Short pulse laser milling effects on surface integrity

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Abstract

Laser milling of engineering materials is a viable alternative to conventional methods for machining complex micro components. The laser source employed to perform such micro structuring has a direct impact on achievable surface integrity. At the same time, the trade offs between high removal rates and the resulting surface integrity should be taken into account when selecting the most appropriate ablation regime for performing laser milling. In this paper the effects of pulse duration on surface quality and material microstructure are investigated when ablating a material commonly used for manufacturing micro tooling inserts. When performing ultra short pulsed laser ablation some heat is dissipated into the bulk but not sufficient to trigger significant structural changes.

Keywords: Laser micro machining, Micro machining and Laser pulse duration

1. Introduction

The laser milling of engineering materials has become a viable alternative to conventional methods for producing tooling inserts for micro replication or for machining micro features in components. By applying this technology, material is removed in a layer by layer fashion to produce the desired 3D structures. Direct interfaces to 3D CAD modeling packages exist to assist in the machining of complex free form surfaces. Being a non contact material removal process, some of the main advantages of laser milling are that the process does not suffer from any problems associated with tool breakage, does not require inclusion of collision checking routines in machining programmes and it is easy to access areas that are very deep in cavities. Also, if ultra-short pulsed lasers are utilised, almost any material can be machined and the thermal load is significantly reduced resulting in high surface integrity.

Laser radiation can be delivered to the work piece in an ordered sequence of pulses with a predetermined pulse length (duration) and repetition rate (frequency). This allows the accumulated energy to be released in relatively short time intervals, which is a prerequisite for the formation of extremely high peak powers. Additionally, the laser beam can be focused on a spot with very small dimensions, from sub micrometer to 50 μm, which results in a significant energy density (fluence) and intensity (power density) in the spot area.

Therefore, an extremely high density can be achieved in the laser-material interaction zone that could not be achieved by any conventional machining technology. This explains the capability of laser milling to process materials that are difficult to machine [1]. In addition, such a high fluence is very important when producing micro structures that require a high surface finish, and hence atom cluster and atomic processing. In particular, to carry out machining at such a scale it is necessary to remove material with units from 1-100 nm to 0.01-1 nm with a corresponding increase of the specific processing energy from $10^3 – 10^4$ [J cm^{-3}] to $10^5 – 10^6$ [J cm^{-3}] [2] that is attainable with ultra-short pulse laser ablation.

The laser source employed has a direct impact on achievable surface integrity. In recent years a wide range of laser sources have become commercially available. Laser pulse durations may vary from microseconds to a few femtoseconds [3]. In this research the effects of pulse duration on surface integrity are investigated when ablating a material commonly used for manufacturing micro tooling inserts. The paper starts with a discussion of the physical phenomena that take place during laser milling with different pulse durations. Then, the set ups used to carry out this experimental study are outlined and the results of the metallographic and surface profile analyses are provided. Finally, conclusions are made on the effects of pulse duration on the resulting surface integrity.

2. Material removal mechanisms

When pulsed laser machining is performed the actual process of ablating a material takes place within the pulse. Several mechanisms exist for material removal, depending on the laser pulse duration, and some material specific time parameters [4, 5, and 6].

The following important material dependent time constants in regard to the substrate material and the laser source are considered:

- τ_e - electron cooling time;
- τ_i - lattice heating time;
- τ_L - laser pulse duration;

As a rule $\tau_e \ll \tau_i$ and for most materials τ_i is in the picosecond range. According to the laser pulse duration, three different ablation regimes can be defined:

- femtosecond - $\tau_L < \tau_e < \tau_i$;
- picosecond - $\tau_e < \tau_L < \tau_i$;
- nanosecond and longer pulses - $\tau_e < \tau_i < \tau_L$.

The femtosecond and picosecond ablation mechanisms are similar. In these two regimes, the laser radiation is initially absorbed locally in the electron system because the ions are heavier and cannot follow the fast oscillations of the electromagnetic field [7]. The collisions between the energetic electrons, and then the electrons and the atomic lattice result in their thermalisation. However, only a small fraction of energy can be transmitted by each electron – lattice collision due to the large mass difference between electrons and ions. Thus, a multiple of electron-phonon relaxation time has to pass to achieve thermodynamic equilibrium between the electron system and the atomic lattice. Therefore, if τ_L is much shorter than the time required to reach this thermodynamic equilibrium, the ablation process can be regarded as a direct solid-vapour transition (sublimation), with negligible thermal conduction into the substrate and almost no heat affected zone (HAZ) [8, 9, 10 and 11]. In particular, each pulse creates some “solid plasma”, a substance consisting of loosely bound ions and electrons, which leaves the substrate after the end of the pulse by expanding in a highly ionized state. The electrons are lighter and are the first to leave the substrate followed by the ions. The latter are all positively charged and repel one another, which facilitate their removal from the substrate. During this expansion the solid plasma takes away most of the energy, and consequently the thermal load on the substrate is very low. In the picosecond regime, in spite of the formation of a molten zone and the existence of some heat conduction, the dominant removal mechanism is still a solid-vapour transition [7].

In general, to perform atom cluster and atomic processing with pulsed lasers, τ_L should be shorter than the time necessary to achieve thermodynamic equilibrium between the electron system and the atomic lattice. For example, for metals with strong electron-phonon coupling such as steel τ_L should be in the range from 3 to 5 ps, while for aluminium and copper, materials with weak coupling, it needs to be one or two orders of magnitude higher [7]. A further reduction of τ_L would not bring additional benefits in terms of material machining response. Nonlinear effects, due to interactions between the ultra-short laser pulse and atmospheric gas in the focal region, occur that lead to a wave-front disruption of the beam, profile distortion and increased beam divergence. In particular, these are the side effects when performing laser ablation in the femtosecond regime [7].

For optimal machining results a proper match between the laser source and the material should be achieved. Generally, higher absorption efficiency leads to a more effective laser milling process.

3. Experimental set-ups

A series of experiment were conducted to assess the impact of the laser pulse duration on surface integrity of a substrate. Two main effects were studied, in particular changes in material microstructure and surface quality by carrying out metallographic and surface profile analyses. In particular, to estimate the thermal load exercised on the substrate, the processed areas were analysed for phase transformations and changes in the grain structure.

Two different laser milling systems were employed having femto- and pico- second pulse durations, respectively, to ablate a field with dimensions 1 × 1 mm. The characteristics of the laser sources employed in this experimental study are shown in Table 1. The experiments were conducted at two different sites within a day on the same workpiece and included:

Familiarisation with the material. The two partner organizations involved in this study did not have experience with the selected material for the trials. Thus, some test features were produce to find the best processing window within the available time frame. It should be stressed that these may not be the optimal parameters, however the effects on surface integrity of the substrate could be considered representative for performing ablation in these two different regimes.

Machining of a series of 1 x 1 mm fields. A few test structures were produced on each system by varying laser milling parameters within the identified processing window. However, the available time did not allow the analysis of the machined surfaces to be carried out immediately after the tests. Therefore, as was already indicated, the obtained surface roughness may not be the best achievable with these two laser sources. For further analysis in this research, the fields with the best surface roughness for each of the two studied ablation regimes were selected.

Table 1 Laser sources characteristics

Laser Source	**Laser process parameters**	**Ra µm**
Femtosecond Laser source SP Hurricane (amplified Ti:Sapphire) Wavelength = 800nm Rep. Rate = 5kHz Pulse = 130fs	Power = 20 mW Scanning Speed = 1.67 mm/s Number of passes = 4 Step = 0.01 mm Fluence = 0.25 J/cm^2	0.35
Picosecond laser source – Stacatto (Lumera) Wavelength = 1064 nm Rep. Rate = 50 kHz Pulse = 12 ps	Power = 100 mW Scanning Speed = 100 mm/s Number of passes = 10 Step = 0.002 mm Fluence = 1.13 J/cm^2	0.29

The experiments were conducted on a BS EN ISO 4957 - X40CrMoV5-1 annealed tool steel workpiece (0.35%C, 1%Si, 5%Cr, 1.4%Mo, 1% V). This material was selected because it is commonly used to manufacture tooling inserts for micro injection moulding and hot embossing, and thus to endure many thermal cycles.

The workpiece used in this experimental study was polished before it was processed with the two different laser sources in succession. After completing the machining, all fields on the work piece were cleaned in an ultrasonic bath with light degreaser to preserve the topology of the resulting surfaces. The fields were inspected with a white light profiling microscope before dicing the substrate in pieces. Then, for a better edge retention the pieces were embedded in an epoxy based resin. Finally, the specimens were polished and developed with picral (recommended for structures consisting of ferrite and carbides) and nital (the most common etchant for revealing alpha grain boundaries of Fe, carbon and alloy steels) reagents in order to analyse the material microstructure. In particular, this was done to highlight the boundaries of the ferrite grains (α-phase) and carbide sets. An analysis of the material microstructure was carried out employing the Buehler-Omnimet software[12]. Trough image recognition grains boundaries are identified and diameter/area calculated, as well as grains count. Statistical report is generated with all data.

The changes in the grain structure were the main criterion for estimating the heat affected zones. The material microstructure of the workpiece was uniform before performing any processing. After the ablation, a grain refinement was observed in the area surrounding the machined surface. Such changes are the result of the thermal wave propagation into the substrate, which is immediately followed by a quick cooling down at the end of the pulse.

To analyse the affected regions in this experimental study, they were split into three zones taking into account the extent of these changes. Zone 1 covers the area, where the most of the heat was absorbed, and therefore the changes are clearly visible. In Zone 2, some changes can still be observed, but at the same time there is a steady decrease of the thermal impact. Finally, in Zone 3, the materials microstructure can be considered to be the same as in non-processed areas of the substrate.

To make the comparison of microstructure changes easier it was assumed that these three characteristic zones cover the same area in depth for pico- and femto- second ablation regimes -
Zone 1 below 10 µm, Zone 2 from 10 to 30 µm, and Zone 3 above 30 µm. A quantitative assessment of the microstructure changes was carried out by calculating the number of grains in each zone, and their maximum, minimum and means diameters with the Buehler-Omnimet software.

4. Results

4.1 Surface roughness

The surface maps of fields laser milled with different pulse durations were studied in order to understand the effects of the two ablation mechanisms on the resulting surface roughness, as was mentioned in Section 3.All roughness measurements were taken using a white light profiling microscope. The size of the scanned areas was chosen according to ISO 4288:1996 and ISO 11562:1996 [13].

The parameter used to evaluate the surface roughness was the arithmetic mean roughness (Ra) because relative heights in micro topographies are more representative, especially when measuring flat surfaces. In Figure 1, the surface profiles of the fields machined

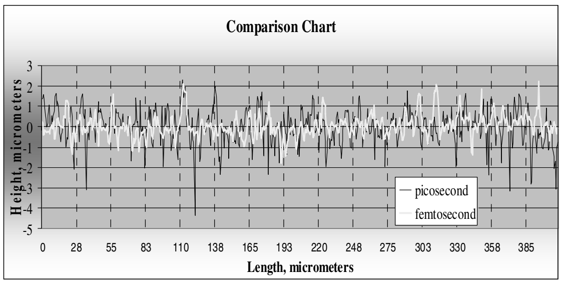

Figure 1 A direct comparison of the surface profiles of the fields machined with the ps and fs laser sources

with the ps and fs laser sources are superimposed for direct comparison.

4.2 Material microstructure

Micrographic pictures were obtained in polarised light in order to enhance the appearance of the crystallographically identical ferrite grains. The area and equivalent circular diameter of each individual grain were

have a quantitative measure for assessing the thermal effects on the processed surfaces, and ultimately to judge the thermal load exercised on the substrate in each ablation regime.

The changes of the material microstructures in the three characteristic zones after processing in different ablation regimes can be summarised as follows:

4.2.1 Picosecond pulse duration

In Figure 2, a micrograph depicting the three characteristic zones used for analysing the thermal load of short pulsed lasers is provided. The results obtained showed that mean and maximum diameters of the grains in Zones 1 and 2 were 2.3 µm and 4.1 µm, and 9.3 µm and 21.5 µm, correspondingly. No changes in the grain sizes were observed in Zone 3, above 30 µm. In particular, the measured mean and maximum diameters were equal to 8.2 µm and 31 µm, which were the same as those for unprocessed areas of the substrate.

4.2.2 Femtosecond pulse duration

The analysis of the material microstrucrure was carried out again by splitting the micrograph in three zones as shown in Figure 3. In Zone 1 the estimated mean diameter of the grains was approximately 1.6 µm while the maximum diameter measured was 8.2 µm. In Zone 2, from 10 to 30 µm, the mean and maximum diameters were 4 µm and 17.5 µm, respectively. Again, above 30 µm from the ablated surface there were no changes in the grain structure, and the mean and maximum diameters were 8.2 and 31 µm, correspondingly.

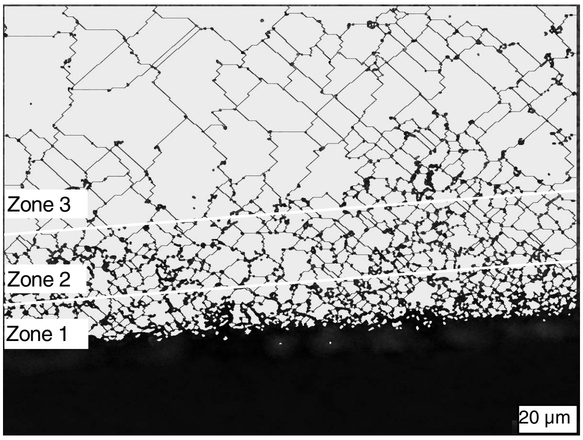

Figure 2 A micrograph depicting the three characteristic zones after machining with ps laser

5. Discussion

5.1 Surface roughness

The surface roughness measured on the surface ablated with the fs laser was Ra 0.35 µm compared to Ra 0.29 µm achieved with the ps one. This could be explained with nonlinear effects that are typical when processing materials at this regime, and also with the specific machining response of the tooling steel to the selected processing parameters.

5.2 Material microstructure

Pulse duration is a major factor affecting the surface integrity of processed areas. In particular, it is important to understand the effects of heat dissipation into the regions nearest to the machined surface. In this research, these effects were studied by analysing the changes in material grain structure, and thus indirectly to make a judgement about the specific thermal load of each ablation regime.

Melt/vapour proportion determines the amount of heat which is dissipated into the substrate, and eventually causes secondary effects such as microcracks, phase transformations and grain size changes. As reported by Breitlung D. et all. [7], the melt/vapour ratio depends on pulse duration and fluence, and decreases with the reduction of the interaction time. The presence of melt instigates more intensive heat transfer to the substrate, and subsequently larger HAZ.

In ps and fs laser ablation regimes, the overall energy transfer is very small, and thus the changes of the microstructure are almost negligible. A direct de-sublimation of the atoms occurs and the energy is taken immediately away from the substrate. In spite of that, some changes in material microstructure can still be observed in the micrographs for both regimes. In case of ps laser ablation they are more evident (see Figure 2), while for the fs regime if there are any they are only within 1 to 2 µm in depth (Figure 3).

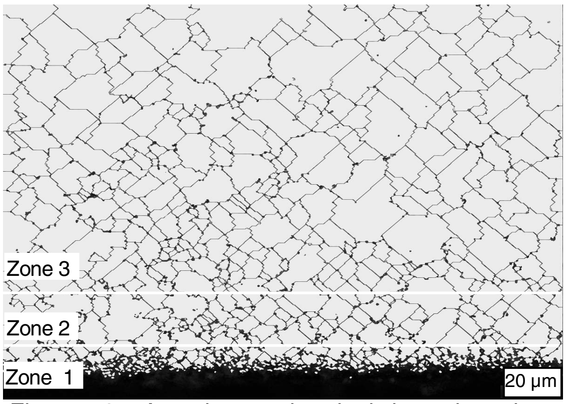

Figure 3 A micrograph depicting the three characteristic zones after machining with fs laser

6. Conclusions

In this research, the effects of pulse duration of two different laser sources on surface integrity are investigated. In particular, an attempt is made to assess the impact of two distinctly different laser regimes on surface quality and material microstructure. These are the issues that have to be taken into account when considering the trade offs between high removal rates and the resulting surface integrity. This is a particular dilemma when selecting the most appropriate ablation regime for performing micro structuring.

The following generic conclusions could be drawn from this experimental study:

-When performing ultra short pulsed laser ablation, some heat is transferred into the bulk, but it is not sufficient to trigger significant structural changes. Heat penetration is small and grain refinement is minimal. The effects of pulse duration on the resulting material microstructure are more evident in the micrograph of the field exposed to ps laser ablation than that of the area which underwent processing with fs laser pulses.

-In this research, a marginally better surface quality was achieved when performing laser milling with a ps laser source. This could be explained with nonlinear effects that are typical for processing materials at fs regimes, and also with the specific machining response of the tooling steel to the selected processing parameters, especially the laser's wavelength.

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