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Performance of Laser Polishing in Finishing of Metallic Surfaces

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Abstract: Laser polishing is presently regarded as one of the most promising technologies hoped to eventually replace the need for time-consuming and error-prone manual polishing operations. During laser polishing, a very thin layer of material is being melted as a result of its exposure to laser beam energy. Since molten metal is characterized by increased relocation capabilities, laser polishing is typically accompanied by a more or less significant decrease in the surface roughness. The primary objective of the current study is to present a comprehensive snapshot of the advancements made over more than one decade with respect to theoretical and experimental investigation of laser polishing. However, in addition to the usual review of the state-of-the-art in the field, the study places an increased emphasis on the finishing performance of the process, defined through the perspective of pre- and post-polishing surface roughness. The implementation of this metric with strong practical implications has revealed that under appropriate process parameters, certain classes of metallic materials can reduce their average surface roughness by more than 80%, possibly to R_a = 5 nm. Nonetheless, a more rigorous and fundamental understanding of the intrinsic mechanisms underlying laser polishing remains one of the currently unfulfilled premises toward a wider industrial adoption of the process.

Keywords: laser polishing, metallic materials, polishability, process parameters, surface finish, average roughness

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Abstract: Laser polishing is presently regarded as one of the most promising technologies hoped to eventually replace the need for time-consuming and error-prone manual polishing operations. During laser polishing, a very thin layer of material is being melted as a result of its exposure to laser beam energy. Since molten metal is characterized by increased relocation capabilities, laser polishing is typically accompanied by a more or less significant decrease in the surface roughness. The primary objective of the current study is to present a comprehensive snapshot of the advancements made over more than one decade with respect to theoretical and experimental investigation of laser polishing. However, in addition to the usual review of the state-of-the-art in the field, the study places an increased emphasis on the finishing performance of the process, defined through the perspective of pre- and post-polishing surface roughness. The implementation of this metric with strong practical implications has revealed that under appropriate process parameters, certain classes of metallic materials can reduce their average surface roughness by more than 80%, possibly to R_a = 5 nm. Nonetheless, a more rigorous and fundamental understanding of the intrinsic mechanisms underlying laser polishing remains one of the currently unfulfilled premises toward a wider industrial adoption of the process.

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1. Introduction

Surface finish is commonly acknowledged as one of the standard quality metrics for mechanical components. The assessment of the surface finish attained through a specific manufacturing process is typically performed through three major indicators namely: i) topographic quality, ii) functionality, and iii) aesthetic properties. Typical definitions of these terms propose strong interdependencies between: i) topographic quality and accuracy, precision, and surface macro/micro-asperities, ii) surface functionality and tribological, optical and other physical-mechanical properties, and iii) aesthetics and visual appearance of the component. While various manufacturing methods were devised to address each of these indicators on an individual basis, polishing is one of the presently available options capable to enhance practically all of them in an efficient and consistent manner.

It is important to point out here that conventional polishing techniques (*e.g.* manual, mechanical, chemical) are typically applied in consecutive steps that require intermediate cleaning and this decreases dramatically the overall productivity of the process. Beyond this, several other factors, including the need for highly qualified personnel, the necessity to enforce extensive measures to prevent the accidental damage of the already polished surface as well as the limited extent of the automation make these techniques less attractive for manufacturers [1].

To address these known drawbacks of the conventional polishing, the contemporary manufacturing arena has been greatly enriched by the advent of enabling polishing technologies. This rapidly evolving category encompasses laser polishing (LP) as one of the newest thermal energy-based methods to be used to attain highly superior surface finish levels. While it is relatively difficult to pinpoint a specific chronological moment when this technology was invented or at least used for the first time, it can be mentioned here that a relatively similar concept was used at the end of 1980s in a microelectronics-related context [2,3].

During LP process, laser beam energy is delivered to workpiece surface in an attempt to remodel its topographic profile through laser-material interactions. While the theoretical foundations of the LP are yet to be fully understood, most researchers tend to agree in principle that the core of the process is formed by its intrinsic remelting mechanism that is essentially caused by the "liquefaction" of a superficial and thin layer of material [4]. Remelting constitutes the predominant mechanism of LP, regardless if performed in its macro- or micro-polishing variants. The molten pool of material formed tends then to redistribute around the area adjacent to each initial surface asperity under the multidirectional action of surface tension. As a result, the vast majority of peak-valley heights of the surface are reduced after the quick solidification of melted layer and surface asperities are typically reduced in case of correctly executed LP operations (Figure 1a), such that important reductions in the surface roughness become apparent (Figure 1b) regardless if analyzed in one or two dimensions. The 3D effect of LP on surface topography/texture is typically best captured with an optical white light profilometer which is capable to clearly outline the differences between the initial milled surface and the one obtained after polishing (Figure 1c). On a macroscropic level, these differences in surface quality often translate in a visible dissimilarity in the reflectivity of the surface (Figure 1d). However, it is perhaps important to note here that the complex – and currently difficult to predict – balance of internal forces that are generated during the solidification process could also be responsible for significant degradations in surface quality, an idea which underscores once more the importance of acquiring a better understanding of the internal mechanics of LP.

Laser polishing offers several significant advantages over conventional polishing. First of all, the process can be fully automated without the need for dedicate equipment, since laser head can be installed easily on a wide majority of readily available multi-axis computer numerically-controlled (CNC) stages. Regardless if used in a dual (LP and machining) or singular (LP-only) configuration, the superior ability to control all laser beam parameters (*i.e.* spot size, beam shape, beam orientation, beam energy, etc.) combine with the complete control over the motions of the CNC stage provides the LP with excellent versatility characteristics. These traits were already exploited towards high precision selective LP performed on mechanical components with intricate shapes [5,6]. Obviously, beyond the aforementioned enhanced control over process parameters, LP has inherited some of the advantages that are often cited in context of the more mature laser machining technology, namely the absence of the mechanical forces/deformation at tool/workpiece interface, along with the lack of physical wear on the polishing "tool".

Starting with the beginning of the past decade, LP has received a gradually increasing attention from both research- and application-oriented communities. It is important to note that while the original demonstrations on the capabilities of LP process were extremely promising for highly demanding mold-making and implant manufacturing industries [5], it became soon clear that a more in-depth understanding of the process will be required before its wide adoption by the industry.

The primary objective of the present study is to present a critical snapshot of the performance of the laser polishing process as reported so far in the available scientific literature. Since LP remains in essence a finishing process, the emphasis will be placed on the characterization/comparison of the process capabilities through the only parameters that is consistently reported in most of the prior works in this field, namely the average roughness. This piece of information, coupled with other associated process or setup parameters are intended to provide a minimal guidance towards the type of LP equipment to be used in a particular polishing application. As the vast majority of the current or intended applications of the LP are still geared towards metals, only this class of materials will be considered in the present study although the process has already been successfully applied on many other categories of materials.

2. Laser Polishing System: Configuration and Control Parameters

A schematic representation of the principal elements of a typical LP system is presented in Figure 2. LP systems encompass a number of electromechanical and optical components that can be divided between laser and mechanical subsystems, each of them being controlled by a broad palette of parameters.

Laser subsystem includes laser source, laser head along with its mounting on the multi-axis CNC stage, as well as the optics required to focus beam energy at the desired location. The primary role of the laser subsystem is to provide means to produce and then deliver the generated energy into the LP processing zone, which is located at or in the close vicinity of the outer surface of the workpiece.

On the other hand, the mechanical subsystem has a structure absolutely similar to that of most standard multi-axis CNC machine tools since is comprised of base, electrodrives and translation/rotation stages whose role is to enable the required relative motions between the effector tool (*i.e.* laser beam) and workpiece. In some of the builds, 2D or 3D galvanometric scanning heads are added to provide additional degrees of freedom (DOFs) to the laser beam. Since laser beam motions induced by the scanning head are optically controlled, their rates can be much faster than those provided through the mechanical stages. However, the range of motions delivered by the scanning head is extremely limited compared to their mechanical counterparts.

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

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

3. State of the Art in Laser Polishing Technology

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

3.1 Experimental Analysis

Due to the inherent complexity and novelty of the laser polishing process, a large number of studies were concerned almost exclusively with experimental investigations aiming to determine a set of parameters that will noticeably improve the quality of the polished surface. Obviously, this approach reduces dramatically the path towards rapid adoption of the technology within the results-oriented industrial environment. The experimental studies on LP tend to focus on the illustration of the effect of various input parameters on the process performance in terms of surface finish and/or processing time/volume. The selection of input parameters depends entirely on LP process type (micro or macro), workpiece surface (mechanical and thermal properties, initial surface topography etc.), and the desired level of surface finish. The current section will review the main research efforts reported so far in this category.

In one of the first attempts made in this direction, Bereznai *et al.* [7] have studied the effect of two excimer laser parameters (fluence and number of incident pulse) on the microstructure and roughness of titanium disk samples prepared through conventional machining operations. By simply varying the two aforementioned parameters, the roughness was reduced to 25 nm, a value that ensures inhibition of plaque development and maturation in dental implants, one of the common applications of the polished material. Obviously, without a proper optimization of the LP process parameters, the quality of the surface obtained will be far away from the optical precision (R_a = 4-5 nm, form accuracy = 0.5 μm) that can be achieved through more conventional polishing operations involving abrasive tools [8,9].

Many other early attempts were made to demonstrate applicability of the new technology to a broad variety of industrial applications ranging from tribological [10,11] and microfluidics [12] to medical implants and moulds [5,6,13-15], although in implant manufacturing scenario, the laser beam is expected to produce a controlled, but not necessarily extremely low roughness in order to favor the osteointegration process. In many of these studies, the selection of the process parameters was based on rather empirical principles whose details were not disclosed by the study. Nevertheless, the quality of the polished surfaces reached impressively low levels of R_a = 200 nm [6] or R_a = 150 nm [5] especially when a two step polishing approach (roughing/finishing) was adopted. The materials used in these studies included tool and stainless steel as well as cobalt-chromium alloys.

In more recent experimental studies, the number of process parameters analyzed simultaneously was increased in an attempt to maximize their impact on surface finish. In this sense, Steyn *et al.* [16] chose to vary laser power, defocus and number of layers applied on a tool steel surface, while maintaining constant pulse frequency, feed rate and step over. Their experiments revealed that quality of the polished surface depends strongly on the amount of energy delivered by the laser beam to each point of the surface, since this has a major impact on the temperature and hence the mechanism controlling the local behavior of the material. Supporting this idea, their experiments showed that higher power densities and number of layers applied will essentially lead to superior surface finishes, going to R_a = 250 nm. However, all LP parameters used in the process have to be correlated with the type of material being polished since their thermo-physical properties could span over broad ranges. The experiments performed by Dobrev *et al.* [17] with different laser offsets outlined that while almost no roughness improvements were obtained for copper, the surface finish of stainless steel could be improved by 30%. All their trials were performed with pretested and otherwise common, but essentially unoptimized LP parameters. Interestingly, they have also noticed that while stainless steel behaved identical with respect to symmetric positive and negative offsets, copper did not. The individual effect of several process parameters like feed rate, laser energy, pulse duration and pulse frequency on surface roughness and topology of DF2 tool steel was investigated in a series of studies by Hua *et al.* [18,19] and Guo [20]. While no significant roughness reductions were reported – as in most instances surface quality was dimininshed – the authors emphasized that for a given laser, the feed rate has a more prominent influence on surface finish than all other factors analyzed and later proposed used an expression of the temperature field in the polished area to explain this finding [21]. Furthermore, as the amount of energy delivered to the surface increases, the prevalent mechanism associated with laser-material interaction evolves from melting to ablation, and this in turn will degrade the overall performance of LP [22].

However, in addition to the parameters exhibiting similarities with laser machining or even other types of material removal operations, Nüsser *et al.* [23] have pointed out that beam energy distribution (*e.g.* Gaussian or top-hat) as well as beam shape (*e.g.* circular or square) are also important in LP. Their comparative analyses revealed that superior surface finishes are determined by circular-shaped beams with top-hat intensity distributions. Moreover, for a square beam, surface roughness was lower when beam advanced in a direction parallel with its edges than when moved diagonally across surface. Strong correlations were found between initial surface topography and duration of the pulses: while shorter pulses have prevalent effects on the high frequency components of the roughness (microasperities), lower frequency components (surface waviness) seemed to be more affected by longer pulses.

Without performing explicit parameter optimization studies, a different team of researchers [24] has practically reinforced the significance of previously studied LP parameters like laser power, beam size/offset distance, feed rate and step over distance/tool path overlap. Their polishing experiments involving two different types of steel and a material obtained through selective laser sintering have shown that in order to avoid the occurrence of surface over melting mechanism during polishing – that is typically associated with surface quality degradation – the energy density of the laser should be directly correlated with thermal absorption capacity of the polished material. As such, materials with low absorption capacities should be polished with lower energy densities that can be easily obtained with defocused and hence larger beam sizes. As in the previous reported cases, polishing of heterogeneous materials with large variations in their thermal properties seems to remain a challenge difficult to accommodate, such that maximum roughness decreases (70%) were measured for homogeneous materials with low heat absorption coefficients. However, depending on the actual composition of the heterogeneous material, good surface finishes seemed to attainable, as demonstrated by Yermachenko *et al.* [25] while polishing cylindrical samples of VT16 titanium, a high strength alloy belonging to Ti-Al-Mo-V system. The authors proved that a five-fold decrease in surface roughness (down to 416 nm) is possible for this material whose microhardness increases by 50-70% after LP. Similar investigations were also reported by Kumstel and Kirsch [26] who performed adjustments of the laser power, beam size and feed rate of the LP operation in order to attain significant improvements of surface quality for Ti6Al4V and Inconel 718 alloys (84% and 89% R_a reductions, respectively). The spectrum of materials that are suitable candidates for LP-based surface quality improvements enlarges permanently. As such, in addition to more conventional uses of LP on steels and titanium alloys, recent studies have proved that the surface of nickel alloys [27] as well as that of sintered bronze [28] can be smoothened through laser radiation.

A more systematic approach in investigation of the LP parameters was taken by Lamikiz *et al.* [29,30] and Ukar *et al.* [31-33] who concentrated their research on metallic surfaces produced through selective laser sintering (SLS). Their three level three factor DoE revealed that a certain combination of laser power, feed rate and focal distance – that can be expressed in a lumped form through energy density of the beam – is capable to maximize the amount of roughness reduction that in their experiments peaked around 80% (R_a = 1.2 μm), while leaving the form errors unaffected. The optimal combination of LP parameters determined by means of a simple quadratic fit involving line polishing experiments yielded reasonably good results for both planar area and three dimensional line operations. However, for these later processes, specific settings like step over distance and beam inclination angle became increasingly important. Given the rapid expansion of the additive manufacturing technologies, other research groups identified means to improve the roughness either by imposing bounds to the laser energy density delivered to the surface [34] or by employing the combination of laser surface melting (LSM) and re-melting (LSR) operations [35]. Through an appropriate tuning of the laser power, scan speeds and tool path overlap, up to 90% surface roughness decreases were obtained through LSR for stainless steel 316L (initial R_a = 15 μm) while minimal differences between LSM and LSR were observed for Ti6Al4V.

Although laser polished SLS surfaces exhibited superior homogeneity and integrity characteristics when compared to the original ones, the authors emphasized that application of

LP on materials with different melting points will continue to represent a challenge, an idea also reinforced in the context of lamellar cast iron [36], for which minimal (5%) surface roughness improvements were acquired. Along the same lines of LP process parameters optimization by means of DoE software, Dadbakhsh *et al.* [37] analyzed the effect of laser power, beam spot size and feed rate on surface roughness of flat Inconel 718 samples obtained through laser material deposition. The optimal combination of LP process parameters yielded an 80% reduction in surface roughness, corresponding to R_a = 2 μm. Once again, the strong effect of laser energy density on surface quality was reiterated, and an optimal beam spot diameter was determined, although within the analyzed parameter ranges its influence was observed as less significant than that of laser power or feed rate. A relatively similar DoE-based optimization approach was also taken by Giedl-Wagner *et al.* [38] who chose to vary laser power, pulse repetition rate, pulse overlap, step over distance, focal position and the number of repeats while performing laser ablation polishing on samples whose surfaces were generated through high speed milling. The polished samples were produced from 4 different materials (40CrMnNiMo8-6-4, X37CrNoV5-1, AlZnMgCu1.5, CuAl10Fe5Ni5-C) and both picosecond (355 nm in UV range) and nanosecond (532 nm in visible range) pulses were used. Depending on the material, important roughness reductions (around 90%) were achieved for picosecond pulses, with resulting surface finishes going down to R_a = 60 nm (X37CrNoV5-1). The other 3 materials investigated recorded lower roughness decreases, especially in case of non-steel alloys. The best results for picosecond pulses were obtained with low power and defocused beams, thus working at the ablation threshold. Since roughness reductions achieved with nanosecond pulses were considerably smaller, even when low energy densities were used, it was concluded that best results are generated by ultra-short pulses that practically affect only a superficial layer of the polished material and are also capable to produce a certain degree of material melting capable to fill the submicron craters of the surface.

It is perhaps important to note here that recent research [32] has suggested that the amount of heat absorbed by the polished surface is dependent – in addition to its thermal properties – on its initial topology/configuration and on the type/wavelength of the laser used. By performing comparative studies on tool steel, the authors have demonstrated that despite having a more defocus-sensitive beam, high-power diode lasers are capable to perform better than CO_2 lasers both in terms of productivity and accuracy of the resulted surface, even with smaller energy densities of the beam. The significant difference in their wavelengths (906 nm vs. 1060 nm) triggers completely different responses in the polished material, such that the optimal value of energy density for diode laser is capable to induce extremely high (around 90%) decreases in R_a values, going down to 0.86 μm for ball-end milled and to 0.36 μm for EDM semi-finished surfaces. However, when semi-finished surface quality improves, the observed roughness reductions tend to become less significant. Metallurgical analyses performed in this study practically supported that idea that once the optimal energy density has been reached for a certain surface, its further increases will do nothing but determine a switch of predominant polishing mechanism from shallow surface melting (SSM) to surface over melting (SOM), with predictable degradations of the polished surface quality. According to the authors, SSM is equivalent with a superficial melting of the microasperities that will eventually fill the "valleys" of the surface with molten material under the action of the capillary pressure and liquid curvature. By contrast, SOM regime translates into deeper melting effects that will result in a surface profile with lower peak-valley frequencies but higher amplitudes that may in fact increase of the final roughness of the surface. Furthermore, the authors noted that higher than optimal energy densities tend to amplify the micro-crack nucleation process, and this in turn has undesirable consequences on the polished component durability. The effect of laser power, scan speed and initial surface topography was also investigated by Gisario *et al.* [39], who concluded by increases in the laser power or the speed at which laser beam moves across surface are more likely to generate a superior quality of the post-polished surface (approximately 80% decrease in R_a from 1.5 μm). Unlike most other studies, the authors applied LP on flat patches produced through face milling performed on the circumference of a shaft.

Given that the practically any surface topography is characterized by a random variation of the height of its micro-asperities, conventional statistical tools and metrics can be used to draw insightful conclusions based on pre- and post- laser polishing profiles of the surface. Building on this idea, Chow *et al.* [40] relied on material ratio function, autocorrelation function, autospectrums and transfer functions to assess the performance of LP when applied on Ti6Al4V. Their results confirmed that LP is capable to improve the roughness profile through the redistribution of high frequency components into the lower range of the spectrum. As such, surface waviness was found to be slightly increased as a result of this material redistribution, even if R_a decreased moderately from 577 nm to 452 nm (21.3%). By means of the same statistical-oriented approach Chow *et al.* [41] have demonstrated that changes in laser focal offset distance (FOD) are sufficient to determine the switch of the laser-material interaction between three distinct regimes: ablation, melting and heating. Moreover, the authors have proved that the initial roughness of the surface, laser power, number of overlapping LP passes as well as the initial waviness of the surface also have a significant impact on the final roughness of the surface. By performing univariate parameter analyses, Chow *et al.* have generated surfaces with line profiling finishes varying between 32% reduction in R_a (FOD between 1.47 to 1.62 mm and initial R_a = 726 nm) to over 60% R_a reduction observed for more than five LP passes (power of 13 W and FOD from 1.42 to 1.51 mm), laser power of 13 W (FOD = 1.5 mm), initial R_a = 700 nm (power of 13W, FOD of 2.13 mm and ten LP passes) or 50 μm stepover distance between the micromilled tracks used to generate the initial surface (13 W power and ten LP passes, FOD between 1.44 and 1.57 mm). Analogous techniques were used by Hafiz *et al.* [42] to determine the optimum amount of overlap between adjacent polishing tracks required to ensure the effectiveness of a continuous wave laser while performing area polishing on AISI H13 tool steel. For a 95% overlap between neighboring tracks, the authors have shown that average areal topography surface roughness (S_a) has dropped to 0.23 μm and this corresponds to an 83% improvement in the quality of the surface. The subsequent LP operation performed with a lower energy pulsed laser was capable to enhance even further the quality of the surface down to S_a = 0.18 μm (86.7% total improvement).

Aside from all aforementioned studies focused on identification, evaluation and optimization of LP parameters from experimental perspectives lacking well defined practical applications, very few researchers have illustrated the performance of the process in the context of a specific and a more geometrically-complex workpiece. However, one of the most convincing demonstrations in this regard was probably performed by Temmler *et al.* [43] who have finished through LP the outer surface of an implantable left ventricular assist device, one of the components of an artificial heart pump. While side-to-side comparisons have not shown dramatic, but rather moderate improvements of R_a obtained through LP as opposed to that yielded through manual operations, the time associated with the finishing operation was significantly cut through the involvement of LP from 3.5 hours to 10 minutes. The spectral analysis performed in this study has revealed that the multi-step LP used for finishing was the most effective for wavelengths smaller than 5 μm when the R_a of the initial surface (0.020 - 0.030 μm) dropped up to 30 times in the vicinity of 0.001 μm.

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

3.2 Modeling and Simulation Studies

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

Since many of the early LP studies were focused on polishing of surfaces manufactured through SLS technology, some of the first modeling attempts were strongly related to this particular type of initial surface topology. In this regard, Ramos *et al.* [44] have proposed initially a simple assimilation of the SLS surface asperities with hemispherical caps. Their predictions of the resulting surface roughness for 420 stainless steel/bronze infiltrated SLS parts as a function of laser power, scan speed and initial particle size yielded reasonably good matches with empirical data. This simplified representation of the initial surface was later incorporated in a SSM model used to explain reductions of the polished surface roughness as a result of the molten material redistribution under the action of capillary and viscous drag pressures that tend to minimize the differences in curvature of the local liquid surface [45]. A thermo-physical model has also been developed for SOM mechanism caused by deep melting of the polished surface [46]. The proposed model, incorporating surface curvature effects, was able to predict with acceptable accuracy the roughness of the resulting surface. The authors also pointed that that the low frequency high amplitude wave formed as a result of SOM are in fact determinant for roughness increases generally associated with this type of polishing regime. Furthermore, while the transition from SSM to SOM was believed be primarily influenced by laser energy density and initial surface roughness, beam velocity across surface was found to have a significant effect on the final roughness achieved after LP. However, the best experiments reported in this study for faster moving beams did not produce R_a values under 2 microns. By taking an approach relatively similar to that used in tribological investigations, Shao *et al.* [47] proposed a model capable to predict the final roughness of the surface based on the simplification of the asperity shape to three principal geometric primitives: circular cone, hemisphere and cylinder. By employing their model in polishing of several common engineering materials (Fe, Al, Ti and 304 stainless steel) the authors have demonstrated that laser pulse duration should be kept under a certain critical value in order to obtain the targeted temperature gradient in the underlying substrate material. The theoretical approach was verified experimentally in nanosecond laser polishing of DF-2 cold work steel in which R_a values of 99.5 nm were obtained (28.9% average roughness improvement).

Since laser polishing is associated with significant solid/liquid phase changes, some authors have proposed for this process models that were derived from classical problem of moving phase boundary, also known as Stefan problem. One example in this sense is constituted by the work of Mai and Lim [48], who developed their own numerical techniques/codes to simulate the transient laser melting process, essentially implemented as a hybrid between fixed and variable domain methods. Validation of the proposed method was performed through comparisons between the 2D geometry of the molten pool obtained through both numerical and physical experiments performed during the laser polishing of 304 stainless steel. Beyond the development of the aforementioned numerical models, the study also outlined the importance of laser power density and dwell time on the depth of melt region that was capable to seal the micropores (less than 1 μm in size) of the raw surface. The most effective reduction of surface roughness (61% reduction, from 195 nm to 75 nm) was achieved through adjustments brought to the off-focus distance of the beam.

Many recent studies have demonstrated that in addition to the inherent thermodynamics of the LP process, the initial surface topography also plays a significant role on the final quality of the polished surface. In this regard, Perry *et al.* [49-51] were the first to emphasize importance of minimum critical spatial frequency as a valuable predictor of the polishing effectiveness in the spatial frequency domain. The proposed metric represents in fact a veritable threshold capable to delimitate the spectrum of frequencies prone to experience significant reductions of the surface topography amplitudes. As such, smaller critical frequencies are desirable since a broader span of spatial frequencies will be attenuated and this in turn will enhance the overall efficiency of the LP operation. Following the initial unidimensional finite element analyses used to estimate the melt depth induced by a laser single pulse, Perry and his colleagues have demonstrated the validity of the proposed concept by performing LP experiments on microfabricated/micromilled Ni and Ti6Al4V samples. The largest (sevenfold) drops of the R_a were noticed for surface profiles with lowest harmonic frequencies slightly above the critical frequency value [50]. As suggested by simulations, R_a tends to improve with longer pulses, a hypothesis that was tested by comparing the results of 300 ns and 650 ns laser pulses that were responsible for 30% and 50% surface roughness, respectively [50]. For Ti6Al4V samples, the best LP results translated into a 66% reduction of R_a, from 0.206 to 0.070 μm [51]. In a recent extension of this work, Vadali *et al.* [52] have expanded the applicability of critical spatial frequency towards other widely used metallic materials like 316L stainless steel, nickel, Ti6Al4V, Al-6061-T6. The comparison of the analytical and experimental results – obtained in both line (316L) and area polishing (rest of them) conditions – have shown that critical frequency represents an effective predictor of the performance of the LP process. Since the precision of the previously proposed 1D finite element model diminished significantly for longer pulses, the authors have relied on a time dependent axisymmetric approach to predict the duration of the molten state for 0.65 and 5 μs pulses. In terms of LP performance, the best results were obtained for micromilled titanium alloy, whose average areal roughness decreased by 54.6% to S_a = 82.2 nm. However, the applicability of stationary capillary flow models – like the ones used in Perry *et al.* [49-51] – is limited to LP processes in which thermocapillary effects are negligible, *e.g.* both melt durations and thermal gradients are relatively small. As such, Pfefferkorn *et al.* [53] have developed numerical axisymmetric 2D models to better describe LP scenarios in which the effect of thermocappilary flow becomes predominant. Since these operations are associated with large decreases in the surface roughness that tend to be accompanied by unwanted ripples/undulations, it makes sense to attempt to smoothen them further through a slower capillary flow-based polishing process.

The results of this two-step process as applied on Ti6Al4V suggest that the initial average areal roughness of 172 nm can be reduced down to 47 nm. Neither of the two analyzed types of polishing mechanisms was capable of such performance when used individually. Once again, the balance between thermocapillary and capillary regimes seems to play a decisive role on the final quality of the polished surface (72.7% decrease in S_a).

Recent developments in the area of LP modeling emphasize that in addition to the more frequent 1D and 2D analyses, 3D formulations are also possible. For instance, Ukar *et al.* [54] have developed a 3D thermal model incorporating solid-state transformations and capable to predict the amount of roughness decrease obtained during LP of DIN 1.2379 steel. The developed model – which was validated on a periodical structure obtained through ball-end milling – showed a relatively good agreement (between 10 and 15% difference) between measured and predicted values of the surface roughness. Furthermore, the study has outlined that – for the analyzed tool steel – any deviations from the optimal value of the energy density of about 1150 J/cm^2 will actually translate in increases of the R_a from its experimentally measured minimum value of 0.783 μm (89% decrease).

4. Discussion

As previous sections imply, the final quality of the surface polished through laser irradiation depends on a large number of laser, workpiece and process parameters. A quick glance into the settings used so far (Table 1 in Electronic Annex) suggests that: i) a relatively small amount of commonalities exist between studies and ii) end results – typically reported in the form of final average roughness ($R_{a\ \mathrm{final}}$ or $S_{a\ \mathrm{final}}$) – can vary dramatically even when some of the prior LP settings are partially mimicked in a new study. While it is absolutely clear that more comprehensive and in-depth theoretical insight is required to clarify the primarily empirical observations available today, recent publications seem to agree that one of the most important – if not *the* most important – factors influencing the final quality of the polished surface is represented by the energy/power density of the laser beam. Nevertheless, while attempting to compile the data presented in Table 1 (Electronic Annex) with a focus on this particular LP parameter, it was found that the inconsistencies in the reported data makes its determination – and thus its retrospective analysis – virtually impossible.

From a practical perspective, another valuable dependence would link the achiavable quality of the polished surface to the type of the workpiece material. As the graphs shown Figure 4a indicate, much of the prior research efforts were focused on polishing of hot and cold worked steels typically used by mold and die industry. In many of these instances, the attainment of nanometric range surface quality constitutes a feasible option (Figure 4b) that can be pursued. While final mirror-like polished surfaces are not uncommon, optical quality ($R_{a\,\mathrm{final}} \leq$ cca. 10 nm) remains relatively rare. However, in addition to tool steels, other materials such as nickel and titanium alloys (Ti6Al4V) seem to be reasonable facilitators of superior LP performance, as characterized in terms of $R_{a\,\mathrm{final}}$ and the percentage of roughness decrease.

The plot shown in Figure 5a demonstrates once again the wide variability that is inherent to LP performance and perhaps the best example in this sense is represented by AISI O1 steel whose reported decrease in surface roughness varies from approximately 90% to cca. 20% increase. Evidently, when it comes to the most "laser polishable" metallic materials, Figure 5b suggests that some of the best performance can be achieved for AISI H11 and AISI H13 steels (chromium hot work steels), nickel and titanium as well as two of their widely used alloys, namely Inconel 718 and Ti6Al4V, respectively. While various theories have been proposed in the past to explain why some materials can be polished through laser irradiation much better than others, no widely accepted explanation has been put forward yet.

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

5. Conclusions

To date, the performance of LP in finishing of the metallic surfaces have been successfully demonstrated on a variety of metallic materials ranging from tool and stainless steels to nickel and titanium alloys. As a result, the applicability of the process has greatly enhanced from the initial mold and die industry into aerospace and biomedical sectors. At this time, the general consensus within the scientific community is that the final roughness of the laser polished surface can be lowered into the nanometric or even optical quality domain through the adequate tuning of the process parameters.

Since the intricate thermal, flow and phase-changing mechanisms underlying the LP process continues to remain partially obscure, no reliable, robust and universally-applicable model has been yet proposed to predict the process parameters required to achieve the highest post-polishing quality of the surface. This continues therefore to remain one of the primary challenges associated with this finishing technique, especially when it comes to the simulation of the laser/material interaction down to microasperity level. Furthermore, before its large scale adoption by the manufacturing industry, LP still has to demonstrate its superiority with respect to productivity indices, range of materials as well as complexity of the surfaces that can be polished through laser irradiation. Also, little is known about the microstructural changes induced by the laser energy at the surface of the material although they could have a critical effect of the functionality of the component like, for instance, in the context of extreme wear (tribology) or less conventional environments (biomedical).

To conclude, the results obtained so far warrant further developments of the LP process which continues to remain one of the most promising successors of the manual finishing operations. However, more in-depth analyses of the mechanisms underlying laser/material interactions will be required to replace the present largely empirical investigations with more solid theoretical premises.

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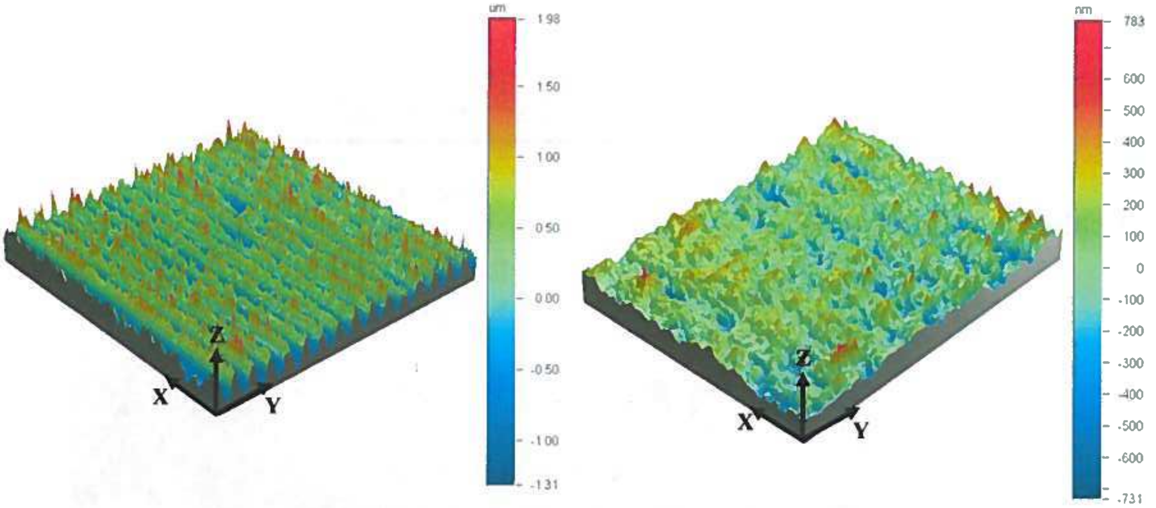
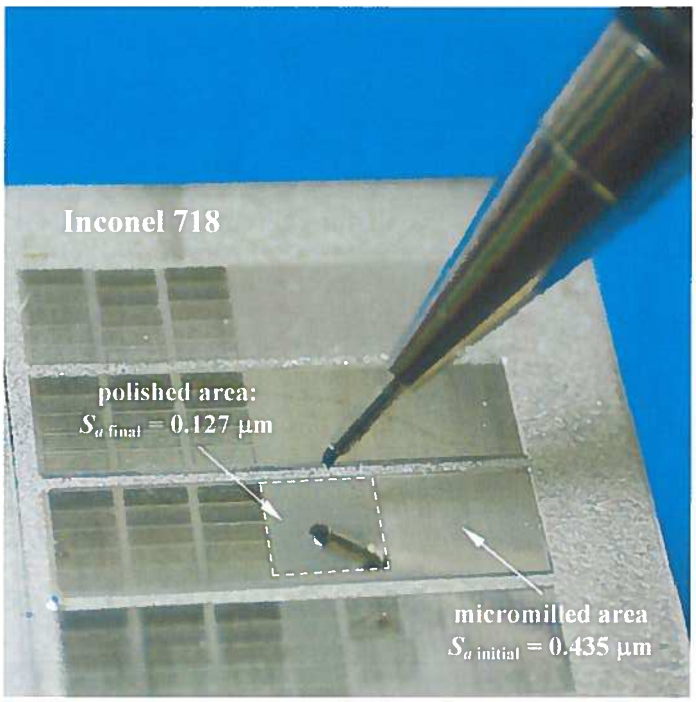
List of Figures

Electronic Annex

Table 1. Summary of the reported laser polishing settings/parameters

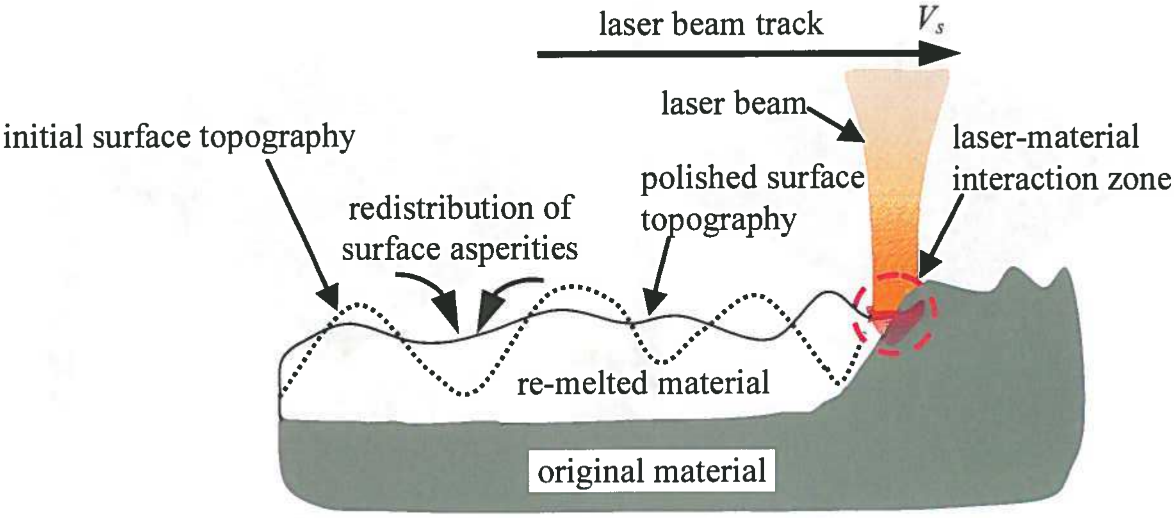


c)

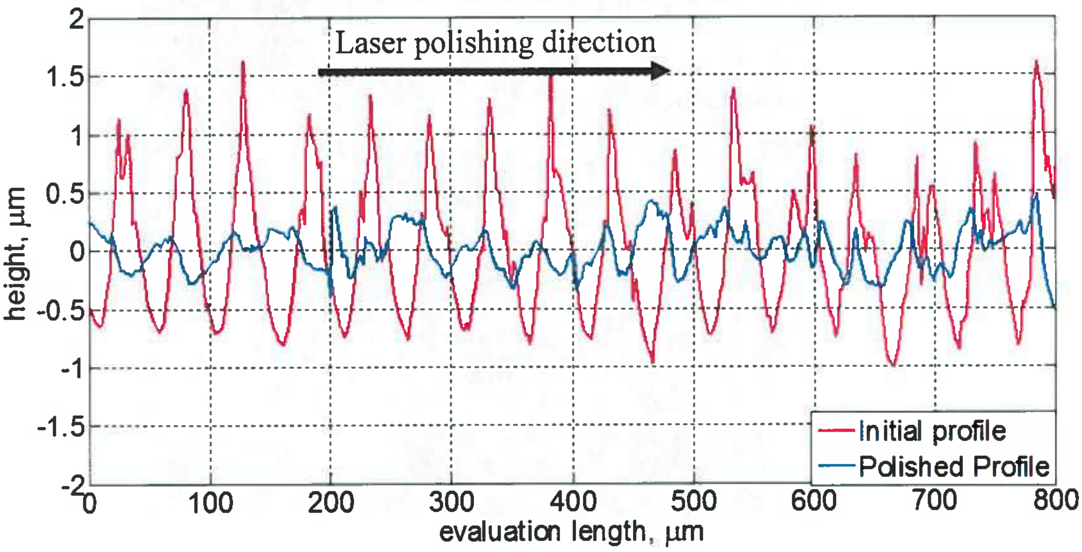


d)

Figure 1. Overview of laser polishing: a) schematic of the remelting mechanism; b) the effect of laser irradiation on surface microasperities; c) the effect of laser irradiation on surface topography in area polishing; and d) physical appearance of a polished sample


laser beam track
V_s
laser beam
initial surface topography
laser-material interaction zone
polished surface topography
redistribution of surface asperities
re-melted material
original material

a)


Laser polishing direction
height, μm
evaluation length, μm
Initial profile
Polished Profile
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
100
200
300
400
500
600
700
800

b)

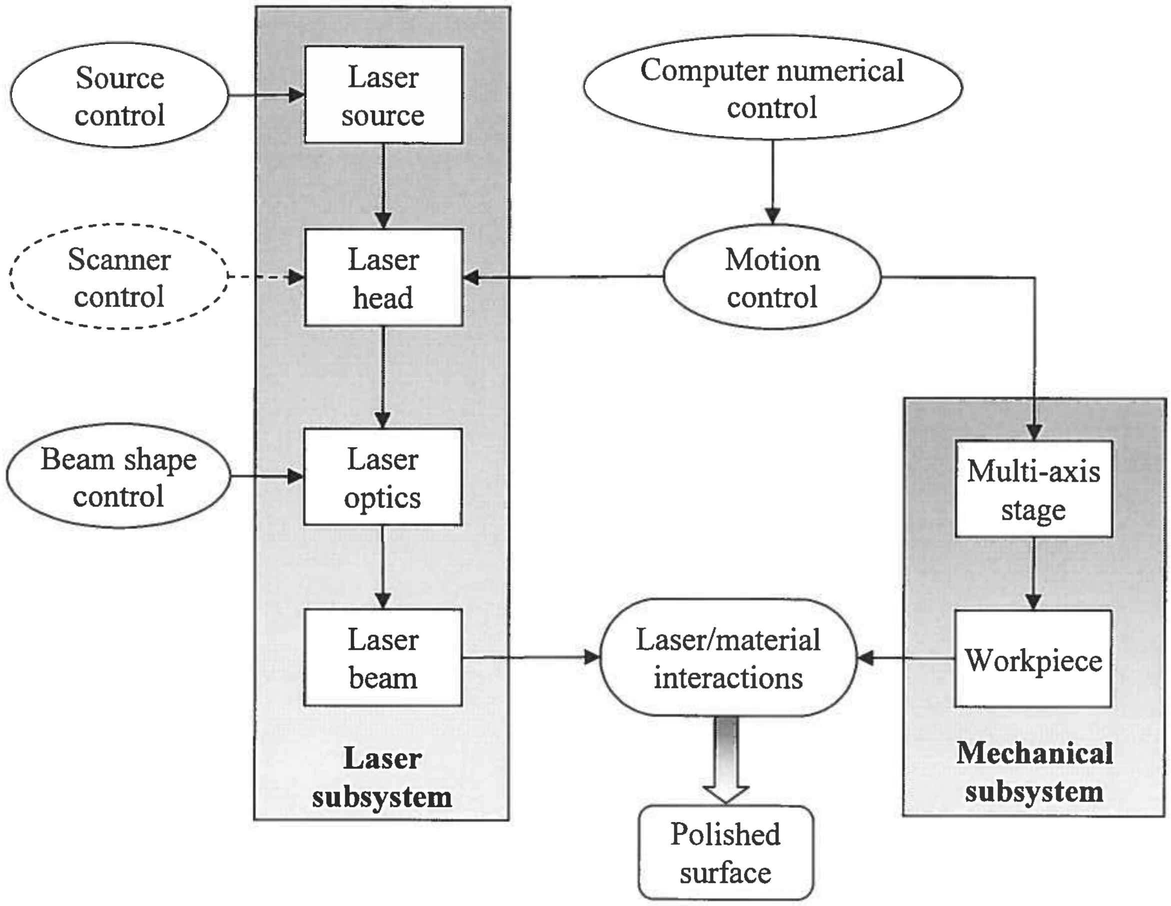


Figure 2: Configuration and control of LP systems

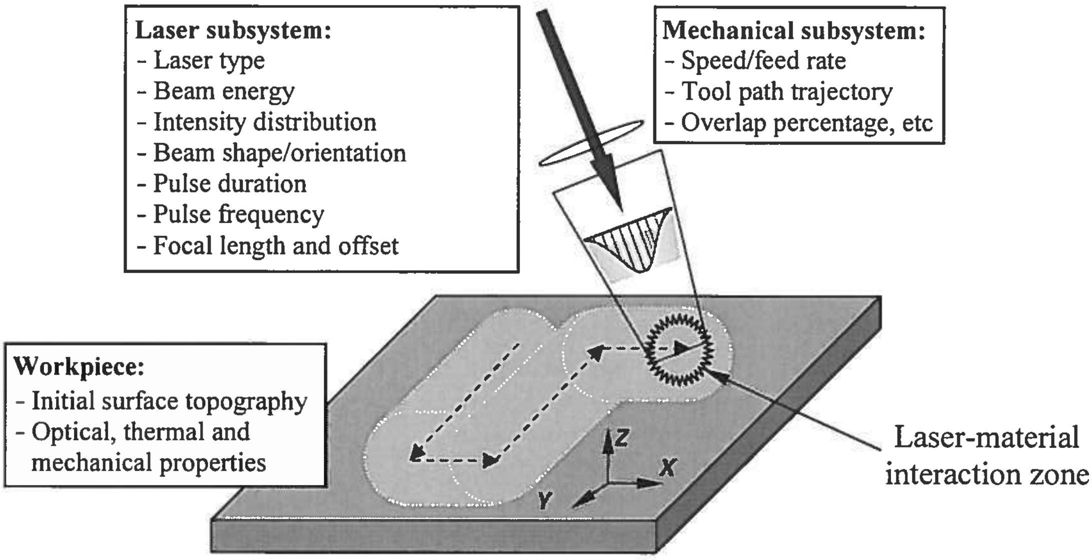
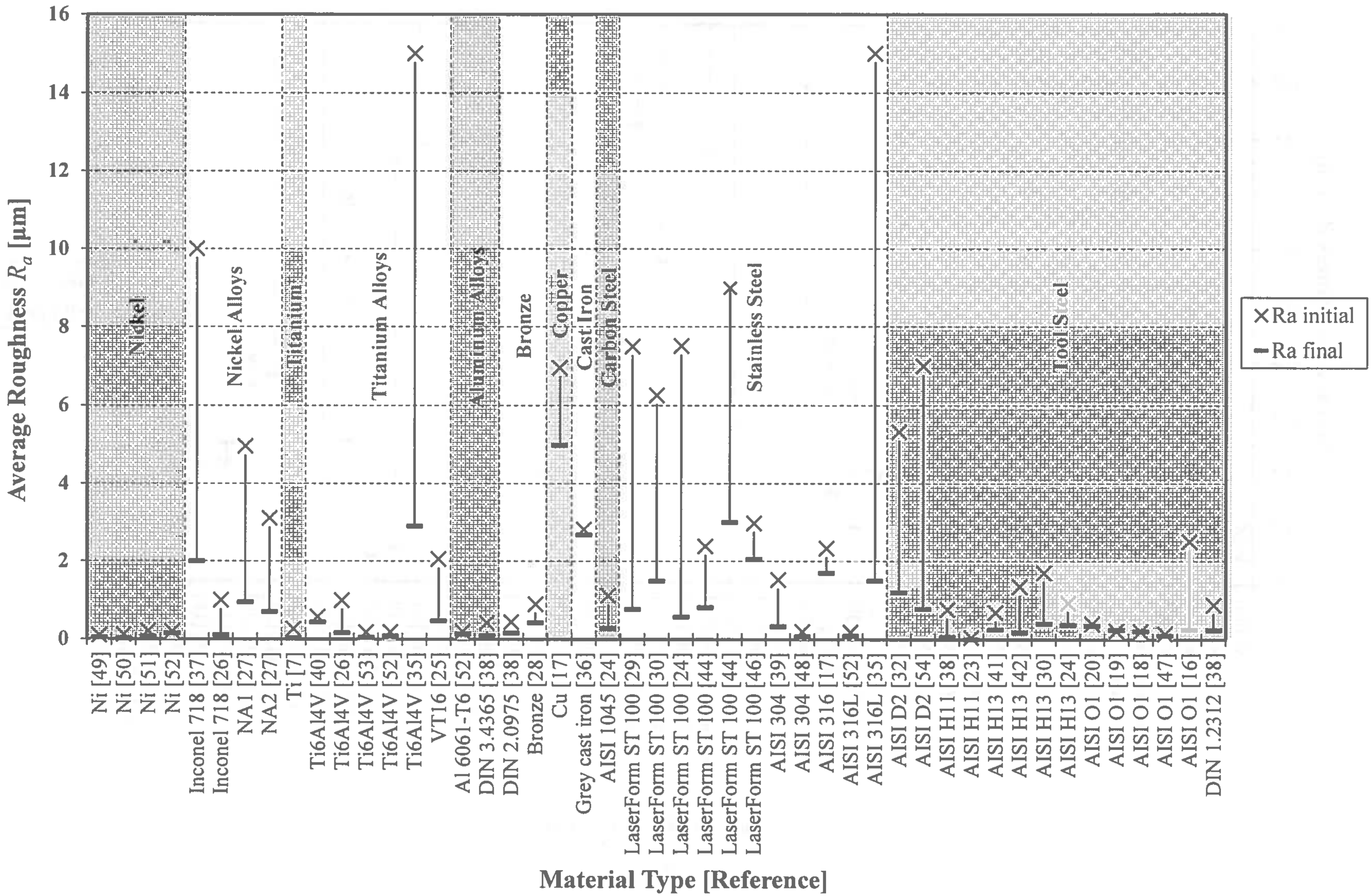
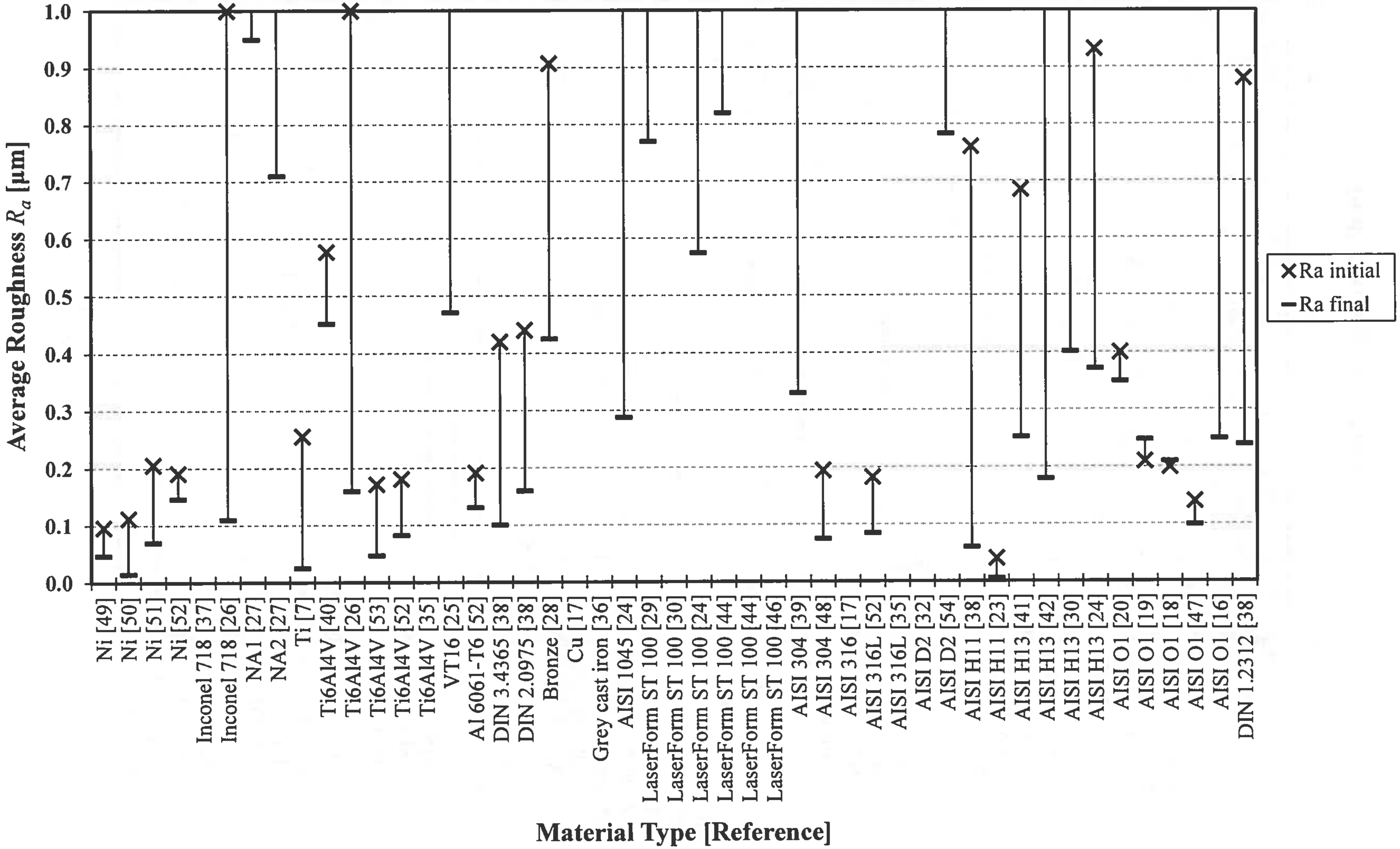


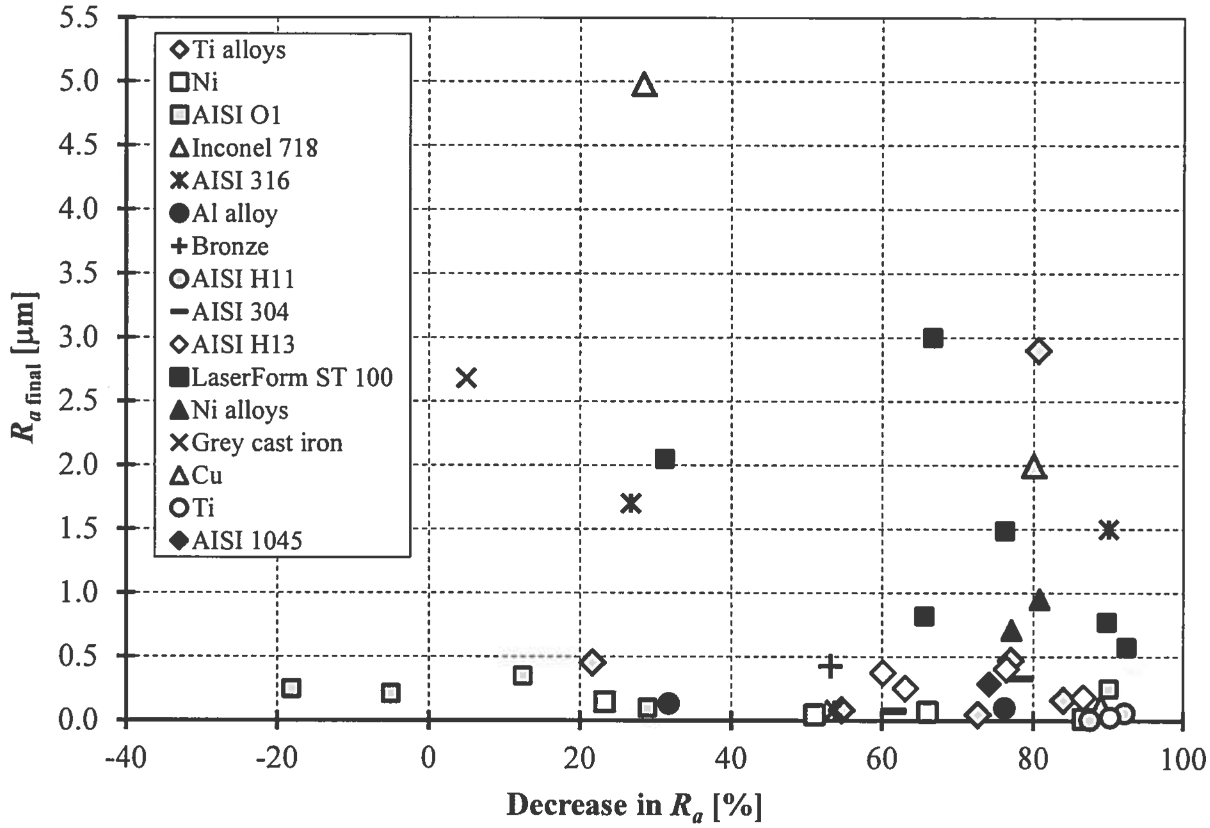
Figure 3. Principal parameters with effect on LP process


Average Roughness R_a [µm]
16
14
12
10
8
6
4
2
0
Nickel
Nickel Alloys
Titanium
Titanium Alloys
Aluminum Alloys
Bronze
Copper
Cast Iron
Carbon Steel
Stainless Steel
Tool Steel
Ra initial
Ra final
Ni [49]
Ni [50]
Ni [51]
Ni [52]
Inconel 718 [37]
Inconel 718 [26]
NA1 [27]
NA2 [27]
Ti [7]
Ti6Al4V [40]
Ti6Al4V [26]
Ti6Al4V [53]
Ti6Al4V [52]
Ti6Al4V [35]
VT16 [25]
Al 6061-T6 [52]
DIN 3.4365 [38]
DIN 2.0975 [38]
Bronze [28]
Cu [17]
Grey cast iron [36]
AISI 1045 [24]
LaserForm ST 100 [29]
LaserForm ST 100 [30]
LaserForm ST 100 [24]
LaserForm ST 100 [44]
LaserForm ST 100 [44]
LaserForm ST 100 [46]
AISI 304 [39]
AISI 304 [48]
AISI 316 [17]
AISI 316L [52]
AISI 316L [35]
AISI D2 [32]
AISI D2 [54]
AISI H11 [38]
AISI H11 [23]
AISI H13 [41]
AISI H13 [42]
AISI H13 [30]
AISI H13 [24]
AISI O1 [20]
AISI O1 [19]
AISI O1 [18]
AISI O1 [47]
AISI O1 [16]
DIN 1.2312 [38]
Material Type [Reference]
a)

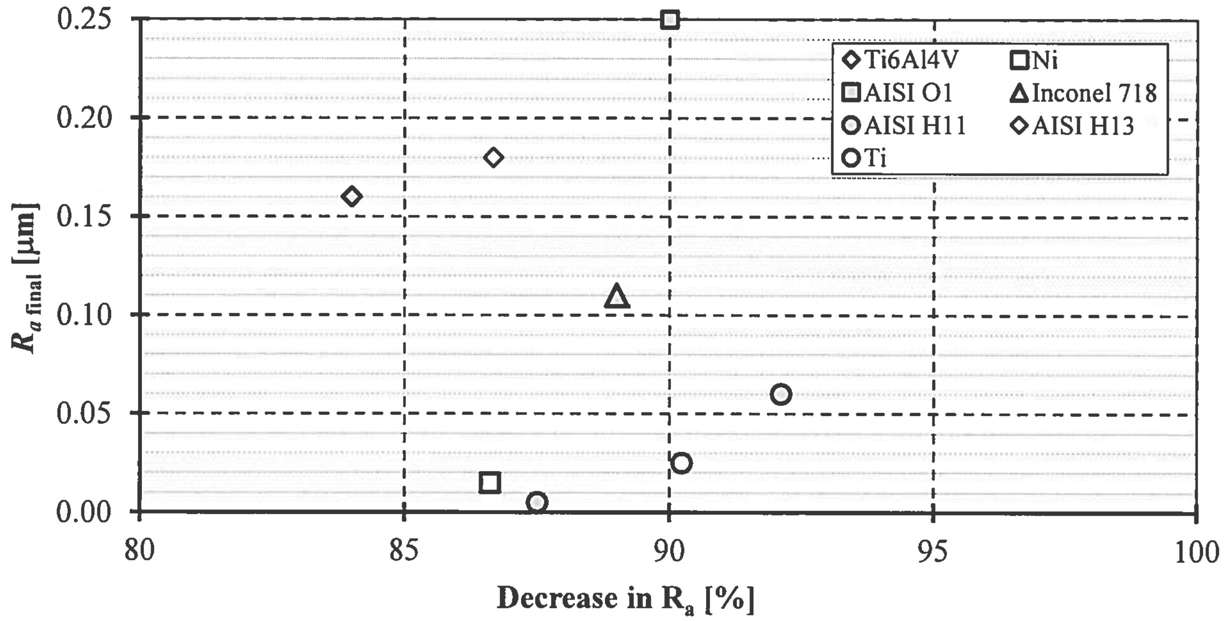


b)

Figure 4. Synopsis of the effect of laser polishing on surface roughness:
a) overall dependence on workpiece material; b) enlarged view of the nanometric range of $R_{a\ \mathrm{final}}$



a)



b)

Figure 5. Synopsis of laser polishing performance:
a) overview of dependence on workpiece material;
and b) highly polishable metallic materials