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Title:

Experimental Analysis of Applicability of a Picosecond Laser for Micro-Polishing of Micromilled Inconel 718 Superalloy

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ABSTRACT

An increasing number of recent technological advancement is linked to the widespread adoptions of ultra-short pulsed lasers, namely picosecond and femtosecond lasers in various applications of material processing. The superior capability of ultra-short pulsed lasers, such as picosecond (ps) lasers is associated with the precise control of laser-material interaction as a consequence of extremely short interaction times resulting in almost-negligible heat affected zones. Therefore, ps lasers are widely used to perform laser micromachining, texturing, patterning/structuring, scribing, cutting and drilling. In this context, the present study explores the applicability of a picosecond laser in laser micro-polishing (L μ P) of Ni based superalloy Inconel 718 (IN718). The melting regime, a mandatory phase for L μ P process, is determined experimentally by the variation of the focal offset for attaining the desired level of fluence. The initial surface topography was prepared by the micromilling operation with a stepover of 50 μ m and scallop height of 2 μ m. The L μ P experiments were performed at 5 different levels of fluence associated with the melting regime by changing the focal offset, a parameter that denotes the working distance between workpiece surface and focusing lens focal plane. The L μ P performance is evaluated based on the distribution of line profiling average surface roughness (R_a) along laser path trajectory at various spatial wavelength intervals. Furthermore, additional statistical metrics, such as material ratio and power spectral density functions are analyzed in order to establish the process parameters associated with best achievable surface finish. The applicability of ps L μ P is demonstrated in two regimes – 1D (line) and 2D (area) polishing. During 1D L μ P, significant (~52%) improvement of the surface quality was achieved by reducing an R_a value from 0.50 μ m before polishing to an R_a value of 0.24 μ m along laser path trajectory on initially grinded surface. In addition, an initially micromilled area of 4.5 mm $\times$ 4.5 mm was L μ Ped resulting in the reduction of an areal topography surface roughness (S_a) value from 0.435 μ m to 0.127 μ m (70.8% surface quality improvement).

Keywords:

Laser micro polishing, Inconel 718, picosecond laser, melting regime, focal offset, laser fluence, surface quality

INTRODUCTION

The texture and finish of the surface topography of mechanical components has important effects on their functionality, visual appearance and tribological properties. The significance of such surface properties 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 [1, 2]. The conventional finishing methods, such as manual polishing, mechanical polishing, chemical-mechanical polishing are ineffective in the case of miniaturized products due to the difficulties associated with high processing time and limited accessibility for selective area polishing [3]. By contrast, micro-polishing by pulsed laser radiation is presently regarded as a valuable alternative for alteration of the surface topography. In this process, a thin layer of workpiece material is melted as a result of laser-material interaction under the melting regime. The reduction of surface asperities results from the volumetric redistribution of molten material under the influence of surface tension followed by rapid solidification. Laser micro-polishing (L μ P) is performed predominantly by nanosecond (ns) pulsed lasers employing a pulse width between 20 ns and 1000 ns [2–5]. 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 [3,6]. In general, the L μ P process is based on the thermo-mechanical properties of the workpiece material and original surface topography. The surface quality of almost all known engineering materials can be enhanced through laser polishing.

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 types of material processing technologies, including, micromachining, micro-texturing/patterning and micro-drilling owing to their superior ability to form narrow heat affected zones as a result of extremely short laser-material interaction time [7–10]. In perspective of such extensive implementations of ps lasers for materials processing, the current research presents an experimental study on the applicability of a ps laser for micro-polishing of Ni based superalloy Inconel 718 (IN718) sample with a top surface prepared by the micromilling operation. The preliminary tests were required to establish the appropriate range of laser fluence in order to obtain the melting regime. This task was carried out through varying the fluence by changing the focal point location with respect to the sample surface. The sample of IN718 alloy with top surface prepared by the grinding process was initially used in experiments as grinding forms surface topography with a broad spectrum of spatial frequencies. Then, final polishing experiments were performed on a micromilled sample using a fluence level corresponding to the melting regime initially identified experimentally. Polishing performance was evaluated with respect to the line profiling average surface roughness (R_a) distributed within various spatial wavelength intervals. Finally, additional statistical analysis using power spectral density function and material ratio function (MRF) was carried out to determine the efficiency of L μ P in changing surface topography amplitudes and their distribution at various spatial frequencies.

PICOSECOND PERSPECTIVE OF L μ P PROCESS

Ultra-short (e.g. ps) pulsed 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 the 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 [9]. However, as this study will show, 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.

The ps laser material interaction in the context of formation of the melting regime and its comparison with the melting regime formed by an ns laser is schematized in Fig. 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 [11, 12]. 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 [13]. 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.

Figure 1

Ultra-short ps lasers offer several advantages over longer pulsed lasers, e.g. ns lasers. The superior capabilities of these lasers are associated with the short pulse duration along with the repetition rates ranges in several MHz; the higher repetition rate divides the total pulse 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 Fig. 1) [10]. 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 material processing with the same micromachining system set-up.

METHODOLOGY

Experimental set-up and material considerations

The modular multi-functional micromachining system MICROGANTRY nano5X by Kugler GmbH (Salem, Germany) was used in this study. This system integrates several micromachining technologies along with measurement instrumentation. Micromachining technologies are micromilling with an 180,000 rpm spindle, fly cutting with a 2,000 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. The system is installed at the National Research Council of Canada (NRC) in London, Ontario, Canada.

Fig. 2 shows a schematic diagram and photograph of the ps L μ P experimental set-up. The ps

MOPA laser having a maximum power of 12 W, pulse width of 10.5 ps and repetition rate up to 8.2 MHz was operated with a wavelength of 1064 nm. In order 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 laser-material interaction zone (Fig. 2). 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 L μ P experiments.

Figure 2

Polishing experiments were performed on a flat sample of Ni-based superalloy Inconel 718 (IN718). 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) [14]. 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 [15–17].

Determination of the melting regime

As stated earlier in this paper, the ablation and the melting phenomena by picosecond laser-material interactions primarily depend on the applied fluence (amount of energy per pulse on a unit area). The highest level of the fluence is generated when the beam is precisely focused on

the top surface of the workpiece for a given set of process parameters, such as, travel speed, pulse repetition rate and pulse energy. The fluence value at the focal point would be sufficient to cause ablation provided that it exceeds the ablation threshold of the material to be processed. By offsetting the focal point at a certain distance above or below the workpiece top 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.

Fig. 3 illustrates the formation of ablation, transition and melting process regimes at different offset distances. The ablation regime is formed when the beam is focused primarily on or near the workpiece top 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, usually called as working distance, coincides with the focal length f . In general, working distance is the sum of the focal length f 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/below the workpiece, the ablation regime persists within an interval from zero to the focal offset threshold of transition regime h_t , as shown in Fig. 3. 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 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.

Figure 3

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 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 identification of the three main processing regimes is detailed in the following subsections.

Table 1

Formation of the ablation regime. The conventional assessment of material ablation employs the total depth and the rate of material removal per pulse [18, 19]. 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. Note that 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, Fig. 4 shows the surface topography of an ablated laser track and corresponding average cross-section surface profile across the laser path trajectory created at a 0.6 mm focal offset. The laser ablated trench can be noticed along the laser processing direction (Fig. 4a and 4b) 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). 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 Fig. 4b. 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/cm² (see Table 1). The parameters associated with this regime are highly relevant when performing micromachining through laser ablation.

Figure 4

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 1). The surface topography of the laser track created in this regime is shown in Fig. 5. 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.

Figure 5

Formation of melting regime. The melting regime was found within the focal offset range of 0.8–1.2 mm with the corresponding fluence range of 0.18–0.13 J/cm². The presence of this regime is compulsory for the L μ P with its set goal of improving surface finish. Fig. 6 presents the surface topography of the melted track created at the offset of 1.0 mm and the fluence of 0.16 J/cm².

Figure 6

The surface profile in melting regime is generated by successive re-distribution and re-solidification of molten material resulted from laser material interactions. Therefore, based on the initial surface topography and the melting depth, the surface cross-section heights in the processing zone will differ in the form of distinct height profile. For an instance, molten material from the surface peak is driven towards the valley by surface tension. Therefore, the cross-section surface height profile along the peaks and the valleys is decreased and increased, respectively. In this regard, Fig. 7 presents the surface cross-section height profile along a specific initial peak and a valley for the surface profile shown earlier in Fig. 6. Relative decrement and increment of surface profile heights along the surface peak and the valley are observed in Fig. 7 as it has been stated previously.

Figure 7

It is worthwhile to mention that relative increment of average surface cross-section in the laser processing zone may generate from the ripples resulted from the higher amount of peripheral melting of the surface profile [20, 21]. The rippling phenomenon is not prevalent in ps L μ P. However, melting depth resulted from the ps laser-material interaction is adequately high to cause redistribution of initial surface spatial components into a new domain.

Additionally, average line profiling roughness (R_a) cross-section profiles across the laser path trajectory were calculated in order to study the melting regime. Fig. 8 demonstrates the R_a cross-section profile along with the top view of laser processed track shown in Fig. 6. The profile shown in Fig. 8a 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 position of 60 μ m, specified on the profile with a red dot (see Fig. 8a), was calculated by averaging all the dispersed

R_a values along the red dotted line at 60 μm evaluation position in the direction of the laser path trajectory (see Fig. 8b). It can be inferred from Fig. 8a, the R_a value of 0.50 μm for the unpolished profile was decreased to a R_a value of 0.24 μm within the laser processing zone. As such, the identified melting regime and corresponding process parameters become extremely important when attempting to improve the surface quality through the ps L μ P process.

Figure 8

For the evaluation of laser polishing performance, average line profiling surface roughness and waviness (R_a and W_a , respectively) were determined along the laser path trajectory by following the procedure depicted in authors' previous publication based on the standard ISO 4288 [22,23]. It involved: (1) measurement of surface profile by the optical profilometer for a sampling length associated with certain range of expected R_a value, (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. The cut-off length between the surface roughness and the waviness was chosen to be 800 μm for an expected R_a range of 0.1–2.0 μm [23]. A summary of these results presented in Table 2 shows that the ps laser did not alter the surface waviness rather reduced the roughness to some extents. 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 2

Methodology: surface roughness distribution at spatial wavelength intervals

The calculated results of the surface topography conventional indexes presented in Table 2 are influenced significantly by the measurement scale and the cut-off length specified by the

standard ISO 4288. Since surface quality improvement in laser polishing can be statistically represented as the redistribution of initial spatial frequency 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 context, polished surface topography and its quality parameters within different wavelength intervals were estimated by the discrete convolution between the primary profile and the weighing function of the low-pass Gaussian filter that defines required wavelength intervals [24]. The Gaussian filter for discrete convolution was developed by the algorithm prescribed by Yuan *et al.* [25].

The Gaussian filter is recommended by the ASME B46.1 and ISO 16610-21 standards in order to separate surface waviness and roughness profiles [25–27]. The weighting function of this filter is given by [25]:

$$f(\ell, \lambda) = \frac{1}{\alpha\lambda} e^{-\pi\left(\frac{\ell}{\alpha\lambda}\right)^2} \quad (1.0)$$

where, $\alpha = 0.4697$, ℓ is the independent variable in the spatial domain known as the surface profile evaluation length (sampling length), and λ 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 λ . It is worthwhile to mention that $h(\ell)|_0^\infty$ represents the initial surface profile that theoretically contains all the wavelength components from 0 to ∞ , where short and long wavelengths components are represented by high and low spatial frequency components, respectively. In general, the initial profile $h(\ell)|_0^\infty$ 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. LuP), it is important to treat these components separately by considering their

importance in the context of the 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 Gaussian filter fitted with a predefined cut-off wavelength (λ_c) the roughness and the waviness can be separated after that. The average line profiling surface roughness (R_a) value can then be calculated for n measured points on a roughness profile from the following equation:

$$R_a = \frac{1}{n} \sum_{i=1}^n |r(z_i)| \quad (2.0)$$

where, $r(z_i)$ for $i=1.....n$ is the roughness profile designated as profile $h(\ell)|_0^{\lambda_c}$. In practical measurements, the surface roughness profile $h(\ell)|_0^{\lambda_c}$ is extracted from the primary profile $h(\ell)|_0^{\infty}$ using the λ_c to be selected based on the expected R_a in accordance to the standard ISO 4288. However, in order to perform discrete convolution at various spatial wavelength intervals for hypothetical λ_i , the extraction of interval roughness profiles are obtained by successive convolution and subtraction operations as depicted as follows:

$$h(\ell)|_{\lambda_1}^{\infty} = f(\ell, \lambda_1) * h(\ell)|_0^{\infty} \quad (3.1)$$

$$h(\ell)|_0^{\lambda_1} = h(\ell)|_0^{\infty} - h(\ell)|_{\lambda_1}^{\infty} \quad (3.2)$$

$$h(\ell)|_{\lambda_2}^{\infty} = f(\ell, \lambda_2) * h(\ell)|_0^{\lambda_1} \quad (4.1)$$

$$h(\ell)|_{\lambda_1}^{\lambda_2} = h(\ell)|_0^{\lambda_1} - h(\ell)|_{\lambda_2}^{\infty} \quad (4.2)$$

$$h(\ell)|_{\lambda_i}^{\infty} = f(\ell, \lambda_i) * h(\ell)|_0^{\lambda_{i-1}} \quad (5.1)$$

$$h(\ell)|_{\lambda_{i-1}}^{\lambda_i} = h(\ell)|_0^{\lambda_{i-1}} - h(\ell)|_{\lambda_i}^{\infty} \quad (5.2)$$

In this case, 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:

$$R_a \Big|_{\lambda_{i-1}}^{\lambda_i} = \frac{1}{n} \sum_{i=1}^n |h(\ell_i)|_{\lambda_{i-1}}^{\lambda_i} \quad (6.0)$$

In the present study, the same cut-off wavelength (λ_c) of 800 μm was considered for a probable R_a range of 0.1–2.0 μm in accordance to the standard ISO 4288. The surface waviness profile was defined to be entailed within the interval of 800–1600 μm , where the maximum value of this interval was determined by doubling the λ_c value. This λ_c of 800 μm 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 μm . 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 μm , 12.5–25 μm , 25–50 μm , 50–100 μm , 100–200 μm , 200–400 μm and 400–800 μm . The use of Eq. 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 used typically 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 in perspective of polishability of the wavelength component is illustrated in Fig. 9, 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 λ_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 L μ P, a step-over value of λ_2 can be recommended as the step-over for initial micromilling in the context of the highest level of polishability. It is also important to note that machining time for surface preparation with λ_3 step-over will be twice as long as for machining with a step-over of λ_2 .

Figure 9

An example of the R_a distribution at various spatial wavelength intervals for the grinded surface is presented alongside its roughness cross-section profile in Fig. 10. The average value of rough cross-section is 0.70 μm calculated for the wavelength interval of 0 to 800 μm (Fig. 10a). On the contrary, 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.

Figure 10

Analysis of ps L μ P of grinded IN718 sample

Based on the surface roughness analysis methodology described in the previous subsection,

the polishing results presented in Table 2 were recalculated and presented in Fig. 11. In this case, the spatial R_a spectrum was calculated across the initial grinding marks and 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 ps L μ P was found to be more effective at lower (less than 200 μm) wavelength intervals as shown in Fig. 11. However, for spatial components longer than 800 μm wavelength, the process was found to be virtually ineffective. 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 five trials. This observation implies that the primary manufacturing process, e.g., micromilling should induce a surface profile with the periodicity not exceeding 12.5 μm for attaining the best possible surface quality.

Figure 11

Typically, surface polishing is preceded by other primary manufacturing processes; those roles are to define the main geometric features of the components, a task that generally cannot be accomplished through the polishing operation. In the present study, it was intended to employ micromilling to generate the initial surface topography considering its versatile applications in fabricating wide categories of functional micro components. Nevertheless, generating a surface profile with a small periodicity of 12.5 μm by micromilling is fairly time consuming and often inappropriate for a difficult-to-cut alloy like IN718. In contrast to that, a surface profile with a very high periodicity is not polishable as revealed by the illustration depicted in Fig. 11. In this perspective, it is imperative to select an appropriate level of step-over for initial micromilling with regards to both practical feasibility as well as surface quality improvements attributed by polishability.

Experimental: ps L μ P of micromilled IN718 sample

In the present study, the initial surface to be later micro-polished by picosecond laser was prepared by the micromilling process with a 0.6 mm ball end cutter and a machining step-over of 50 μm resulting in an average amplitude height (peak-to-valley value) of $\sim 2 \mu\text{m}$ and areal topography surface roughness (S_a) of 0.53 μm . The step-over of 50 μm was chosen as it is a widely accepted parameters used in the mold and die industry. Moreover, from the analysis presented in Fig. 11, a reasonable reduction 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, the 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.

Fig. 12 shows the surface topographies and the cross-sections of the grinded and the micromilled profiles for an evaluation length of 800 μm . The cross-section profiles presented in Fig. 12c and 12d were taken across the initial grinding marks and the micromilled track, respectively. These two figures clearly indicate that the micromilled profile is more consistent than the grinded 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 $0.49 \pm 0.2 \mu\text{m}$. Since the L μ P is preferably performed in a direction perpendicular to the micromilling tracks, this high consistency and regularity of the micromilled surface will ensure a predictable behavior of the micro-polishing operation.

While performing ps L μ P 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. As such, the five polishing tracks were produced with focal offsets of 0.8 mm, 0.9 mm, 1.0 mm, 1.1 mm and 1.2 mm, and fluence values 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 Fig. 12b). Both initial (pre-polished micromilled) and final (L μ Ped) surface profiles were measured using WYKO NT1100 optical profilometer and were subsequently analyzed in a systematic and consistent manner based on the previously referred ISO 4288 standard.

Figure 12

RESULTS AND ANALYSIS

Effect of the focal offset distance

The polishing results on micromilled profile in terms of line profile average roughness (R_a) at various spatial wavelength intervals are shown in Fig. 13. It is relatively apparent from Fig. 13 that the ps L μ P process is highly effective for components within the spatial wavelength intervals of 25–50 μ m and 50–100 μ m, which practically entail the initial periodicity of 50 μ m. Drops of R_a in these intervals imply that ps L μ P could effectively improve the initial surface texture by redistributing the spatial wavelength components corresponding to the periodicity of initial profile into a new spatial domain. This effectiveness is also present at lower (<25 μ m) spatial wavelength intervals.

Figure 13

From the physical perspective of laser-material interaction these observations indicate that the applied fluence level in the melting regime induced sufficient melting depth to generate an appropriate level of surface tension for the effective redistribution of the molten materials of the initial milled profile. For longer spatial components (> 200 μ m), the L μ P process was also found to be effective but to a lesser extent. Consequently, 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 LμP 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 μm and 50–100 μm (see Fig. 13) beside other spatial wavelength intervals, in a separate plot a comparative analysis of the surface quality improvement for this particular polished profile is outlined (Fig. 14). Here the comparison is made with 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 Fig. 14).

Figure 14

Statistical analysis of the polished profiles

The spatial wavelength interval based roughness analysis (see Fig. 13) 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. From a theoretical perspective, the PSD function is a result of a Fourier transform of the autocorrelation function representing a distribution of amplitudes in frequency domain. Fig. 15 shows a comparison of the PSD function calculated for the initial (micromilled) and 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 nm²*mm. It is to be noted that the associated spatial wavelength of 50 μm represents the periodicity of the micromilled surface profile (see Fig. 12). The drastic

reduction of the amplitude down to $2.86 \text{ nm}^2 \cdot \text{mm}$ for this periodicity restates the effectiveness of ps L μ P in improving the primary surface topography obtained by the micromilling operation (see Fig. 15).

Figure 15

Since the surface roughness reduction by L μ P is owed to the volumetric redistribution of the molten material followed by re-solidifications in the melting regime, it is expected that the resulting surface profile from by L μ P will also so be characterized by the uniform distribution of the surface spatial components. In this regard, to further investigate the changes in the amplitude distributions after ps L μ P, material ratio (MR) functions for the initial as well as polished profiles were determined. The MR function is a measure of the material distribution between the highest and the lowest peaks of the surface and quantifies the amount of material located above and below a surface zero-level line [22]. The MR curve is represented by a zero level horizontal line in an ideal case of a perfectly flat surface, i.e. without any surface irregularities. However, for real surfaces the MR curve is characterized by three distinct regions, namely upswing left maximum, middle negatively inclined straight line and downswing right minimum [22, 28, 29]. The upswing left maximum value and the downswing right minimum values are nothing but the maximum peak height (R_p) and maximum valley depth (R_v) of the surface cross-section profile. Based on the prior analyses, it is expected that material redistribution after ps L μ P will practically affect all the three components of MR function through the reductions of the amplitudes of R_p and R_v values, as well as in the slope between the middle straight and the zero-level lines.

Fig. 16 shows the effect of L μ P on the MR curves for initial (pre-polished) and final (polished) profiles, respectively. A summary of the parameters obtained from these plots is

presented in Table 3. It can be noticed that L μ P has reduced the number of sharp high peaks and deep valleys represented by upswing (e.g. from 1.4 μ m to 0.48 μ m in case of polished track created with 1.1 mm focal offset) and downswing (e.g. from 1.00 μ m to 0.38 μ m in case of polished track created with 1.1 mm focal offset) values. It also made the surface micro-topography more uniform, an attribute represented by the line slope reduction of the middle zone for all the polished tracks when compared to the initial profile with a slope of -20.4 nm/% (see Table 3). 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, -5.35 nm/% and -5.86 nm/% of the middle straight line.

Figure 16

Table 3

Example of ps L μ Ped surface

As a demonstration of the applicability of ps laser for micro-polishing of IN718, a flat area of 4.5 mm $\times$ 4.5 mm, initially micromilled with a step-over of 50 μ m was micro-polished using the following process parameters: laser travel speed of 600 mm/min, focal offset of 1.1 mm and laser fluence of 0.14 J/cm². The polishing resulted in 70.8% surface quality improvement through the reduction of an initial areal topography surface roughness (S_a) value of 0.435 μ m to a final S_a of 0.127 μ m. Surface characteristics and photograph of the polished area are shown in Fig. 17.

Figure 17

SUMMARY AND CONCLUSIONS

This study demonstrates the applicability of an ultra-short (picosecond) pulsed laser for potential micro-polishing applications. In particular, laser micro-polishing (L μ P) of a Ni based

super alloy Inconel 718 (IN718) samples with initially grinded and micromilled surface were investigated experimentally. The fluence level required to obtain the melting regime - an indispensable component to induce L μ P as opposed to laser ablation - was established through the incremental variations of the focal offset in order to differentiate the ablation, transitional and melting regimes. The 1D (line) L μ P experiments were performed with increasingly higher focal offsets of 0.8 mm, 0.9 mm, 1.0 mm, 1.1 mm and 1.2 mm, and fluence values of 0.18 J/cm², 0.17 J/cm², 0.16 J/cm², 0.14 J/cm² and 0.13 J/cm², respectively. Laser micro-polishing performance was evaluated through the analysis of the distribution of line profiling surface roughness (R_a) within discrete spatial wavelength intervals. Finally, initial and polished profiles were statistically analyzed using power spectral density and material ratio functions.

The following main conclusions can be drawn from the obtained results and their analysis:

- (1) An ablation regime is formed within a fluence range between 0.19 J/cm² and 0.24 J/cm² which corresponds to a focal offset between 0.6 mm and 0.0 mm (in focus). The ablation regime was determined from the changes in surface profile cross-section profile.
- (2) A narrow transition regime exists around the 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 should be avoided when performing any type of material processing operations.
- (3) A melting regime is formed when fluence values range between 0.13 J/cm² and 0.18 J/cm² 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 can be observed in this process regime (e.g. an initial R_a of 0.5 μm was reduced to 0.24 μm for the profile created at 1.0 mm focal offset).

- (4) L μ P trials were performed at 5 different focal offsets, namely 0.8 mm, 0.9 mm, 1.0 mm, 1.1 mm and 1.2 mm on a sample preprocessed by micromilling. The analysis of R_a distribution at various spatial wavelength ranges indicates that L μ P can effectively reduce surface roughness as calculated at discrete wavelength intervals, e.g. surface quality improvement up to 78.5% was found within the wavelength interval of 50–100 μm . However, the effectiveness of L μ P decreases at high spatial wavelengths. This observation is important for understanding how initial surface affects the performance of polishing by picosecond laser radiation.
- (5) Statistical analysis using power spectral density functions has also shown that L μ P can effectively reduce amplitude of the dominant frequency component associated with the periodicity of micromilled tracks from an initial value of 35.89 $\text{nm}^2 \cdot \text{mm}$ to a final value of 2.86 $\text{nm}^2 \cdot \text{mm}$. Therefore, real parts and geometries can be machined with constant step-over distance preparing surface topography for the most effective finishing operation by L μ P.
- (6) Material ratio functions of initial and polished tracks were evaluated to study the effect of L μ P on the amplitude distribution of surface roughness. The results have shown that L μ P not only reduces the heights of surface peaks and valleys but also causes surface asperities to become more smooth and uniform as demonstrated through the reduction of slopes of the MR curves with respect to zero-level mean line.
- (7) The applicability of ps L μ P is demonstrated in two regimes – 1D (line) and 2D (area) polishing. During 1D L μ P, a significant (~52%) improvement of the surface quality was achieved by reducing the R_a value from 0.50 μm before polishing to an R_a value of 0.24 μm

along laser path trajectory on an initially grinded surface. In addition, an initially micromilled area of $4.5\text{ mm} \times 4.5\text{ mm}$ was $L\mu\text{Ped}$ resulting in the reduction of an areal topography surface roughness (S_a) value from $0.435\text{ }\mu\text{m}$ to $0.127\text{ }\mu\text{m}$ (70.8% surface quality improvement).

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Table 1: Formation of different laser processing regimes at various focal offset and fluence level

Focal offset (mm)	Beam width (μm)	Fluence (J/cm^2)	Process regime
0.00	31.40	0.24	Ablation
0.10	31.70	~0.24	Ablation
0.20	32.50	0.23	Ablation
0.30	33.00	0.22	Ablation
0.40	33.60	0.21	Ablation
0.50	35.50	0.20	Ablation
0.60	35.60	0.19	Ablation
0.70	-	-	Transition
0.80	38.16	0.18	Melting
0.90	39.99	0.17	Melting
1.00	41.22	0.16	Melting
1.10	43.09	0.14	Melting
1.20	45.10	0.13	Melting

Table 2: Average line profiling surface roughness and waviness along the tool path trajectory for the profile created in the melting regime

Focal offset (mm)	Fluence (J/cm ²)	Average line profiling surface roughness, R_a (μm)		Average line profiling surface waviness, W_a (μm)	
		Initial profile	Polished profile	Initial profile	Polished profile
0.80	0.18	0.73	0.65	0.10	0.10
0.90	0.17	0.80	0.50	0.20	0.20
1.00	0.16	0.80	0.60	0.20	0.20
1.10	0.14	0.84	0.55	0.20	0.15
1.20	0.13	0.69	0.44	0.10	0.10

Table 3: Summary of the parameters generated by material ratio (MR) functions

Focal offset (mm)	Maximum peak height, R_p (μm)	Maximum valley depth, R_v (μm)	Slope coefficient (nm/%)
0.00	1.40	1.00	-20.4
0.80	0.58	0.70	-7.48
0.90	0.53	0.56	-5.90
1.00	0.50	0.51	-5.35
1.10	0.48	0.38	-5.86
1.20	0.48	0.85	-7.20

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(a)

(b)

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