Applicability of a Picosecond Laser for Micro-Polishing of Metallic Surfaces

Abdullah Mohammad Khalid Hafiz
*The University of Western Ontario*

Supervisor
Dr. O. Remus Tutunea-Fatan
*The University of Western Ontario* Joint Supervisor
Dr. Evgueni Bordatchev
*The University of Western Ontario*

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ABSTRACT

An increasing number of recent technological advancements is linked to the adoptions of ultra-short pulsed picosecond (ps) lasers in various material processing applications. The superior capability of this laser is associated with precise control of laser-material interaction resulted from extremely short interaction time. In this context, the present study explored the applicability of a ps laser in laser micro-polishing (LµP) of Inconel 718 (IN718) and AISI H13 tool steel. The melting regime – a mandatory phase for LµP – was determined experimentally by the variation of focal offset to attain desired laser fluence. The finite element formulation of heat transfer equation and its solution were also estimated in order to develop a theoretical foundation for the heat transfer mechanism in ps laser-material interaction.

The initial one dimensional (1D) line polishing experiments were performed on ground IN718 and H13 tool steel samples with the parameters related to the melting regime of corresponding material. The knowledge of this initial experimental investigation was later utilized to prepare the surface topography by micromilling with a specific step-over and scallop height, followed by LµP experiments with the same set of aforementioned parameters. The performance of LµP was evaluated by average surface roughness ($R_a$) spectrum at different spatial wavelength intervals along the laser path trajectory. Additionally, statistical measures, such as power spectral density (PSD) function, transfer function (TF) and material ratio (MR) curve were analyzed in order to establish the process parameters resulting the best possible surface quality. From the analysis of this experimental investigation, surface quality improvement up to 78.5% and
75.7% were reported for the spatial wavelength interval of 50–100 µm for IN718 and H13 tool steel respectively.

As a next step, two dimensional (2D) areal polishing of micromilled IN718 and H13 tool steel were performed, where surface quality improvement up to 69.32% and 77.28% were observed for the spatial wavelength interval of 50–100 µm for IN718 and H13 tool steel, respectively. Overall, ps LµP was found to be an effective way of enhancing desired surface quality as demonstrated by the reduction of surface asperities as well as their volumetric uniform redistributions.

Keywords: Picosecond laser micro-polishing, melting regime, heat transfer, polishability, focal offset, laser fluence, surface topography and surface quality
ACKNOWLEDGMENTS

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Contents

Abstract ......................................................................................................................................... ii
Acknowledgment ........................................................................................................................... iv
List of tables .................................................................................................................................... x
List of figures ................................................................................................................................... xi
Nomenclature ................................................................................................................................... xvi
Chapter 1 ......................................................................................................................................... 1
  1 Introduction ................................................................................................................................. 1
    1.1 Background ............................................................................................................................... 1
    1.2 Laser polishing system: configuration and process parameters .............................................. 5
    1.3 Laser polishing technology: state-of-the-art .......................................................................... 8
      1.3.1 Experimental analysis ....................................................................................................... 8
      1.3.2 Modeling and simulation studies ....................................................................................... 19
      1.3.3 Discussion ......................................................................................................................... 24
    1.4 Picosecond laser for micro-polishing applications .................................................................... 30
    1.5 Research scopes and objectives ............................................................................................. 33
    1.6 Organization of the thesis ........................................................................................................ 34
Chapter 2 ......................................................................................................................................... 36
  2 Picosecond perspective of laser micro-polishing ......................................................................... 36
    2.1 Introduction ............................................................................................................................... 36
    2.2 Melting mechanism ................................................................................................................... 36
    2.3 Formation of melting regime in ps laser-material interaction ................................................. 38
    2.4 Materials and system setup ..................................................................................................... 40
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>Determination of melting regime for IN718</td>
<td>43</td>
</tr>
<tr>
<td>2.5.1</td>
<td>Formation of ablation regime</td>
<td>45</td>
</tr>
<tr>
<td>2.5.2</td>
<td>Transition regime</td>
<td>47</td>
</tr>
<tr>
<td>2.5.3</td>
<td>Formation of melting regime</td>
<td>48</td>
</tr>
<tr>
<td>2.6</td>
<td>Determination of melting regime for H13 tool steel</td>
<td>51</td>
</tr>
<tr>
<td>2.6.1</td>
<td>Formation of ablation and transition regime</td>
<td>53</td>
</tr>
<tr>
<td>2.6.2</td>
<td>Formation of melting regime</td>
<td>55</td>
</tr>
<tr>
<td>2.7</td>
<td>Discussion</td>
<td>58</td>
</tr>
<tr>
<td>2.8</td>
<td>Closure</td>
<td>59</td>
</tr>
</tbody>
</table>

Chapter 3 Heat transfer mechanism in melting regime | 60 |
| 3.1 | Introduction | 60 |
| 3.2 | Governing equations in ps laser-material interaction | 60 |
| 3.3 | Numerical solution of heat transfer equation | 66 |
| 3.3.1 | FEM formulation | 66 |
| 3.3.2 | Result and discussion | 71 |
| 3.4 | Closure | 78 |

Chapter 4 Analysis of surface topography: methodology | 80 |
| 4.1 | Introduction | 80 |
| 4.2 | Determination of surface roughness and waviness profiles | 80 |
| 4.3 | Roughness spectrum at different wavelength intervals | 83 |
| 4.4 | Statistical analysis of the surface profile | 88 |
| 4.4.1 | Power spectral density function | 89 |
| 4.4.2 | Transfer function | 90 |
7 Investigation of 2D areal polishing by ps laser ......................................................... 131
  7.1 Introduction ............................................................................................................. 131
  7.2 Experimental methodology ................................................................................ 132
  7.3 Result and analysis of polishing IN718 samples ..................................................... 135
    7.3.1 Effect of polishing track step-over on surface topography ......................... 137
    7.3.2 Ps LµP example: micro-polishing of IN718 .................................................. 142
  7.4 Result and analysis of polishing H13 tool steel samples ....................................... 144
    7.4.1 Effect of polishing track step-over on surface topography ......................... 144
    7.4.2 Ps LµP example: micro-polishing of H13 tool steel ................................. 148
  7.5 Discussion ............................................................................................................. 150
  7.6 Closure .................................................................................................................. 151
Chapter 8 .................................................................................................................... 153
  8 Conclusions and recommendations ........................................................................ 153
    8.1 Introduction.......................................................................................................... 153
    8.2 Conclusions of the present work ....................................................................... 153
    8.3 Recommendations for future study ................................................................... 161
      8.3.1 Process planning for polishing 3D surfaces and functional components ... 161
      8.3.2 Physical and metallurgical properties of polished samples ....................... 162
      8.3.3 Theoretical analysis and multi-physics simulation ................................... 163
      8.3.4 Other challenges and opportunities ......................................................... 164
  Appendix A ............................................................................................................... 166
    A Laser power measurement .................................................................................... 166
      A.1 Laser Power Measurement ........................................................................... 166
  Appendix B ............................................................................................................... 169
    B Electron cooling and lattice heating time .......................................................... 169
B.1 Calculations of electron cooling and lattice heating time .......................... 169

Appendix C ........................................................................................................... 171

C MATLAB codes .................................................................................................. 171

C.1 Gaussian filter .................................................................................................. 171

C.2 Material ratio function ...................................................................................... 172

Reference .................................................................................................................. 174

Vita ......................................................................................................................... 189
List of Tables

2.1 Formation of different laser processing regimes at various levels of focal offset and laser fluence .................................................................44

2.2 Formation of different laser processing regimes at various levels of focal offset and laser fluence for H13 tool steel ........................................52

3.1 Simulation parameters ........................................................................................................71

3.2 Estimated melt depth for IN718 based on relative position of melt front ..........74

3.3 Estimated melt depth for H13 steel based on relative position of melt front ....75

5.1 Average line profiling surface roughness ($R_a$) and waviness ($W_a$) along the tool path trajectory for the profiles created on IN718 sample in the melting regime ..........97

5.2 Summary of the parameters generated by material ratio (MR) functions of the initial and the laser polished profiles for ground IN718 samples ..............................102

5.3 Average line profiling surface roughness ($R_a$) and waviness ($W_a$) along the tool path trajectory for the profiles created in the melting regime on H13 sample ..........104

5.4 Summary of the parameters generated by material ratio (MR) functions of the initial and the laser polished profiles for ground H13 samples........................................109

6.1 Summary of the parameters generated by MR functions for micromilled IN718....124

6.2 Summary of the parameters generated by MR functions for micromilled H13 tool steel..........................................................................................129

7.1 Process parameters for 2D LµP of IN718 and H13 tool steel.................................133

7.2 Summary of the average MR function parameters for IN718............................142

7.3 Summary of the average MR function parameters for H13 tool steel...............148

A.1 Laser power and pulse energy at different set voltage and laser frequency .........167
List of Figures

1.1 Surface quality improvement through laser polishing: (a) remelting mechanism; (b) sample of experimentally validated enhancement in average surface roughness ..............4

1.2 Configuration and control of LP systems ...............................................................6

1.3 Principal parameters associated with LP process .....................................................7

1.4 Synopsis of the effect of laser polishing on surface roughness: (a) overall dependence on workpiece material; (b) detailed view for the nanometric range of final average roughness ($R_a$) ..................................................................................................................26

1.5. Synopsis of laser polishing performance: (a) overview of dependence on workpiece material; and (b) highly polishable metallic materials .....................................................29

1.6. Schematic depiction of relative advantages of ps laser over ns laser .....................32

2.1 Schematic representation of ps laser-material interaction in perspective of melting regime formation ..................................................................................................................38

2.2 Schematic representation of various process regimes formed at different levels of focal offset in picosecond laser material interactions .........................................................39

2.3 System setup of LµP (a) schematic representation (b) experimental setup ..............41

2.4 Change in laser fluence and beam diameter with the increase of focal offset in ps laser processing of IN718 ..................................................................................................44

2.5 Sample track ablated at 0.6 mm focal offset and 0.19 J/cm$^2$ fluence: (a) surface topography and (b) average cross section profile .................................................................46

2.6 Surface topography of the track from transition regime created at 0.7 mm focal offset .......................................................................................................................................48

2.7 Surface topography of laser melted track created at the focal offset of 1.0 mm and the fluence of 0.16 J/cm$^2$ .............................................................................................................49

2.8 Surface cross section along the peak and the valley presented in initial surface profile for the profile created at the focal offset of 1.0 mm and the fluence of 0.16 J/cm$^2$ ........50

2.9 Surface profile created at the focal offset of 1.0 mm and the fluence of 0.16 J/cm$^2$ (a) average roughness cross section across the laser processing track (b) top view of the surface topography ........................................................................................................51
2.10 Change in laser fluence and beam diameter at different focal offsets in ps laser processing of H13 tool steel ................................................................. 53

2.11 Ablated track created at 0.4 mm focal offset and 0.10 J/cm² fluence (a) surface topography (b) average cross section profile ......................................................... 54

2.12 Surface topography of the track from transition regime created at 0.5 mm focal offset ........................................................................................................... 55

2.13 Surface topography of the laser melted track created at 0.6 mm focal offset and 0.09 J/cm² of fluence ................................................................................. 56

2.14 Surface cross section along the peak and the valley for the profile created at the focal offset of 0.6 mm and the fluence of 0.09 J/cm² ........................................ 57

2.15 Average roughness cross section profile across the laser processing track created at the focal offset of 0.6 mm .................................................................. 57

3.1 Schematic representation of temporal distribution of laser intensities .......... 68

3.2 Geometric representation of the workpiece and the laser path trajectory ........ 69

3.3 Generation of mesh in finite element formulation of ps LµP ............................ 70

3.4 Surface temperature distribution for the profile created at the focal offset of 0.8 mm on IN718 (a) 3D temperature profile of the workpiece top surface (b) temporal distribution along the cross section across the trajectory of laser path ....................... 72

3.5 Comparison of surface peak temperatures for the profiles created in the melting regime of IN718 .................................................................................. 73

3.6 Temperature distribution along the thickness for profile created at the focal offset of 0.8 mm on IN718 ............................................................................. 74

3.7 Comparison of surface peak temperatures for the profiles created in the melting regime of AISI H13 tool steel .................................................. 75

3.8 Schematic representation of a surface asperity with the height and spatial length of $h$ and $L \mu$m, respectively ................................................................. 77

4.1 (a) Surface primary profile and waviness profile (b) surface roughness profile at the cutoff wavelength of 800 µm (0.8 mm) ............................................. 83

4.2 Hypothetical example of LµP of three surface profiles with different wavelengths and polishability values demonstrating an approach for selecting appropriate step-over distance ........................................................................................................... 87

4.3 $R_a$ spectrum at different spatial wavelength intervals for the ground IN718 sample ........................................ 88
4.4 Power spectral density (PSD) function plot for a ground IN718 sample ..................90
4.5 Schematic illustration of transfer function (TF) based statistical modeling of LµP process ......................................................................................................................91
4.6 TF plot between the initial and the polished profile for laser polishing of AISI tool steel sample (Hafiz et al., 2012)..................................................................................................................91
4.7 Illustration of material ratio (MR) curve ........................................................................94
4.8 MR curve for the surface topography of a ground H13 tool steel sample .............94
5.1 $R_a$ spectrum at various wavelength intervals for laser polishing trials performed on a ground IN718 sample .................................................................................................................98
5.2 Surface quality improvements associated with the profile polished at 0.8 mm focal offset in case of ground IN718 sample .................................................................................................................99
5.3 PSD function of the initial and the polished profile created at focal offset of 0.8 mm in case of ground IN718 samples ..............................................................................................................100
5.4 TF plot between initial and the polished profile created at focal offset of 0.8 mm in case of ground IN718 samples ..............................................................................................................101
5.5 MR curves for the initial and the polished profiles created on ground IN718 sample .................................................................................................................................101
5.6 (a) Linear fitting of the middle straight line of MR curve for the profile created at the focal offset of 1.1mm (b) residual plot for corresponding linear fitting.............................103
5.7 $R_a$ spectrum at various wavelength intervals for laser polishing trials performed on a ground H13 sample .................................................................................................................105
5.8 Surface quality improvements associated with the profile polished at 1.0 mm focal offset in case of ground H13 tool steel sample .................................................................................105
5.9 PSD function plots of the initial and the polished profiles created at focal offset of (a) 0.6 mm and (b) 1.0 mm in case of ground H13 samples .................................................................106
5.10 TF plots for the profiles created at focal offset of 0.6 mm and 1.0 mm in case of ground H13 samples ..........................................................................................................................108
5.11 MR curves of the initial and the polished profiles for ground H13 samples ......109
5.12 Schematic of formation of surface topography in the form of recast materials as a result of laser-material interaction (Temmler et al., 2011) .................................................................112
6.1 Ground and micromilled surface profile for IN718: (a) surface topography of ground profile (b) surface topography of micromilled profile (c) cross section of ground profile
across the initial grinding marks (d) cross section of micromilled profile across the micromilled tracks (e) PSD function of ground profile and (f) PSD function of micromilled profile

6.2 $R_a$ spectrum at various spatial wavelength intervals for different laser polishing trials performed on a micromilled IN718 sample

6.3 Surface quality improvements associated with the profile polished at 1.1 mm focal offset on IN718

6.4 Comparison of PSD functions between the initial and the polished profiles produced at 1.1 mm focal offset with a fluence of 0.14 J/cm$^2$ for IN718

6.5 TF plot between the initial and the polished profile created at focal offset of 1.1 mm and PSD plot of the initial profile in case of micromilled IN718 sample

6.6 MR curves of the initial and the polished profiles for IN718

6.7 $R_a$ spectrum at various spatial wavelength intervals for different laser polishing trials performed on a micromilled H13 tool steel sample

6.8 Surface quality improvements for the profile polished at 0.6 mm focal offset on micromilled H13 tool steel sample

6.9 Comparison of PSD functions between the initial and the polished profile created at 0.6 mm focal offset with the fluence of 0.09 J/cm$^2$ on H13 tool steel

6.10 TF plot between the initial and the polished profile created at focal offset of 0.6 mm and PSD plot of the initial profile in case of micromilled tool steel sample

6.11 MR curves of the initial and the polished micromilled surface profiles for H13 tool steel

7.1 Schematic representation of 2D areal polishing using zigzag trajectory

7.2 Visual illustration of a workpiece slab, polished samples, measured sub-areas and patches (not in scale)

7.3 2D surface profile of (a) initial and (b) polished block in case of sample created with a step-over of 20 µm

7.4 Average areal topography surface roughness ($S_a$) spectrum at various spatial wavelength intervals for the initial and the polished area created with varied step-over on a micromilled IN718 sample

7.5 Comparison of average PSD plots for the initial and the polished area created with a step-over of 2.5 µm and 20 µm on the micromilled IN718 sample
7.6 Comparison of average TF amplitude plots for the polished area created with a step-over of 2.5 µm and 20 µm on the micromilled IN718 sample

7.7 Average MR function plots for the initial and the polished areal profile on IN718 sample

7.8 (a) Photograph of polished surface profile as a demonstration of the applicability of ps laser for micro-polishing of IN718 (b) corresponding surface quality improvements associated with the 2D areal polished profile

7.9 $S_u$ spectrum at various spatial wavelength intervals for different laser polishing trials performed on a micromilled H13 tool steel sample

7.10 Average PSD plot for the initial micromilled 2D profile and 2D profile created with a step-over of 10 µm on H13 tool steel sample

7.11 Magnitude of the average TF between initial micromilled and laser polished areas on H13 tool steel sample

7.12 Average MR functions for the initial and the polished 2D surface profiles for H13 tool steel

7.13 2D areal LµP of micro milled H13 tool steel surface by ps laser (a) surface topography (b) surface micrograph

7.14 Surface quality improvements associated with the 2D areal polished with a step-over of 10 µm on micromilled H13 tool steel sample

A.1 (a) Laser power, and (b) pulse energy (energy per pulse) as function of pulsing frequency at different level of set voltage
NOMENCLATURE

Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>FEA</td>
<td>Finite element analysis</td>
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<tr>
<td>FEM</td>
<td>Finite element method</td>
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<tr>
<td>FS</td>
<td>Femtosecond</td>
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<tr>
<td>HAZ</td>
<td>Heat affected zone</td>
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<tr>
<td>LµP</td>
<td>Laser micro-polishing</td>
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<td>LP</td>
<td>Laser polishing</td>
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<tr>
<td>MOPA</td>
<td>Master Oscillator Power Amplifier</td>
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<tr>
<td>MR</td>
<td>Material ratio</td>
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<tr>
<td>NS</td>
<td>Nanosecond</td>
</tr>
<tr>
<td>Ps LµP</td>
<td>Picosecond laser micro-polishing</td>
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<tr>
<td>PS</td>
<td>Picosecond</td>
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<td>PSD</td>
<td>Power spectral density function</td>
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<td>TF</td>
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</table>

Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Area</td>
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<tr>
<td>$A_c$</td>
<td>Absorptivity</td>
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<tr>
<td>$C$</td>
<td>Heat capacity</td>
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<tr>
<td>$G$</td>
<td>Electron-lattice coupling factor</td>
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\[ \begin{align*}
\text{d} & \quad \text{Laser spot diameter} \\
\text{E} & \quad \text{Energy} \\
\text{f} & \quad \text{Focal length} \\
\text{g} & \quad \text{Number of atom per embryo} \\
\text{h} & \quad \text{Height} \\
\text{I} & \quad \text{Intensity} \\
\text{k} & \quad \text{Thermal conductivity} \\
\text{l} & \quad \text{Length} \\
\text{m} & \quad \text{Mass} \\
\text{N} & \quad \text{Electron per unit volume} \\
\text{Q} & \quad \text{Heat flux} \\
\text{R}_a & \quad \text{Average line profiling roughness} \\
\text{R}_f & \quad \text{Reflectivity} \\
\text{R}_p & \quad \text{Maximum peak height} \\
\text{R}_v & \quad \text{Maximum valley depth} \\
\text{r} & \quad \text{Radius} \\
\text{S}_a & \quad \text{Average areal topography surface roughness} \\
\text{T} & \quad \text{Temperature} \\
\text{T}_B & \quad \text{Boltzmann constant} \\
\text{t} & \quad \text{Time} \\
\text{u} & \quad \text{Velocity} \\
\text{x} & \quad \text{Coordinate in the direction of laser processing track} \\
\text{y} & \quad \text{Coordinate across the direction of laser processing track}
\end{align*} \]
\( z \) Coordinate perpendicular to the surface to be processed

\( \alpha \) Thermal diffusivity

\( \gamma \) Surface tension

\( \theta \) Incident angle

\( \lambda \) Wavelength

\( \mu \) Dynamic viscosity, micro

\( \chi \) Thermal diffusivity

\( \rho \) Density

\( \sigma \) Standard deviation

\( \tau \) Time index

\( s \) Solid

\( l \) Liquid
Chapter 1

Introduction

1.1 Background

Surface finish is commonly acknowledged as one of the standard quality metrics for mechanical components. The assessment of the surface finish attained through a specific manufacturing process is typically performed through three major indicators namely: i) topographic quality, ii) functionality, and iii) aesthetic properties. Typical definitions of these terms propose strong interdependencies between: i) topographic quality and accuracy, precision and surface macro/micro-asperities, ii) surface functionality and tribological, optical and other physical-mechanical properties, and iii) aesthetics and visual appearance of the component. While various manufacturing methods were devised to address each of these indicators on an individual basis, polishing is one of the presently available options capable to enhance practically all of these attributes in an efficient and consistent manner. It is important to point out here that conventional polishing techniques (e.g. manual, mechanical, chemical) are typically applied in consecutive steps that require intermediate cleaning and this decreases
dramatically the overall productivity of the process. Beyond this, several other factors, including the need for highly qualified personnel, the necessity to enforce extensive measures to prevent the accidental damage of already polished surface as well as the limited extent of the automation make these techniques less attractive for manufacturers (Jarosch et al., 2003).

To address these known drawbacks of the conventional polishing, the contemporary manufacturing arena has been greatly enriched by the advent of enabling polishing technologies. This rapidly evolving category encompasses laser polishing (LP) as one of the newest thermal energy-based methods to be used to attain highly superior surface finish levels. While it is relatively difficult to pinpoint a specific chronological moment when this technology was invented or at least used for the first time, it can be mentioned here that a relatively similar concept was used at the end of 1980s in a microelectronics-related context (Tuckerman and Weisberg, 1986; Mukai et al., 1987).

During LP process, laser beam energy is delivered to workpiece surface in an attempt to melt a thin layer of peripheral surface through laser-material interactions. While the theoretical foundations of the LP are yet to be fully understood, most researchers tend to agree in principle that the core of the process is formed by its intrinsic remelting mechanism that is essentially caused by the “liquefaction” of a superficial and thin layer of material (Willenborg, 2011). Remelting constitutes the predominant mechanism of LP, regardless if performed in its macro- or micro-polishing variants. The molten pool of material formed tends to redistribute around the area adjacent to each initial surface asperity under the action of surface tension. As a result, the vast majority
of peak-valley heights of the surface are reduced after the quick solidification of melted layer and surface asperities are typically reduced in case of correctly executed LP operations (Figure 1a), such that important reductions in the surface roughness become apparent (Figure 1b). However, it is perhaps important to note here that the complex – and currently difficult to predict – balance of internal forces that are generated during the solidification process could also be responsible for significant degradations in surface quality, an idea which underscores once more the importance of a better understanding of the internal mechanics of LP.

Laser polishing offers several significant advantages over conventional polishing. First of all, the process can be fully automated without the need for dedicate equipment, since laser head can be installed easily on a wide majority of readily available multi-axis computer numerically-controlled (CNC) stages. Regardless if used in a dual (LP and machining) or singular (LP-only) configuration, the superior ability to control all laser beam parameters (i.e. spot size, beam shape, beam orientation, beam energy, etc.) combine with the complete control over the motions of the CNC stage provides the LP with excellent versatile characteristics. These traits were already exploited towards high precision selective LP performed on mechanical components with intricate shapes (Willenborg et al., 2003; Poprawe et al., 2003). Obviously, beyond the aforementioned enhanced control over process parameters, LP has inherited some of the advantages that are often cited in context of the more mature laser machining technology, namely the absence of the mechanical forces/deformation at tool/workpiece interface, along with the lack of physical wear on the polishing “tool”.
Starting with the beginning of the past decade, LP has received a gradually increasing attention from both research- and application-oriented communities. It is important to note that while the original demonstrations on the capabilities of LP process were extremely promising for highly demanding mold-making and implant
manufacturing industries (Willenborg et al., 2003), it became soon clear that a more in-depth understanding of the process will be required before its wide adoption by the industry.

1.2 Laser Polishing System: Configuration and Process Parameters

A schematic representation of the principal elements of a typical LP system is presented in Figure 1.2. LP systems encompass a number of electromechanical and optical components that can be divided between laser and mechanical subsystems, each of them being controlled by a broad palette of parameters. Laser subsystem includes laser source, laser head along with its mounting on the multi-axis CNC stage, as well as the optics required to focus beam energy at the desired location. The primary role of the laser subsystem is to provide means to produce and then deliver the generated energy into the LP processing zone, which is located at or in the close vicinity of the outer surface of the workpiece. On the other hand, the mechanical subsystem has a structure absolutely similar to that of most standard multi-axis CNC machine tools since is comprised of base, electrodrives and translation/rotation stages whose role is to enable the required relative motions between the effector tool (i.e. laser beam) and workpiece. In some of the builds, 2D or 3D galvanometric scanning heads are added to provide additional degrees of freedom (DOFs) to the laser beam. Since laser beam motions induced by the scanning head are optically controlled, their rates can be much faster than those provided through the mechanical stages. However, the range of motions delivered by the scanning head is extremely limited compared to their mechanical counterparts.
Figure 1.2: Configuration and control of LP systems

Similar to other manufacturing processes involving laser-material interactions, the final polished surface as LP outcome yields through the overlap of complex physical, mechanical and thermodynamical processes that are in turn controlled by three principal types of parameters related to: i) laser subsystem, ii) mechanical subsystem, and iii) workpiece (Figure 3). Although extensive, the list of parameters presented in the figure is in fact non-exhaustive, since the all compound ones were actually left out. Two of the most notable examples in this category are energy density (fluence) – i.e. laser energy per
unit area – which is expressed as a function of laser power, spot diameter and feed rate along with pulse overlap which is dependent on focal spot diameter, travel/scanning speed and pulse frequency.

It is important to note here that the wide majority of these parameters (independent or not) are in fact dictated by the overall balance of laser-material interactions, their primary role being to ensure a satisfactory reduction of the surface roughness. However – as it will be underscored in the subsequent sections – when it comes to the final roughness of the polished surface, in addition to the predictable parameters that are introduced by laser and mechanical subsystems, the other relevant ones are dependent on the workpiece in the form of material properties and initial surface topography.
1.3 Laser polishing technology: state-of-the-art

In order to demonstrate the effectiveness of LP in the high volume production context specific to industrial applications, the development of a more comprehensive knowledge base in this area is essential from both theoretical and experimental perspectives. As such, the wide majority of research studies conducted so far on this topic can be more or less accurately divided into two somewhat disjoint subsets that were focused either on empirical/experimental or on modeling and simulation aspects of the LP process. Each of these two categories will be discussed in more details in the upcoming sections.

1.3.1 Experimental analysis

Due to the inherent complexity and novelty of the laser polishing process, a large number of studies were concerned almost exclusively with experimental investigations aiming to determine a set of parameters that will noticeably improve the quality of the polished surface. Obviously, this approach reduces dramatically the path towards rapid adoption of the technology within the results-oriented industrial environment. The experimental studies on LP tend to focus on the illustration of the effect of various input parameters on the process performance in terms of surface finish and/or processing time/volume. The selection of input parameters depends entirely on LP process type (micro or macro), workpiece surface (mechanical and thermal properties, initial surface topography etc.), and the desired level of surface finish. The current section will review the main research efforts reported so far in this category.
In one of the first attempts made in this direction, Bereznai et al. (2003) have studied the effect of two excimer laser parameters (fluence and number of incident pulse) on the microstructure and roughness of titanium disk samples prepared through conventional machining operations. By simply varying the two aforementioned parameters, the roughness was reduced to 25 nm, a value that ensures inhibition of plaque development and maturation in dental implants, one of the common applications of the polished material. Obviously, without a proper optimization of the LP process parameters, the quality of the surface obtained will be far away from the optical precision \(R_a = 4\text{-}5\) nm, form accuracy = 0.5 \(\mu\)m) that can be achieved through more conventional polishing operations involving abrasive tools (Gessenharter et al., 2003; Brinksmeier et al., 2004).

Many other early attempts were made to demonstrate applicability of the new technology to a broad variety of industrial applications ranging from tribological (Singh et al., 2002; Raeymaekers et al., 2010) and microfluidics (Heng et al., 2006) to medical implants and moulds (Poprawe and Schultz, 2003; Willenborg et al., 2003; Trtica et al., 2006; Trtica et al. 2009; Milanovici et al., 2010), although in implant manufacturing scenario, the laser beam is expected to produce a controlled, but not necessarily extremely low roughness in order to favor the osteointegration process. In many of these studies, the selection of the process parameters was based on rather empirical principles whose details were not disclosed by the study. Nevertheless, the quality of the polished surfaces reached impressively low levels of \(R_a = 200\) nm (Poprawe and Schultz, 2003) or \(R_a = 150\) nm (Willenborg et al., 2003) especially when a two step polishing approach
(roughing/finishing) was adopted. The materials used in these studies included tool and stainless steel as well as cobalt-chromium alloys.

In more recent experimental studies, the number of process parameters analyzed simultaneously was increased in an attempt to maximize their impact on surface finish. In this sense, Steyn et al. (2007) chose to vary laser power, defocus and number of layers applied on a tool steel surface, while maintaining constant pulse frequency, feed rate and step over. Their experiments revealed that quality of the polished surface depends strongly on the amount of energy delivered by the laser beam to each point of the surface, since this has a major impact on the temperature and hence the mechanism controlling the local behavior of the material. Supporting this idea, their experiments showed that higher power densities and number of layers applied will essentially lead to superior surface finishes, going to $R_a = 250$ nm. However, all LP parameters used in the process have to be correlated with the type of material being polished since their thermo-physical properties could span over broad ranges. The experiments performed by Dobrev et al. (2008) with different laser offsets outlined that while almost no roughness improvements were obtained for copper, the surface finish of stainless steel could be improved by 30%. All their trials were performed with pretested and otherwise common, but essentially unoptimized LP parameters. Interestingly, they have also noticed that while stainless steel behaved identical with respect to symmetric positive and negative offsets, copper did not.

The individual effect of several process parameters like feed rate, laser energy, pulse duration and pulse frequency on surface roughness and topology of DF2 tool steel was investigated in a series of studies by Hua et al. (2004, 2007) and Guo (2007). While no
significant roughness reductions were reported – as in most instances surface quality was diminished – the authors emphasized that for a given laser, the feed rate has a more prominent influence on surface finish than all other factors analyzed and later proposed used an expression of the temperature field in the polished area to explain this finding (Guo, 2009). Furthermore, as the amount of energy delivered to the surface increases, the prevalent mechanism associated with laser-material interaction evolves from melting to ablation, and this in turn will degrade the overall performance of LP (Guo and Tam, 2012).

In addition to the parameters exhibiting similarities with laser machining or even other types of material removal operations, Nüsser et al. (2011) have pointed out that beam energy distribution (e.g. Gaussian or top-hat) as well as beam shape (e.g. circular or square) are also important in LP. Their comparative analyses revealed that superior surface finishes are determined by circular-shaped beams with top-hat intensity distributions. Moreover, for a square beam, surface roughness was lower when beam advanced in a direction parallel with its edges than when moved diagonally across surface. Strong correlations were found between initial surface topography and duration of the pulses: while shorter pulses have prevalent effects on the high frequency components of the roughness (microasperities), lower frequency components (surface waviness) seemed to be more affected by longer pulses.

Without performing explicit parameter optimization studies, a different team of researchers (Marinescu et al., 2008) has practically reinforced the significance of previously studied LP parameters like laser power, beam size/offset distance, feed rate
and step over distance/tool path overlap. Their polishing experiments involving two different types of steel and a material obtained through selective laser sintering have shown that in order to avoid the occurrence of surface over melting mechanism during polishing – that is typically associated with surface quality degradation – the energy density of the laser should be directly correlated with thermal absorption capacity of the polished material. As such, materials with low absorption capacities should be polished with lower energy densities that can be easily obtained with defocused and hence larger beam sizes. As in the previous reported cases, polishing of heterogeneous materials with large variations in their thermal properties seems to remain a challenge difficult to accommodate, such that maximum roughness decreases (70%) were measured for homogeneous materials with low heat absorption coefficients. However, depending on the actual composition of the heterogeneous material, good surface finishes seemed to attainable, as demonstrated by Yermachenko et al. (2009) while polishing cylindrical samples of VT16 titanium, a high strength alloy belonging to Ti-Al-Mo-V system. The authors proved that a five-fold decrease in surface roughness (down to 416 nm) is possible for this material whose microhardness increases by 50-70% after LP. Similar investigations were also reported by Kumstel and Kirsch (2013) who performed adjustments of the laser power, beam size and feed rate of the LP operation in order to attain significant improvements of surface quality for Ti6Al4V and Inconel 718 alloys (84% and 89% $R_a$ reductions, respectively). The spectrum of materials that are suitable candidates for LP-based surface quality improvements enlarges permanently. As such, in addition to more conventional uses of LP on steels and titanium alloys, recent studies
have proved that the surface of nickel alloys (Lambarri et al., 2013) as well as that of sintered bronze (Gisario et al., 2010) can be smoothened through laser irradiation.

A more systematic approach in investigation of the LP parameters was taken by Lamikiz et al. (2007a, 2007b) and Ukar et al. (2010a, 2010b, 2010c) who concentrated their research on metallic surfaces produced through selective laser sintering (SLS). Their three level three factor DoE revealed that a certain combination of laser power, feed rate and focal distance – that can be expressed in a lumped form through energy density of the beam – is capable to maximize the amount of roughness reduction that in their experiments peaked around 80% ($R_a = 1.2 \, \mu m$), while leaving the form errors unaffected.

The optimal combination of LP parameters determined by means of a simple quadratic fit involving line polishing experiments yielded reasonably good results for both planar area and three dimensional line operations. However, for these later processes, specific settings like step over distance and beam inclination angle became increasingly important. Given the rapid expansion of the additive manufacturing technologies, other research groups identified means to improve the roughness either by imposing bounds to the laser energy density delivered to the surface (Ramos-Grez and Bourell, 2004) or by employing the combination of laser surface melting (LSM) and re-melting (LSR) operations (Yasa et al., 2011). Through an appropriate tuning of the laser power, scan speeds and tool path overlap, up to 90% surface roughness decreases were obtained through LSR for stainless steel 316L (initial $R_a = 15 \, \mu m$) while minimal differences between LSM and LSR were observed for Ti6Al4V.
Although laser polished SLS surfaces exhibited superior homogeneity and integrity characteristics when compared to the original ones, the authors emphasized that application of LP on materials with different melting points will continue to represent a challenge, an idea also reinforced in the context of lamellar cast iron (Vincent et al., 2008), for which minimal (5%) surface roughness improvements were acquired. Along the same lines of LP process parameters optimization by means of DoE software, Dadbakhsh et al. (2010) analyzed the effect of laser power, beam spot size and feed rate on surface roughness of flat Inconel 718 samples obtained through laser material deposition. The optimal combination of LP process parameters yielded an 80% reduction in surface roughness, corresponding to $R_a = 2 \, \mu m$. Once again, the strong effect of laser energy density on surface quality was reiterated, and an optimal beam spot diameter was determined, although within the analyzed parameter ranges its influence was observed as less significant than that of laser power or feed rate. A relatively similar DoE-based optimization approach was also taken by Giedl-Wagner et al. (2007) who chose to vary laser power, pulse repetition rate, pulse overlap, step over distance, focal position and the number of repeats while performing laser ablation polishing on samples whose surfaces were generated through high speed milling. The polished samples were produced from 4 different materials (40CrMnNiMo8-6-4, X37CrNoV5-1, AlZnMgCu1.5, CuAl10Fe5Ni5-C) and both picosecond (355 nm in UV range) and nanosecond (532 nm in visible range) pulses were used. Depending on the material, important roughness reductions (around 90%) were achieved for picosecond pulses, with resulting surface finishes going down to $R_a = 60 \, \text{nm}$ (X37CrNoV5-1). The other 3 materials investigated recorded lower
roughness decreases, especially in case of non-steel alloys. The best results for picosecond pulses were obtained with low power and defocused beams, thus working at the ablation threshold. Since roughness reductions achieved with nanosecond pulses were considerably smaller, even when low energy densities were used, it was concluded that best results are generated by ultra-short pulses that practically affect only a superficial layer of the polished material and are also capable to produce a certain degree of material melting capable to fill the submicron craters of the surface.

It is perhaps important to note here that recent research (Ukar et al., 2010b) suggested that the amount of heat absorbed by the polished surface is dependent – in addition to its thermal properties – on its initial topology/configuration and on the type/wavelength of the laser used. By performing comparative studies on tool steel, the authors have demonstrated that despite having a more defocus-sensitive beam, high-power diode lasers are capable to perform better than CO$_2$ lasers both in terms of productivity and accuracy of the resulted surface, even with smaller energy densities of the beam. The significant difference in their wavelengths (906 nm vs. 1060 nm) triggers completely different responses in the polished material, such that the optimal value of energy density for diode laser is capable to induce extremely high (around 90%) decreases in $R_a$ values, going down to 0.86 µm for ball-end milled and to 0.36 µm for EDM semi-finished surfaces. However, when semi-finished surface quality improves, the observed roughness reductions tend to become less significant. Metallurgical analyses performed in this study practically supported that idea that once the optimal energy density has been reached for a certain surface, its further increases will do nothing but
determine a switch of predominant polishing mechanism from shallow surface melting (SSM) to surface over melting (SOM), with predictable degradations of the polished surface quality. According to the authors, SSM is equivalent with a superficial melting of the microasperities that will eventually fill the “valleys” of the surface with molten material under the action of the capillary pressure and liquid curvature. By contrast, SOM regime translates into deeper melting effects that will result in a surface profile with lower peak-valley frequencies but higher amplitudes that may in fact increase of the final roughness of the surface. Furthermore, the authors noted that higher than optimal energy densities tend to amplify the micro-crack nucleation process, and this in turn has undesirable consequences on the polished component durability. The effect of laser power, scan speed and initial surface topography was also investigated by Gisario et al. (2011), who concluded by increases in the laser power or the speed at which laser beam moves across surface are more likely to generate a superior quality of the post-polished surface (approximately 80% decrease in $R_a$ from 1.5 µm). Unlike most other studies, the authors applied LP on flat patches produced through face milling performed on the circumference of a shaft.

Given that the practically any surface topography is characterized by a random variation of the height of its micro-asperities, conventional statistical tools and metrics can be used to draw insightful conclusions based on pre- and post- laser polishing profiles of the surface. Building on this idea, Chow et al. (2010) relied on material ratio function, autocorrelation function, autospectrums and transfer functions to assess the performances of LP when applied on Ti6Al4V. Their results confirmed that LP is capable to improve
the roughness profile through the redistribution of high frequency components into the lower range of the spectrum. As such, surface waviness was found to be slightly increased as a result of this material redistribution, even if $R_a$ decreased moderately from 577 nm to 452 nm (21.3%). By means of the same statistical-oriented approach Chow et al. (2012) have demonstrated that changes in laser focal offset distance (FOD) are sufficient to determine the switch of the laser-material interaction between three distinct regimes: ablation, melting and heating. Moreover, the authors have proved that the initial roughness of the surface, laser power, number of overlapping LP passes as well as the initial waviness of the surface also have a significant impact on the final roughness of the surface. By performing univariate parameter analyses, Chow and his colleagues have generated surfaces with line profiling finishes varying between 32% reduction in $R_a$ (FOD between 1.47 to 1.62 mm and initial $R_a = 726$ nm) to over 60% $R_a$ reduction observed for more than five LP passes (power of 13 W and FOD from 1.42 to 1.51 mm), laser power of 13 W (FOD = 1.5 mm), initial $R_a = 700$ nm (power of 13W, FOD of 2.13 mm and ten LP passes) or 50 μm stepover distance between the micromilled tracks used to generate the initial surface (13 W power and ten LP passes, FOD between 1.44 and 1.57 mm). Analogous techniques were used by Hafiz et al. (2012) to determine the optimum amount of overlap between adjacent polishing tracks required to ensure the effectiveness of a continuous wave laser while performing area polishing on AISI H13 tool steel. For a 95% overlap between neighboring tracks, the authors have shown that average areal topography surface roughness ($S_a$) has dropped to 0.23 μm and this corresponds to an 83% improvement in the quality of the surface. The subsequent LP
operation performed with a lower energy pulsed laser was capable to enhance even further the quality of the surface down to $S_a = 0.18 \mu m$ (86.7\% total improvement).

Aside from all aforementioned studies focused on identification, evaluation and optimization of LP parameters from experimental perspectives lacking well defined practical applications, very few researchers have illustrated the performances of the process in the context of a specific and a more geometrically-complex workpiece. However, one of the most convincing demonstrations in this regard was probably performed by Temmler et al. (2010) who have finished through LP the outer surface of an implantable left ventricular assist device, one of the components of an artificial heart pump. While side-to-side comparisons have not shown dramatic, but rather moderate improvements of $R_a$ obtained through LP as opposed to that yielded through manual operations, the time associated with the finishing operation was significantly cut through the involvement of LP from 3.5 hours to 10 minutes. The spectral analysis performed in this study has revealed that the multi-step LP used for finishing was the most effective for wavelengths smaller than 5 $\mu m$ when the $R_a$ of the initial surface (0.020 - 0.030 $\mu m$) dropped up to 30 times in the vicinity of 0.001 $\mu m$.

To summarize, while the research efforts presented in this section can be regarded as satisfactory with respect to their investigational objectives, it became increasingly clear that further progress towards the understanding of the inherent mechanisms underlying LP can only be acquired through the development of appropriate theoretical models. As such, the progress made so far in this direction will be detailed in the following section.
1.3.2 Modeling and simulation studies

These studies are intended to establish quantitative interdependence relationships between various variables of the LP process by means of appropriate theoretical models. Their primary goal is to enable accurate predictions on LP behaviour, generally expressed through input/output parameters’ dependencies. Often, the functionality of the proposed model comes on the expense of significant simplifications and/or assumptions that have to be made in order to enable determination of the desired quantitative formulations. While some of the theoretical models suggested in the past for LP were validated through numerical – typically finite element – simulations, others relied only on experimental procedures to demonstrate the applicability of the proposed theories.

Since many of the early LP studies were focused on polishing of surfaces manufactured through SLS technology, some of the first modeling attempts were strongly related to this particular type of initial surface topology. In this regard, Ramos et al. (2001) have proposed initially a simple assimilation of the SLS surface asperities with hemispherical caps. Their predictions of the resulting surface roughness for 420 stainless steel/bronze infiltrated SLS parts as a function of laser power, scan speed and initial particle size yielded reasonably good matches with empirical data. This simplified representation of the initial surface was later incorporated in a SSM model used to explain reductions of the polished surface roughness as a result of the molten material redistribution under the action of capillary and viscous drag pressures that tend to minimize the differences in curvature of the local liquid surface (Ramos and Bourell, 2002). A thermo-physical model has also been developed for SOM mechanism caused by
deep melting of the polished surface (Ramos et al., 2003). The proposed model, incorporating surface curvature effects, was able to predict with acceptable accuracy the roughness of the resulting surface. The authors also pointed that that the low frequency high amplitude wave formed as a result of SOM are in fact determinant for roughness increases generally associated with this type of polishing regime. Furthermore, while the transition from SSM to SOM was believed be primarily influenced by laser energy density and initial surface roughness, beam velocity across surface was found to have a significant effect on the final roughness achieved after LP. However, the best experiments reported in this study for faster moving beams did not produce $R_a$ values under 2 microns. By taking an approach relatively similar to that used in tribological investigations, Shao et al. (2005) proposed a model capable to predict the final roughness of the surface based on the simplification of the asperity shape to three principal geometric primitives: circular cone, hemisphere and cylinder. By employing their model in polishing of several common engineering materials (Fe, Al, Ti and 304 stainless steel) the authors have demonstrated that laser pulse duration should be kept under a certain critical value in order to obtain the targeted temperature gradient in the underlying substrate material. The theoretical approach was verified experimentally in nanosecond laser polishing of DF-2 cold work steel in which $R_a$ values of 99.5 nm were obtained (28.9% average roughness improvement).

Since laser polishing is associated with significant solid/liquid phase changes, some authors have proposed for this process models that were derived from classical problem of moving phase boundary, also known as Stefan problem. One example in this sense is
constituted by the work of Mai and Lim (2004), who developed their own numerical
techniques/codes to simulate the transient laser melting process, essentially implemented
as a hybrid between fixed and variable domain methods. Validation of the proposed
method was performed through comparisons between the 2D geometry of the molten
pool obtained through both numerical and physical experiments performed during the
laser polishing of 304 stainless steel. Beyond the development of the aforementioned
numerical models, the study also outlined the importance of laser power density and
dwell time on the depth of melt region that was capable to seal the micropores (less than
1 μm in size) of the raw surface. The most effective reduction of surface roughness (61%
reduction, from 195 nm to 75 nm) was achieved through adjustments brought to the off-
focus distance of the beam.

Many recent studies have demonstrated that in addition to the inherent
thermodynamics of the LP process, the initial surface topography also plays a significant
role on the final quality of the polished surface. In this regard, Perry et al. (2009a-c) were
the first to emphasize importance of minimum critical spatial frequency as a valuable
predictor of the polishing effectiveness in the spatial frequency domain. The proposed
metric represents in fact a veritable threshold capable to delimitate the spectrum of
frequencies prone to experience significant reductions of the surface topography
amplitudes. As such, smaller critical frequencies are desirable since a broader span of
spatial frequencies will be attenuated and this in turn will enhance the overall efficiency
of the LP operation. Following the initial unidimensional finite element analyses used to
estimate the melt depth induced by a laser single pulse, Perry and his colleagues have
demonstrated the validity of the proposed concept by performing LP experiments on micro-fabricated/micromilled Ni and Ti6Al4V samples. The largest (sevenfold) drops of the $R_a$ were noticed for surface profiles with lowest harmonic frequencies slightly above the critical frequency value (Perry et al., 2009b). As suggested by simulations, $R_a$ tends to improve with longer pulses, a hypothesis that was tested by comparing the results of 300 ns and 650 ns laser pulses that were responsible for 30% and 50% surface roughness, respectively (Perry et al., 2009b). For Ti6Al4V samples, the best LP results translated into a 66% reduction of $R_a$, from 0.206 to 0.070 μm (Perry et al., 2009c). In a recent extension of this work, Vadali et al. (2012) have expanded the applicability of critical spatial frequency towards other widely used metallic materials like 316L stainless steel, nickel, Ti6Al4V, Al-6061-T6. The comparison of the analytical and experimental results – obtained in both line (316L) and area polishing (rest of them) conditions – have shown that critical frequency represents an effective predictor of the performance of the LP process. Since the precision of the previously proposed 1D finite element model diminished significantly for longer pulses, the authors have relied on a time dependent axisymmetric approach to predict the duration of the molten state for 0.65 and 5 μs pulses. In terms of LP performance, the best results were obtained for micromilled titanium alloy, whose average areal roughness decreased by 54.6% to $S_a = 82.2$ nm. However, the applicability of stationary capillary flow models – like the ones used in Perry et al. (2009a-c) – is limited to LP processes in which thermocapillary effects are negligible, e.g. both melt durations and thermal gradients are relatively small. As such, Pfefferkorn et al. (2013) have developed numerical axisymmetric 2D models to better
describe LP scenarios in which the effect of thermocapillary flow becomes predominant. Since these operations are associated with large decreases in the surface roughness that tend to be accompanied by unwanted ripples/undulations, it makes sense to attempt to smoothen them further through a slower capillary flow-based polishing process. The results of this two-step process as applied on Ti6Al4V suggest that the initial average areal roughness of 172 nm can be reduced down to 47 nm. Neither of the two analyzed types of polishing mechanisms was capable of such performances when used individually. Once again, the balance between thermocapillary and capillary regimes seems to play a decisive role on the final quality of the polished surface (72.7% decreases in $S_a$).

Recent developments in the area of LP modeling emphasize that in addition to the more frequent 1D and 2D analyses, 3D formulations are also possible. For instance, Ukar et al. (2012) have developed a 3D thermal model incorporating solid-state transformations and capable to predict the amount of roughness decrease obtained during LP of DIN 1.2379 steel. The developed model – which was validated on a periodical structure obtained through ball-end milling – showed a relatively good agreement (between 10 and 15% difference) between measured and predicted values of the surface roughness. Furthermore, the study has outlined that – for the analyzed tool steel – any deviations from the optimal value of the energy density of about 1150 J/cm$^2$ will actually translate in increases of the $R_a$ from its experimentally measured minimum value of 0.783 $\mu$m (89% decrease).
1.3.3 Discussion

The synopses of some of the works depicted in previous section are presented in a graphical format in Figure 1.4 in order to use it as a process reference. In perspective to type of laser system for polishing application, Nd:YAG laser with 1064 nm wavelength is the most widely regarded system used both in laser macro and micro polishing applications. Laser systems, such as, continuous wave CO$_2$, diode laser etc. are generally used for macro scale polishing. In contrast to that, pulsed fiber laser, excimer laser etc. are the other types of systems possessing common adoptions for micro-scaled LP applications besides the low power Nd:YAG lasers. With regards to type of materials being polished by laser, LP of pure titanium, Ti-alloys, copper, stainless steels, different kinds of tool steel, nickel alloys and aluminum alloy are so far been reported.

In experimental investigations of LP process, the typical process variables being analyzed were laser power, feed rate, pulse duration, focal offset distance, tool path overlap percentage (in case of 2D area polishing) and lumped parameters in the form of energy density and laser fluence. Polishing performance evaluations were carried out predominantly by surface amplitude based parameters, e.g., average surface roughness ($R_a$) or root mean square roughness value ($R_q$). It is to be noted here that, not many works had specified the parameters of roughness calculation and measurement, i.e., evaluation length and cut-off frequency (in case of roughness and waviness separation). Selection of these parameters is critical in context to accurate evaluation of polishing performance in terms of surface amplitude based parameters.
Figure 1.4: Synopsis of the effect of laser polishing on surface roughness: (a) overall dependence on workpiece material; (b) detailed view for the nanometric range of final average roughness ($R_a$)
CHAPTER 1. INTRODUCTION

The research works related to modeling and simulation of LP process focused primarily on analytical deduction of functional relationship between the input variables, e.g. laser optics and motion based parameters, initial surface topography, and the output parameter, namely, surface roughness distribution. The parameters inferred in this regards are temperature distribution (thermal field), irradiation time and melt depth. Numerical techniques, like finite element analysis and finite difference methods were often used in order to deduce those aforementioned parameters. Due to inherent complexities associated with laser polishing, some basic assumptions in terms of heat transfer mechanism, material homogeneity, beam shape and intensity distributions were made. However, these assumptions can be spared with satisfactory level of experimental validation depicted in most of the studies.

From a practical perspective, another valuable dependence would link the achievable quality of the polished surface to the type of the workpiece material. As the graphs shown Figure 1.4a indicate, much of the prior research efforts were focused on polishing of hot and cold worked steels typically used by mold and die industry. In many of these instances, the attainment of nanometric range surface quality constitutes a feasible option (Figure 1.4b) that can be pursued. While final mirror-like polished surfaces are not uncommon, optical quality ($R_{a_{\text{final}}} \leq \text{cca. 10 nm}$) remains relatively rare. However, in addition to tool steels, other materials such as nickel and titanium alloys (Ti6Al4V) seem to be reasonable facilitators of superior LP performance, as characterized in terms of $R_{a_{\text{final}}}$ and the percentage of roughness decrease.
The plot shown in Figure 1.5a demonstrates once again the wide variability that is inherent to LP performance and perhaps the best example in this sense is represented by AISI O1 steel whose reported decrease in surface roughness varies from approximately 90% to cca. 20% increase. Evidently, when it comes to the most “laser polishable” metallic materials, Figure 1.5b suggests that some of the best performance can be achieved for AISI H11 and AISI H13 steels (chromium hot work steels), nickel and titanium as well as two of their widely used alloys, namely Inconel 718 and Ti6Al4V, respectively. While various theories have been proposed in the past to explain why some materials can be polished through laser irradiation much better than others, no widely accepted explanation has been put forward yet.

As a closure of this section, it should be underscored here that while most of the surveyed studies tend to adhere – in a more or less explicit manner – to standard techniques for roughness calculation (ASME B46.1/1995), a considerably smaller subset of them would disclose full details of the actual assessment protocol used. A typical example in this sense is represented by the frequent case of $R_a$ determination along a straight polished path, during which the method used to select the location of the roughness assessment line within the laser track is rarely unveiled by the researchers. As such, while some might have chosen to report the lowest $R_a$ value, others could prefer to average $R_a$ for a preset number of parallel assessment lines. Analogous observations can be made with respect other geometric metrics of the surface texture. Possible explanations of this relative ambiguity could be linked to more or less accurate interpretations of the standard as well as some physical limitations of the optical
profilometers, especially when it comes to the size of the field of view. However, regardless of the actual scenario, the message to be retained is that most of reported $R_a$ values should be treated with a certain dose of scientific circumspection.

Figure 1.5: Synopsis of laser polishing performance: (a) overview of dependence on workpiece material; and (b) highly polishable metallic materials
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1.4 Picosecond Laser for Micro-polishing Applications

It was stated earlier that the texture and finish of the surface topography of mechanical components has significant effects on their functionality. The importance of surface topography is further exacerbated in micro- and nano-scale domains that are often characterized by features with dimensional tolerances and surface roughness in the same micro/nano-range of values (Tay et al., 2005 and Perry et al., 2009). The conventional
finishing methods are ineffective in case of miniaturized products due to the difficulties associated with high processing time and limited accessibility for selective area polishing. By contrast, micro-polishing laser radiation is presently regarded as a valuable alternative for alteration of the surface topography. (Nüsser et al., 2011). Laser micro-polishing (LµP) is performed predominantly by nanosecond (ns) pulsed lasers employing a pulse width between 20 ns and 1000 ns (Perry et al., 2009; Nüsser et al., 2011; Willenborg, 2011 and Mai et al., 2004). These processes have demonstrated their efficiency achieving a processing rate as high as 3.3 s/cm² and have been used for selective polishing of complex 3D surfaces parts, and components (Nüsser et al., 2011 and Temmler et al., 2010).

An increasing number of recent technological advancements in material processing are linked to the development of ultra-short pulsed lasers, i.e., picosecond and femtosecond lasers. Ultra-short pulsed lasers, like the one in picosecond (ps) regime have been widely adopted in various type of materials processing, including, micromachining, micro-texturing/patterning and micro-drilling owing to their superior ability to form narrow heat affected zone (HAZ) as a result of extremely short laser-material interaction time (Qiu et al., 1992; Willis et al., 2002; Weingarten, 2009 and Risch et al., 2011). These lasers offer several advantages over longer pulsed ns lasers. The superior capabilities of ps lasers are associated not only with the short pulse duration but also with the repetition rates range in several MHz; the higher repetition rate divides the total pulsing energy into a large number of short pulses resulting in the induction of sufficient fluence to generate the melting regime. As a consequence, melting of surface topography
takes place in a more precise and localized manner with lesser volume and depth of the heat affected zone compared to ns laser processing (see Figure 1.6) (Risch et al., 2011). The unique combination of ultra-short pulses and high repetition rate enables the selection of a wide range of process parameters for various types of laser materials processing with the same micromachining system set-up.

![Figure 1.6: Schematic depiction of relative advantages of ps laser over ns laser](image)

The ps lasers possess the unique capability of delivering the required level of fluence more rapidly than it takes for the pulse energy to diffuse into the material. During its interaction with the workpiece material, a significant portion of the laser pulse energy is absorbed by electrons in the excited state. This enables rapid laser ablation with no or insignificant heat affected zone provided that the applied fluence is higher than the ablation threshold of the material (Weingarten, 2009). However, an appropriate control of the laser fluence and therefore heat localization allows a gradual shift of the ps laser performance from an “ablation only” to a “melting only” regime fully avoiding or significantly reducing any form of ablation.
1.5 Research Scopes and Objectives

The applicability of picosecond laser for micro-polishing of metallic materials was investigated. The polishing performance was evaluated in terms of surface quality improvement denoted by the reduction of surface roughness. The study on applicability of ps laser for micro-polishing applications were performed for two widely used alloys, namely, nickel based superalloy Inconel 718 (IN718) and AISI H13 tool steel. The specific objectives of this study were:

- To determine appropriate process regime in order to perform picosecond laser micro-polishing (ps LµP)
- To develop a thermal model of ps laser-material interaction
- To establish the concept of polishability in terms of the spatial content of the surface topography and formulate an appropriate quantitative measure for surface profile analysis
- To perform statistical analysis of the initial and the polished profiles to infer the transformation between these two profiles
- To demonstrate the process capability of ps laser for polishing of metallic materials

This research is pertained to be the pioneering work in utilizing the process capability of ps laser for micro-polishing applications. The accomplishment of the aforementioned goals of this research would facilitate the advancement of ps laser for
potential micro-polishing applications on numerous other metallic materials. In this regard, the results obtained from this research included:

- Experimentally evaluated and determined melting regimes based on different level of laser fluence for a given set of process parameters
- A finite element analysis (FEA) based model to determine the thermal field and the melt depth associated with melting regime
- A novel quantitative measure based on statistical signal processing algorithm to investigate the polishability of individual spatial components of the initial surface profile
- Experimental evidence of the effectiveness of ps laser in improving the surface quality validated by the aforesaid measure and other statistical quantitative analysis
- Successful demonstration of the process capability of ps LµP for 2D area polishing applications

1.5 Organization of the Thesis

This thesis is organized into 8 chapters. Chapter 1 has already given an overview of the laser polishing process emphasizing its performance in surface quality improvement through the reduction of roughness. This chapter also has depicted the objectives and the scopes of the present study. Chapter 2 describes the picosecond perspective of laser polishing, i.e., the evolution of melting regime in ps laser-material interaction. The method of experimental determination of melting regime is also detailed in this chapter,
including the experimental setup and the materials to be processed by ps laser. Chapter 3 illustrates the numerical modeling method of heat transfer in melting regime and its FEA based solution to deduce corresponding thermal field and melt depth. The concept of polishability is addressed and the methodology of surface profile analysis based on average roughness distribution at different spatial wavelength intervals is discussed in the subsequent Chapter of 4. Additionally, statistical methods for surface profile analysis are also depicted in this chapter. Chapter 5 presents the results and analysis of initial experimental investigations performed on ground IN718 and H13 tool steel samples. The results and analysis on ps LμP of micromilled surface profiles are provided in Chapter 6, where the initial micromilled profiles were created based on the findings depicted in Chapter 4. Afterwards, 2D area polishing by ps laser is discussed in Chapter 7. The process capability of ps LμP is also exhibited in this chapter for polishing 2D area. Finally, the thesis ends in Chapter 8 with the conclusions and the contributions of this work, and the recommendations for future studies.
Chapter 2

Picosecond Perspective of Laser Micro-polishing

2.1 Introduction

The preliminary task in performing picosecond laser micro-polishing (ps LµP) constitutes the establishment of the appropriate laser fluence range corresponding to the melting regime. This chapter presents the details about the formation mechanism and the methodology of determining melting regime in picosecond laser-material interaction. The basic procedure of obtaining different fluence level by varying the focal offset has been discussed along with a complete experimental investigation relating establishment of corresponding process regimes. The qualitative and quantitative measures to determine these regimes are also detailed with examples in this chapter.

2.2 Melting Mechanism

During the interaction of short laser pulses with metallic surfaces the laser fluence is absorbed by free electrons, due to a phenomenon called “inverse Bremsstrahlung” (Chichkov et al., 1996). The fundamental mechanism of Bremsstrahlung (i.e. “braking
radiation” or “deceleration radiation”) – likely discovered by Tesla towards the end of the 19th century – is associated to the electromagnetic energy (e.g. photons) generated when a charged particle is deflected by another charged particle, such as an electron deflected by a nucleus. Although the underlying theory of Bremsstrahlung is still not fully understood, it has been established that the inverse Bremsstrahlung heating associated with laser-material interaction involves in fact two types of interaction namely between electrons and external laser field as well as between electrons and ions.

The ps laser material interaction in context to the formation of the melting regime is schematized in Figure 2.1. The short pulsed melting of the peripheral workpiece surface by ps laser involves the following three basic steps: (1) absorption of photons (optical pulse) energy by the free electrons in the excited state, (2) transfer of thermal energy between the free electron and the lattice, and (3) phase change of the lattice as a consequence of energy propagation (Qiu et al., 1993 and Kuo et al., 1996). In physical perspective, after a few picoseconds of the laser pulses being deposited over the workpiece surface, the atoms start oscillating around their equilibrium position as a result of its rapid heating. Over the next few picoseconds, the regular atomic structure totally breaks down, which results in the emergence of liquid phase (Linde, 2003). However, if the applied fluence does not reach the ablation threshold for a particular material, then the micro-range thermal diffusion takes place resulting in the occurrence of the melting only regime. Thus, controlling adequately the laser fluence, picosecond lasers can be used only to melt the workpiece material, a sine qua non phase of laser micro-polishing.
CHAPTER 2. PICOSECOND PERSPECTIVE OF LASER MICRO-POLISHING

2.3 Formation of Melting Regime in PS Laser-material Interaction

As stated in previous section, the ablation and the melting phenomena in ps laser-material interaction primarily depend on the applied fluence. The highest level of fluence is generated when the beam is precisely focused on the top surface of the workpiece for a given set of process parameters: namely, laser power, travel speed, pulse duration and repetition rate. This fluence at the focal point would be sufficient to cause ablation provided that it exceeds the ablation threshold of the material to be processed. The attainment of this fluence is facilitated by the laser beam diameter that reaches its minimum value at the focal point. By offsetting the focal point at a certain distance above or below the workpiece surface, the effective laser beam diameter as measured on the workpiece surface level will change. Since beam diameter will increase with offset distance, this will be accompanied by corresponding reduction in fluence value. As such, the laser process regime will gradually shift from ablation to melting after passing typically through a transition zone.

Figure 2.1: Schematic representation of ps laser-material interaction in perspective of melting regime formation
CHAPTER 2. PICOSECOND PERSPECTIVE OF LASER MICRO-POLISHING

Figure 2.2 illustrates the formation of ablation, transition and melting process regimes at different offset distances. The ablation regime is formed when the beam is focused on the workpiece surface. In this case, the focal plane is located at the workpiece surface level and the distance between the workpiece surface and the objective lens, known as working distance, is coincided with the focal length \( f \). In general, working distance is the sum of the focal length and the focal offset \( h \), which is the distance between the focal plane and the sample surface. As the focal plane is moved up above the workpiece, ablation regime persists within an interval from zero to the focal offset threshold of transition regime \( h_t \) as shown in Figure 2.2. The transition regime occurs when focal plane is located between \( h_t \) and the focal offset threshold of melting regime \( h_m \), where inconsistent ablation of material takes place. Further increments of the focal offset lead to the melting regime.

![Figure 2.2: Schematic representation of various process regimes formed at different levels of focal offset in picosecond laser material interactions](image)
offset beyond $h_m$ fluence level will shift once more the nature of the laser-material interaction process to the melting regime enabling the ps LµP process. The melting regime becomes negligible with further increasing focal offset when the heating regime occurs resulting in the discoloration of sample surface. The methodology of attaining melting regime as a function of laser fluence and focal offset has been detailed in the following subsection.

2.4 Materials and System Setup

The schematic diagram and the photograph of the ps LµP experimental set-up are shown in Figure 2.3. The ps Master Oscillator Power Amplifier (MOPA) laser having a maximum power of 12 W, pulse width of 10.5 ps and repetition rate (pulse repetition frequency) up to 8.2 MHz was operated with a laser wavelength of 1064 nm. In the system, laser power for a particular frequency can be varied by changing the set-voltage. Pulse energy (energy per pulse) can be calculated after that from the ratio of laser power and the frequency. Laser power and pulse energy at varied set-voltage and frequencies are detailed in Appendix A.

To create a neutral processing zone, a constant flow of argon along the laser beam path was directed through a conical-shape nozzle towards the vicinity of laser-material interaction zone (Figure 2.3). The laser system was mounted on a modular multi-functional micromachining system MICROGANTRY nano5X by Kugler GmbH (Salem, Germany). This system integrates several micromachining technologies along with measurement instrumentation. Micromachining technologies are micromilling with an
180,000 rpm spindle, fly cutting with a 2000 rpm spindle and micromachining with a picosecond laser (Duetto, from Time-Bandwidth Products, Inc., Switzerland). A Renishaw™ touch probe with a measurement accuracy of ±500 nm is used for measuring workpiece geometry before and after machining and during alignment. The system is also equipped with a Blum™ laser tool setting sensor for measuring actual cutting tool geometry (e.g. diameter and length) having a measurement repeatability of 100 nm±2σ.

Motion stages of this system are equipped with air bearings with an actual position measuring resolution of 10 nm and with a positioning accuracy within ±250 nm in X-Y direction and ±500 nm in Z direction. Straightness is within ±800 nm per 100 mm travel for all linear axes. The system is also equipped with an automatic tool changer able to accommodate up to 60 cutting tools. Furthermore, a workpiece was mechanically mounted on the A/C-axis tilt/swivel stage and it was aligned along X- and Z-axis within ±250 nm deviation using Renishaw™ touch probe. Such alignment procedure applied for each experiment gave advanced ability to remove the workpiece from the system and place it back with high repeatability as needed for measuring surface topography before
and after the LµP experiments. The total system was installed at the National Research Council of Canada (NRC) in London, Ontario, Canada.

Polishing experiments were performed on flat samples of Ni-based superalloy Inconel 718 (IN718) and AISI H13 tool steel. The IN718 has high temperature strength in terms of creep resistance as well as high corrosion resistance. Therefore this alloy is used extensively as a component in aerospace applications, particularly in the hot sections of aircraft engines, for instance, gas turbine engine (Dudzinski et al., 2003). Other similar applications of IN718 include fabrication of functional components operating at elevated temperature and corrosive environment, such as, instruments for steam turbines and nuclear power plants, chemical and petrochemical equipment, rocket and missile parts, pumps and tooling (Rahman et al., 1997; Ezugwu et al., 2003; Pawade et al., 2008 ). On the other hand, the H13 tool steel possesses unique combinations of high hardness, abrasion resistance and high thermal resistance capabilities. In perspective of micro component, H13 tool steel is used mainly for micro molding applications, where surface texture is considered as an important quality index (Carvalho et al., 2006). Both IN718 and H13 tool steel samples were prepared initially by grinding operation. The grinding process forms surface topography with a broad spectrum of spatial frequencies, which enables laser micro-polishing to be related with the initial surface topography in context to the polishability of the spatial components (discussed details in Chapter 4).
2.5 Determination of Melting Regime for IN718

To identify the three main laser processing regimes (ablation, transition and melting), linear (1D) laser tracks were created with the following process parameters: pulse repetition rate of 7.45 MHz, laser beam travel speed of 20 mm/s, laser power of 12 W, and varying the focal offsets starting from 0 mm (at the focal plane) with a step of 0.1 mm. The process parameters were determined based on the initial trials. The laser processing regimes were identified through the analysis of the surface roughness and the change in surface cross section heights depth across the laser path trajectory. Table 1 summarizes the acquired experimental data. The topographies of laser tracks were measured using a WYKO NT1100 optical profilometer having 1 Å height measurement resolution. The results presented in Table 2.1 are shown graphically in Figure 2.4. An increase in laser spot diameter (measured on the workpiece surface) and decrease in laser fluence level were observed with the increase of focal offset, which leads to the shift in process regime from ablation to melting through a transition. The identification of the three main processing regimes is detailed in the following subsections.
Table 2.1: Formation of different laser processing regimes at various level of focal offset and laser fluence for IN718

<table>
<thead>
<tr>
<th>Focal offset (mm)</th>
<th>Beam width (µm)</th>
<th>Fluence (J/cm²)</th>
<th>Process regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>31.40</td>
<td>0.24</td>
<td>Ablation</td>
</tr>
<tr>
<td>0.10</td>
<td>31.70</td>
<td>~0.24</td>
<td>Ablation</td>
</tr>
<tr>
<td>0.20</td>
<td>32.50</td>
<td>0.23</td>
<td>Ablation</td>
</tr>
<tr>
<td>0.30</td>
<td>33.00</td>
<td>0.22</td>
<td>Ablation</td>
</tr>
<tr>
<td>0.40</td>
<td>33.60</td>
<td>0.21</td>
<td>Ablation</td>
</tr>
<tr>
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<td>35.50</td>
<td>0.20</td>
<td>Ablation</td>
</tr>
<tr>
<td>0.60</td>
<td>35.60</td>
<td>0.19</td>
<td>Ablation</td>
</tr>
<tr>
<td>0.70</td>
<td>-</td>
<td>-</td>
<td>Transition</td>
</tr>
<tr>
<td>0.80</td>
<td>38.16</td>
<td>0.18</td>
<td>Melting</td>
</tr>
<tr>
<td>0.90</td>
<td>39.99</td>
<td>0.17</td>
<td>Melting</td>
</tr>
<tr>
<td>1.00</td>
<td>41.22</td>
<td>0.16</td>
<td>Melting</td>
</tr>
<tr>
<td>1.10</td>
<td>43.09</td>
<td>0.14</td>
<td>Melting</td>
</tr>
<tr>
<td>1.20</td>
<td>45.10</td>
<td>0.13</td>
<td>Melting</td>
</tr>
</tbody>
</table>

Figure 2.4: Change in laser fluence and beam diameter with the increase of focal offset in ps laser processing of IN718
2.5.1 Formation of ablation regime

The conventional assessment of material ablation employs the total depth and the rate of material removal per pulse (Hu et al., 2010 and Wolynska et al., 2011). In this study, the ablation regime was determined qualitatively by visual analysis and quantitatively by calculating the profile of average cross section surface height across the laser path trajectory. Each point of the cross section surface profile was calculated in the direction of laser travel speed. The maximum depth of the cross section surface profile in the laser processing zone is also compared with the maximum profile valley depth ($R_v$) of the initial surface topography. For example, Figure 2.5 shows the surface topography of an ablated laser track and corresponding average cross section surface profile across the laser path trajectory created at 0.6 mm focal offset. The laser ablated trench can be noticed along the laser processing direction (Figure 2.5a and 2.5b) having a highly consistent profile along the laser path trajectory with a uniform depth of 51.28 µm and width of 35.6 µm justifying consistent laser-material removal process (ablation).
Figure 2.5: Sample track ablated at 0.6 mm focal offset and 0.19 J/cm² fluence: (a) surface topography and (b) average cross section profile.
CHAPTER 2. PICOSECOND PERSPECTIVE OF LASER MICRO-POLISHING

Furthermore, the maximum depth of the ablated track (51.28 µm) is considerably deeper than the $R_v$ of the initial profile indicating material removal by ablation as shown in Figure 2.5b. These metrics allow relatively facile identification of the ablation regime for a focal offset varying between 0 mm and 0.6 mm with a corresponding fluence value calculated between 0.24–0.19 J/cm$^2$ (see Table 2.1). The parameters associated with this regime are highly relevant when performing micromachining through laser ablation.

2.5.2 Transition regime

Between the melting and the ablation regimes, a transitional regime characterized by uneven removal of workpiece material was found to be formed for a narrow range of focal offsets between 0.6 mm and 0.8 mm (Table 2.1). The surface topography of the laser track created in this regime is shown in Figure 2.6. The fluence associated with this regime was not calculated due to the difficulty of determining the width of the laser track attributed by inconsistent ablation process. The instable phenomenon of transition regime in terms of non-uniform variation of the width and the depth is the result of corresponding fluence and laser-material interaction time as such the fluence in this regime barely exceeds the ablation threshold that normally results in persistent ablated track. The instability and inconsistency of the transition regime prohibits its usage for practical applications.
Formation of melting regime

The melting regime was found within the focal offset range of 0.8–1.2 mm with corresponding fluence range of 0.18–0.13 J/cm². The presence of this regime is compulsory for LµP with its set goal to improve the surface finish. Figure 2.7 presents the surface topography of the melted track created at the offset of 1.00 mm and the fluence of 0.16 J/cm². The surface profile in melting regime is generated by successive redistribution and resolidifications of molten material resulted from laser material interaction. Therefore, based on the initial surface topography and the melt depth, the surface cross section heights in the processing zone will differ in the form of distinct height distributions. For an instance, molten material from the surface peak is driven towards the valley by surface tension. Therefore, the surface cross section height distribution along the peaks and the valleys are decreased and increased accordingly. In
CHAPTER 2. PICOSECOND PERSPECTIVE OF LASER MICRO-POLISHING

Figure 2.7: Surface topography of laser melted track created at the focal offset of 1.0 mm and the fluence of 0.16 J/cm²

In this regard, Figure 2.8 presents the surface cross section height distribution along a specific initial peak and a valley for the surface profile shown earlier in Figure 2.7. Relative decrement and increment of surface profile heights along the surface peak and the valley are observed in Figure 2.8 as it stated previously.

It is worthwhile to mention that relative increment of average surface cross section in laser processing zone may generate from the ripples resulted from the higher amount of peripheral melting of the surface profile (Pirch et al., 2006 and Temmler et al., 2011). The rippling phenomenon is not prevalent in ps LµP. However, melt depth resulted from the ps laser-material interaction is adequately high to cause redistribution of initial surface spatial components into a new domain.
Figure 2.8: Surface cross section along the peak and the valley presented in initial surface profile for the profile created at the focal offset of 1.0 mm and the fluence of 0.16 J/cm²

Additionally, average line profiling roughness ($R_a$) cross section profiles across the laser path trajectory were calculated in order to ascertain the melting regime. Figure 2.9 demonstrates the $R_a$ cross section profile along with the top view of laser processed track exhibited in Figure 2.7. The profile shown in Figure 2.9a was determined by calculating the average of the $R_a$ values distributed in the direction of laser path trajectory. For example, the $R_a$ value at the evaluation length of 60 µm, specified on the profile with a red dot (see Figure 2.9a), was calculated by averaging all the dispersed $R_a$ values along the red dotted line at 60 µm evaluation length in the direction of laser path trajectory (see Figure 2.9b). It can be inferred from Figure 2.9a the $R_a$ value of 0.50 µm for unpolished profile was reported to reduce to a $R_a$ value of 0.24 µm within the laser processing zone.
2.6 Determination of Melting Regime for H13 Tool Steel

In order to determine the melting regime for H13 tool steel, the experimental trials were performed with the following parameters, namely, pulse repetition rate of 8.2 MHz, laser beam travel speed of 10 mm/s, laser power of 12 W and finally focal offsets from 0 mm with a step of 0.1 mm. Similar procedures to determine the process regimes in laser-material interaction of IN718 were followed. The experimental results for H13 tool steel are summarized in Table 2.2 and shown graphically in Figure 2.10. Relative
increase in beam diameters and decrease in fluence level resulted from the increase of focal offset transformed the process regime from ablation to melting through a narrow transition regime (see Figure 2.10a and 2.10b).

Table 2.2: Formation of different laser processing regimes at various level of focal offset and laser fluence for H13 tool steel

<table>
<thead>
<tr>
<th>Focal offset (mm)</th>
<th>Beam width (µm)</th>
<th>Fluence (J/cm²)</th>
<th>Process regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>34.31</td>
<td>0.15</td>
<td>Ablation</td>
</tr>
<tr>
<td>0.10</td>
<td>36.60</td>
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<td>Ablation</td>
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<td>37.85</td>
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<td>Ablation</td>
</tr>
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<td>39.80</td>
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<td>Ablation</td>
</tr>
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<td>42.23</td>
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<td>-</td>
<td>-</td>
<td>Transition</td>
</tr>
<tr>
<td>0.60</td>
<td>44.54</td>
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<td>Melting</td>
</tr>
<tr>
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<td>Melting</td>
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</tr>
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<td>Melting</td>
</tr>
<tr>
<td>1.10</td>
<td>49.60</td>
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</tr>
</tbody>
</table>
Figure 2.10: Change in laser fluence and beam diameter at different focal offsets in ps laser processing of H13 tool steel

2.6.1 Formation of ablation and transition regimes

Ablation regime was formed within the focal offset range of 0.0–0.4 mm with corresponding fluence range of 0.15–0.10 J/cm² for H13 tool steel. Figure 2.11 presents the surface topography of an ablated laser track and corresponding average cross section surface profile across the laser path trajectory created at a 0.4 mm focal offset as an example of laser ablated profile. A consistent ablated profile with a uniform depth of 3.1 µm and width of 42.23 µm can be noticed along the laser path trajectory. Additionally, the maximum depth of ablated track (3.1 µm) exceeds the $R_v$ of 2.29 µm of the initial profile representing material removal by ablation mechanism (see Figure 2.11b). The parameter associated to this ablation regime can used to perform micromachining of AISI H13 tool steel.

Further increase of focal offset a narrow transition regime is formed for a focal offset of 0.5 mm as shown in Figure 2.12. Based on this representation in Figure 2.12, it
Figure 2.11: Ablated track created at 0.4 mm focal offset and 0.10 J/cm² fluence (a) surface topography (b) average cross section profile

can be noted that the transition regime is practically characterized by inconsistent laser-material interactions irregularly mixing melting and ablation processes. As a result, the
laser track created in this regime has non-uniform variation of the width and depth formed by craters and grooves created by ablation and separated by areas of re-solidified materials formed by the melting process (Figure 2.12). The instability and inconsistency of the transition regime prevents its practical applications for materials processing.

2.6.2 Formation of melting regime

For H13 tool steel the melting regime was formed within the offset range of 0.6–1.1 mm with corresponding fluence range, 0.09–0.07 J/cm². Figure 2.13 presents the surface topography created at the focal offset of 0.6 mm as a demonstration of melted track. Similar to the case of melting regime in processing IN718, the laser processed track on H13 tool steel sample was generated from redistributions of molten material, which
Figure 2.13: Surface topography of the laser melted track created at 0.6 mm focal offset and 0.09 J/cm² of fluence can be realized from the relative decrement and increment in the cross section of initial peak and valley shown in Figure 2.14.

Additionally, surface quality improvement up to 34.4% is observed attributed by the reduction of initial $R_a$ value of 0.61 µm to a final $R_a$ value of 0.4 µm within the laser processing zone, represented by the roughness cross section profile outlined in Figure 2.15.
CHAPTER 2. PICOSECOND PERSPECTIVE OF LASER MICRO-POLISHING

Figure 2.14: Surface cross section along the peak and the valley for the profile created at the focal offset of 0.6 mm and the fluence of 0.09 J/cm²

Figure 2.15: Average roughness cross section profile across the laser processing track created at the focal offset of 0.6 mm
2.7 Discussion

In the present study, melting regimes for IN718 and H13 tool steel were determined for pulse repetition rates of 7.45 MHz and 8.2 MHz, respectively. Both of these two repetition rates imply very high level of pulse frequencies with respect to the existing picosecond laser system. The higher level of pulsing frequencies was selected intuitively to ensure smallest possible beam diameter enabling selective polishing of smaller region. To state it more explicitly, high repetition rate results in the distribution of total laser power among higher number of laser pulses. This phenomenon contributes to the decrement of energy per laser pulse, which will lead to a decrease of laser fluence for a given set of other process parameters. The decrement of laser fluence can be correlated with the decrease of focal offset associated with the melting regime. The lower value of focal offset generates smaller beam diameter compare to higher level of focal offset. For that reason, it renders more flexibility in terms of selective polishing of a small region on a micro-scaled component. Melting regime can be determined for smaller repetition rates as well. However, since it will result in increment of energy per pulse, the focal offset has to be set at higher distance to maintain the laser fluence associated with the melting regime. This in turn will lead to the formation of larger beam diameter on the workpiece surface.

A similar conclusion can be drawn for the selection of laser beam speeds. In the present study, relatively high domain of speed values were selected, which are constrained by the acceleration and the deceleration time of the velocity profile of
corresponding CNC system. However, sometimes a lower level of speed is desirable. For instance, while polishing a feature with very small lateral length, a high laser beam speed may not be reachable because of the aforesaid acceleration and deceleration time of the velocity profile. As a consequence, the desired level of surface finish will not be attainable. On the contrary, smaller value of speed involves longer laser-material interaction time and higher percentage of pulse overlap, which might significantly affect the target surface quality. Therefore, other parameters, namely laser power, repetition rate and focal offset have to be adjusted in accordance with the lower level of laser speed to attain required surface quality.

2.8 Closure

This chapter presented the formation mechanism of melting regime in ps laser-material interaction and its determination for the alloys, namely, IN718 and H13 tool steel. To determine the melting regime, experimental investigations were performed for fixed process parameters, i.e., laser power, pulse repetition rate and speed, but varied focal offset starting from zero at the focal point on the workpiece surface with a gradual incremental step of 0.1 mm. Based on the qualitative analysis, i.e. visual analysis of laser processed track and the quantitative measures, namely surface cross sections and $R_a$ cross section profile across the laser processed track, melting regimes were determined within the focal offset range of 0.8-1.2 mm for IN718 and 0.6-1.10 mm for H13 tool steel. The process parameters associated with this regime are considered for potential ps LμP applications on IN718 and H13 tool steel samples.
Chapter 3

Heat Transfer Mechanism in Melting Regime

3.1 Introduction

One of the preliminary tasks to be accomplished in modeling of any thermal energy-based process, including laser micro-polishing (LµP), is related to the determination of the thermal field. This knowledge can be utilized later as an input to other mechanisms associated with the process - such as the fluid flow model of molten pool - in order to perform an accurate prediction of the changes in surface profile as a result of LµP. In this regard, this chapter discusses the heat transfer mechanism and its evolution within the melting regime of ps laser material interaction. The chapter also details a finite element formulation of the heat transfer equation along with its solution, which provides insight on peripheral melt depth in ps LµP.

3.2 Governing Equations in PS Laser Material-Interaction

Material absorption plays a very significant role in laser-material interaction. This phenomenon is a complex mechanism and alongside the thermo-mechanical
characteristic of workpiece material, it also depends on the temperature of the sample, laser wavelength and the applied laser fluence.

In case of longer pulsed laser, such as the one that operates in nanosecond regime, the thermal energy transport by conduction mechanism in the solid and the liquid phase is governed by the heat diffusion equation based on Fourier’s law of conduction (Mai et al., 2004 and Perry et al., 2008):

$$ \frac{\partial}{\partial z} (k \frac{\partial T}{\partial z}) + Q(z) = \rho c_p \frac{\partial T}{\partial t} $$

(3.1)

Where, $z$ is thermal diffusion direction perpendicular to the workpiece surface, $Q(z)$ is the heat flux (laser power generation per unit area) in the domain D (W/ m$^2$), $k$ is the thermal conductivity in the $z$ directions (W m$^{-1}$ K$^{-1}$), $c_p$ is the specific heat capacity (J kg$^{-1}$ K$^{-1}$), $\rho$ is the density (kg /m$^3$), $t$ is the time (s). The Equation 3.1 is the classic model of heat diffusion based on Fourier’s law of heat conduction. However, it’s applicability to model the lasers that operates in ultra short regime, namely, picosecond (ps) and femtosecond (fs) regimes require additional validation.

Before proceeding further, it is worthwhile to reiterate and detail few aspects related to the laser power absorption mechanism. During short laser pulse interaction with metallic materials, the laser fluence is absorbed by free electrons due to the inverse Bremsstrahlung (Chichkov et al., 1996; also see Figure 2.1). It has been established that the inverse Bremsstrahlung heating associated with laser-material interaction involves in fact two types of interaction namely between electrons and external laser field as well as
between electrons and lattices. The complexity of these interactions practically makes any type of analytical solutions extremely difficult.

The diffusion of the thermal energy delivered by the laser from the surface of the workpiece towards its core involves a variety of mechanisms such as thermalization within the electron subsystem, energy transfer to the lattice, as well as losses of energy as a result of the electron heat transport into the target material (Chichkov et al., 1996). By assuming that a phenomenon of rapid thermalization within the electron subsystem is present and that electron and lattice subsystems have different temperatures \((T_e \text{ and } T_l)\), thermal diffusion \((i.e.\) the underlying heat transfer mechanism) can be described by means of three time-related variables to be detailed further.

According to Anisimov (1968), heat transfer in electron and lattice can be modeled by the following 1D two-temperature diffusion model:

\[
C_e \frac{\partial T_e}{\partial t} = -\frac{\partial Q(z)}{\partial z} - G(T_e - T_l) \tag{3.2a}
\]

\[
C_i \frac{\partial T_i}{\partial t} = G(T_e - T_l) \tag{3.2b}
\]

\[
Q(z) = -k_e \frac{\partial T_e}{\partial z} \tag{3.2c}
\]

where, \(Q(z)\) is the heat flux \((w/m^2)\), \(C_e\) and \(C_i\) are the heat capacities (per unit volume) of the electron and lattice subsystems \((J \text{ kg}^{-1} \text{ K}^{-1})\), \(G\) is the parameter characterizing the electron-lattice coupling factor \((10^{17} \text{ Wm}^3 \text{ K}^{-1})\), \(k_e\) is the electron thermal conductivity
The thermal conductivity in the lattice subsystem (phonon component) is to be neglected (Chichkov et al., 1996).

In perspective of Equation 3.2, the three critical time indices can be defined as:

(i) electron cooling time \( \tau_e = \frac{C_e}{G} \); (ii) lattice heating time \( \tau_i = \frac{C_i}{G} \), and (iii) laser pulse duration \( \tau_L \). Since the electronic heat capacity is much smaller than the lattice heat capacity, electron cooling time is much smaller than lattice heating time \( \tau_e \ll \tau_i \).

With this in mind, three of the most common types of ultrashort or short-pulsed lasers can be characterized as a function of the comparative relationships between the three time related indices above (Chichkov et al., 1996):

(i.) \( \tau_L \ll \tau_e \ll \tau_i \rightarrow \) femtosecond regime

(ii.) \( \tau_e \ll \tau_L \ll \tau_i \rightarrow \) picosecond regime

(iii.) \( \tau_e \ll \tau_i \ll \tau_L \rightarrow \) nanosecond regime

For nanosecond lasers, pulse duration is considered to be longer than lattice heating time allowing thermalization/diffusion of the incident laser energy within the time duration of laser pulse, which in turn leads to a relative equalization of lattice and electron temperatures. As such, the two-temperature model (TTM) in Equation 3.2 reduces to the one-temperature model (OTM) in Equation 3.1.

By contrast, some of the studies in the surveyed literature have hypothesized that in case of ps lasers thermalization occurs within the period defined by the pulse duration in the scale of picosecond (Kuo et al., 1996, Willis et al., 2002, Nagasaki et al., 2004). In a
more recent work, Letfullin et al. (2008) have suggested that for a laser operated at 25 ps pulse duration, an OTM provides a more reasonable prediction of the thermal field compared to a TTM. Along the same lines, the present study is centered on the determination of the aforementioned time indices, in an attempt to establish whether a one- or two-temperature model would be capable to generate more accurate predictions of the thermal field induced by the analyzed ps laser.

It is perhaps important to note that the coupling factor \( G \) – a parameter that depends on the material’s property– in turn defines the aforesaid time scales of \( \tau_i \) and \( \tau_e \). Also it is critical to know the value of heat capacitance parameters, namely \( C_e \) and \( C_l \). As heat diffusion mechanisms by TTM in short pulsed lasers were first proposed in 1964, a plethora of studies have been published on this topic since then. However, it is extremely important to point out that almost all prior studies were focused on the effect of laser on pure metals such as gold, copper and nickel. Further to this, no prior study has explicitly state the values of the aforementioned time-related indices.

To address this gap of knowledge, the present study aims to determine the electron cooling time \( (\tau_e) \) and thermalization time, \( i.e. \) the lattice heating time \( (\tau_i) \) for nickel and iron as principal constituents of IN718 and H13 tool steel, respectively. The related time scale calculations were performed based on the parameters published by Lin et al. (2006, 2007 and 2008) for a room temperature condition (300 K). The electron cooling time \( (\tau_e) \) in metal is related to thermal conductivity \( (k) \) through the following relation (Kittel, 1976 and Willis, 2001):
where \( m_e \) indicates electron mass (kg), \( N_e \) is the number of electrons per unit volume, \( K_B \) represents Boltzman constant and \( T_l \) is the lattice temperature (°C). Equation 3.3 yields the relaxation time for nickel yields at approximately 4.8 fs (see Appendix B). On the other hand, electron-lattice coupling factor \( (G) \) is related to the electron cooling time \( (\tau_e) \) by the following equation (Qiu et al., 1994):

\[
G = \frac{\pi^2 m_e N_i u_i^2}{6\tau_e T_e}
\]

(3.4)

where \( u_i \) is the speed of sound (m/s). The value of \( G \) for metals is obtained from experimental data, and its value ranges from \( 10^{16}–10^{18} \) W/m\(^3\)K (Qiu et al., 1992; Willis, 2001, and Lin et al., 2006, 2007 and 2008). The electron-lattice thermalization time, i.e. the heating time of lattice can be estimated by (Qiu et al., 1993):

\[
\tau_i = \frac{C_i}{G}
\]

(3.5)

Based on Equations 3.3–3.5, the electron relaxation/cooling time and thermalization time for nickel were estimated as \( \tau_e = 4.8 \) fs and \( \tau_i = 202.2 \) fs, whereas for iron these time indices were estimated as \( \tau_e = 3.2 \) fs and \( \tau_i = 453.9 \) fs, respectively (see Appendix B). Since thermalization times for both nickel and iron were found to be much shorter than pulse duration (10.5 ps) of the ps LµP system used by the present
study, it can be assumed that in the context of the current research OTM presented in
Equation 3.1 will provide more accurate representations of the temperature field.

3.3 Numerical Solution of Heat Transfer Equation

Numerical calculations were performed by means of finite element method (FEM)
to estimate the transient heat transfer modeled by Equation 3.1. The approach detailed
further requires solving of the aforesaid energy balance equation with appropriate initial
and boundary conditions. The following work assumptions were made while generating
the heat transfer model: (1) transfer of thermal energy through radiation and convection
from spot area to its vicinity is negligible, (2) workpiece material is opaque to energy
absorption at its surface, (3) net heat input to the material is equivalent to the heat flux
absorbed at the surface when constant absorptivity is assumed, (4) the effect of secondary
chemical processes - such as oxidation - can be neglected, (5) the defocusing effect of the
laser beam caused by height of the surface asperities can be neglected, and (6) material is
deemed isotropic and characterized by invariant thermal properties.

3.3.1 FEM formulation

For a 3D case, Equation 3.1 can be rewritten as:

\[ k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + Q(x, y, z) = \rho_c c_p \frac{\partial T}{\partial t} \]  \hspace{1cm} (3.6)

To represent the heat flux, one end of the domain has a time dependent Neumann
boundary condition equal to the absorbed laser power, as such:
CHAPTER 3. HEAT TRANSFER IN MELTING REGIME

\begin{equation}
Q(x, y, z) = \rho c_p \frac{\partial T}{\partial t}
\end{equation}

(3.7)

Additionally, the initial temperature condition included:

\begin{equation}
T(0, z) = T_0(z)
\end{equation}

(3.8)

where \( T_0(z) \) indicates initial room temperature.

Developed melting regime continues to grow with the absorption of laser energy and the energy balance at the solid-liquid interface – accounting for absorption and release of latent heat \( (L) \) during phase change – is given by:

\begin{equation}
k_i \left( \frac{\partial T}{\partial z} \right)_i - k_s \left( \frac{\partial T}{\partial z} \right)_s = \rho L \frac{ds}{dt}
\end{equation}

(3.9)

where \( \rho \) is the density of the liquid (kg/m\(^3\)), \( k_s \) is the thermal conductivity of the solid phase (W m\(^{-1}\) K\(^{-1}\)), and \( k_i \) is the thermal conductivity of the liquid phase (W m\(^{-1}\) K\(^{-1}\)).

Furthermore, the temperature at the solid-liquid interface must be equal to the temperature of the melt (Perry et al., 2008):

\begin{equation}
T(x = S(t), t) = T_m
\end{equation}

(3.10)

From Equation 3.10, it becomes clear that from the temperature distribution along the thickness, melt depth can be estimated for a particular interaction time.

A triangular distribution of laser intensity has been assumed, with peak intensity reached at half of the pulse width (Figure 3.1). The relation between intensity, \( I_i(t) \) and time \( t \) is given by (Willis, 2001):
$$I_i(t) = 2I_{i,\text{max}} \frac{t}{\tau} \quad 0 < \frac{\tau}{2}$$  \hspace{1cm} (3.11)$$

In Equations 3.11 and 3.12, \(I_{i,\text{max}} \) (J/cm\(^2\)) represents the peak value of laser intensity (Willis, 2001):

$$I_{i,\text{max}} = \frac{2E}{\tau}$$  \hspace{1cm} (3.13)$$

where \(E\) is laser pulse energy (J) delivered on an irradiated area (m\(^2\)) of \(A\).

A commercial finite element package (COMSOL 4.2a) was used to perform the finite element analysis of ps laser-material interaction. Workpiece geometry was constituted by a block of 40 mm \(\times\) 20 mm \(\times\) 1.5 mm, and laser path trajectory was defined as a 3D straight line, expressed in a parametric form as such:
CHAPTER 3. HEAT TRANSFER IN MELTING REGIME

\[ X = x_0 + vt \]  
\[ Y = y_0 \]  
\[ Z = z_0 \]

(3.14a, 3.14b, 3.14c)

Here \((x_0, y_0, z_0)\) and \((vt, 0, 0)\) indicate two ends of a line defining the laser path trajectory and \(v\) is the laser beam travelling speed denoting laser beam as a moving heat source along the laser path trajectory (see Figure 3.2).

![Figure 3.2: Geometric representation of the workpiece and the laser path trajectory](image)

The physical properties of IN718 and AISI H13 materials were extracted from COMSOL’s database. Apart from that, heat capacitance \(c_p\) was assumed to be temperature dependent parameter, which has two different values based on the physical states of the materials, namely solid and liquid states. Heat input was defined by means of an analytical function assuming a Gaussian distribution of laser power:
where $Q_0$ is total heat input (W), $R_c$ represents reflection coefficient, $A_c$ stands for absorption coefficient ($m^{-1}$), and $\sigma_x, \sigma_y$ correspond to standard deviation of Gaussian distribution. The initial assumption made was $R_c = 0$ meaning that none of the incident laser beam was reflected back and the entire amount of incoming heat flux (Equation 3.15) was in fact absorbed by the top surface of the workpiece. The triangular form of the laser pulse (Figure 3.1 and Equations 3.11, 3.12) was incorporated as a multiplier.

Figure 3.3 illustrates the mesh generated for numerical simulation purposes. More accurate predictions of the thermal gradients within the vicinity of laser material interaction were facilitated through the refinement of the mesh size along the laser path trajectory. A variable mesh size was used (gradually becoming coarser outwards) outside of the region of interest.

![Refinement of mesh on laser path trajectory](image)

![Relatively coarse mesh on workpiece](image)

Figure 3.3: Generation of mesh in finite element formulation of ps LµP
Table 3.1 outlines a synopsis of the simulation parameters used to control the numerical iterations. The simulations were carried out for a period of one second depicting a distance equivalent to laser beam speed. Beam sizes used during simulation were similar to measured beam diameters shown in Tables 2.1 and 2.2.

Table 3.1: Simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse width ($\tau_L$)</td>
<td>10.5 ps</td>
</tr>
<tr>
<td>Repetition rate ($f$)</td>
<td>7.45 MHz (IN718) and 8.2 MHz (H13)</td>
</tr>
<tr>
<td>Laser beam speed ($v$)</td>
<td>20 mm/s (IN718) and 10 mm/s (H13 tool steel)</td>
</tr>
<tr>
<td>Period ($t$)</td>
<td>$\frac{1}{f \times 10^6}$ s</td>
</tr>
<tr>
<td>Time step ($\tau$)</td>
<td>$Period \times 100$ s</td>
</tr>
<tr>
<td>End time</td>
<td>1 s</td>
</tr>
</tbody>
</table>

3.3.2 Result and discussion

The first alloy subjected to the numerical analysis was IN718. Figure 3.4 presents the 3D temperature profile of the workpiece top surface and corresponding temporal distribution along the cross section across the laser path trajectory for the profile created at the focal offset of 0.8 mm. The temporal distribution is subjected to a Gaussian distribution of laser intensities, where the peak temperature is estimated to be 1528.3 °C. A comparative analysis in terms of this peak temperature is depicted in Figure 3.5 for all of the 5 profiles associated with the melting regime of IN718. Here the profiles 1–5 represent the polished profile created at the focal offsets of 0.8–1.2 mm, respectively. Obviously increase in focal offsets resulted in the reduction of fluence level, that
Figure 3.4: Surface temperature distribution for the profile created at the focal offset of 0.8 mm on IN718 (a) 3D temperature profile of the workpiece top surface (b) temporal distribution along the cross section across the trajectory of laser path eventually led to the decrement of surface temperature. Nevertheless, the lowest surface peak temperature for the profile created at the focal offset of 1.2 mm (see Profile 5 in
Figure 3.5: Comparison of surface peak temperatures for the profiles created in the melting regime of IN718

Figure 3.5) is likely to be adequate in order to induce a melting regime on IN718 in perspective of its melting point (1344 °C).

Figure 3.6 delineates the distribution of temperature along the workpiece thickness for the profile created at the focal offset 0.8 mm. Melt depth can be estimated to be 0.21 mm i.e. 210 µm according to Equation 3.10.
Figure 3.6: Temperature distribution along the thickness for profile created at the focal offset of 0.8 mm on IN718

Table 3.2 outlines the dependence between melt depth and focal offset. The values shown in the table imply a very high melt depth compare to surface topography peak to valley height, which usually range in microns (Hafiz et al., 2012).

Table 3.2: Estimated melt depth for IN718 based on relative position of melt front

<table>
<thead>
<tr>
<th>Focal offset (mm)</th>
<th>Melt depth (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>210</td>
</tr>
<tr>
<td>0.9</td>
<td>180</td>
</tr>
<tr>
<td>1.0</td>
<td>160</td>
</tr>
<tr>
<td>1.1</td>
<td>120</td>
</tr>
<tr>
<td>1.2</td>
<td>90</td>
</tr>
</tbody>
</table>

A second and analogous numerical investigation was performed on AISI H13 tool steel. In this regard, Figure 3.7 depicts a comparative analysis of surface peak temperature for all the 6 profiles associated with the melting regime for H13 tool steel.
The surface peak temperatures underscored in Figure 3.6 were reasonably higher than that of the melting temperature of 1427 °C for H13 tool steel.

![Figure 3.7: Comparison of surface peak temperatures for the profiles created in the melting regime of AISI H13 tool steel](image)

The dependence between melt depth and focal offset for the profiles created in the melting regime of H13 tool steel is delineated in Table 3.3. Similar to previous case of IN718, the values presented in this table are sufficiently high compare to surface topography heights.

**Table 3.3: Estimated melt depth for H13 steel based on relative position of melt front**

<table>
<thead>
<tr>
<th>Focal offset (mm)</th>
<th>Melt depth (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>287</td>
</tr>
<tr>
<td>0.7</td>
<td>280</td>
</tr>
<tr>
<td>0.8</td>
<td>274</td>
</tr>
<tr>
<td>0.9</td>
<td>250</td>
</tr>
<tr>
<td>1.0</td>
<td>246</td>
</tr>
<tr>
<td>1.1</td>
<td>225</td>
</tr>
</tbody>
</table>
A condition of equilibrium between a crystal and its melting state requires the free energy of each phase to be equal (Willis, 2001). A difference in the free energy in the form of supply or removal of energy will trigger a consequence of phase change. Thus, it is essential for the interface temperature to be higher than the equilibrium melting temperature in order to induce a melting regime. From the surface temperature plots outlined in Figure 3.5 and 3.7, it is evident that the surface peak temperatures were reasonably high to generate corresponding melting regimes. It is to be noted that the boiling point for IN718 and H13 tool steel are 2917 °C and 3200 °C. Therefore, Figure 3.5 and 3.7 also revealed that the surface temperature did not reach to the boiling points for the profiles created at the melting regimes for IN718 and H13 tool steel.

The polishability of any material subjected to LµP is directly related with three major material’s properties, namely thermal diffusivity ($\chi$), density ($\rho$) and dynamic viscosity ($\mu$). All of these properties are strong functions of temperature and therefore directly related to the melt volume resulted from laser-material interaction. To illustrate the significance of melt depth let us assume a hypothetical surface asperity characterized by a height and length of $h$ μm and $L$ μm, respectively as schematized in Figure 3.8. As stated earlier in Chapter 1, reduction of surface asperities resulted from the redistribution of molten materials under the influence of surface tension. Since the effect of gravity is negligible, the primal factor that balances surface tension is the dynamic viscosity.
Figure 3.8: Schematic representation of a surface asperity with the height and spatial length of $h$ and $L$ µm, respectively.

The timescale $\tau_{\text{viscous}}$ for the asperity presented in Figure 3.8 to smooth out completely satisfies (Bohun et al., 2011):

$$\frac{\gamma h}{L^3} = \frac{\mu L}{\tau_{\text{viscous}} h^3}$$  \hspace{1cm} (3.16)

where $\gamma$ and $\mu$ represent surface tension (N/m$^3$) and dynamic viscosity (N-s/m$^2$), respectively. Furthermore, the diffusion time i.e. the time required only to heat up the volume of a single asperity can be calculated as (Bohun et al., 2011):

$$\tau_{\text{diffuse}} = \frac{h^2 \rho c_p}{k}$$  \hspace{1cm} (3.17)

From the calculation of timescales presented in Equation 3.16 and 3.17, it was shown that time require for an asperity to smooth out completely ($\tau_{\text{viscous}}$) is much longer than that of its diffusion time ($\tau_{\text{diffuse}}$) for any particular case of laser polishing (Bohun et al., 2011). Therefore, a much deeper layer beyond the valley depth of surface asperity
(\(R_o\)) is required to be heated up for enabling the mobility of more of the molten materials, so that it takes longer time for heat to diffuse away (Bohun et al., 2011). In this perspective the values of melt depth presented in Table 3.2 and 3.3 imply that focal offsets associated with the melting regime are more likely to enable laser micro-polishing due to their sufficient melt depth.

It is perhaps important to note that in rapid heating phenomenon taking place in ps laser-material interaction, the interface temperature is no longer influenced by heat flow, rather by interface kinetics (Willis, 2001). This is because in rapid heating, a finite amount of time is required to excite the atoms from the solid to the liquid phase change. For metals, melt interface growth can be best described by a mechanism called collision limited growth model (MacDonald et al., 1989 and Willis, 2001). Therefore, prediction of melt depth from the relative position of melt front may not be accurate, which also require further validation. In fact, in perspective of initiation of melting phase the interface temperature is assumed to be slightly deviate from the equilibrium melting temperature considering this difference in free energy would provide driving force for phase change (Willis, 2001).

3.4 Closure

This chapter has provided insight on heat transfer mechanism involved in ps laser-material interactions. The effects of non-balanced heating of electron and lattice were discussed for ultra-short pulsed lasers and the concept of two-temperature model for electron and lattice temperature distribution was presented in the context of the three
important time indices, namely: electron cooling time, lattice heating time and pulse duration. Numerical estimations of their values revealed that the duration of a pulse for the analyzed ps laser is sufficient to allow thermalization. As such, the hyperbolic one-temperature model based on the Fourier model of heat flow was deemed to provide accurate predictions on the thermal gradients induced in the workpiece instead of the two temperature model (TTM) defining separate temperature distributions for electrons and corresponding neighboring lattices.

In the next steps, the aforementioned diffusion equation was solved by means of finite element method (FEM) for a prescribed set of parameters associated with the melting regime of each of the two analyzed materials. This allowed the computation of the melt depth based on the relative position of melt front. The results obtained can be used as a basis for the development of future multiphysics simulation of ps laser-material interactions.
Chapter 4

Analysis of Surface Topography: Methodology

4.1 Introduction

This chapter discusses the methodology of surface topography analysis, before and after being polished by a ps laser. The conventional surface topography measure involving determination of surface roughness and waviness has been discussed initially followed by the formulation of a novel Gaussian filter based quantitative technique for rigorous analysis of the spatial components of surface topography. In addition, surface profile characterizations by statistical tools used in random process analysis have also been exemplified in details.

4.2 Determination of Surface Roughness and Waviness Profiles

In general, the surface profile is comprised of four major spatial components, namely surface form, primary, waviness, and roughness profiles. In order to perform surface topography analysis resulted from an applied process (e.g. LµP), it is important to treat these components separately by considering their importance in functional performance
of the part or the product to be processed. In this regard, the separation of surface primary profile from the form profile can be performed by removing the linear trend from the measured data dispersed in total evaluation length. From the primary profile, using a filter fitted with a predefined cut-off wavelength ($\lambda_c$) the roughness and the waviness can be separated. The Gaussian filter is recommended by ASME B46.1 and ISO 16610-21 standards in order to separate surface waviness and roughness profiles (ASME B46.1, 1995 and ISO 16610, 2011). The weighting function of this filter is given by (Yuan et al., 2000):

$$f(l, \lambda_c) = \frac{1}{\alpha \lambda_c} e^{-\pi \left(\frac{l}{\alpha \lambda_c}\right)^2} \quad (4.1)$$

where, $\alpha = 0.4697$, $l$ is the independent variable in the spatial domain known as the surface profile evaluation length (sampling length), and $\lambda_c$ is the cut-off wavelength of the filter (in the same units as $l$). This weighting function is used as a low-pass filter that blocks the surface profile spatial components with the wavelengths smaller than $\lambda_c$. The waviness profile can be deduced from the convolution between the weighing function in Equation 4.1 and the surface primary profile $h(l)_0^\infty$:

$$m(l_t)\big|_{\lambda_c}^\infty = h(l)_0^\infty * f(l, \lambda_c) \quad (4.2)$$

where, $m(z)\big|_{\lambda_c}^\infty$ is the waviness profile. The roughness profile can be obtained by subtracting the waviness profile from the primary profile as shown in Equation (4.3):
The average line profiling surface waviness ($W_a$) and roughness ($R_a$) values can then be calculated for $n$ measured points on a waviness and roughness profile from the following equations:

$$W_a = \frac{1}{n} \sum_{i=1}^{n} |m(l_i)|_{l_i}^c$$

$$R_a = \frac{1}{n} \sum_{i=1}^{n} |r(l_i)|_{l_i}^c$$

As an example, Figure 4.1 presents the surface primary, waviness and roughness profile for the ground sample of IN718, where $W_a$ and $R_a$ are calculated as 0.16 µm and 0.7 µm, respectively. The standard procedure for the measurement and the calculation of these values involves: (1) measurement of surface profile by the optical profilometer for a predefined sampling length, (2) repetition of the aforesaid measurement in five different places for the same surface profile, and finally (3) taking the average of these 5 measurements for each of the evaluated profiles (ISO 4288, 1996 and Hafiz et al., 2012). The cut-off length between the surface roughness and the waviness is chosen to be 800 µm for an expected $R_a$ range of 0.1−2.0 µm (ISO 4288, 1996).
The calculated conventional indexes of surface topography presented in previous section are influenced significantly by the measurement scale and the cut-off length. Since surface quality improvement in laser polishing can be statistically represented as
the redistribution of initial spatial components, scale dependent parameters like \( R_a \) or \( W_a \) are not sufficient to address the changes in different spatial components of the surface profile resulted from the laser-material interactions. In this regard, polished surface topography and its quality parameters within different wavelength intervals are estimated by the discrete convolution between the primary profile and the weighting function of the low-pass Gaussian filter that defines required wavelength intervals (Wieland et al., 2000). The Gaussian filter for discrete convolution was developed by the algorithm prescribed by Yuan et al., 2000 (see Appendix B).

In order to perform discrete convolution at various spatial wavelength intervals for hypothetical \( \lambda_i \), the extraction of interval roughness profiles are obtained by successive convolution and subtraction operations as depicted below:

\[
h(l)_{\lambda_i}^{r} = f(l, \lambda_i) \ast h(l)_{0}^{r} \quad (4.6a)
\]

\[
h(l)_{0}^{r} = h(l)_{0}^{r} - h(l)_{\lambda_i}^{r} \quad (4.6b)
\]

\[
h(l)_{\lambda_2}^{r} = f(l, \lambda_2) \ast h(l)_{0}^{r} \quad (4.7a)
\]

\[
h(l)_{\lambda_3}^{r} = h(l)_{0}^{r} - h(l)_{\lambda_2}^{r} \quad (4.7b)
\]

\[
h(l)_{\lambda_i}^{r} = f(l, \lambda_i) \ast h(l)_{0}^{r} - h(l)_{\lambda_i-1}^{r} \quad (4.8a)
\]

\[
h(l)_{\lambda_i-1}^{r} = h(l)_{0}^{r} - h(l)_{\lambda_i}^{r} \quad (4.8b)
\]

Finally, the average line profiling surface roughness \((R_a)\) for an interval roughness profile
defined by the wavelength bandwidth $[\lambda_{i-1}, \lambda_i]$ can be calculated as:

$$R_a^{[\lambda_{i-1}, \lambda_i]} = \frac{1}{n} \sum_{i=1}^{n} |h(\ell_i)|^{\lambda_i}_{\lambda_{i-1}}$$ (4.9)

In the present study, the same cut-off wavelength ($\lambda_c$) of 800 $\mu$m was considered for a probable $R_a$ range of 0.1–2.0 $\mu$m in accordance with ISO 4288 standard. The surface waviness profile was defined to be entailed within the interval of 800–1600 $\mu$m, where the maximum value of this interval was determined by doubling the $\lambda_c$ value. This $\lambda_c$ of 800 $\mu$m was also used as the primary wavelength for calculating the average line profiling surface roughness ($R_a$) for the wavelength interval of 6.25–800 $\mu$m. For a more detailed analysis of the polishability of each spatial sub-component of the roughness, the roughness bandwidth was distributed into several wavelength intervals of descending order, where the maximum value of a specific interval was the minimum value of the preceding wavelength interval and the minimum value was deemed as the half of corresponding maximum value of the same interval. Thus, the roughness bandwidth was divided into seven wavelength intervals of 6.25–12.5 $\mu$m, 12.5–25 $\mu$m, 25–50 $\mu$m, 50–100 $\mu$m, 100–200 $\mu$m, 200–400 $\mu$m and 400–800 $\mu$m. The use of ‘2’ as a multiplier/divider is associated with the physical understanding of the intervals with respect to the practical surface profile and machining technology used to generate the initial surface topography. For instance, micromilling technology with a ball end cutting tools is typically used for the micro-fabrication of parts with complex 3D geometry. In this case, a sinusoidal curve can be considered as a fairly close approximation of the real surface profile, which also represents a critical machining parameter, namely, the step-
over distance. Therefore, the analysis regarding the interval possessing the highest level of polishability expressed, for instance by the percentage of the surface quality improvement, would enable selecting the appropriate step-over distance for micromilling.

The aforementioned depiction of roughness profile analysis with regards to the polishability of the wavelength component is outlined in Figure 4.2, where three hypothetical surface profile components before and after polishing with different percentages of surface quality improvement are delineated. In this illustration, all of the three surface profiles have equivalent amplitudes but different wavelengths in a descending manner as such each wavelength is half of its previous wavelength. Therefore, if the initial wavelength is $\lambda_1$, the following other two wavelengths would be $\lambda_2 = \lambda_1/2$, $\lambda_3 = \lambda_2/2 = \lambda_1/4$. If these three profiles presumably exhibit surface quality improvement of 25%, 60% and 55% respectively as a result of LµP, a step-over value of $\lambda_2$ can be recommended as the step-over for initial micromilling in perspective of the highest level of polishability. It is to be noted that machining time for surface preparation with $\lambda_3$ step-over will be twice as long as for machining with a step-over of $\lambda_2$. 
Figure 4.2: Hypothetical example of LµP of three surface profiles with different wavelengths and polishability values demonstrating an approach for selecting appropriate step-over distance.

An illustration of the $R_a$ spectrum, distributed at various spatial wavelength intervals for the ground surface (see Figure 4.1) is presented in Figure 4.3. The $R_a$ spectrum was calculated for the discrete wavelength intervals starting from the interval of 6.25–12.5 µm to the interval of 400–800 µm. The highest interval of 800–1600 µm pertains to the surface waviness profile.
4.4 Statistical Analysis of the Surface Profile

The theory of random process analysis is now well established in the field of surface metrology. A major breakthrough in recent years in the characterization of surface has been the use of some of the mathematical tools used in communication theory for random process analysis (Whitehouse, 1997). The surface roughness profile of any component can be viewed as a nondeterministic phenomenon, which can be best described by a stochastic process. In this regard, this section discusses the application of statistical tools for surface profile analysis by treating the distribution of surface amplitude as a random process.
4.4.1 Power spectral density function

Power spectral density (PSD) function is a useful tool to examine the periodic structure of the spatial components of surface topography in spatial frequency domain. It represents a smoothed Fourier transform of the autocorrelation function, which shows the strongest points of the variations as a function of spatial frequency. In other word, PSD shows the strength of the variations of topography amplitudes as a function of spatial frequency. The energy within a specific frequency range can be obtained by integrating PSD within that frequency range. The PSD is determined directly by First Fourier Transformation (FFT) of the autocorrelation function of surface profile. Mathematically, it can be expressed as:

\[
S_\chi (f) = \int_{-\infty}^{\infty} c(x)e^{-2\pi jfx} \, dx
\]  

(4.10)

where, \( c(x) \) is the autocorrelation function and the \( f \) is the spatial frequency. In perspective of surface topography, autocorrelation function - a measure of randomness of surface profile height distribution - can be defined as a mathematical tool to determine repeating patterns, such as the presence of a periodic spatial component obstructed by low amplitude short wavelength components (high spatial frequency components), or to identify the missing fundamental spatial component (Whitehouse, 1997).

Figure 4.4 presents the PSD plot for the ground profile of IN718 as an example of PSD function. In general, a ground sample comprises a wide spectrum of spatial components. However, here PSD plot revealed the presence of some of the dominating
frequency components presented at the frequency of 1.02 mm\(^{-1}\), 26.5 mm\(^{-1}\) and 50 mm\(^{-1}\) with corresponding amplitude of 13.5 nm\(^2\)×mm, 9.6 nm\(^2\)×mm and 6.1 nm\(^2\)×mm (Figure 4.4). From L\(\mu\)P perspective, these amplitudes are expected to be reduced along with shifts in corresponding phases as a consequence volumetric redistribution of molten material resulted from laser-material interaction.

Figure 4.4: Power spectral density (PSD) function plot for a ground IN718 sample

4.4.2 Transfer function

Since both the initial and the final polished profile are nondeterministic random processes, L\(\mu\)P can be viewed as a dynamic operator transforming an initial surface profile into a polished surface for any given set of process parameters (Hafiz et al., 2012). Therefore, a transfer function (TF) can be deduced using correlation/spectrum analysis in order to correlate these two profiles by considering the former and the later one as the input and output signals respectively. A schematic representation of this transformation is outlined in Figure 4.5.
Based on the aforesaid depiction of LµP process, it can be considered as a mathematical operator, $w(\cdot)$ that transforms initial profile, $z(x)$ into polished profile, $h(x)$ surface topography in 1D case for surface cross sections. In space domain this transformation can be described by classic convolution integral as (Bendat et al., 1993 and Levine et al., 1996):

$$h(x) = \int_{-\infty}^{\infty} w(\eta) z(x - \eta) d\eta$$

(4.11)

where $w(\eta)$ is the weighting function. Fourier transformation of Equation (4.11) produces a direct frequency-domain description of the LµP given as (Bendat et al., 1993 and Levine et al., 1996):

$$S_{hz}(j\omega) = W_{zh}(j\omega) S_{zz}(\omega)$$

(4.12a)

$$S_{hh}(j\omega) = |W_{zh}(j\omega)|^2 S_{zz}(\omega)$$

(4.12b)

where $w_{zh}(j\omega)$ is the transfer function of LµP process; $S_{hz}(j\omega)$, $S_{zz}(\omega)$ and $S_{hh}(\omega)$ are
the cross power spectral density and power spectral density of the initial and the polished surface profile, respectively; $\omega$ is the spatial frequency; and $j = \sqrt{-1}$ is the imaginary unit.

Figure 4.6 presents an example of 1D TF between the initial and the polished profile of AISI H13 tool sample steel processed by a continuous wave (CW) laser (Hafiz et al., 2012). The TF gain plotted in Fig. 4.6 is the measure of the ability of a system to transmit the power and/or amplitude of a signal from the input to the output. Within the scope of the current analysis, a TF positive gain will denote an increment of waviness or roughness component based on its presence in corresponding frequency domain. When comparing two samples, negative gain will indicate an improvement in surface quality. For instance, the TF plot in Figure 4.6 falls of monotonically exhibiting negative gains throughout the whole bandwidth of spatial frequency domain. As such the following case in Figure 4.6 denotes a surface quality improvement resulted from LP of H13 tool steel sample.

Figure 4.6: TF plot between the initial and the polished profile for laser polishing of AISI tool steel sample (Hafiz et al., 2012)
TFs can be used to characterize the resolution-dependent “topographical fingerprint” of a surface treatment process, such as: LµP process, which once known, can be utilized to perform reserve-calculation of the effect of this surface treatment on the initial surfaces with different topographies (Wieland et al., 2000). For example, the effect of micromilling followed by LµP resulting in gradual decrement of surface roughness can be followed in a quantitative way.

4.4.3 Material ratio curve

The change in distribution of amplitudes can be evaluated by means of material ratio (MR) curve, also known as Abbott-Firestone curve or bearing area curve (BAC). It indicates the distribution of materials between the highest and lowest peaks on the surface, implying how much material located above and below a zero-level line. Mathematically it represents the cumulative distribution function (CDF) of the surface profile's heights with some difference with the actual CDF plots in terms of scaling and plot orientation (ISO 487, 1999).

The MR plot is illustrated in Figure 4.6 through a schematic representation. Here, the material ratio (%) refers to the ratio of the material filled length \(L_1 + L_2 + \ldots + L_n\) to the evaluation length (cut-off length), \(l_n\) at the profile section level C and can be expressed as:

\[
mr(\%) = \frac{1}{l_n} (L_1 + L_2 + \ldots + L_n) \times 100 \tag{4.13}
\]
Figure 4.7: Illustration of material ratio (MR) curve

The MR curve is inferred by calculating material ratio at various levels from the maximum peak height \( R_p \) to maximum valley depth \( R_v \) (see Figure 4.7).

Figure 4.8 presents a MR curve for a H13 tool steel sample prepared by grinding process. This plot depicts an epitome of an MR curve in a case of a practical surface. In an ideal case of perfectly flat surface with no surface irregularities, MR curve will be represented by a zero level horizontal line. However, for a practical surface topography, MRF is a curve with three distinctive regions – left side upswing, middle negatively inclined straight line and right downswing (see Figure 4.8).

Figure 4.8: MR curve for the surface topography of a ground H13 tool steel sample
It is expected that material redistribution after LµP affects all the aforementioned MRF components. Generally speaking, amplitudes of upswing and downswing will be decreased and the slope between middle straight line and zero-level line will be reduced in case of surface quality improvement by LµP.

4.5 Closure

In this chapter, the methodology of surface topography analysis in LµP was detailed with examples. The conventional surface topography indices, namely roughness and waviness were discussed with their limitations in addressing evolution of surface topography as a result of laser-material interaction. A novel technique that simultaneously takes into account the wavelength and the amplitude of the surface components was introduced in this context, which also highlights the polishability of individual scale depended spatial components. The adoption of some of the statistical tools for random process analysis, namely power spectral density function, transfer function and MR curve were also illustrated, which are highly relevant in order to carry out rigorous analysis of surface profile resulted from LµP process.
Chapter 5

Picosecond LµP of Ground Surface

5.1 Introduction

After defining the methodologies for surface profile analysis in Chapter 4, the present chapter delineates their implementations in analyzing the results obtained in melting regime of ps laser-material interaction (see Chapter 2). The polishing results are presented in terms of conventional surface topography indices, i.e. $R_a$ and $W_a$ as well as $R_d$ spectrum, distributed at various levels of wavelength intervals. Besides, additional statistical analyses are performed in order to establish functional correlations between the initial and the polished surface profile.

5.2 LµP of Ground IN718 Samples

The melting regime for IN718 was formed within the focal offset range of 0.8–1.2 mm with corresponding fluence range of 0.18–0.13 J/cm². Since, the determination of melting regime involved laser processing of ground IN718 sample, the experimental trials performed in this regime are pertained to ps LµP of this particular sample. As such,
5.2.1 Polishing results and analysis

Polishing results in terms of $R_a$ and $W_a$ are presented in Table 5.1. The surface topography indices presented in this table were calculated across the initial grinding marks (i.e. along the laser polishing track) by considering it to be the worst case scenario in terms of surface roughness attributed by the grinding marks. The similar direction of measurement was maintained for all of the other surface profile measurements afterwards. From the results presented in Table 5.1, one can observe that the ps laser did not alter the surface waviness rather significantly reduced the roughness. For instance, an initial $R_a$ value of 0.69 µm was reduced to 0.44 µm in the case of a profile created with a focal offset of 1.2 mm attributed to a surface quality improvement of 36.20% in terms of roughness reduction.

Table 5.1: Average line profiling surface roughness ($R_a$) and waviness ($W_a$) along the tool path trajectory for the profile created on IN718 sample in the melting regime

<table>
<thead>
<tr>
<th>Focal offset (mm)</th>
<th>Fluence (J/cm$^2$)</th>
<th>Average line profiling surface roughness, $R_a$ (µm)</th>
<th>Average line profiling surface waviness, $W_a$ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Initial profile</td>
<td>Polished profile</td>
</tr>
<tr>
<td>0.80</td>
<td>0.18</td>
<td>0.73</td>
<td>0.65</td>
</tr>
<tr>
<td>0.90</td>
<td>0.17</td>
<td>0.80</td>
<td>0.50</td>
</tr>
<tr>
<td>1.00</td>
<td>0.16</td>
<td>0.80</td>
<td>0.60</td>
</tr>
<tr>
<td>1.10</td>
<td>0.14</td>
<td>0.84</td>
<td>0.55</td>
</tr>
<tr>
<td>1.20</td>
<td>0.13</td>
<td>0.69</td>
<td>0.44</td>
</tr>
</tbody>
</table>
In order to perform more inclusive analysis, the polishing results were recalculated in terms of $R_a$ spectrum at various wavelength intervals and presented in Figure 5.1. The ps LµP was found to be more effective at shorter (less than 100 µm) wavelength intervals as shown in Figure 5.1. However, for spatial components longer than this wavelength, the process was found to be less effective; which is further exacerbated at longer wavelength intervals and become virtually unchanged. The highest level of surface quality improvement is reported within the wavelength interval of 6.25−12.5 µm, where the initial $R_a$ of 0.09 µm was reduced to a final range of $R_a$ values between 0.017−0.025 µm for all of the trials. Among all these trials, profile created at the focal offset of 0.8 mm has the lowest level $R_a$ spectrum at different wavelength intervals. Therefore, in a separate plot in Figure 5.2, the surface quality improvement at various spatial wavelength intervals for this particular profile is outlined as a demonstration of ps LµP performance. Surface quality improvement of 80.83% is reported for the shortest wavelength interval of 6.25-12.5 µm

![Graph showing $R_a$ spectrum at various wavelength intervals for laser polishing trials performed on a ground IN718 sample](image-url)
Figure 5.2: Surface quality improvements associated with the profile polished at 0.8 mm focal offset in case of ground IN718 sample as it can be seen from Figure 5.2. On the contrary, a lower level of surface quality improvement is reported for longer wavelength intervals.

5.2.2 Statistical analysis of polished profiles on ground IN718

LP plays a prominent role on a number of statistical measures associated with surface micro-topography owing to the fact that it induces a redistribution of spatial frequency components (Chow et al., 2010 and Hafiz et al., 2012). Based on this observation, the influence of ps LµP on some standard statistical indices, described in Chapter 4, was analyzed in an attempt to investigate its effect on initial surface topography generated by grinding process.

Figure 5.3 presents the PSD function for the initial and the polished profile created at 0.8 mm focal offset. At spatial frequency domain lower than 20 mm\(^{-1}\), LµP is found to be less effective, whereas significant improvements of surface quality characterized by
drastic reduction of PSD amplitudes can be observed for the spatial components entailed by the spatial frequency bandwidth of 20-75 mm\(^{-1}\). It should be noted that high and low spatial frequency components of surface profile correspond to short and long wavelength components respectively. Consequently, the observation from the PSD plots in Figure 5.3 reiterates the findings from the \(R_a\) spectrum presented Figure 5.1 that the ps L\(\mu\)P is more effective in polishing high spatial components, i.e. short wavelength spatial components of the initial surface profile. In the present context, spatial frequency of 20 mm\(^{-1}\) acts as a critical boundary beyond which a significant improvement is achievable by ps L\(\mu\)P.

![Figure 5.3: PSD function of the initial and the polished profile created at focal offset of 0.8 mm in case of ground IN718 samples](image)

Similar observation can be made from the TF plot presented in Figure 5.4. The reduction of surface asperities is revealed by the negative gains throughout the frequency domain. However, consistent decrement of TF gain is reported up to the spatial frequency of 20 mm\(^{-1}\), which becomes less apparent at higher frequency domain. This observation denotes ps laser to be is more effective in polishing spatial frequency components higher than the spatial frequency of 20 mm\(^{-1}\).
To analyze the amplitude distributions after LμP, MR functions for the initial and the polished profiles are inferred and plotted in Figure 5.5. The summary of the parameters deduced from these plots are depicted in Table 5.1. The slope coefficients, presented in Table 5.1, were calculated from the linear fitting of middle straight line of the MR curves in order to address the state of material distribution as a result of ps LμP. The negative signs of the slope coefficient imply the downward slope of the MR curves.

Figure 5.4: TF plot between the initial and the polished profile created at focal offset of 0.8 mm in case of ground IN718 samples

Figure 5.5: MR curves for the initial and the polished profiles created on ground IN718 sample
Table 5.2: Summary of the parameters generated by the material ratio (MR) functions of the initial and the laser polished profiles for ground IN718 samples

<table>
<thead>
<tr>
<th>Focal offset (mm)</th>
<th>Maximum peak height, $R_p$ (µm)</th>
<th>Maximum valley depth, $R_v$ (µm)</th>
<th>slope coefficient (nm/%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A (initial profile)</td>
<td>1.58</td>
<td>2.28</td>
<td>−20.7</td>
</tr>
<tr>
<td>0.80</td>
<td>1.42</td>
<td>1.11</td>
<td>−12.1</td>
</tr>
<tr>
<td>0.90</td>
<td>1.34</td>
<td>2.27</td>
<td>−12.4</td>
</tr>
<tr>
<td>1.00</td>
<td>1.05</td>
<td>0.94</td>
<td>−16.6</td>
</tr>
<tr>
<td>1.10</td>
<td>0.81</td>
<td>1.07</td>
<td>−20.0</td>
</tr>
<tr>
<td>1.20</td>
<td>0.77</td>
<td>1.01</td>
<td>−18.9</td>
</tr>
</tbody>
</table>

Figure 5.6 exemplifies an instance of linear fitting of middle straight line along with corresponding residual plots for the laser polished track created at 1.1 mm focal offset. The residual plot shown in Figure 5.6b possesses no discernible pattern, and dispersed within a narrow range (0.026 to -0.058 µm) justifying a good fit of the middle straight line. From the MR parameters presented in Table 5.1, it is evident that ps LµP not only reduces the number of sharp high peaks and deep valleys represented by upswing and downswing values, it also makes the surface micro-topography more uniform that is reflected by a reduced absolute value of the slope coefficients. Among all the laser polished tracks, the profile created at the focal offset of 0.8 mm and 0.9 mm demonstrated the lowest value of slope coefficients. The profile created at the focal offset of 1.2 mm demonstrated the highest level of $R_p$ and $R_v$ reduction but on the contrary, the redistribution of surface asperities were less uniform as exhibited by the slope coefficient value.
5.3 LµP of ground AISI H13 tool steel samples

For H13 tool steel sample the melting regime was formed for the focal offset range of 0.6–1.1 mm with corresponding fluence range: 0.09–0.07 J/cm². Details about the polishing results and analysis for ps LµP of ground H13 tool are discussed in the following subsections.
5.3.1 Polishing results and analysis

Table 5.3 presents the polishing results in terms of $R_a$ and $W_a$, calculated across the initial grinding marks, i.e., along the laser polishing track. Similar to polishing of IN718, surface waviness profile remains unaffected after ps LµP as reflected by the $W_a$ values presented in Table 5.3. However, significant improvements in terms of reduction of $R_a$ can be observed; for example, an initial $R_a$ value of 0.52 µm was reduced to 0.28 µm constituting a surface quality improvement of 46.15% for the polished profile created with the focal offset of 1.0 mm.

Table 5.3: Average line profiling surface roughness ($R_a$) and waviness ($W_a$) along the tool path trajectory for the profile created in the melting regime on H13 sample

<table>
<thead>
<tr>
<th>Focal offset (mm)</th>
<th>Fluence (J/cm²)</th>
<th>Average line profiling surface roughness, $R_a$ (µm)</th>
<th>Average line profiling surface waviness, $W_a$ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Initial profile</td>
<td>Polished profile</td>
</tr>
<tr>
<td>0.60</td>
<td>0.09</td>
<td>0.59</td>
<td>0.39</td>
</tr>
<tr>
<td>0.70</td>
<td>0.08</td>
<td>0.61</td>
<td>0.45</td>
</tr>
<tr>
<td>0.80</td>
<td>0.08</td>
<td>0.57</td>
<td>0.35</td>
</tr>
<tr>
<td>0.90</td>
<td>0.08</td>
<td>0.55</td>
<td>0.34</td>
</tr>
<tr>
<td>1.00</td>
<td>0.07</td>
<td>0.52</td>
<td>0.28</td>
</tr>
<tr>
<td>1.10</td>
<td>0.07</td>
<td>0.51</td>
<td>0.36</td>
</tr>
</tbody>
</table>

The $R_a$ spectrums at different wavelength intervals for ground H13 tool steel are outlined in Figure 5.7. The ps LµP was found to be more effective at wavelength intervals shorter than 100 µm as implied by the $R_a$ spectrum in Figure 5.7. However, for spatial components longer than wavelength of 100 µm, $R_a$ value is found to be increased for most of the profiles. Such increases of $R_a$ for longer wavelength components may be
Figure 5.7: $R_a$ spectrum at various wavelength intervals for laser polishing trials performed on a ground H13 sample attributed by the redistribution of high spatial frequency components to the lower frequency domain. Among all the trials, profile created at the focal offset of 1.0 mm appeared to have lowest level of $R_a$ spectrum at different wavelength intervals. In a separate plot in Figure 5.8, surface quality improvement in terms $R_a$ reduction at different wavelength intervals is presented. Highest level of surface quality improvement (74.2%) was reported for the wavelength interval of 12.5–25.0 µm (see Figure 5.8).

Figure 5.8: Surface quality improvements associated with the profile polished at 1.0 mm focal offset in case of ground H13 tool steel sample
In order to validate the aforesaid hypothesis of spatial components redistribution, PSD function for the profile created at 0.6 mm and 1.0 mm are deduced and shown in Figure 5.9. Here, the former and the later profiles demonstrated $R_a$ increase and decrease respectively at longer wavelengths intervals (>100 µm) as shown previously in Figure 5.7. From the plot in Figure 5.9a, drastic reductions of amplitudes in the frequency domain higher than 10 mm$^{-1}$ are observed. However, an increment of amplitudes in case of polished profile is reported below that particular spatial frequency value, which does

![Figure 5.9a](image1)

![Figure 5.9b](image2)

Figure 5.9: PSD function plots of the initial and the polished profiles created at focal offset of (a) 0.6 mm and (b) 1.0 mm in case of ground H13 samples
correspond nothing but the spatial wavelength of 100 µm. In contrast, for the PSD plot in Figure 5.9b slight reductions of amplitudes at low spatial frequency domain (less than 10 mm\(^{-1}\)) is reported with no discrepancies with respect to previous case in Figure 5.9a at higher spatial frequency domain.

To further substantiate the findings from PSD plots in Figure 5.9, the TF between the initial and the polished profiles are determined and presented in Figure 5.10 for those two specific profiles created at the focal offset of, namely 0.6 mm and 1.0 mm. The TF plots shown in the figure are plotted for the frequency bandwidth of 0–10 mm\(^{-1}\) in order to discern the state of the change in gain within this illustrious frequency of 10 mm\(^{-1}\). The presence of TF gains attributed by the positive TF amplitudes in case of the profile created at the focal offset of 0.6 mm can be observed up to the spatial frequency of 5 mm\(^{-1}\), which is reported to be falling off monotonically afterwards. The gain in TF amplitudes can be correlated with the \(R_a\) increment at longer spatial wavelength components (Figure 5.7) and PSD amplitude increment at lower spatial frequency domain shown in Figure 5.9a. On the other hand, negative gains of TF amplitudes denote an improvement of surface quality correlating reduction of \(R_a\) at longer wavelength intervals (Figure 5.7) as well amplitude reduction at low spatial frequency domain (Figure 5.9b) for the second profile created at the focal offset of 1.0 mm (see Figure 5.10).
To analyze the amplitude distribution as a result of laser-material interaction, MR functions for the initial and the polished profiles are determined for ground H13 tool steel samples. Figure 5.11 presents the MR curves, where the summary of the parameters deduced from these curves are tabularized in Table 5.4. The MR parameters shown in Table 5.4 reveals the reduction of $R_p$ and $R_v$ values and the uniform distribution of surface micro-topography validated the reduced absolute values of the slope coefficients. For individual case, the profile created at the focal offset of 1.0 mm demonstrated the lowest value of slope coefficient depicting the best achievable surface quality in terms uniform amplitude distribution.
5.4 Discussion

From the analysis of $Ra$ spectrum at different wavelength intervals it is clear that not all the spatial components are polishable by ps laser. In particular, poor polishability is reported at longer spatial wavelength intervals ($>100 \mu m$) for both IN718 an H13 tool steel. The polishability factor can be correlated directly with the applied laser fluence and
its ability to induce volume of molten material resulting in sufficient surface tension for melted material reallocations. However, increasing the fluence to increase volume of molten material may result in the shift of process regime from melting to ablation. Therefore, it is rather convenient to prepare the initial surface topography with the desired wavelength components. LµP – being a secondary manufacturing method – is essentially preceded by other primary manufacturing processes, which defines the initial topographic features. In this regard, the study of polishability may enable determining process parameters in order to generate initial surface profile favorable to laser micro-polishing applications.

From material’s perspective, the polishability of any material depends on its three major properties, namely thermal diffusivity ($\chi$), density ($\rho$) and dynamic viscosity ($\mu$). These properties are influenced significantly by the applied temperature. Additionally, polishability is also significantly influenced by the spatial contents of the surface topography, namely the length, the amplitude and the distribution of spatial wavelength components. Therefore, melt depths presented in Table 3.2 and 3.4 do not have any direct correlation with the $R_a$ spectrum presented in Figure 5.1 and 5.7.

An interesting observation regarding the raise of $R_a$ value in some of the polishing trials is made for longer spatial wavelength components, i.e., low spatial frequency components. The increment of $R_a$ at low spatial frequency domain can be explained by the redistribution of high spatial frequency components to low spatial frequency domain as it was shown by the PSD plots. Additionally, since LµP is a melting dominated process, the event delineating the reductions of $R_a$ in entire spatial frequency domain can
be explained by the uniform distribution of surface amplitudes as an outcome of laser-material interaction. The phenomenon of uniform amplitude distributions can be realized from slope coefficients of middle straight line of corresponding MR curve. For an instance, let us consider the case of previously stated surface profiles created at the focal offset of 0.6 mm and 1.0 mm for H13 tool steel sample. A noticeable reduction of slope coefficient with respect to the slope coefficient of initial profile is reported for the profile created at 1.0 mm unlike the profile created at the focal offset of 0.6 mm (see Table 5.4). The higher amount of reduction of slope coefficient confirms that surface asperities for this particular profile were more uniformly distributed that resulted in the reduction $R_a$ at all of the spatial wavelength intervals.

The volumetric redistribution of molten material and as such the increment of $R_a$ can be best described by the formation mechanism of polished topography. This mechanism is based on the physical correlations between the volume of melt pool and the movement of the three phase line, defined by solid, liquid and mushy phase (Pirch et al., 2006 and Temmler et al., 2011). This movement determines the resulting surface topography as a consequence of the variation of the melt pool volume. A schematic representation of the formation of surface topography as a recast material is illustrated in Figure 5.12.
Figure 5.12: Schematic of formation of surface topography in the form of recast materials as a result of laser-material interaction (Temmler et al., 2011)

The movement of the aforesaid three phase line is caused by the exertion of shear force by surface tension over the liquid surface due to a temperature difference between the laser beam and the solidifying zone. As the thermal gradients reduce, dynamic viscosity with the presence of surface curvature counteracts this external shear forces and lead to restoration the surface height of the melt pool to the free level (Ramos et al., 2003). However, viscous forces may delay this relaxation process to some extends that the complete relaxation is not fully achieved due to the rapid solidification of melt pool (Mumtaz and Hopkinson, 2012). This phenomenon – combining with the spatial contents of the initial surface topography – gives rise to the ripples in the form of short wavelength components and contributes to the increment of $R_d$ in corresponding spatial wavelength intervals.
CHAPTER 5. PICOSECOND L\(\mu\)P OF GROUND SURFACE

5.5 Closure

This chapter presents the result and analysis for ps L\(\mu\)P of IN718 and H13 tool steel prepared by grinding method. Polishing results in terms of \(R_a\) and \(W_a\) shows that ps L\(\mu\)P did not change the surface waviness but significantly reduced \(R_a\). Rigorous analyses in terms \(R_a\) spectrum distributed at different wavelength interval demonstrated that ps laser is more effective in polishing short wavelength components – usually shorter than 100 \(\mu\)m – than that of the long wavelength components. In some observations of L\(\mu\)P trials, \(R_a\) at long wavelength intervals is found to be increased after being polished by ps laser. The relative increment of \(R_a\) at long wavelength intervals and decrement in short wavelength intervals can be correlated with the distribution high spatial frequency components to the low spatial frequency domain as depicted by PSD plots. The change in surface asperities had also been analyzed by TF plots, where a negative gain of TF amplitude denoted surface quality improvement.

To comprehend the distribution of surface amplitude after L\(\mu\)P, MR curves for the initial and the polished profiles were derived and resulting MR parameters, namely \(R_p\), \(R_v\) and slope coefficients were calculated. From these parameters it was revealed that ps L\(\mu\)P resulted in the reduction of both \(R_p\) and \(R_v\) and distributed surface micro-topographic features more uniformly constituted by the reduction of slope coefficients. The uniform distribution of spatial components resulted in decrement of \(R_a\) in entire spatial wavelength intervals as delineated by the reduction of slope coefficients of corresponding MR curves. Overall, the result obtained from the analysis of laser polished ground
surface incorporated the concept of polishability in practical implication. Since the ground profile comprises a wide spectrum of surface spatial components, the present study will give intuitive ideas on how the initial profiles are to be featured in order to achieve best possible surface quality.
Chapter 6

Picosecond LμP of Micromilled Surface

6.1 Introduction

Chapter 5 described how the spatial components of surface profile designated by a specific set of spatial wavelength intervals are more effectively polishable through ps laser beam irradiation. Under this framework, the present chapter discusses the result and the analysis of experimental investigations on LμP of surface profile encompassing a specific periodicity generated by micromilling process. The step-over distance between two consecutive micromilled tracks for preparing the initial profile was determined based on the experimental results discussed in Chapter 5. Parameter associated with the melting regime for IN718 and H13 tool steel were utilized to perform 1D laser polishing trials. Polishing performance was evaluated by means of $R_a$ spectrum distributed at various wavelength intervals as well as statistical analysis in terms of PSD, TF and MR functions.

6.2 Initial Surface Profile Preparation by Micromilling

It was mentioned earlier in Chapter 5 that ps LμP was more effective for spatial
wavelength components lower than 100 µm. The best possible surface quality improvements were reported at spatial wavelength intervals as low as 6.25–12.5 µm for IN718 (see Figure 5.2) and 12.5–25.0 µm for H13 tool steel (see Figure 5.8). Based on these findings it can be concluded that achieving superior quality of surface finish is highly related with the presence of spatial periodic components between 6.25 µm to 12.5 µm for IN718 and 12.5 µm to 25.0 µm for H13 tool steel within the initial surface profile.

The primary manufacturing process, such as micromilling can be used to generate surface profile with the desired aforementioned periodicities. However, in a realistic situation, generating surface profiles with such low periodicities would be quite time consuming and cost intensive. Consequently, it is imperative to induce a periodicity that is not only easy to generate but also demonstrates reasonably higher level of polishability in terms of surface quality improvement. In this perspective, the initial surface to be later micro-polished by ps laser was prepared by the micromilling process with a 0.6 mm ball end cutter and machining step-over of 50 µm resulting in an average amplitude height (peak-to-valley value) of ~2 µm and areal topography surface roughness ($S_a$) of 0.53 µm for IN718 and 0.56 µm for H13 tool steel. The step-over of 50 µm was chosen as it is a widely accepted parameters used in the industry. Moreover, from the analysis presented in Figure 5.2 and 5.8 in Chapter 5, reasonable reductions of surface roughness can be observed within the spatial wavelength range of 25–100 µm designated by the intervals 25–50 µm and 50–100 µm. For instance, initial $R_a$ of 0.17 µm and 0.18 µm were reduced to the final range of $R_a$ of 0.05–0.08 µm and 0.09–0.13 µm for the interval of 25–50 µm and 50–100 µm, respectively for IN718. A similar observation can be made for H13 tool
steel, where surface quality improvement of 63.1% and 40.8% were reported for the spatial wavelength intervals of 25–50 µm and 50–100 µm, respectively.

Figure 6.1 shows the surface topographies, cross sections and PSD plots of the ground and the micromilled profiles for an evaluation length of 800 µm in case of IN718. The cross sections profiles and PSD plots presented in Figure 6.1c, 6.1d, 6.1e and 6.1f were calculated across the initial grinding marks and the micromilled track, respectively. These figures of cross sections clearly indicates that micromilled profile is more consistent than ground profile in terms of surface topography having a correlation coefficient calculated as 0.98 and surface quality having a line profile surface roughness ($R_a$) of 0.49±0.2 µm. Additionally, PSD plots of the micromilled profile for IN718 (see Figure 6.1f) depicts the presence of the most dominant spatial component at the spatial frequency of 20 mm$^{-1}$, unlike the PSD plot of ground profile, which constitutes more than one prominent components (see Figure 6.1e). Here, the spatial frequency of 20 mm$^{-1}$ denotes nothing but the spatial wavelength of 50 µm. As such it can be concluded that the presence of other surface wavelength components is negligible in micromilled profile and the surface roughness profile in this context is mainly contributed by the spatial component entailing a periodicity of 50 µm. Since the LµP will be performed in a direction perpendicular to the micromilled tracks, this high consistency and regularity of the micromilled surface will ensure a predictable behavior of ps LµP.
Figure 6.1: Ground and micromilled surface profile for IN718: (a) surface topography of ground profile (b) surface topography of micromilled profile (c) cross section of ground profile across the initial grinding marks (d) cross section of micromilled profile across the micromilled tracks (e) PSD function of ground profile and (f) PSD function of micromilled profile
6.3 LµP of Micromilled IN718 Samples

While performing ps LµP experiments, focal offset was varied from 0.8 mm to 1.2 mm with a step of 0.1 mm, whereas all other parameters were kept at their predetermined values known to induce the melting regime for IN718. Therefore, five polishing tracks were created with the focal offset of 0.8 mm, 0.9 mm, 1.0 mm, 1.1 mm and 1.2 mm, and the laser fluences of 0.18 J/cm², 0.17 J/cm², 0.16 J/cm², 0.14 J/cm² and 0.13 J/cm², respectively. Polishing experiments were performed in the direction perpendicular to the initial micromilled tracks (see Figure 6.1b). Both initial (pre-polished micromilled) and final (LµPed) surface profiles were measured using WYKO NT1100 white light interferometer and were subsequently analyzed in a systematic and consistent manner as it was previously performed for ground IN718.

6.3.1 Effect of focal offset

The polishing results on micromilled profile in terms of line profile average roughness ($R_a$) at various spatial wavelength intervals are shown in Figure 6.2. It is relatively apparent from this figure that the ps LµP process is highly effective for components within the spatial wavelength intervals of 25–50 µm and 50–100 µm, which practically entail the initial periodicity of 50 µm. Drops of $R_a$ in these intervals imply that ps LµP could effectively improve the initial surface texture by redistributing the spatial wavelength components correspond to the periodicity of initial profile into a new spatial domain. This effectiveness is also present at shorter (<25 µm) spatial wavelength intervals that is somewhat agrees with previous findings regarding LµP of ground IN718.
Figure 6.2: $R_a$ spectrum at various spatial wavelength intervals for different laser polishing trials performed on a micromilled IN718 sample

From the physical perspective of laser-material interaction these observations indicate that the applied fluence level in the melting regime induced sufficient melt volume to generate an appropriate level of surface tension for the effective redistribution of the molten materials of the initial milled profile. For spatial components longer than 200 $\mu$m, the L$\mu$P process was also found to be effective but to a lesser extent. As a result, it can be concluded that the applied fluence level in this regard was not adequate to cause similar volumetric redistribution of long spatial wavelength components. This phenomenon reinforces once more the importance of the primary manufacturing processes forming the most suitable surface profile for possible ps L$\mu$P applications. Since the polished profile created at the focal offset of 1.1 mm has the lowest $R_a$ value in the interval of 25–50 $\mu$m and 50–100 $\mu$m (see Figure 6.2) beside other spatial wavelength intervals, in a separate plot a comparative analysis of the surface quality improvement for this particular polished profile is outlined (Figure 6.3). Here the comparison is made with
Figure 6.3: Surface quality improvements associated with the profile polished at 1.1 mm focal offset on IN718 respect to the initial micromilled profile for various wavelengths intervals. Surface quality improvement in term of $R_a$ reduction up to 78.5% is reported for the wavelength interval of 50–100 µm (see in Figure 6.3).

6.3.2 Statistical analysis of polished profiles

The spatial wavelength interval based roughness analysis (see Figure 6.2) has demonstrated that the ps laser could effectively reduce the $R_a$ for the entire spectrum of spatial wavelength intervals. To examine the periodic structure of the surface amplitudes in the frequency domain, the power spectral density (PSD) function was calculated and analyzed for the polishing track profile created with a 1.1 mm focal offset as an illustration. Figure 6.4 shows a comparison of the PSD function calculated for the initial (micromilled) and the final (polished) profile created with 1.1 mm focal offset. On the initial profile, the noticeable sharp rise in amplitude corresponds to a spatial frequency of 20 mm$^{-1}$ having an amplitude of 35.89 nm$^2$*mm (also shown in Figure 6.1f).
associated spatial wavelength of 50 μm represents the periodicity of the micromilled surface profile (see Figure 6.2). The drastic reduction of the amplitude down to 2.86 nm²*mm for this periodicity restates the effectiveness of ps LµP in improving the primary surface topography obtained by the micromilling operation. Overall, the PSD amplitudes of the initial profile are reduced in entire domain of spatial frequency denoting improvements as a result of ps LµP for all of the spatial components.

![Graph comparing PSD functions between initial and polished profiles](image)

**Figure 6.4:** Comparison of PSD functions between the initial and the polished profiles produced at 1.1 mm focal offset with a fluence of 0.14 J/cm² for IN718

The improvement of surface quality for the profile created at 1.1 mm is further validated by the TF plot between the initial profile and the polished profile as presented in Figure 6.5. Since both PSD and TF plot essentially entails the same axis of spatial frequency, Figure 6.5 also outlines the PSD of initial micromilled profile to use it as a reference for depicting relative gains of TF amplitudes in spatial frequency domain. The surface quality improvement as a result of LµP is substantiated by the negative gains of TF amplitudes throughout entire spatial frequency domain as shown in Figure 6.5. More
importantly, the most dominating spatial component of the initial micromilled profile at spatial frequency of 20 mm$^{-1}$ is attributed by constant negative gain of $-12.3$ dB. This constant gain emphasized that all of the major spatial contents denoted by the spatial periodicity of 50 µm were equally reduced by LµP indicating the initial surface topography to be favorable for LµP. Furthermore, relatively lower value of negative gains at spatial frequency domain higher than 30 mm$^{-1}$ reiterates the finding that ps LµP is more effective for high frequency spatial components, i.e. the short wavelength surface components.

Figure 6.5: TF plot between the initial and the polished profile created at focal offset of 1.1 mm and PSD plot of the initial profile in case of micromilled IN718 sample

The effects of LµP on the MR curves for initial (pre-polished) and final (polished) profiles are shown in Figure 6.6. In accordance to that, a summary of the parameters obtained from these plots is presented in Table 6.1. It can be noticed that LµP has reduced the number of sharp high peaks and deep valleys represented by upswing (e.g. from 1.4 µm to 0.48 µm in case of polished track created with 1.1 mm focal offset) and
Figure 6.6: MR curves of the initial and the polished profiles for IN718

Table 6.1: Summary of the parameters generated by MR functions for micromilled IN718

<table>
<thead>
<tr>
<th>Focal offset (mm)</th>
<th>Maximum peak height, ( R_p ) (( \mu m ))</th>
<th>Maximum valley depth, ( R_v ) (( \mu m ))</th>
<th>Slope coefficient (nm/%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>1.40</td>
<td>1.00</td>
<td>−20.04</td>
</tr>
<tr>
<td>0.80</td>
<td>0.58</td>
<td>0.70</td>
<td>−7.20</td>
</tr>
<tr>
<td>0.90</td>
<td>0.53</td>
<td>0.56</td>
<td>−6.35</td>
</tr>
<tr>
<td>1.00</td>
<td>0.50</td>
<td>0.51</td>
<td>−5.90</td>
</tr>
<tr>
<td>1.10</td>
<td>0.48</td>
<td>0.38</td>
<td>−5.86</td>
</tr>
<tr>
<td>1.20</td>
<td>0.48</td>
<td>0.85</td>
<td>−7.48</td>
</tr>
</tbody>
</table>

downswing (e.g. from 1.00 \( \mu m \) to 0.38 \( \mu m \) in case of polished track created with 1.1 mm focal offset) values. It also made the surface topography more uniform, an attribute represented by the slope coefficient reduction of the middle zone for all the polished tracks compared to the initial profile (see Table 6.1). Among all the MR plots obtained for various offsets, the polished tracks created with the focal offset of 1.0 mm and 1.1 mm exhibited the most uniform distribution of amplitudes as expressed by the lowest slopes, namely, −5.90 nm/% and −5.86 nm/% of the middle straight line.
6.4 LμP of Micromilled H13 Samples

The ps LμP trials on micromilled H13 tool steel involves the variation of focal offset from 0.6 mm to 1.1 mm with a step of 0.1 mm, while all other parameters were kept at their predetermined values associated with the melting regime for H13 tool steel. As a result, six polishing tracks were created with the focal offset of 0.6mm, 0.7 mm, 0.8 mm, 0.9 mm, 1.0 mm and 1.1 mm. Polishing trials were conducted in the direction perpendicular to the initial micromilled tracks as it was carried out earlier for IN718.

6.4.1 Effect of focal offset

The results of LμP experiments on micromilled H13 tool steel are depicted in Figure 6.2 in terms of $Ra$ spectrum at different spatial wavelength intervals. Similar to micro-polishing of IN718, the ps LμP process is found to be more effective for components within the spatial wavelength intervals of 25–50 $\mu$m and 50–100 $\mu$m. Significant reduction of $R_a$ in these intervals entailing the initial spatial periodicity of 50 $\mu$m imply that ps LμP could effectively improve the initial surface texture. The effectiveness of ps laser is also prevalent at spatial wavelength intervals less than 25 $\mu$m as it was previously revealed in LμP of ground tool steel sample. For longer spatial components (> 100 $\mu$m), the LμP process was also found to be less effective as it was also observed previously in polishing ground sample. Since the polished profile created at the focal offset of 0.6 mm exhibited lowest $R_a$ values at different wavelength intervals,
Figure 6.7: $R_a$ spectrum at various spatial wavelength intervals for different laser polishing trials performed on a micromilled H13 tool steel sample (see Figure 6.7), a comparative analysis of the surface quality improvement for this particular polished profile is outlined in a separate plot in Figure 6.8. Here the comparison is made with respect to the initial micromilled profile for various wavelengths intervals, where surface quality improvement in term of $R_a$ reduction up to 75.7% is reported for the wavelength interval designated by 50–100 µm (see Figure 6.8).

Figure 6.8: Surface quality improvements for the profile polished at 0.6 mm focal offset on micromilled H13 tool steel sample
6.4.2 Statistical analysis of polished profiles

Figure 6.9 presents a comparison of the PSD function calculated for the initial micromilled and final polished profile created with 0.6 mm focal offset. On the initial profile, the noticeable sharp rise in amplitude corresponds to a spatial frequency of 20 mm\(^{-1}\) (corresponds to initial surface periodicity of 50 µm) having an amplitude of 54.78 nm\(^2\)*mm can be noticed, which is reduced down to 2.86 nm\(^2\)*mm for polished profile. In general, the PSD amplitudes of the initial profile are reduced in entire domain of spatial frequency delineating surface quality improvements as a result of ps LµP.

![PSD function comparison](image)

Figure 6.9: Comparison of PSD functions between the initial and the polished profile created at 0.6 mm focal offset with the fluence of 0.09 J/cm\(^2\) on H13 tool steel

The improvement of surface quality for the profile created at 0.6 mm is also evaluated by the TF plot between the initial profile and the polished profile in Figure 6.10. The figure outlines PSD of initial micromilled profile as well as a reference for illustrating relative gains of TF amplitudes as it was done previously for IN718. The
surface quality improvement as a result of LµP is confirmed by the negative gains of TF amplitudes throughout entire spatial frequency domain as shown in Figure 6.10. The spatial component that corresponds to the initial micromilled profile at spatial frequency of 20 mm\(^{-1}\) is characterized by constant negative gain of \(-12.4\) dB (see Figure 6.10).

Figure 6.10: TF plot between the initial and the polished profile created at focal offset of 0.6 mm and PSD plot of the initial profile in case of micromilled tool steel sample

The MR curves for the initial and the polished profiles are presented in Figure 6.11 and the parameters inferred from these plots are summarized in Table 6.2. From these parameters, it is confirmed that LµP has resulted in the reduction of both \(R_v\) and \(R_p\) values and also made the surface micro-topography more uniform as represented by the line slope reduction of the middle zone for all the polished tracks compared to the initial profile with a slope of \(-22.7\) nm/% (see Table 6.2). Among all the MR plots obtained for various offsets, the polished track created with the focal offset of 0.6 mm demonstrated the most uniform distribution of amplitudes as represented by the lowest slope coefficient of \(-6.8\) nm/% of the middle straight line.
CHAPTER 6. PICOSECOND LµP OF MICROMILLED SURFACE

Figure 6.11: MR curves of the initial and the polished micromilled surface profiles for H13 tool steel

Table 6.2: Summary of the parameters generated by MR functions for micromilled H13 tool steel

<table>
<thead>
<tr>
<th>Focal offset (mm)</th>
<th>Maximum peak height, $R_p$ (µm)</th>
<th>Maximum valley depth, $R_v$ (µm)</th>
<th>Slope coefficient (nm/%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.38</td>
<td>0.97</td>
<td>-22.7</td>
</tr>
<tr>
<td>0.6</td>
<td>0.60</td>
<td>0.43</td>
<td>-6.8</td>
</tr>
<tr>
<td>0.7</td>
<td>0.73</td>
<td>0.85</td>
<td>-8.7</td>
</tr>
<tr>
<td>0.8</td>
<td>0.65</td>
<td>0.61</td>
<td>-8.8</td>
</tr>
<tr>
<td>0.9</td>
<td>0.69</td>
<td>0.57</td>
<td>-8.8</td>
</tr>
<tr>
<td>1.0</td>
<td>0.77</td>
<td>0.61</td>
<td>-10.3</td>
</tr>
<tr>
<td>1.1</td>
<td>0.69</td>
<td>0.57</td>
<td>-10.4</td>
</tr>
</tbody>
</table>

6.5 Discussion

From $R_a$ spectrum analysis presented in Figure 6.2 and 6.7, it was confirmed that initial surface topography comprising 50 µm of periodicity demonstrated a superior polishability. Unlike the previous case of ground H13 tool steel, no noticeable rise of $R_a$ was observed at longer spatial wavelength intervals. This observation can also be tied
with the presence of other spatial components in a lesser quantity. The superior
polishability is also substantiated by the uniform distributions of surface asperities as
exhibited by significant reductions of slope coefficients of MR curves. Overall, the
findings from the present study emphasized the significance of the primary
manufacturing process, which must be planned in accordance with the desired level of
surface quality attainable by LµP.

6.6 Closure

The study presented in this chapter demonstrated LµP of micromilled IN718 and
H13 tool steel. Both of the initial micromilled profiles were created with the periodicity
of 50 µm, a parameter that was selected based on the previous experimental
investigations presented in Chapter 5. Analyses performed in terms of $R_a$ spectrum, PSD
and TF delineated that LµP could effectively induce a superior quality surface finish both
for IN718 and H13 tool steel. The initial periodicity of 50 µm exhibited a good
polishability as such a highest level of $R_a$ reductions were reported at the wavelength
intervals of 25-50 µm and 50-100 µm for both IN718 and H13 tool steel sample. For an
instance, surface quality improvements up to 78.5% and 75.7% were reported for IN718
and H13 respectively for the spatial wavelength interval of 50–100 µm. The PSD and TF
plots demonstrated amplitude reductions in entire frequency domain for the profile with
the best possible surface quality. The reduction of $R_p$ and $R_v$ along with the uniform
distribution of surface asperities of initial profile represented by the parameters of MR
function confirmed the superior quality surface profile after being polished by ps laser.
Chapter 7

Investigation of 2D Areal Polishing by PS Laser

7.1 Introduction

The majority of the LµP experiments in this work were one dimensional (1D) line polishing experiments. Nevertheless, considering the practical significance of ps LµP, the process capability should be extended towards polishing of functional two and three dimensional (2D and 3D) micro scale parts and products. Therefore, the next step in this study involved 2D areal polishing by picosecond laser. This chapter will explore 2D areal polishing on IN718 and H13 tool steel. The initial surface topographic profiles for both of the materials were prepared by micromilling process. Experimental trials were performed by varying the step-over distance between two consecutive laser polishing tracks, while keeping the other process parameters constant to the predetermined values from previous study presented in Chapter 6. The conventional zigzag pattern was used to design the tool path trajectory; the step-over distances were determined as such a certain level of overlap between two adjacent tracks is being maintained. Polishing performances were evaluated in terms of areal topography surface roughness ($S_a$) spectrum at different wavelength
CHAPTER 7. INVESTIGATION OF 2D AREAL POLISHING BY PS LASER

intervals. Additional statistical analysis in terms of averaged value of power spectral density (PSD), transfer function (TF) and materials ratio (MR) function are also carried out for the measured areal surface profiles in the direction of LµP.

7.2 Experimental Methodology

Typically, a 2D polished area is generated by successive line polishing tracks with a certain level of overlap between them. In area polishing, the amount of step-over is an important factor since on one hand a large step-over cannot alter significantly the initial area profile and therefore induces higher values of surface roughness. On the other hand, a small step-over causes excessive heating, which in turn deteriorate mechanical properties and surface integrity by causing burning, uneven surface re-solidification and various surface defects, e.g., bulging (Chow et al., 2011 and Hafiz et al., 2012). One important consideration in area polishing is represented by tool path generation. The most common tool trajectory for this operation is represented by the classical zigzag pattern illustrated by Figure 7.1. Apart from the process parameters associated with 1D LµP, one new variable can be identified in Figure 7.1, namely the step-over distance (Δx, mm).

In the present study, area polishing of micromilled IN718 and H13 tool steel are carried out with varied step-over but invariable other process parameters, namely pulse repetition rate, laser beam speed/feed, focal offset and laser power. The initial surfaces of IN718 and H13 tool steel were micromilled with a periodicity of 50 µm. The fixed laser polishing parameters were determined based on the analysis presented in Chapter 6. In particular, focal offset for corresponding material was selected based on the polishing
Figure 7.1: Schematic representation of 2D areal polishing using zigzag trajectory

performance in terms of lowest value of $R_a$ spectrum distributed at various wavelength intervals for 1D line polishing experiments. A summary of the process parameters involved in 2D LµP is presented in Table 7.1. The table also includes corresponding beam diameters, measured on the workpiece surface, which enabled determining the highest level of step-over with the requirement of maintaining reasonable overlap between two adjacent laser polishing tracks.

Table 7.1: Process parameters for 2D LµP of IN718 and H13 tool steel

<table>
<thead>
<tr>
<th>Workpiece material</th>
<th>Fixed LµP parameters</th>
<th>Beam diameter (µm)</th>
<th>Step-over distance (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN718</td>
<td>$f = 7.455$ MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$v_f = 20.0$ mm/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$h = 1.1$ mm</td>
<td>43.09</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$P = 11.0$ W</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>20.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30.0</td>
<td></td>
</tr>
<tr>
<td>AISI H13 tool steel</td>
<td>$f = 8.2$ MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$v_f = 10.0$ mm/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$h = 0.6$ mm</td>
<td>44.54</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$P = 11.0$ W</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>20.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>40.0</td>
<td></td>
</tr>
</tbody>
</table>
The experimental methodology consisted of four basic steps: (a) measurement of the initial surface topography on samples to be polished; (b) performing LµP experiments on the sample surface; (c) measurement of the polished surface topography; and finally (d) calculation of the surface topography parameters according to ISO standards, and their comparison and analysis for initial and polished surfaces. Laser polishing experiments were performed on 15.0 cm × 10.0 cm × 1.0 cm slabs of IN718 and H13 tool steel, where areas of 5 mm × 2 mm were polished with the specified step-over. The sample surface topographies before and after polishing were measured using a WYKO NT1100 white light interferometer having a 1Å height measurement resolution as an array.

In analysis of 2D areal surface topography, surface indices, such as average areal topography surface roughness (\(S_a\)) is used. It can be determined— for a predefined cut-off length and width of \(\lambda_l\) and \(\lambda_w\), respectively— from an array of surface profile data set, \(Z(x, y)\) as:

\[
S_a(\lambda_l, \lambda_w) = \frac{1}{A} \int_0^{\lambda_l} \int_0^{\lambda_w} Z(x, y) dx dy
\]  

(7.1)

where, \(A\) is the measured surface area formed by X and Y dimensions. In specific case of abovementioned cut-off length and width, ‘\(A\)’ can be expressed as:

\[
A = l_c l_w
\]  

(7.2)

where, \(l_c\) and \(l_w\) are the sampling length and width for surface profile measurement.
The calculation of parameters of initial and polished surface topographies is the most critical step in the analysis of experimental results. In this regard, three sub-areas having dimensions of 4 mm × 0.8 mm were extracted from each sample area as illustrated schematically in Figure 7.2. Further, each sub-area was divided into five 0.8 mm × 0.8 mm squared patches. Surface parameter, namely areal topography surface parameter was calculated for each patch. As a result, each surface topography parameter was calculated fifteen times and it was estimated by its mean value and standard deviation using uncertainty analysis. The lengths and the widths of sub-areas and patches were selected based on recommendation from ISO 4288 standard, which suggests a cut-off length of 0.8 mm for the expected average surface roughness between 0.1 µm and 2.0 µm.

7.3 Result and Analysis of Polishing IN718 Sample

It was stated earlier in case of 1D LµP – the evaluation of surface profile in terms of amplitude roughness parameter, such as average line profiling surface roughness (Ra)
often cannot provide adequate information about the actual surface topography. For an instance, the performance of two surfaces in terms of functionally may defer, despite the fact that they possess a same roughness value. Similar phenomenon is applicable for 2D areal polishing, where the surface index, e.g., average areal topography surface roughness ($S_a$) is used as a conventional topographic measure. Nevertheless, in context to surface topographic analysis $S_a$ depicts only an integrated estimation of evolution of surface topography during the LµP process. Such a parameter may be important for overall understanding of the LµP results. However, the surface topography as an array of three-dimensional data $z(x,y)$ also has specific amplitude (amplitude distribution along Z axis) and spatial (amplitude distributions along X and Y axes) statistical distributions and characteristics and can be treated as a random 2D process. For an example, Figure 7.3 shows visual interpretation how the initial surface topography is transformed into surface topography polished with a step-over of 20 µm. Two major changes in the surface topography can be noticed. First of all, LµP changes main orientation of the surface topography. Initially, surface topography is formed by micromilled tracks along Y-axis having a periodical structure along X-axis. The LµP was applied along X-axis, perpendicular to the micromilled tracks. Therefore, polished surface topography has obtained new main orientation of surface topology forming a periodical structure along Y-axis. This phenomenon causes change in the spatial distribution of periodic components forming the resultant surface topology. In addition, the LµP significantly changes the range of topography amplitude distribution from $[-1.31 \, \mu m \ldots 1.98 \, \mu m]$ for the initial surface to $[-0.731 \, \mu m \ldots 0.783 \, \mu m]$ for the polished surface. This signifies a
dramatic reduction of the amplitude range by 54% (from 3.29 µm to 1.514 µm).

![2D surface profile of (a) initial and (b) polished block in case of sample created with a step-over of 20 µm](image)

**Figure 7.3:** 2D surface profile of (a) initial and (b) polished block in case of sample created with a step-over of 20 µm

### 7.3.1 Effect of polishing track step-over on surface topography

Obviously, not all amplitude and frequency components of the surface topography
will be equally modified by LµP process. Therefore, in order to discern polishing performance of the profiles created with varied step-over distances, $S_a$ spectrum at different wavelength intervals are required to be determined. The $S_a$ spectrum at different wavelength intervals for polishing micromilled IN718 with varied step-over distance is presented in Figure 7.4. Drastic reductions of $S_a$ in the spatial wavelength range of 25–100 µm defined by the wavelength intervals, namely, 25–50 µm and 50–100 µm are reported. However, above the spatial wavelength of 100 µm, $S_a$ values are found to be increased for the profiles created with 2.5 µm and 5.0 µm. For other three profiles, $S_a$ reductions can be observed at longer spatial wavelength intervals (>100 µm) but to very lesser extents as compared to the shorter ones.

![Figure 7.4: Average areal topography surface roughness ($S_a$) spectrum at various spatial wavelength intervals for the initial and the polished area created with varied step-over on a micromilled IN718 sample](image)

The increase of $S_a$ at longer spatial wavelength intervals perhaps attributed by the volumetric redistribution of molten material, which can be realized from the average PSD
plots of the polished area. Figure 7.5 presents a comparative analysis of the average PSD plots for the initial micromilled area and the polished areas with a step-over of 2.5 µm and 20 µm. The average PSD plot for each of the sample was determined by averaging seven 1D PSD plots in the direction of LμP i.e. across the initial micromilled track. Similar procedure will be followed in determining other average statistical measures, namely TF plot and MR functions (will be discussed later). As it can be observed from Figure 7.5, in case of surface profile created with a step-over of 2.5 µm, an increase of PSD amplitude (3.9 nm²*mm) is reported at low spatial frequency domain, which is resulted from the redistribution higher frequency spatial components (mainly presented at the spatial frequency of 20 mm⁻¹). This redistribution phenomenon can be correlated with the presence of high volume of melt pool adjacent to already processed track as explained above. On the contrary, drastic reduction of surface amplitudes for the profile created with a step-over of 20.0 µm can be observed (from initial amplitude of 23.5 nm²*mm to

![Figure 7.5: Comparison of average PSD plots for the initial and the polished area created with a step-over of 2.5 µm and 20 µm on the micromilled IN718 sample](image)
a final value of 1.1 nm²*mm), where it is envisaged that it might be attributed by the uniform distribution of the initial surface asperity at spatial frequency of 20 mm⁻¹.

To perform further analysis, the average TF between the initial and the polished profiles are determined for these aforesaid polished profiles (see Figure 7.6). The TF plots shown in Figure 7.6 are plotted for the frequency bandwidth of 0–25 mm⁻¹ to illustrate the change in gain within this prescribed frequency bandwidth. The presence of TF gains of 1.2 dB for the profile created with a step-over of 2.5 µm can be observed at the spatial frequency of 7.5 mm⁻¹, which is reported to be falling off monotonically afterwards. The gain in TF amplitudes can be correlated with the Ra increment at longer spatial wavelength intervals above 100 µm (see Figure 7.4) as well as raise in PSD amplitudes at lower spatial frequency domain (see Figure 7.5). On the other hand, negative gains of TF amplitudes signify an improvement of surface quality relating the reduction of Ra at entire wavelength ranges defined by discrete intervals (Figure 7.4)

Figure 7.6: Comparison of average TF amplitude plots for the polished area created with a step-over of 2.5 µm and 20 µm on the micromilled IN718 sample
as well as amplitude reduction at low frequency domain (Figure 7.5) for the second profile created with a step-over of 20.0 µm.

To analyze the amplitude distribution as a result of laser-material interaction, average MR functions for the initial and the polished profiles are determined. Figure 7.7 shows the MR curves; the summary of the parameters deduced from these curves are presented in Table 7.2. The MR parameters shown in Table 7.2 depict the reduction of $R_p$ and $R_v$ values and the uniform distribution of surface micro-topography validated the reduced absolute values of the slope coefficients. For individual case, the profile created with a step-over of 20 µm demonstrated the lowest value of slope coefficient depicting the best achievable surface quality in terms uniform amplitude distribution. Point to be noted that slightly higher values of slope coefficients for the profiles created with a step-over of 2.5 µm and 5 µm can be correlated with the increment of surface asperities at longer spatial wavelength intervals (see Figure 7.4).

Figure 7.7: Average MR function plots for the initial and the polished areal profile on IN718 sample
Table 7.2: Summary of the average MR function parameters for IN718

<table>
<thead>
<tr>
<th>Step-over (µm)</th>
<th>Maximum peak height, $R_p$ (µm)</th>
<th>Maximum valley depth, $R_v$ (µm)</th>
<th>Slope coefficient (nm/%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial profile</td>
<td>0.883</td>
<td>0.755</td>
<td>-16.17</td>
</tr>
<tr>
<td>2.5</td>
<td>0.410</td>
<td>0.301</td>
<td>-6.14</td>
</tr>
<tr>
<td>5.0</td>
<td>0.251</td>
<td>0.253</td>
<td>-5.23</td>
</tr>
<tr>
<td>10.0</td>
<td>0.267</td>
<td>0.339</td>
<td>-4.25</td>
</tr>
<tr>
<td>20.0</td>
<td>0.245</td>
<td>0.237</td>
<td>-4.02</td>
</tr>
<tr>
<td>30.0</td>
<td>0.292</td>
<td>0.339</td>
<td>-4.64</td>
</tr>
</tbody>
</table>

7.3.2 PS LµP example: micro-polishing of IN718

Overall, profile created with a step-over of 20 µm demonstrated the highest level of surface quality improvement depicted by the reduced value of $S_a$ spectrum at different spatial wavelength intervals (see Figure 7.4). Moreover, the surface asperities are also uniformly distributed at it was revealed from MR parameters (see Table 7.2) for this particular profile. Therefore, a 4.5 mm × 4.5 mm area was micro-polished using the associated parameters of this profile to demonstrate the process capability of ps laser in micro-polishing IN718. Figure 7.8 presents the photograph of this area along with corresponding surface quality improvements at different wavelength intervals. Surface quality improvements as high as 67.57% and 69.32% for the spatial wavelength intervals of 25–50 µm and 50–100 µm are reported as depicted by Figure 7.8b.
Figure 7.8: (a) Photograph of polished surface profile as a demonstration of the applicability of ps laser for micro-polishing of IN718 (b) corresponding surface quality improvements associated with the 2D areal polished profile
7.4 Result and Analysis of Polishing H13 Tool Steel Sample

In order to avoid bulging formation at higher overlap between two adjacent tracks, LµP of H13 tool steel involves step-over starting from 5 µm. The other step-over values were 10 µm, 20 µm, 30 µm and 40 µm. In the following subsections the details about the result and analysis of area polishing of H13 tool are discussed.

7.4.1 Effect of polishing track step-over on surface topography

Figure 7.9 outlines the $S_a$ spectrum at different wavelength intervals for 2D LµP of micromilled H13 tool steel. The $S_a$ spectrum presented in Figure 7.9 delineates a dramatic reductions of $S_a$ in the spatial wavelength range of 25–100 µm (defined by the wavelength intervals, 25–50 µm and 50–100 µm) for all the 5 profiles. Conversely, above the spatial wavelength of 100 µm, ps LµP is found to be less effective. Nevertheless, unlike the previous case of IN718, no noticeable increase of $S_a$ is reported at longer spatial interval levels for the profile created with a step-over of 5 µm. It is worthwhile to mention that the depicted phenomenon of roughness increase fully depends on the thermo-mechanical characteristics of a particular material for given set of laser process parameters and initial surface condition. In other word, the given experimental conditions and parameters did not induce a melting volume, which would lead to the formation of apparent surface ripples characterized by long spatial wavelength. In fact, the induced melting volume was not sufficient enough to cause a volumetric redistribution of longer spatial components, as such ps LµP is found to be less effective for the components having periodicities longer than 100 µm.
Figure 7.9: $S_a$ spectrum at various spatial wavelength intervals for different laser polishing trials performed on a micromilled H13 tool steel sample

Among all the trials presented in Figure 7.9, profile polished with a step-over of 10 $\mu$m exhibited lowest values of $S_a$ at different wavelength intervals. To examine the change in periodic structure of the initial micromilled profile, the average PSD functions of the initial and the laser polished profile created with a step-over of 10 $\mu$m were calculated and analyzed in the spatial frequency domain (see Figure 7.10). The drastic reduction of the initial amplitude of 34.3 nm$^2$*mm down to 0.67 nm$^2$*mm for this periodicity states the effectiveness of ps LµP in improving the primary surface topography obtained by the micromilling operation. In general, the PSD amplitudes of the initial profile are reduced in entire domain of spatial frequency delineating an improvement as a result of ps LµP for all of the spatial components.
Figure 7.10: Average PSD plot for the initial micromilled 2D profile and 2D profile created with a step-over of 10 µm on H13 tool steel sample.

The improvement of surface quality for the profile created with a step-over of 10.0 µm, it is also evaluated by the average TF plot between the initial profile and the polished profile in Figure 7.11. The Figure also includes the average PSD of the initial profile in order to use it as a reference. As depicted earlier in Figure 6.10, the surface quality improvement as a result of LµP is confirmed by the negative gains of TF amplitudes in entire spatial frequency domain. The spatial component of the initial micromilled profile at spatial frequency of 20 mm⁻¹ is characterized by constant negative gain of −17.22 dB (see Figure 7.11).
Figure 7.1: Magnitude of the average TF between initial micromilled and laser polished areas on H13 tool steel sample

The average MR curves for the initial and the polished profiles are presented in Figure 7.12 and the parameters deduced from these functions are summarized in Table 7.3. From these parameters, it is confirmed that LµP has resulted in the reduction of both $R_v$ and $R_p$ values as well as resulted in more uniform surface micro-topography as denoted by the reduced absolute value of the slope coefficient of the middle zone for all the polished profiles compared to the initial profile with a slope coefficient of $–19.91 \text{ nm/%}$. Among all the MR plots, the polished track created with a step-over of 10.0 µm exhibited the most uniform distribution of amplitudes as represented by the lowest slope coefficient of $–3.09 \text{ nm/%}$ of the middle straight line. Therefore, based on the $S_a$ spectrum and MR function analysis, the profile created with a step-over of 10 µm is found to attain the most superior quality of surface profile.
Figure 7.12: Average MR functions for the initial and the polished 2D surface profiles for H13 tool steel

Table 7.3: Summary of the average MR function parameters for H13 tool steel

<table>
<thead>
<tr>
<th>Step-over (µm)</th>
<th>Maximum peak height, $R_p$ (µm)</th>
<th>Maximum valley depth, $R_v$ (µm)</th>
<th>Slope coefficient (nm/%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial profile</td>
<td>1.22</td>
<td>0.95</td>
<td>-19.91</td>
</tr>
<tr>
<td>5.0</td>
<td>0.24</td>
<td>0.21</td>
<td>-3.08</td>
</tr>
<tr>
<td>10.0</td>
<td>0.26</td>
<td>0.25</td>
<td>-3.09</td>
</tr>
<tr>
<td>20.0</td>
<td>0.41</td>
<td>0.39</td>
<td>-7.06</td>
</tr>
<tr>
<td>30.0</td>
<td>0.50</td>
<td>0.50</td>
<td>-9.29</td>
</tr>
<tr>
<td>40.0</td>
<td>0.54</td>
<td>0.48</td>
<td>-10.25</td>
</tr>
</tbody>
</table>

7.4.2 Example of ps LµPed surface: LµP of H13 tool steel

As a demonstration of the applicability of ps laser for micro-polishing of H13 tool steel, a flat area of 4.5 mm × 4.5 mm, initially micromilled with a step-over of 50 µm was micro-polished using the following process parameters: laser travel speed of 10 mm/s, focal offset of 0.6 mm, repetition rate of 8.2 MHz, laser power of 11 W and step-over of 10 µm. Figure 7.13 presents the surface topography and the micrograph for the resulted
profile. Corresponding surface quality improvement at different wavelength intervals is outlined in Figure 7.14, which depicts surface quality improvement of 72.74% and 77.28% for the interval, 25–50 µm and 50–100 µm, respectively.

Figure 7.13: 2D areal LµP of micro milled H13 tool steel surface by ps laser (a) surface topography (b) surface micrograph
Figure 7.14: Surface quality improvements associated with the 2D areal polished with a step-over of 10 µm on micromilled H13 tool steel sample

7.5 Discussion

The increase of $S_a$ at longer spatial wavelength intervals for IN718 might be attributed by the ripples generated through the volumetric redistribution of molten materials as it was observed earlier in case of ground samples of H13 tool steel (see section 5.4 of Chapter 5). However, in present study it was attributed by repetitive redistribution of molten materials over a segment, which is already been polished.

While polishing a 2D areal profile – maintaining a certain overlap between two adjacent tracks causes partial reprocessing of previously polished segments. For an instance, the present study of polishing IN718 with a step-over 2.5 µm – utilizing a beam spot of 43.09 µm on workpiece surface – will result in 94.2% of overlap between two consecutive laser polishing tracks. Thus, the polished segment designated by the laser processed track is exposed to further partial remelting phenomenon. Since, the direction
of the solidification follows the melt pool surface (see Figure 5.12) – the melt pool surface is bulged outwards due to the change in density from solid to liquid and thermal dilatation as a result of the presence of the melt pool. The solidification now follows the bulged surface, which results in the increment of surface topography heights. Since the part of the laser processed track is already attributed by uniformly distributed surface amplitudes with very low value of roughness, the solidified materials persist as longer the spatial wavelength components and attribute towards the increase of roughness at longer spatial wavelength intervals (see profiles with 2.5 µm and 5 µm step-over in Figure 7.5).

In general, a very small step-over constituting a high value of overlap between two adjacent tracks may deteriorate the initial surface topography by giving rise of the $S_a$ in the form of surface ripples (for example, profile created with step-overs of 2.5 µm and 5 µm in case of IN718). On the contrary, a very high step-over value does not render the best attainable surface profiles (see Figure 7.4 and 7.10). Therefore, selection of an appropriate step-over is critical. In general, for the given set of experimental results, H13 tool steel seemed to demonstrate better level of polishability as depicted by the $S_a$ spectrum analysis.

7.6 Closure

The study presented in this chapter constituted the experimental investigation on 2D areal polishing of micromilled IN718 and H13 tool steel. Both of the initial micromilled profiles were created with the periodicity of 50 µm, a parameter that was selected based on the previous experimental investigations discussed in Chapter 6.
Experimental trials were performed for varied step-over distance and unvaried other process parameters. Analyses performed in terms of $S_a$ spectrum, PSD, TF and MR function delineated that LμP could effectively induce a superior quality surface finish both for IN718 and H13 tool steel. Nevertheless, at spatial wavelength intervals, longer than 100 μm, ps laser was found to demonstrate poor polishability designated by the increase of $S_a$ for IN718 for smallest step-over distances of 2.5 μm and 5.0 μm. These increments were assumed to be attributed by surface ripples formed as a consequence of high volume of melting pool that is distributed over the segment that has already been processed by laser. In case of H13, such increase of $S_a$ was not reported but no noticeable improvement were observed at longer spatial wavelength intervals.

The statistical analysis in terms of average PSD and TF functions demonstrated amplitude reductions in entire frequency domain for the profile with the best possible surface quality (profile created with a step-over of 20 μm for IN718 and 10 μm for H13 tool steel). The reduction of $R_p$ and $R_v$, plus the uniform distribution of surface asperities of initial profile represented by the parameters of MR function confirmed the superior quality surface profile resulted from ps LμP.

In order to demonstrate the process capability of ps LμP, two areal profiles on micromilled IN718 and H13 tool steel were polished using the parameters that resulted in best possible surface qualities. As these profiles exhibited, with respect to surface quality improvement, 69.32% reduction of initial $S_a$ was reported for IN718 for the interval of 50–100 μm. In case of H13, the improvement was reported to be 77.28% for the same spatial wavelength interval of 50–100 μm.
Chapter 8

Conclusions and Recommendations

8.1 Introduction

The work presented in this thesis is the pioneer work in adopting the process capability of a picosecond laser for potential micro-polishing applications. In this regard, it has outlined many fundamental aspects of ps laser micro-polishing (LµP) through extensive experimental investigations and initial theoretical analysis. This chapter presents a summary on the overall aspect of this work as well as some of the scopes for future development of this particular enabling technology.

8.2. Conclusions of the Present Work

Apart from the present chapter on the summary of the thesis, the whole thesis was divided into seven chapters. Chapter 1 presented state-of-the-art of laser polishing technology, which gave an intuitive idea about the potentiality of laser polishing (LP) process. It also highlighted the motivations and the objectives of this study of implementing ps laser for LµP. The major findings from Chapter 1 were:
• The conventional polishing technologies are time consuming and cost intensive. These are also limited by the size and the shape of the parts to be processed due to the difficulties associated with limited accessibility. In particular for micro-scales parts, these techniques are very ineffective.

• LP process can be placed as a plausible alternative to conventional polishing technologies. In particular for micro-polishing applications, it is regarded as one of the very enabling technologies available now a days.

• LP has been studied since last decade, particularly for the applications of continuous wave (cw) and pulse laser (typically in the range of nanoseconds). Particularly, LµP is performed employing a pulse width between 20 ns and 1000 ns and a processing rate as high as 3.3 s/cm$^2$.

• Picosecond laser can be used for micro-polishing application by tuning its fluence in order to induce a melting phase – a mandatory phase for LµP applications. The relative advantages of ps laser over ns laser includes more precise control of peripheral melting along with less heat affected zone (HAZ).

Chapter 2 presented the formation mechanism and methodology of determining melting regime. The chapter also detailed the experimental setup and the practical significance of workpiece materials to be processed, which included Inconel 718 (IN718) and AISI H13 tool steel. In perspective of melting regime, the chapter depicted the formation of different process regimes, namely ablation, transition and melting regime as a function of laser fluence at different level of focal offset. Qualitative measure, i.e.,
visual analysis and qualitative measures, including determination surface cross section heights, average roughness profiles etc. were utilized to differentiate a process regime associated with a specific focal offset and laser fluence. The important aspects of the study depicted in this chapter were:

- For IN718, an ablation regime was formed within a fluence range between 0.19 J/cm\(^2\) and 0.24 J/cm\(^2\) which corresponds to a focal offset between 0.6 mm and 0.0 mm (in focus). A narrow transition regime existed around 0.7 mm focal offset distance. This regime is characterized by inconsistent formation of groves and slots from ablation. Because of this instability, this regime is required to be avoided when performing any type of material processing operations. A melting regime was formed when fluence values ranged between 0.13 J/cm\(^2\) and 0.18 J/cm\(^2\) corresponding to a focal offset of 1.2–0.8 mm. The regime was resulted in the decrease and increase of surface profile cross section profile along the initial peak and valleys tracks, respectively; as such, the molten material from the peak was driven towards the valley by the surface tension. Significant reductions of average surface roughness (\(R_a\)) along the surface cross section could be observed in this process regime (e.g. an initial \(R_a\) of 0.5 \(\mu\)m was reduced to 0.24 \(\mu\)m for the profile created at 1.0 mm focal offset).

- In case of H13 tool steel, ablation regime was formed for a fluence range of 0.1–0.24 J/cm\(^2\) associated with a focal offset range: 0.4–0.0 mm. A narrow transition regime was found around 0.5 mm focal offset distance. On the
contrary, melting regime was formed for fluence values ranged between 0.075 J/cm$^2$ and 0.09 J/cm$^2$ corresponding to a focal offset of 1.1–0.6 mm. The regime was characterized by significant reductions of average surface roughness ($R_a$) along the surface cross section. For instance, initial $R_a$ of 0.61 µm was reduced to final value of 0.4 µm.

Chapter 3 developed a theoretical foundation in studying ps laser for micro-polishing applications, which depicted the heat transfer mechanism in ps laser-material interaction. The effects of non-equilibrium heating of electron and lattice were detailed for ultra short pulsed lasers. The concept of two-temperature model for electron and lattice temperature distribution was introduced in this regard. The time scales, namely electron cooling time, lattice heating time and pulse duration, were also illustrated. From the estimation of these time scales, it was shown that thermalization between electron and lattice had occurred within the time duration denoted by the pulse duration of ps LµP system. Therefore, hyperbolic two temperature model was not required to address the heat transfer in ps laser-material interaction. The one-temperature diffusion equation based on the Fourier model of heat flow was deemed sufficient for modeling the heat transfer mechanism.

The diffusion equation was solved for a prescribed set of parameters associated with the melting regime by finite element method (FEM). From the temperature field deduced by FEM, melt depth was estimated based on the relative position of melt front. From the findings of surface temperatures and melt depths, it was concluded that process parameters associated with melting regime would likely to enable ps LµP of IN718 and
AISI H13 tool steel samples. Overall, the study would be the basis for further development in context to multi-physics simulation of ps laser-material interaction.

The methodology of analyzing surface profile for ps LμP of IN718 and H13 tool steel are detailed in Chapter 4. The chapter introduced the concept of polishability and delineated a novel Gaussian filter based technique that would calculate the roughness spectrum distributed at different wavelength intervals. The chapter also discussed theoretical foundation and implementation of different statistical signal processing techniques for the evaluation of surface topography. These included, power spectral density function (PSD) and transfer function (TF) for the evaluation of surface profile at spatial frequency domain, as well as material ratio function to address the distributions of surface asperities as a result of LμP.

The initial experimental investigation on ground IN718 and H13 tool steel were discussed in Chapter 5. The grinding method was chosen to generate a wide range of spatial components, which can be correlated with the process parameters in terms of polishability. The important observations made in this chapter included:

- The analyses in terms average line profiling roughness ($R_a$) spectrum at different wavelength intervals demonstrated that ps laser is more effective in polishing wavelength components shorter than 100 μm. In some observations of LμP trials, $R_a$ at long wavelength intervals is found to be increased. In terms of surface quality improvement up to 80.83% surface roughness reduction was reported for IN718 for the spatial wavelength
intervals of 6.25–12.5 µm. On the other hand, H13 tool steel demonstrated surface quality improvement of 74.2% for the spatial wavelength intervals of 12.5–25.0 µm.

- The relative increment and decrement, as depicted above can be correlated with the distribution of high spatial frequency components to the low frequency domain as depicted by the PSD plots. The change in surface asperities was analyzed by TF plots as well, where a negative gain of TF amplitudes denoted surface quality improvement.

- To analyze the distributions of surface amplitudes after LµP, MR curves for the initial and the polished profiles were derived and corresponding MR parameters, namely, surface maximum peak height ($R_p$), surface maximum valley depth ($R_v$) and slope coefficients were calculated. From these parameters it was revealed that ps LµP resulted in the reduction of both $R_p$ and $R_v$ and distributed surface micro-topographic features more uniformly constituted by the reduction of slope coefficients for both IN718 and H13 tool steel.

Based on the analysis presented in Chapter 5 and considering practical significance in perspective of industrial applications, initial profile to be polished by ps laser were generated by micromilling process with a periodicity of 50 µm. Chapter 6 discussed the experimental investigations of LµP of these micromilled profiles on IN718 and H13 tool steel. The major findings from this chapter were:
• As the $R_a$ spectrum exhibited, ps laser could effectively reduced the surface asperity that corresponded to an initial periodicity of 50 $\mu$m contributing to surface quality improvements of 78.5% and 75.7% for IN718 and H13 respectively in the spatial wavelength interval designated by the range 50–100 $\mu$m. The aforesaid improvements were demonstrated for the profiles created at the focal offsets of 1.1 mm for IN718 and 0.6 mm for H13 tool steel. The analysis presented by PSD and TF also revealed the reduction of surface asperities in entire domain of spatial frequency for these two specific cases.

• From the analysis presented by MR functions, it was clear that ps L$\mu$P resulted in the reduction of both $R_p$ and $R_v$. It also led to uniform distribution of surface micro-topographic features for both IN718 and H13 tool steel.

As a next step of practical applications, 2D areal polishing by ps laser were investigated by varying the step-over between two consecutive laser polishing track, while keeping the other parameters to their predetermined values (as obtained from the analysis presented in Chapter 6). Chapter 7 detailed these experimental analyses. Instead of $R_a$ spectrum, average areal topography surface roughness ($S_a$) spectrum at different wavelength intervals were calculated; whereas, statistical analysis of surface profile were carried out in terms of average PSD, TF and MR functions in the direction of L$\mu$P. The important findings from the experimental results presented in chapter 7 included:
• Analysis performed by $S_a$ spectrum depicted that ps LµP could effectively induce a superior quality surface finish both for IN718 and H13 tool steel. However, at longer spatial wavelength intervals (>100 µm), ps laser was observed to show poor polishability specified by the increase of $S_a$ for IN718 for the smallest step-over distances of 2.5 µm and 5.0 µm. These increments were considered to be attributed by the ripples formed as a result of high volume of melting pool that later distributes over the laser processed segments. In case of H13, such increase of $S_a$ was not reported.

• The statistical analyses performed by average PSD and TF functions demonstrated significant amplitude reductions in entire frequency domain for the profile with the best possible surface quality (profile created with a step-over of 20 µm for IN718 and 10 µm for H13 tool steel). The reduction of $R_p$ and $R_v$, as well as uniform distribution of surface asperities of initial profile denoted by MR function parameters confirmed the superior quality surface profile generated by ps LµP.

• As a demonstration of ps LµP process capability, two areal profiles on micromilled IN718 and H13 tool steel were polished. In perspective of surface quality improvement, 69.32% reduction of initial $S_a$ was reported for IN718 for the interval of 50–100 µm. For H13, this improvement was reported to be 77.28% for the same spatial wavelength interval.
8.3 Recommendations for Future Study

The work presented in this thesis, constituted the very first endeavor in adopting ps laser for micro-polishing applications. Despite the rigorous investigations made in this thesis, there are still rooms for further development and improvement. In this regard, there are three major areas that should be the focus of future works on ps LµP process.

8.3.1 Process Planning for Polishing 3D Surfaces and Functional Components

As a next step to extend the process capability of ps laser, it is imperative to undertake the study related to 3D surface micro-polishing by ps laser. Since some of the simple (typically developable) 3D surfaces can be decomposed – to some extent – into multiple 2D zones, generic area polishing knowledge obtained from the 2D areal polishing investigation presented in this chapter can be successfully transferred to the 3D case. While area polishing is mainly directed towards flat or quasi-flat surfaces, 3D surface polishing is typically intended for complex freeform surfaces. Nonetheless, freeform surface polishing remains a challenging task, whose main difficulty is represented by the synchronization of the motions provided by the mechanical and optical subsystems. Furthermore, the orientation of the incident laser beam has to be continuously adjusted in order to simultaneously avoid gouging, as well as to increase the overall performances of LµP process. It is important to note that inclination angle also alters beam shape at laser-material interaction zone. For instance, due to inclined beam orientation, its circular profile changes into an ellipse and this in turn changes completely
the energy distribution of the laser beam. As a result, further process optimizations are required to accommodate the variable tool orientation involved in 3D surface polishing. It is also important to note that the real functional components may comprise of small features, which cannot be polished at very high speed by considering the limitation of acceleration and deceleration time imposed by the CNC system.

The present study utilized a relatively high value of laser speed. In real life, functional part or product sometimes comprises a small feature, where a high laser beam speed may not be reachable because of the acceleration and deceleration time of the velocity profile of corresponding CNC system. Therefore, the desired level of surface finish will not be attained. The smaller value of speed constitutes longer laser-material interaction time and higher percentage of pulse overlap, which might prohibit in attaining desired level of surface finish. In this regard, other parameters, including laser power, repetition rate and focal offset are needed to be tuned in accordance with the lower level of laser speed. In a nutshell, an integrated process planning approach is to be undertaken in context polishing of functional components. Multi-variable optimization could be another potential area of future development in this regard.

8.3.2 Physical and Metallurgical Properties of Polished Samples

In the present study, no study was performed on the effects of ps laser on the physical characteristics of the metallic surfaces. L\textmu P is a thermally induced process that might change the physical and metallurgical properties of the polished surface. The intense temperature generate by the laser beam may affect the micro-hardness, fatigue
strength, wettability and biocompatibility, and residual stress of the workpiece material, which are needed to be tested after polishing. Moreover, metallurgical study of metal alloys may reveal valuable information regarding grain size and phase structure. So, post-polishing test and analysis of the effects of laser irradiation on the aforementioned physical properties are needed to be accounted. Findings from the investigations of the physical and metallurgical properties would lead to an improvement in ps LµP, therefore enable more potential applications.

8.3.3 Theoretical Analysis and Multi-physics Simulation

The present study developed an initial foundation for the theoretical analysis of ps LµP in terms of temperature filed generation, which is required to be extended for multi-physics simulation. In reality, the dimensional profile of the laser beam focal spot does not confirm with the workpiece profile due to the space-time non-stationary thermodynamic process disturbances in the processing zone, which modifies the physical/chemical properties of the workpiece material leading to changes in the polished area. The final surface profile generated by LµP depends on several factors including initial surface profile, thermo-physical material properties including heat conductivity, absorption coefficient, surface tension, and melting and evaporative temperature. To draw a complete picture of process mechanism and dynamics of ps LµP, potential areas of future development include rigorous theoretical analyses, modeling and multi-physics simulation of ps LµP process.
8.3.4 Other Challenges and Opportunities

In general, it is necessary to consider mode detailed analysis and development towards industrial applications of ps LµP, especially in terms of better understanding of process mechanism, optimization of variety of process parameters for polishing of complex 3D geometries and automatic process planning. The process should be linked with its counterpart ps machining applications, so that a single system can be utilized to perform both machining and polishing of very difficult-to-cut alloy like IN718. The capability of laser polishing is also required to be extended for many of the other alloys..

During ps LµP, as in any laser-based fabrication processes several technical and scientific challenges are expected. The most significant challenges are related to (Bordatchev, et al., 2004, 2007 and 2008):

- Advanced synchronous control of laser functioning (e.g., on/off events) and motions in space and time with respect to the part geometry and tool path trajectory
- Automation of ps LµP process that includes automatic process planning, automatic selection of process parameters and tool path trajectory, post-polishing measurement of surface geometry and automatic correction of process errors correction.

Significant loss of ps LµP quality may occur at the start and end points of the tool path, which correspond to acceleration and deceleration of the stages, and when the tool path trajectory changes direction and velocity of motions abruptly, e.g. sharp corners and
arcs with small radius. During these time and space segments, consecutive laser pulses are located very close to each other, and therefore the processed material absorbs more laser energy per square unit creating a totally different combination of process parameters that leads to distractions and discontinuities in the ps LµP process. Rigorous studies related to synchronization between the motion and laser pulses are essential in this context.
Appendix A

Laser Power Measurement

A.1 Laser Power Measurement

Laser power and pulse energy at different level of set voltage and laser pulse repetition rates (pulse frequency) are summarized in Table A.1. The power was measured using a power meter capable of measuring up to 25 W of laser power. After that pulse energy was calculated from the ratio of laser power and repetition rate.

Figure A.1 presents laser power and pulse energy as function of pulse repetition rate. As shown in Figure A.1a, at lower repetition rate laser power tends to increase, which remains almost stable at higher level of repetition rate. Besides, drastic decrement of pulse energy can be observed for increasing repetition rate, as the total power is divided into large number of pulses at high repetition rate (see Figure A.1b).
Table A.1: Laser power and pulse energy at different set voltage and laser frequency

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Pulse repetition rate (MHz)</th>
<th>Power (W)</th>
<th>Pulse energy (µJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.00</td>
<td>1.00</td>
<td>7.24</td>
<td>7.24</td>
</tr>
<tr>
<td></td>
<td>4.10</td>
<td>7.87</td>
<td>1.92</td>
</tr>
<tr>
<td></td>
<td>7.46</td>
<td>8.01</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td>8.20</td>
<td>8.00</td>
<td>0.98</td>
</tr>
<tr>
<td>2.50</td>
<td>1.00</td>
<td>9.18</td>
<td>9.18</td>
</tr>
<tr>
<td></td>
<td>4.10</td>
<td>9.88</td>
<td>2.41</td>
</tr>
<tr>
<td></td>
<td>7.46</td>
<td>10.10</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td>8.20</td>
<td>10.10</td>
<td>1.23</td>
</tr>
<tr>
<td>3.00</td>
<td>1.00</td>
<td>10.20</td>
<td>10.20</td>
</tr>
<tr>
<td></td>
<td>4.10</td>
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<tr>
<td></td>
<td>7.46</td>
<td>11.10</td>
<td>1.49</td>
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<tr>
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<td>7.46</td>
<td>11.10</td>
<td>1.49</td>
</tr>
<tr>
<td></td>
<td>8.20</td>
<td>11.10</td>
<td>1.35</td>
</tr>
</tbody>
</table>
Figure A.1: (a) Laser power, and (b) pulse energy (energy per pulse) as function of pulsing frequency at different level of set voltage
Appendix B

Electron Cooling and Lattice Heating Time

B.1 Calculations of Electron Cooling and Lattice Heating Time

Sample calculations to determine electron cooling and lattice heating time for IN718 and H13 tool steel are presented in this section. The calculation is performed in MATLAB. The values of coupling factor and lattice heat capacity were considered for a temperature of 300\(^0\) K from the works published by Lin et al., 2006, 2007 and 2008.

% Calculation of relaxation and thermalization time
clc; close all; clear all;

format long
n = 6.022E23; % Avogadro number in atom/mole

roh_ni = 8900; % density of nickel kg/m^3
roh_fe = 7900; % density of nickel kg/m^3

m_per_km = 1000; % mole/kilomole, a measure like ppt

molar_mass_ni = 58.7; % molar mass of nickel in kg/kmole
molar_mass_fe = 55.84; % molar mass of nickel in kg/kmole

me = 9.1086E-31; % mass of an electron in kg
K_T_ni = 90.9; % thermal conductivity in W/(m.K)
K_T_fe = 55.7; % thermal conductivity in W/(m.K)

K_B = 1.38E-23; % Boltzman constant
Gamma_fe = 5.4*10^{17}; % coupling factor at 300 K. Ref: Lin et al., 2006, 2007 and 2008.

Ne_ni = (n*roh_ni*m_per_km)/(molar_mass_ni); % the number of electron per unit volume for nickel
Ne_fe = (n*roh_fe*m_per_km)/(molar_mass_fe); % the number of electron per unit volume for nickel

T = 300; % temperature in Kelvin

% Calculation of electron relaxation time
tau_e_ni = (3*me*K_T_ni)/(pi^2*Ne_ni*K_B^2*T);
tau_e_ni_fs = tau_e_ni/10^{-15}; % in femtosecond

tau_e_fe = (3*me*K_T_fe)/(pi^2*Ne_fe*K_B^2*T);
tau_e_fe_fs = tau_e_fe/10^{-15}; % in femtosecond

S = sprintf( 'Electron relaxation time for nickel, fs: %7.1f', tau_e_ni_fs); disp( S );
S = sprintf( 'Electron relaxation time for iron, fs: %7.1f', tau_e_fe_fs); disp( S );

C_lat_ni = 444*roh_ni-3.79*10^6; % C= C-Ce Ref: Lin et al., 2006, 2007 and 2008.
C_lat_fe = 469*roh_fe-3.46*10^6; % C= C-Ce Ref: Lin et al., 2006, 2007 and 2008.

tau_lat_ni = (C_lat_ni/Gamma_ni)/10^{-15}; % in femtosecond
S = sprintf( 'Thermalization time of nickel, fs: %7.1f', tau_lat_ni); disp( S );

tau_lat_fe = (C_lat_fe/Gamma_fe)/10^{-15}; % in femtosecond
S = sprintf( 'Thermalization time of iron, fs: %7.1f', tau_lat_fe); disp( S );
Appendix C

MATLAB Codes

C.1 Gaussian Filter

The following MATLAB function for Gaussian filter was developed based on the algorithm proposed by Yuan et al., 2000.

```matlab
% I,R,W represents primary, roughness and waviness profile respectively represented by row matrix.

% INPUT:
% Profile_Data - 1D array of primary profile
% AxisY - Y axis
% CutoffLength - predefined cut-off length
% XY_scale_um

% OUTPUT:
% I - 1D array of primary profile (for convenience it was reprinted as output
% R - roughness profile
% W - waviness profile

function [I,R,W]=GaussianFilter(Profile_Data,AxisY,CutoffLength,XY_scale_um)

leng = length(Profile_Data);
eps = 1e-3;
alpha = sqrt(log(2)/pi());

s = XY_scale_um/(CutoffLength*alpha);
m = ceil(sqrt(log(s/(XY_scale_um*eps))/pi())/s +1);
v = exp(-pi() *s *s);
beta2 = v*v;
```
C.2 Material Ratio Function

The following MATLAB function calculates the materials ratio function for an array of surface profile topographic data.

```matlab
% The function calculates Material Ratio Curve (Abbott-Firestone curve) and amplitude distribution functions.

% INPUT:
% DataArray - 1D array of data to analyse
% NPockets - number of pockets (levels), preferably an odd number
% TPockets - width of the pocket

% OUTPUT:
% MRF - material ratio function
% ADF - amplitude distribution function (surface histogram)

function [MRF, ADF] = MRFANDADF( DataArray, NPockets, TPocket )

DataN = length( DataArray ); % size of data array
NPocketsHalf = (NPockets-1)/2;
MRF = zeros( NPockets, 1 );
ADF = zeros( NPockets, 1 ); % amplitude distribution function (surface histogram)

for i=1:DataN
    iTmp = floor( DataArray(i)/TPocket ) + NPocketsHalf + 1;
    if( iTmp < 1 )
        fTmp = DataArray(i);
```
\begin{verbatim}
    iiTmp = DataArray(i)/TPocket;
    iTmp = iTmp;
    end
    ADF(iTmp) = ADF(iTmp) + 1;
end
ADF = ADF ./ DataN;

    % calculate MR as a cumulative probability distribution
    for i=1:NPockets
        MRF(i) = sum( ADF(1:i) );
    end

    MRF = 100 - (MRF .* 100);
\end{verbatim}
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REFERENCES


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VITA

Name: Abdullah Mohammad Khalid Hafiz

Post-secondary Education and Degrees:

Western University
London, Ontario, Canada
2009-Present
Doctor of Philosophy
Mechanical and Materials Engineering

International Islamic University Malaysia
Kuala Lumpur, Malaysia
2006-2008
Master of Science in Engineering
Manufacturing and Materials Engineering

Bangladesh University of Engineering and Technology Dhaka, Bangladesh
2000-2004
Bachelor of Science in Engineering
Industrial and Production Engineering

Honors and Awards:

Western Engineering Scholarship 2009-2013

University Merit Scholarship 2000-2004

Bangladesh Government Scholarship (awarded twice) 2000-2004

Related Work Experience:

Research Assistant, 2009-2013
Western University

Teaching Assistant, 2009-2013
Western University

Research Assistant, 2006-2008
International Islamic University Malaysia

Publications

Journal Articles and Transaction


Journal articles (submitted and in progress)

1. Applicability of a picosecond laser for micro-polishing of Inconel 718 superalloy prepared by micromilling (article under review)

2. Laser polishing of metallic materials: state of the art and the future research direction (article under review)

3. Two step laser polishing of metallic materials: a theoretical and experimental investigation (in progress)

4. Strategies of polishing functional components by pulsed laser radiation (in progress)

5. Analysis techniques of surface topography in micro-manufacturing applications (in progress)

Conference proceedings


