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Experimental statistical analysis of laser micropolishing process

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Abstract—Laser micropolishing (L μ P) is a new advanced material microprocessing technology that attempts to smooth the original surface geometry through laser-material interactions such as melting or material ablation. Despite the significant advantages of L μ P micro features, surfaces, parts, moulds and dies with complex 3D geometries from a wide range of materials, L μ P is a complicated dynamic process that requires very fine tuning of a number of process parameters related to laser, optics, laser beam motions, and material properties. This paper describes a new approach for statistical analysis of L μ P, where L μ P is considered as a single-input (original surface) / single-output (polished surface) dynamic system. Original and polished cross-sections were obtained experimentally and their statistical characteristics, such as, surface roughness, material ratio function and autospectrums were calculated and analysed. In addition, L μ P process was experimentally investigated as a dynamic operator represented by a transfer function and it was analysed using a coherence function *s*. Analysis of these characteristics allowed finding specific characteristics of the L μ P process when surface roughness was improved by 21.3 %, lowering averaged *Ra* value from 577 nm to 452 nm, and significantly reducing *Ra* non-uniformity from 132 nm to 44 nm for a Ti6Al4V sample.

Keywords— laser; micro; polishing; modelling; statistics; experiment; analysis; surface; quality; roughness

I. INTRODUCTION

Surface finish is one of the most important quality characteristics of machined components and products. In general, metallic surfaces of the products that require high surface quality, e.g. optical parts, are polished manually during the finishing process in order to attain the desired surface accuracy after the primary manufacturing process [1]. However, the polishing process often requires advanced technical skills and long lead-time, which ultimately results in high production costs. Alternative methods such as robot-based mechanical and abrasive polishing [2], are also limited to simple geometric profiles and wide-opened surface areas. Another alternative technology is polishing by laser radiation [3], which has been receiving increasing attention from both industrial sectors and research communities over the last 10 years [3-10].

During the laser polishing (LP) process, a laser beam is used as an energy delivery tool to modify the surface geometry

through laser-material interactions within the processing zone along laser beam trajectory. The LP technology has several advantages over the conventional polishing techniques. The absence of mechanical forces and deformations enables the process to even polish complex 3D geometries that have a very thin wall. High-precision selective laser polishing with the ability to control laser/motion related process parameters allows achieving repeatable superior surface quality.

Results achieved at Fraunhofer Institut Lasertechnik [3,4,6-9] have indicated that laser polishing can successfully compete with manual polishing, which has a typical polishing rate of 10–30 min/cm². Efficient laser polishing of injection-moulded tools can be achieved using fiber-coupled Nd:YAG lasers with pulsed and continuous laser radiation of 40-400 W achieving a polishing speed between 0.2 and 5 cm²/min. As an example, a simple geometry on DIN 1.2343 tool steel with an initial electro discharge machined surface was laser polished using a multi-pass approach. Several passes with a polishing rate between 1 and 5 min/cm² were applied to reduce the initial roughness from *Ra* $\approx$ 3 μ m to *Ra* $\approx$ 0.3 μ m producing laser polished surface with a homogenous structure, slightly higher hardness, and no cracking [5].

Poprawe and Schulz [10] performed LP of metal surfaces produced by a selective laser melting process with an initial surface roughness of around *Ra* = 30-50 μ m. The LP with 200 ns laser pulses was applied resulting in reduced surface roughness to *Ra* = 2.7 μ m as the first step. At the second step, surface roughness was improved further up to *Ra* = 0.2 μ m using an “InnoSlab” laser with 15 ns pulse duration and scanning with a polishing rate of about 2 min/cm².

Laser micropolishing (L μ P) has been initially investigated by Perry *et al.* [11-13], where micromilled Ni and Ti6Al4V samples were L μ Ped using a 250 W, 1064 nm, Q-switched Nd:YAG laser. Laser pulses with a duration of 650 ns and a frequency of 4 kHz delivered by a scanning head moving the laser beam with a speed of 35mm/s have produced a line with surface roughness of 77 nm vs original roughness of 115 nm [11]. In addition, the effect of laser pulse duration and feed rate of surface quality of L μ Ped Ni samples was investigated [12]. Results have shown that laser pulses with long duration, e.g. 650 ns vs 300 ns, are more suitable for L μ P surfaces having longer wavelength roughness. Although significant

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efforts have been made modelling and analysing micro- and macro-LP processes, more detailed analysis and development towards practical industrial applications is required, especially in terms of better understanding of LP mechanism, optimization of variety of process parameters for LP of complex 3D geometries, automatic process planning and other research tasks.

This paper demonstrates statistical approach to experimental analysis of L μ P process, where both original and polished surface cross-sections are considered as a 1D random process along laser beam trajectory. Before and after polishing cross-sections are obtained experimentally and their statistical characteristics, such as, autocorrelation function and autospectrums are calculated and analysed. In addition, L μ P process is experimentally investigated as a dynamic operator transforming original surface cross-section (as an input) into polished surface cross-section (as an output) using calculated transfer and coherence functions between these cross-sections. Experimental results support proposed input-output approach for future analysis considering L μ P as a dynamic system.

II. INPUT-OUTPUT APPROACH FOR MODELLING AND ANALYSIS OF LASER MICROPOLISHING PROCESS

Laser polishing process is a CNC-based technology where continuous or pulsed laser beam is applied according to a prescribed laser beam trajectory for material melting and/or removal. Each laser pulse melts a certain quantity of material and produces a smooth spot in the workpiece material. The geometry and the volume of material polished depend on the material properties and the laser-material interaction process parameters related to laser, optics and motion. Fig. 1 shows the schematics of the laser micropolishing process, which has a main functional goal to smooth original surface geometry to the desired polished surface through laser-material interactions and using set of process parameters related to machined material, laser, optics and laser beam motions.

Taking into account main functional goal of LP to modify the geometry of original surface achieving better surface quality, LP process can be understood as a dynamic transformation of the original surface into the polished surface. It is common in manufacturing science representing surface

Figure 1. Generalised schematic of laser micropolishing process (a) and its statistical model (b).

geometry as a 1D (e.g. surface cross-section) or 2D (e.g. surface area) spatial random process, where surface amplitude is a random variable of one, $h(x)$, or two, $h(x, y)$, linear coordinates along the surface, respectively. Therefore, using control theory [14] and correlation/spectral analysis [15] of dynamic systems and L μ P schematics as shown in Fig. 1, L μ P process can be considered as a mathematical operator, $w(\cdot)$, transforming original, $z(x)$, into polished, $h(x)$, surface geometry in 1D case for surface cross-sections. In space domain this transformation can be described by the classical convolution integral as [14,15]:

$$h(x) = \int_{-\infty}^{\infty} w(\eta) z(x - \eta) d\eta \quad (1)$$

where $w(\eta)$ is the weighting function. Fourier transformation of (1) produces a direct frequency-domain description [14,15] of the L μ P given as:

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

where $W_{zh}(j\omega)$ is the transfer function of L μ P process; $S_{hz}(j\omega)$, $S_{zz}(\omega)$ and $S_{hh}(\omega)$ are the cross-spectrum and autospectrums of original and polished surface cross-sections, respectively; ω is the spatial frequency, and $j = \sqrt{-1}$ is the imaginary unit.

Description presented above allows understanding and modelling of L μ P process as a single-input/single-output dynamic system. In this case, complete description of L μ P process is only possible when both statistical characteristics of original and polished surfaces and dynamic characteristics of L μ P process as a dynamic operator are known.

III. EXPERIMENTAL SET-UP AND METHODOLOGY

The experimental set-up for the L μ P process is shown in Fig. 2. The L μ P system was developed at NRC-CAMM and consists of a high-precision 5-axis motion system and a 532 nm, 30 W, Q-switched Nd:YAG laser from Coherent (model AVIA 532 30). The motion system is controlled by a CNC motion controller from Aerotech with a position resolution of 0.1 μ m such that accuracy and repeatability of laser beam motions was ensured. In addition, to allow high-speed 2D scanning within 10x10mm working envelope, the laser beam was directed to a 2-axis Scan Head, manufactured by Nutfield (model XLR8) and with an f-theta objective having a focal length of 160 mm. Laser focal position was confirmed through single spot analysis.

The experimental methodology was consisted of three primary steps: a) measurement of original surface geometry $z(x, y)$ between alignment marks, b) performing L μ P experiments on previously measured surface, and c) measurement of polished surface geometry $h(x, y)$ using marks for alignment with respect to original surface profile. The sample surfaces before and after polishing were measured using a WYKO NT1100 white light interferometer having a 1Å height measurement resolution and with a sampling period of 0.48 μ m. Matching marks were made on the sample to ensure

Figure 2. Experimental set-up for 5-axis laser micropolishing.

the alignment of surface profiles obtained before and after polishing. Fig. 3 shows examples of the surface geometries obtained before and after L μ P.

For the scope of this paper, statistical analysis was applied onto surface cross-sections only. Therefore, cross-section profiles were extracted along laser path trajectory (center of the L μ P line) for both original, $z(\ell)$, and polished, $h(\ell)$, surface cross-sections. Further, statistical analysis of $z(\ell)$ and $h(\ell)$ and dynamic analysis of $W(j\omega)$ was performed. This experimental methodology and data analysis methodology has some advantages over previous research work where initial surface was not taken into account, since real surfaces after machining have non-uniform distribution of geometry across entire surface. In addition, comparison of original and polished geometries can give a better understanding on how exactly particular features of the original surface were transformed into polished surface, e.g. how a distinct high peak or a combination of a high peak and following deep valley will be smoothed.

Additional attention was placed on analysis of components of surface cross-sections, such as form, waviness and roughness profiles. These surface components were separated within well-defined bandwidths according to ISO 4287 and ISO 11562. Separation was performed by filtering with a proper cutoff wavelength (single measured length) of 0.8 mm according to ISO 4288 prior to main statistical analysis to ensure extracting reliable information for establishing proper functional correlation.

IV. STATISTICAL CHARACTERIZATION OF MICROPOLISHED SURFACE

L μ P experiments were performed along single 5 mm line with a laser power of 3 W, focal offset of 1 mm above the surface, laser pulsing frequency of 150 kHz, and scanning feed rate of 15 mm/s under argon shielding. Surface geometries of these L μ P experiments were selected for further statistical and dynamic analysis based on best up-to-date results in L μ P

Figure 3. Examples of surface geometries obtained before and after L μ P.

Ti6Al4V samples. Therefore, effect of each process parameter on geometric quality of L μ P surfaces was not analysed in the current study. All statistical parameters and characteristics were calculated for each 0.8 mm measured segment along total measuring length of 4 mm according to ISO 4288.

Fig. 4 shows a comparison of original and polished surface cross-sections and their waviness and roughness profiles. It is necessary to note, that waviness is not significantly affected by L μ P. Waviness height (peak-to-valley value according to ISO 4287) is changing minimally from 1.52 μ m to 1.43 μ m for original and polished waviness profiles, respectively (see Fig. 4b). Surface roughness profile is affected more significantly by the L μ P lowering averaged R_a value from 577 nm to 452 nm that corresponds to 21.3 % averaged improvement. Roughness for original surface was varying within measured length for each measured segment from 526 nm to 658 nm and definitely affected polished surface roughness. However, deviation within polished roughness was reduced to 44 nm (437 nm...481 nm range) compared to a deviation of 132 nm for original roughness making polished line smoother and more uniform.

Within several ISO standards that estimate amplitude parameters of the surface quality, e.g. ISO 4287, ISO 4288, ISO 11562, ISO 14565, standard ISO 4287 can be more applicable for justifying effect of L μ P. According to ISO 4287, material ratio is the ratio of the material-filled length to the measured length at the profile section level. Material rate as a function of the profile section level forms material ratio curve. Fig. 5 shows comparison of material ratio functions (MRFs) for original and polished surface roughness profiles.

MRF shows the distribution of material between the highest and lowest peaks in the surface. Redistribution of material after L μ P changes the MRF's slope and the amount of material below and above the middle surface line. L μ P not only reduces a number of sharp high peaks and deep trenches, but also it makes surface geometry more smooth and uniformly distributed, which is indicated by levelling MRF (see Fig. 5). In ideal case, when surface is completely flat and uniform, MRF becomes horizontal.

Another classical statistical characteristic of random processes are autocorrelation function and autospectrum [15]. In addition to the above surface height distribution characteristics, these statistical characteristics uncover presence and correlation/spectral properties (e.g. correlation, amplitude, phase, and spatial frequency) of periodical structures (e.g. spatial harmonics) which can result from applied material processing technology.

Fig. 6 shows comparison of auto-correlation functions of original and polished roughness profiles. It is necessary to note that auto-correlation functions have different shape meaning that original and polished roughness profiles have different statistical organization. Another confirmation that polished roughness profile is more smooth and uniform is obtained by comparison of variance values, which are $0.65 \mu\text{m}^2$ and $0.34 \mu\text{m}^2$ for original and polished roughness profiles, respectively.

Figure 4. Comparison of original and polished surface cross-sections (a) and their waviness (b) and roughness (c) profiles.

Figure 5. Comparison of material rate function.

Fig. 7 shows comparison of autospectrums of original and polished cross-sections. Visual analysis of autospectrums indicates that L μ P process does not significantly change low frequency (between 2 mm^{-1} and 15 mm^{-1}) components since two most sizeable periodic components with frequencies of 2.6 mm^{-1} and 6.1 mm^{-1} are presented in both original and polished surfaces. This means that the surface is more dominated by the longer spatial periodicities. This is why polished surface visually tends to look wavy. Bandwidth above 15 mm^{-1} is mostly affected by the L μ P process reducing amplitude of surface roughness.

Detailed analysis of autospectrums of original and polished waviness profiles in frequency bandwidth below 2 mm^{-1} is presented in Fig. 8. Analysis indicates that waviness is increased in the polished surface. This effect takes place probably because of the molten/polished material is redistributed into surface waviness and therefore location and amplitude of spectral components within auto spectrum of the entire surface are changed.

Figure 6. Comparison of autocorrelation functions of original and polished roughness profiles.

Figure 7. Comparison of autospectrums of original and polished surfaces.

V. STATISTICAL ANALYSIS OF LASER MICROPOLISHING PROCESS

The laser micropolishing process is based on thermodynamics, thermofluidics and other physical-mechanical processes which are involved in laser-material interactions, where four major categories of parameters play a critical role in the optimal polishing process. These four categories are – workpiece-, laser-, optics- and motion-related process parameters. Workpiece-related process parameters involve original (unpolished) surface geometry and physical-mechanical properties of workpiece material. It was recognized in several studies that original surface roughness and waviness directly influence the achievable polished surface quality. A laser by itself is a very complex opto-electro-mechanical system, whose major characteristics include laser power, pulse energy, pulse frequency, pulse duration, wavelength, focal distance, focal spot diameter, beam orientation (angles of incidence), etc. These are the main contributors to successful laser polishing. Another critical category of process parameters are related to travel motions and include travel/scanning speed, tool path trajectory, trajectory offset, etc. Integrated process parameters involve parameters from other categories, e.g. pulse overlap is calculated based on focal spot diameter, travel/scanning speed and pulse frequency, or they are induced by the thermodynamics of laser-material interactions, e.g., melting depth, heat affected zone, etc. Taking all of the above mentioned process parameters into account, development of an accurate physical or mathematical model of the LP process will be extremely difficult. Therefore, system approach can be taken as a first approximation considering L μ P process as a dynamic system transforming original surface into polished surface for any given set of process parameters. Characterisation and

experimental identification of L μ P process as a transfer function (TF) (also known as a frequency response function) can be performed using control theory [14] and correlation/spectrum analysis [15]. The physical interpretation of the L μ P TF is straight forward. For an ideal L μ P process it can be understood as a transformation of sinusoidal surface profile with a spatial frequency ω (input) into a sinusoidal surface profile with the same spatial frequency ω (output) but with lower amplitude. Also, as materials melts, fills the cavities and relocates following laser path trajectory during the L μ P, the output sinusoidal surface will be shifted in phase, φ , from the input as follows:

$$z(\ell) = A_z \sin(2\pi\omega\ell) \text{ and } h(\ell) = A_h \sin(2\pi\omega\ell - \varphi) \quad (3)$$

In this study, L μ P TF was experimentally obtained through measuring surface geometry before and after polishing and direct calculation using (2). Fig. 9 shows an experimentally obtained magnitude of the transfer function, $|W_{zh}(j\omega)|$, between original and polished surface profiles including waviness and roughness profiles. Obtained L μ P TF has three distinct features that characterise dynamics of L μ P process.

Fig. 10 shows low frequency bandwidth (below 10 mm $^{-1}$) of $|W_{zh}(j\omega)|$ where a small gain of 0.3 dB within waviness bandwidth can be observed. It confirms the fact already shown in comparison of autospectrums of original and polished surfaces (see Fig. 8) that waviness was slightly increased for performed experiment. Secondly, roughness profile in low frequency bandwidth (between 1.5 mm $^{-1}$ and 10 mm $^{-1}$) and in particular two spectral components with frequencies of 3.1 mm $^{-1}$ and 6.6 mm $^{-1}$ also are increased in the amplitude. It confirms the fact that for applied L μ P process parameters the geometry of roughness profile in high frequency domain (above 15 mm $^{-1}$) was redistributed into low frequency domain (between 1.5 mm $^{-1}$ and 10 mm $^{-1}$) increasing amplitude of existed and/or newly formed surface periodicities. Third observation can be made that the general shape of the L μ P TF falls off monotonically. This observation allows approximate the L μ P TF by a 1st order aperiodic (inertial) dynamic link as

$$W_{zh}(j\omega) = K / (1 + Tj\omega) \quad (4)$$

where K and T are the gain and delay coefficients, respectively. Results of identification of parameters K and T and digital simulation of (4) are shown in Fig. 9.

Figure 8. Detailed analysis of autospectrums of waviness profiles.

Figure 9. Magnitude of the L μ P TF between original and polished surface.

Figure 10. Magnitude of the L μ P TF within low frequency bandwidth.

In addition, in order to understand if obtained L μ P TF can be modelled as a linear or non-linear dynamic operator, a square of coherence function, $G_{zh}^2(j\omega)$, was calculated and shown in Fig. 11. Visual analysis of coherence function indicates that $G_{zh}^2(j\omega)$ falls off monotonically to a value of 0.8 up to a spatial frequency of 23.7 mm $^{-1}$. Based on a statistical and physical meaning of coherence function [15], it is statistically valid to say that L μ P TF can linearly relate original surface, $z(x)$, into polished surface, $h(x)$, with 80% probability, and L μ P TF can be described as a linear single-input (original surface)/single-output (polished surface) dynamic system within a bandwidth up to 23.7 mm $^{-1}$.

Figure 11. Square of coherence function between original and polished surface

VI. SUMMARY AND CONCLUSIONS

This paper introduced and described a statistical analysis of laser micropolishing process. Novelty of the proposed approach consists in description of L μ P as a dynamic transformation of original into polished surface. Several statistical characteristics of measured original and polished geometries, such as, surface roughness, material ratio function and autospectrums were analysed. In addition, a transfer function of L μ P process was experimentally investigated and its parameters were identified. From the results obtained, the following conclusion can be drawn:

- L μ P is a complex physical-thermo-mechanical process, where in addition to laser, optics, material, and motion-related parameters, original surface geometry plays a critical role in formation of the polished surface.
- It was found that L μ P significantly reduces Ra from 577 nm to 452 nm with an improvement of 21.3%. The improvement is also confirmed by the material rate function making polished surface smoother and uniform. However, L μ P was not found to have any radical effect on surface waviness for experiments performed.
- The differences in terms of statistical organization between original and laser polished surface was observed by comparing the autocorrelation functions, autospectrums and transfer function. These characteristics confirmed the L μ P improves roughness profile by redistributing high frequency components (above 15mm $^{-1}$) into lower frequency domain (between 1.5mm $^{-1}$ and 10mm $^{-1}$).
- The L μ P transfer function between original and laser

polished surface was deduced using the experimental data. Analysis of TF exhibits three distinctive features of L μ P, viz. (1) waviness is slightly increased; (2) the geometry of roughness profile was redistributed from high to low frequency domain, and (3) the L μ P TF can be approximated by a 1 st order aperiodic dynamic link as its general shape falls off monotonically.

- Coherence function statistically allowed the L μ P TF to linearly relate the polished to original surface, enabling description of L μ P as a linear single-input/single-output dynamic system within a bandwidth up to 23.7 mm $^{-1}$. This system approach opens a new research topic for modelling, monitoring, optimization and control of L μ P process.

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