Irregular, Adaptive Scan Trajectories for Pulsed Laser Micro Polishing

Madhu Vadali[1], Chao Ma[2], Xiaochun Li[3], Frank E. Pfefferkorn[4] and Neil A. Duffie[5]•

[1]Madhu Vadali; Mechanical Engr., University of Wisconsin - Madison, USA; e-mail: vadali@wisc.edu
[2]Chao Ma; Mechanical Engr., University of Wisconsin - Madison, USA; e-mail: cma25@ wisc.edu
[3]Xiaochun Li; Mechanical Engr., University of Wisconsin - Madison, USA; e-mail: xcli@engr.wisc.edu
[4]Frank E. Pfefferkorn; Mechanical Engr., University of Wisconsin - Madison, USA; e-mail: pfefferk@engr.wisc.edu
[5]Neil A. Duffie; Mechanical Engr., University of Wisconsin - Madison, USA; e-mail: duffie@engr.wisc.edu•

ABSTRACT

The objective of this work is to generate irregular, smooth, adaptive laser scan trajectories for pulsed laser micro polishing (PLµP). Traditionally PLµP, like other surface finishing processes has used zigzag scan paths. Zigzag trajectories are simple in nature, are comprised of sharp turns, the dynamics of the positioning system are not taken into account, and more importantly are not adaptable because the path generation is independent of surface condition. In this paper, the authors present a scan trajectory generation scheme that can overcome these limitations. These trajectories are based on the artificial potential fields method of path planning that take the surface condition into account. Computer simulations are presented to illustrate the characteristics of the path and guidelines are developed for choosing the trajectory generation parameters. Finally, smooth, irregular scan trajectories are generated for a micro end milled Ti6Al4V surface that has a feature that needs no polishing, thus illustrating the versatility of the trajectory generations scheme.

INTRODUCTION

Pulsed laser micro polishing (PLµP) is a non-contact surface finishing process suitable for polishing micro metallic surfaces produced by micro-manufacturing processes (e.g., micro end milling). These manufacturing processes can produce complex metallic parts with surface roughnesses that can approach the size of functional surface features. In PLµP, laser pulses incident on the surface melt a thin layer of material. The surface tension and viscous damping forces within the melt pool drive the surface to a state of lower energy, resulting in a smoother surface upon re-solidification [1-4].

Recently these authors have shown that at longer melt durations, thermocapillary flows (also known as Marangoni flows) can exist within the melt pool [5] resulting in significant improvement in the surface finish. Specifically, the reductions in the amplitudes of low frequency spatial features are significantly enhanced, which would not be possible in the absence of thermocapillary flows (i.e., at short melt durations). The authors have polished micro end milled Ti6Al4V sample surfaces at various melt durations using a traditional zigzag trajectory for laser scanning and have achieved up to 70% reduction in average surface roughness. They have also observed that polishing in the thermocapillary flow regime can introduce residual high frequency processing features on the surface. These residual spatial features are a well-defined function of the zigzag trajectory, i.e., the laser spot overlap and the step-over of the zigzag scanning. An illustration of the zigzag scan trajectory for a 1mm × 1mm area polishing is shown in Fig. 1a. With this trajectory, additional features are created corresponding to 80% of the laser spot diameter (spot overlap) in the scan direction (y direction) and 50% of the laser spot diameter (step-over) in the step-over direction (x direction). A typical surface produced by such a trajectory is shown in Fig. 1b, clearly showing the formation of periodic surface features along the zigzag trajectory. Such residual polishing features may be undesirable in many applications (e.g., optical applications).

Apart from the introduction of the residual processing feature in PLµP in the thermocapillary flow regime, zigzag laser scan trajectories pose other disadvantages such as:

- The laser visits locations on the surface several times due to the "required" overlap (spot overlap and step-over).
- The laser may visit locations with little or no roughness features.
- The temperature rise below the surface may be high, causing unacceptable heating of the substrate or distortion of the workpiece.
- The abrupt changes in the direction of scan trajectory at the corners can place high acceleration demands on beam positioning systems.
- The regularity of the resulting pattern may have significant effects on the performance of the polished surface, such as in contact mechanics or fluid flow.

A fractal path, also known as Hilbert curve [8] was designed to Mizugaki et al [9] that was used for surface finishing of sculptured surfaces using a robotic arm. Though this method takes the surface condition into account, it is comprised of ninety-degree turns and has short path segments that can cause vibrations in the positioning system at high scanning speeds.

• corresponding author

(a)

Surface ripples

(b)
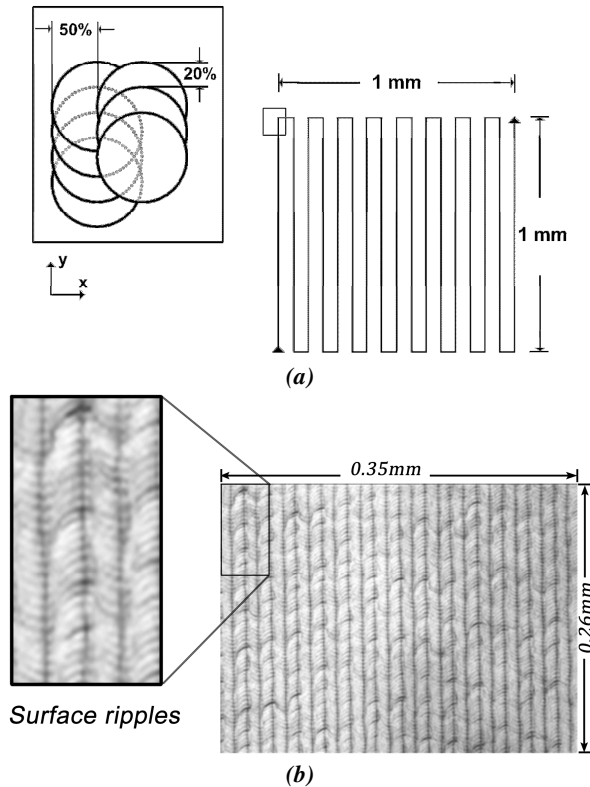
Fig. 1: (a) An illustration of a zigzag trajectory used in PLμP (b) A typical surface produced by a zigzag trajectory in PLμP

A scan trajectory with no regular pattern will not result in regular residual processing features. A trajectory that contains no sharp corners that mimic manual polishing, is more reasonable from the perspective of positioning system design. And most importantly, trajectories need to be adapted to un-polished surface conditions, preferentially polishing the rougher areas and not already smooth areas. The goal of the work reported in this paper was to develop a theoretical formulation for generating irregular, smooth, adaptive PLμP scan trajectories and to explore the potential benefits of such trajectories in comparison to traditional zigzag trajectories.

ZIGZAG SCAN TRAJECTORIES

The raster scan trajectory or zigzag trajectory is the most common path generation scheme used for surface processing. Every location on the surface is visited at least once (several times in practice) in a successive zigzag pattern. A typical zigzag path is shown in Fig. 1a. Such a path has several limitations, when used for PLμP.

A. OVERLAP

In PLμP, the laser beam spot is, in general, circular. Nüsser et al, recently evaluated the effect of geometry of the laser spot on achievable surface finish in PLμP [6]. They concluded, based on experimental results that a laser beam with square intensity distribution led to lower reduction in the surface roughness than a beam with circular intensity profile. The use of circular profile forces the trajectory designer to generate a zigzag trajectory in which there is at least a minimum of 30% spot overlap and step over in order to cover the entire area.

This can be seen in Fig. 2. This means that areas are hit by laser pulses multiple times. This cycle of heating and melting may degrade the properties of the metal substrate for example, introducing liquation and solidification cracking [7].

B. PROCESSING TIME

Due to the need for overlap, the scan speed that produces a 30% overlap at a given pulsing rate is the fastest possible that ensures coverage of the entire surface.

C. DYNAMICS OF POSITIONING SYSTEM

The zigzag trajectory is comprised of sharp turns at the end of individual beam paths. These require high accelerations and decelerations that must be within the practical bandwidth of the positioning system or inaccuracies can be introduced in the polishing path and overheating can occur in positioning hardware. Also decelerations can result in multiple laser hits at corners, unless the laser is turned off, which produce un-wanted surface features and potentially locally overheat the workpiece.

D. NON-ADAPTABLE

The zigzag trajectory does not take into account spatially varying surface condition. This is especially problematic when polishing surfaces with micro geometries that have areas that do not require polishing.
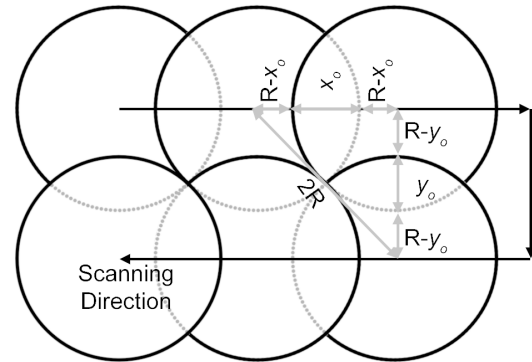
Fig. 2: Spot overlap and step over in a zigzag trajectory

To overcome the limitations of zigzag scanning, irregular, smooth, adaptive scan trajectories are needed. Irregularity is needed to eliminate residual regular process patterns, for example, mimicking the trajectories of manual polishing motion. Smoothness is needed to ensure that there are no sudden changes in direction, staying within the operating limits of positioning systems while processing at higher speeds. Finally, adaptability is needed to enable polishing of selective areas on the surface. In the following sections, a generalized algorithm is discussed that generates trajectories that satisfy these needs.

SCAN TRAJECTORY GENERATION USING ARTIFICIAL POTENTIAL FIELDS

Trajectory generation based on artificial potential fields is a commonly used method for robot motion planning that is specially used in obstacle avoidance [10]. A mathematical potential field, analogous to a gravitational field is constructed

around a goal position (attractive) and obstacles (repulsive). The robotic manipulator is assumed to be a mass moving in this force field. A related strategy is applied in this work, where areas requiring polishing are assigned attractive fields, and areas that do not require polishing are analogous to obstacles and are assigned repulsive fields. The laser beam is assumed to be a unit mass moving within the field in the presence of the attractive and repulsive forces. As described in the following sections, the physics of the system need to be modified to generate appropriate beam motion; nevertheless, the analogy of potential fields can be drawn upon to determine instantaneous acceleration and velocity and, hence, subsequent motion [11-14].

A. POTENTIAL FIELDS

Potential fields that depend on measured surface condition can be generated on a surface. A unit mass, representing the laser beam, then is introduced into the field. It is attracted towards the surface regions requiring polishing (assigned attractive fields – negative by convention), while it is repelled by the regions that do not require polishing (assigned repulsive fields – positive by convention). It is desirable that the fields are assigned such that the magnitude of the force of attraction (or repulsion) is proportional to the surface condition and increases as the distance of the beam from the position of the attractive (or repulsive) point decreases. The path traced out by the beam (the unit mass) then can be used as the scan trajectory for PLμP, generating smoothly curving paths that tend to avoid instantaneous changes in direction.

There are many options for the field function [15]. A simple gravitational model has many of the characteristics for scan trajectory generation, when the field is directly proportional to the surface condition and is inversely proportional to the distance of the laser beam from the attractive (or repulsive) point. This will generate a force that is inversely proportional to the square of the distance. The beam velocity and position then are found by integration. However, this formulation has several drawbacks:

- When the distance from the beam to an attractive point approaches zero, the acceleration of the beam approaches infinity;
- The magnitude of the velocity of the beam is not constant;
- If field is a function of surface condition, then acceleration will decrease as surface is smoothened;
- The beam can escape from the attractive point if the strength of the field decreases.

Ngo et al. [16] proposed an alternative formulation for generating tool motion that can overcome these limitations and can accommodate fields created by many attractive points. The attractive force due to the ith attractive point as a function of distance r_i is given by:

$$\overline{F}_{a,i}(r) = -c_i e^{-kr_i} \hat{r}_i \tag{1}$$

and the force function due to many attractive points on the surface is given by:

$$\overline{F}_{net}(t) = \sum_{i=1}^{N} -c_i(t) e^{-kr_i(t)} \hat{r}_i(t) \tag{2}$$

where N is the number of attractive points, $c_i(t)$ is the force strength due to the ith attractive point, k is a spatial decay constant, and $\hat{r}_i(t)$ is the unit vector in the direction from the ith attractive point to the tool.

While this formulation addresses some of the drawbacks of the gravitational model, it is confined to fields formed by attractive fields. Also, Ngo used a decay constant k that was a function of spacing between the attractive points, however, the velocity of the tool must also be considered.

B. MODIFIED FIELDS WITH REPULSIVE FORCES

In the current work, the basic exponential structure of the force in Eqn. (1) is used, but both attractive and repulsive forces are considered. An attractive force is created according to Eqn. (1) and the repulsive force equation is created according to:

$$\overline{F}_{r,j}(r) = c_j e^{-kr_j} \hat{r}_j \tag{3}$$

The net force then is given by:

$$\overline{F}_{net} = \overline{F}_{att} + \overline{F}_{rep} \tag{4}$$

Considering all forces due to N attractive and M repulsive points on the surface, the net force as a function of time is given by:

$$
\begin{aligned}
\overline{F}_{net}(t) &= \sum_{i=1}^{N} \overline{F}_{a,i}(t) + \sum_{j=1}^{M} \overline{F}_{r,j}(t) \\
&= \sum_{i=1}^{N} -c_i(t) e^{-kr_i(t)} \hat{r}_i(t) + \sum_{i=1}^{M} c_j e^{-kr_j(t)} \hat{r}_j(t)
\end{aligned}
\tag{5}
$$

Note that the attractive force strength c_i changes with time as polishing progresses, but the repulsive force strength c_j does not change with time.

C. MODIFICATION TO PHYSICS

Although the algorithm is based on physics describing the motion of a free mass through a group of attractive and repulsive fields, modifications are necessary to satisfy the requirements of PLμP. PLμP is carried out at a constant laser scan speed. Here, the surface condition changes after each laser pulse, and if the artificial fields associated with surface condition decrease, this may cause the beam to "escape" from the desired polishing area. Hence, a further modification of

trajectory generation is necessary. First, a compensation factor $\psi(t)$ is calculated using:

$$\psi(t) = \frac{U_d - \sum_{i=1}^{M} \frac{c_j}{k} e^{-kr_j(t)} \hat{r}_j(t)}{\sum_{i=1}^{N} \frac{c_i}{k} e^{-kr_i(t)} \hat{r}_i(t)} \qquad (6)$$

where U_d is the desired potential energy. In this work, the desired potential energy is constant and is equal to the kinetic energy of the beam (fixed mass moving at a fixed velocity magnitude). Once the compensation factor has been calculated, the force applied by each attractive point is modified:

$$\overline{F}_{net}(t) = \sum_{i=1}^{N} \psi(t)\overline{F}_{a,i}(t) + \sum_{j=1}^{M} \overline{F}_{r,j}(t)$$

$$= \sum_{i=1}^{N} -\psi(t)c_i e^{-kr_i(t)} \hat{r}_i(t) + \sum_{i=1}^{M} c_j e^{-kr_j(t)} \hat{r}_j(t) \qquad (7)$$

This net force is used to calculate the acceleration of the beam, and this is then integrated to get velocity. Additionally, only the direction of this velocity is used, with the magnitude of velocity held constant at the velocity required for PLμP at the desired constant pulsing rate.

FORCE STRENGTHS BASED ON SURFACE CONDITION

The force strength c of an attractive point is chosen based on surface condition. This allows assignment of higher polishing priority to rougher regions on the surface and assignment of lower priority to smoother regions. Furthermore, regions that require no surface finishing can be assigned a negative field.

In the current work, the force strength for attractive points was chosen as the magnitude of surface height deviation as chosen points. Once the attractive points are chosen and force strengths are assigned, a force field is generated based on the spatial location of the beam. To illustrate this, a typical micro end milled Ti6Al4V is chosen as example (Fig. 3). Fig. 4 shows the artificial attractive force field for the surface shown in Fig. 3, with a decay constant of 68000m[-1].
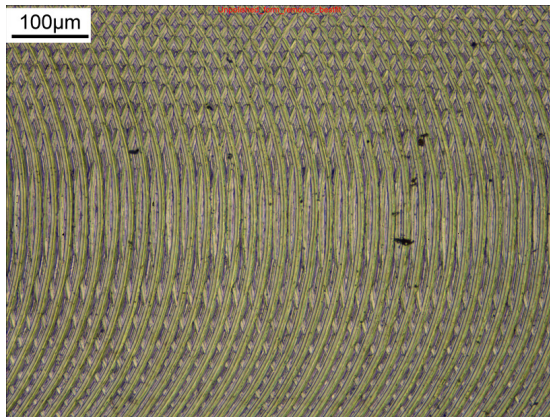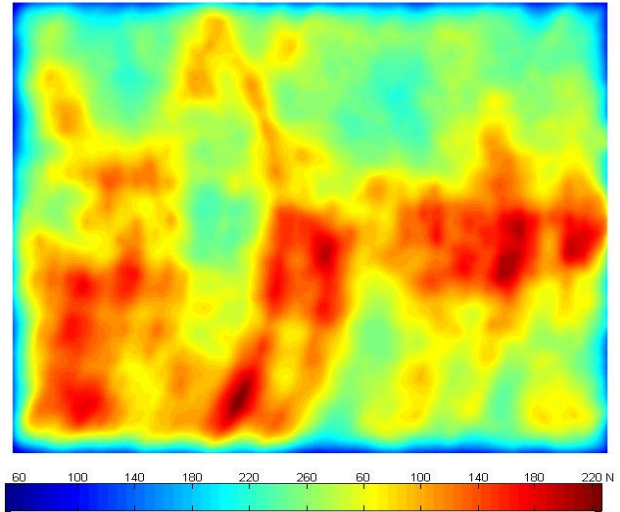

Fig. 3: Micro end milled Ti6Al4V surface

Fig. 4: Attractive force field for the surface shown in Fig. 3
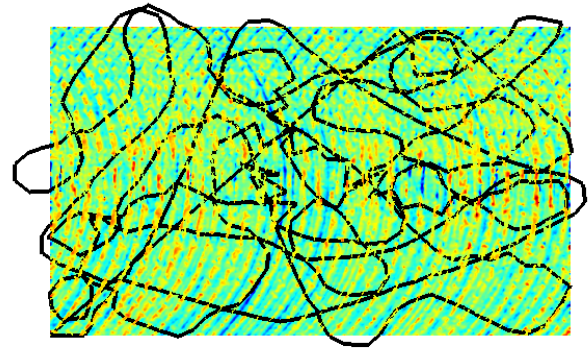
DECAY CONSTANT

The decay constant is an important parameter because it dictates the extent of influence of attractive on repulsive points over the entire surface. If the decay constant is too small, then the field is wide spread and can be nearly uniform throughout the surface. This is undesirable because the beam does not distinguish between rougher regions (stronger attractive points) from smoother regions (weaker attractive points). Also, the beam tends to drift away from the points due to momentum. This is illustrated in Fig. 5a and leads to longer processing times and trajectories outside the region of interest. In Fig. 5b, the decay constant (~68000m[-1]) produces fast coverage of the entire area, while the beam is confined within the area to be polished.

On the other hand, a decay constant that is too high results in a field that is localized around a small region and does not influence beam when it is far away from the point. Although this may be desirable for a repulsive point, this is particularly undesirable for an attractive point because it needs to attract the beam. Also, when there is an intense localized field, the beam can have a tendency to orbit around attractive point and never escape.

The trajectory in Fig. 5 can be decomposed into corresponding x and y components as shown in Fig. 6. Fig. 6a corresponds to low decay constant (~4550m[-1]), and the beam traverses in large arcs and spends considerable time outside the field. The x and y components of the path are relatively slow varying suggesting that the path is comprised of smooth arcs. On the other hand, Fig. 6b corresponds to a more suitable decay constant (~68000m[-1]) and indicates that the path is more irregular and is shorter in duration.
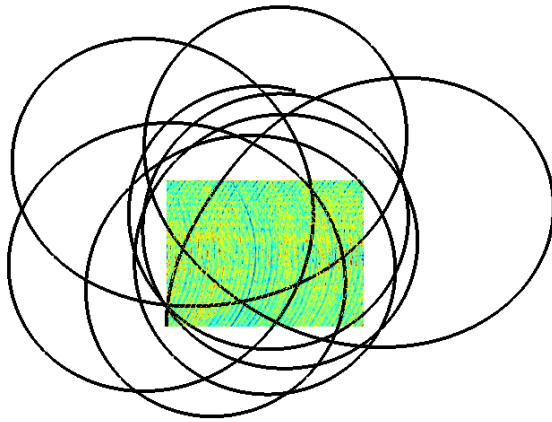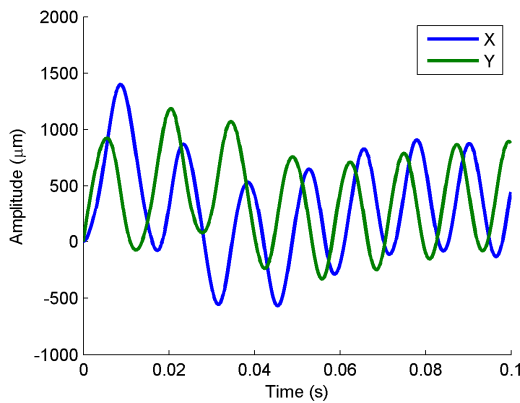
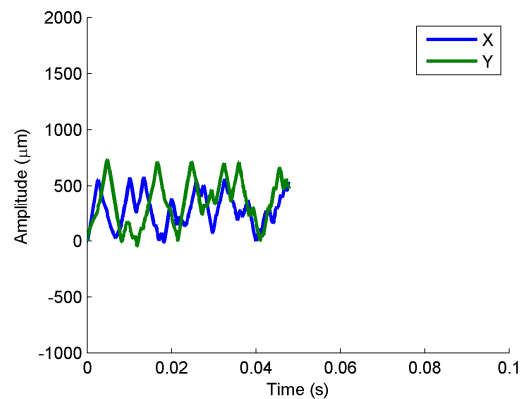(a) k = 4550m⁻¹   (b) k = 68000m⁻¹

Fig. 5: The scan path generated for two values of the decay constant overlaid on the surface image

(a) k = 4550m⁻¹   (b) k = 68000m⁻¹

Fig. 6: Trajectories from Fig. 5 decomposed into x and y components

Hence it is necessary to find a value of the decay constant that satisfies the following:

- The scan trajectory covers nearly the entire area to be polished.
- A fast total processing time is achieved at a given scan speed.
- The beam spends only a small amount of time outside the region to be polished.
- The beam does not orbit about a single attractive point (or a group of attractive points).

The trajectory generation algorithm and its polishing result was simulated for the surface shown in Fig. 3. A laser spot diameter of 25μm and a pulse frequency of 10kHz. The simulations were carried out for 0.1s or until the beam covered 90% of the area at least once. For computational reasons, the distance between points was chosen to be ~3.5μm. The simulations were run for many values of the decay constant k and different scan speeds to understand their dependencies.

It was observed in simulations that the beam often become trapped in an orbit when the product of decay constant and critical distance r_c (defined as the distance travelled by the beam in one pulse period, i.e., $\dfrac{v}{f}$ where v is the scan speed and f is the pulse frequency) was greater than 1.9. Hence, this can be used as a 'rule of thumb' in choosing the decay constant. Secondly, the decay constant can be chosen such that the time spent by the beam outside the area to be polished is less than 10% of the total process time. Fig. 5b corresponds to a decay constant of ~68000m⁻¹ for a scan speed of 250mm/s (corresponding to 0% spot overlap). This resulted in the smallest simulating processing time of 0.0479s to polish an area of 712μm × 540μm.

ADAPTIVE SCAN TRAJECTORIES

A second surface was machined using micro end milling on Ti6Al4V. The surface had a 50μm deep, 1mm diameter circular feature as shown in Fig. 7. For the purposes of illustration, the circular feature was required to remain unpolished while the area surrounding was to be polished. Therefore the points associated with the feature were made repulsive by assigning positive (by convention) force strength. A scan speed of 250mm/s was used with the decay constant of 68000m⁻¹ found as described above. For purposes of illustration, polishing was simulated for only one quadrant as shown

in Fig. 7. The simulations were carried out until 95% of the area (to be polished) was traversed at least once by the beam.

The time evolution of the scan trajectory on the surface is shown in Fig. 8. It can be seen that the algorithm keeps the beam mostly within the area requiring polishing, and mostly out of the (repulsive) feature. The processing time was approximately 0.1s. It can be observed that most of the polishing occurs in the first 50% of this processing time, with the beam spending more time in the second 50% of the processing time traversing regions that already have been visited.
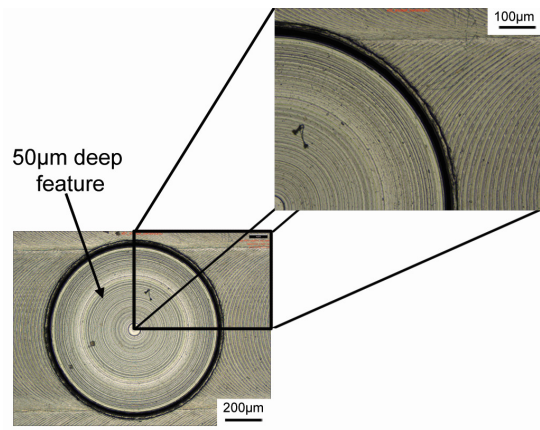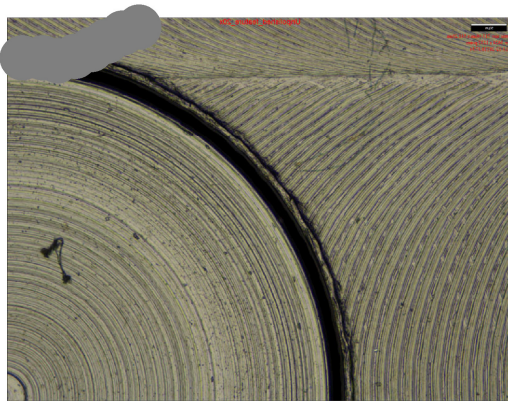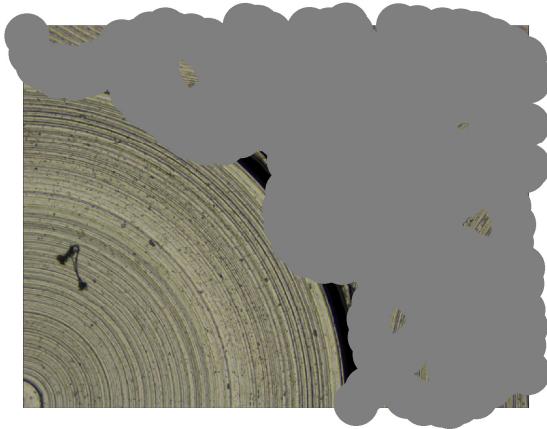

Fig. 7: Micro end milled Ti6Al4V surface with a 50μm deep feature

(a)   t =0.001s

(b)   t =0.025s

(c)   t =0.05s

(d)   t =0.1s

Fig. 8: Time evolution of the scan trajectory

CONCLUSIONS

An artificial potential fields method has been described, the purpose of which is to generate laser scan trajectories for pulsed laser micro polishing (PLμP). The trajectories are based on attractive fields assigned based on the surface condition and repulsive fields assigned to regions where polishing is not desired. The beam motion that is generated is analogous to a unit mass traversing a time-varying force field. The generated trajectories are irregular, smooth and adapt to the changing surface condition of surface being polished, preferentially polishing relatively rough areas. The computer

simulations presented illustrate important characteristics of the trajectories generated. These simulations also provided guidance for choosing decay constant.

Although the processing times of the trajectory shown in Fig. 5b is somewhat more than those corresponding to zigzag trajectory (0.048s versus 0.034s for a 712µm × 540µm area), these trajectories contain no sharp turns and are adaptable to the topography of the surface and the geometric profile of the desired polished area. This trajectory generation method is not only applicable to PLµP, but is also expected to be applicable for other surface finishing processes such as grinding.

This path generation method needs to be experimentally evaluated and the polishing results obtained need to be compared with those obtained using zigzag paths. For example, it is hypothesized that due to the irregular nature of the motion generated, this scheme would not produce regular residual processing features. There may be additional benefits. For example, scanning can be done with no overlap, maintaining a constant (or variable) distance between the spots. This would ensure that a given is not subject to rapid heating and cooling cycles.

REFERENCES

[1] T. L. Perry, D. Werschmoeller, N. A. Duffie, X. C. Li, and F. E. Pfefferkorn, "Examination of Selective Pulsed Laser Micropolishing on Microfabricated Nickel Samples Using Spatial Frequency Analysis," *Journal of Manufacturing Science and Engineering-Transactions of the Asme,* vol. 131, no. 2, 2009.

[2] T. L. Perry, D. Werschmoeller, X. Li, F. E. Pfefferkorn, and N. A. Duffie, "Pulsed laser polishing of micro-milled Ti6Al4V samples," *Journal of Manufacturing Processes,* vol. 11, no. 2, 2009, pp. 74-81.

[3] T. L. Perry, D. Werschmoeller, X. C. Li, F. E. Pfefferkorn, and N. A. Duffie, "The Effect of Laser Pulse Duration and Feed Rate on Pulsed Laser Polishing of Microfabricated Nickel Samples," *Journal of Manufacturing Science and Engineering-Transactions of the Asme,* vol. 131, no. 3, 2009.

[4] M. Vadali, C. Ma, N. A. Duffie, X. Li, and F. E. Pfefferkorn, "Pulsed laser micro polishing: Surface prediction model," *Journal of Manufacturing Processes*, no. 0, 2012.

[5] M. Vadali, C. Ma, X. Li, F. Pfefferkorn, E., and N. Duffie, A., "Effects of Laser Pulse Duration on Pulsed Laser Micro Polishing," *ASME Journal of Micro and Nano Manufacturing*, 2013.

[6] C. Nüsser, I. Wehrmann, and E. Willenborg, "Influence of Intensity Distribution and Pulse Duration on Laser Micro Polishing," *Physics Procedia,* vol. 12, Part A, no. 0, 2011, pp. 462-471.

[7] S. Kou, "Solidification and liquation cracking issues in welding," *JOM,* vol. 55, no. 6, 2003, pp. 37-42.

[8] H. O. Peitgen, H. Jürgens, and D. Saupe, Chaos and Fractals: New Frontiers of Science, Editor: 2004, pp. Pages.

[9] Y. Mizugaki, M. Sakamoto, K. Kamijo, and N. Taniguchi, "Development of Metal-Mold Polishing Robot System with Contact Pressure Control Using CAD/CAM Data," *CIRP Annals - Manufacturing Technology,* vol. 39, no. 1, 1990, pp. 523-526.

[10] O. Khatib, "Real-time obstacle avoidance for manipulators and mobile robots," *The international journal of robotics research,* vol. 5, no. 1, 1986, pp. 90-98.

[11] K. S. Al-Sultan, and M. D. S. Aliyu, "A new potential field-based algorithm for path planning," *Journal of Intelligent & Robotic Systems,* vol. 17, no. 3, 1996, pp. 265-282.

[12] E. Gilbert, and D. Johnson, "Distance functions and their application to robot path planning in the presence of obstacles," *Robotics and Automation, IEEE Journal of,* vol. 1, no. 1, 1985, pp. 21-30.

[13] Y. K. Hwang, and N. Ahuja, "A potential field approach to path planning," *Robotics and Automation, IEEE Transactions on,* vol. 8, no. 1, 1992, pp. 23-32.

[14] V. Pavlov, and A. N. Voronin, "The method of potential functions for coding constraints of the external space in an intelligent mobile robot," *Soviet Automatic Control,* vol. 17, no. 6, 1984, pp. 45-51.

[15] D. E. Koditschek, "Robot planning and control via potential functions," in *Proceedings of the Conference*, pp. 349-367.

[16] C. Ngo, N. A. Duffie, and T. L. Perry, "Generation of Highly Repetitive Irregular Motion for Surface Finishing Processes," in North American Manufacturing Research Conference (NAMRC), Milwaukee, WI, USA, 2006.