerGate = 0.025;

% Fourier Transform of the whole force signal
figure(1);
F=fft(x);\nfm=abs(F);
f=500*(0:length(x)-1)/length(x);
subplot(2,1,1)
plot(f,fm)
xlabel('Frequency (Hz)');
ylabel('(a) FFT of Whole Forces');
zoom on;
grid on;

n=1;
for i=2:L-1
    if (x(i)>=x(i-1) & x(i)>=x(i+1) & x(i)>=UpperGate)
        Num(n)=i;
        Y(n)=x(i);
        n = n+1;
    end
end
values = [Num;Y];
n=1;
M(1)=Num(1);
P(1)=x(M(1));
for i=2:length(Y)
    n=n+1;
end
```
\begin{verbatim}
end

N(i)=n1+n2;
values = [n1,n2];
peaks=[M; P;];
ID(i)=N(i)/SF;
AF=0;
for j=1:N(i)-1
    AF=AF+x(M(i)-n1+j);
end

ASF(i)=AF/(N(i)-1);
IM(i)=AF/SF;
end

AvP=0;
AvSF=0;
Avlm=0;
AvPe=0;

for i=1:n
    AvP=AvP+P(i);
    AvSF=AvSF+ASF(i);
    Avlm=Avlm+IM(i);
    AvPe=AvPe+ID(i);
end

\end{verbatim}

\begin{verbatim}
Fourier Transform of Extracted Impact Events

n=0;
for i=1:length(M)
    for j=1:N(i)-1
        n=n+1;
        w(n)=x(M(i)-N(i)/2+j);
    end
end

F=fft(w);
fn=abs(F);
f=550*(0:length(w)-1)/length(w);
subplot(2,1,2)
plot(f,fn)
xlabel('Frequency (Hz)');
ylabel('d) FFT of Impact Forces');
zoom on;
grid on;
\end{verbatim}

\textbf{D2}
if Num(i)-Num(i-1)>=5
    M(n)=Num(i);
    P(n)=x(M(n));
else if x(Num(i))>=x(Num(i-1))
    n=n-1;
    M(n)=Num(i);
    P(n)=x(M(n));
else
    n=n-1;
    M(n)=Num(i-1);
    P(n)=x(M(n));
end
end

values = [M;P];
TotalNopeaks=length(P)
for i=1:L
    if x(i)>=UpperGate
        w(i)=x(i);
    else
        w(i)=0;
    end
end

l=1; z=length(M);
if M(1)<=SF/60
    l=2;
end

if M(length(M))>=L-SF/60
    z=length(M)-1;
end

for i =1:z
    n1=0; j=0;
    while x(M(i)-j)>=LowerGate
        j=j+1; n1=n1+1;
        if n1>=SF/60, break, end
    end
    if n1<=2
        n1=2;
    end
end

n2=0;k=0;
while x(M(i)+k)>=LowerGate
    k=k+1; n2=n2+1;
    if n2>=SF/60, break, end
    if n2<=2
        n2=2;
end

D3
% calculate the percentage of contact time

% find average max. impact force, average impact force, average impact duration, % average impulse, and contact percentage
% Find standard deviations of average max. impact force, % average impact force, average impact during, and average impulse

dt=1/SF;
AvPeakForce=AvP/length(P)
p1=0; p2=0; s1=0; s2=0; m1=0; m2=0; d1=0; d2=0;
p=length(P);

for i=1:I
   p1=p1+P(i)*P(i); p2=p2+P(i);
   s1=s1+ASF(i)*ASF(i); s2=s2+ASF(i);
   m1=m1+IM(i)*IM(i); m2=m2+IM(i);
   d1=d1+ID(i)*ID(i); d2=d2+ID(i);
end

p2=p2*p2; s2=s2*s2; m2=m2*m2; d2=d2*d2;

% find standard deviation of average max. impact force

StdevP=sqrt((p*p1-p2)/(p*(p-1)));
AvForce=AvSF/z

% find standard deviation of average impact force

StdevASF=sqrt((p*s1-s2)/(p*(p-1)));
AvImpulse=AvIm/z

% find standard deviation of impulse

StdevIM=sqrt((p*m1-m2)/(p*(p-1)));
AvPeriod=AvPe/z

% find standard deviation of single impact impulse

StdevID=sqrt((p*d1-d2)/(p*(p-1)));
PerConTime=sum(N(1:length(N)))*100/L

StatisticValues=[TotalNopeaks;AvPeakForce;AvForce;AvImpulse;AvPeriod;PerConTime]
Standarddeviationsofstatistics=[StdevP;StdevASF;StdevIM;StdevID]
Appendix E

Surface of AA1100-O in dry finishing for 1 min using 9 mm media (a) 2D and (b) 3D

(a)

(b)

E1
Surface of AA1100-O in dry finishing for 5 min using 9 mm media (a) 2D and (b) 3D
Surface of AA1100-O in dry finishing for 10 min using 9 mm media (a) 2D and (b) 3D

(a)

(b)
Appendix H

Surface of AA1100-O in dry finishing for 20 min using 9 mm media (a) 2D and (b) 3D
Surface of AA1100-O in dry finishing for 40 min using 9 mm media (a) 2D and (b) 3D
Appendix J

Surface of AA1100-O in dry finishing for 80 min using 9 mm media (a) 2D and (b) 3D
From videotapes the contact percentage between cylindrical media and the part at the top and at the bottom of the finisher were 24% and 41%, respectively. The relative speed of the cylindrical media past the surface of the aluminum surface was about 36 cm/s and 18 cm/s, with 95% confidence intervals of 25 and 17 cm/s at the top and the bottom of the finisher, respectively.
Numbered References


