On the micro-modelling of surface roughness in pulsed laser machining

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Abstract. The surface roughness and the evolution of its morphology of a pulsed laser irradiated aluminum workpiece, is investigated via numerical simulations and experimental measurements. A three-dimensional transient thermo-structural finite element model is developed to simulate the machining process. The developed finite element material model considers the effects of plastic strain, strain rate and temperature, along with a fracture model. For the experiments, a single laser pulse of 6 ns duration and 0.7 mJ of energy at 532 nm is employed as the heat source, and the surface roughness is measured using white light interferometry set-up and related experimental diagnostics. A step-like linear approximation is used to model the surface roughness. A satisfactory agreement between the experimental data and the simulation results is found. This preliminary study aims to contribute to a better understanding of the initial physical processes involved in pulsed laser machining considering the influence of surface roughness and is beneficial for industrial applications such as laser polishing, engraving and cutting.

1. Introduction

Laser machining is non-conventional machining manufacturing process of high scientific and technologic interest, where complex physical processes take place. Modeling of laser machining is essential to predict the heated matter’s behavior and to better comprehend the fundamentals of the physical problem. The laser parameters, the thermal and optical properties of the material, and the surface morphology are critical factors that influence the laser-solid interaction and the subsequent heated matter’s phase changes [1-7]. Surface roughness is a typically used criterion for characterization of surface quality in all machining processes. The knowledge of the fundamental basis of the laser machining process can be improved by the development of computational models of the matter–radiation interaction by considering the effects of the initial surface roughness. Finite element method (FEM) is a numerical method capable to model complex geometries when the domain changes, the solution lacks of smoothness or the desired precision varies on the whole domain [4,8].

In laser machining studies there is a lack of numerical models that consider the influence of the surface roughness by considering both mechanical and thermal properties of the heated matter. Conde
et al [9, 10] developed a thermal ablation finite element method (FEM) model that incorporates the initial target roughness to explain the target microstructure formation and the laser plume deflection. In laser shock peening, Ran et al [11] developed a FEM structural numerical model, to predict the surface roughness by applying the computed results as inputs to analytical equations and then compare them with experimental results. Hasser et al [12] in order to explore surface roughness effects in laser shock peening developed a structural FEM model and simulated roughness produced by displacing surface nodes using a statistical method.

In our study, a 3D FEM thermal-structural analysis is performed, accompanied with experimental measurements using an optical set-up to record the influence of the surface roughness and the evolution of its morphology under pulsed laser irradiation. An Al-6061 orthogonal part is properly machined for the generation of a periodic rough surface profile. This pre-definition of the type of the resulting roughness provides the ability of developing a simple geometry of a FEM micro-model, capable to carry out the simulation needs of our study. The FEM model considers the phase changes of matter and highlights the induced elastic and plastic effects using a material model that takes into account the effects of plastic strain, strain rate and temperature, along with a fracture model. For the optical measurements, a profilometry configuration based on a Michelson white light interferometer is used. A satisfactory agreement between the experimental data and the simulation results is found. This preliminary study aids to contribute to a better understanding of the initial physical processes involved in pulsed laser machining considering the influence of surface roughness and is beneficial for industrial applications such as laser polishing, engraving and cutting [13-15]. Furthermore, the determination of the influence of surface micro-defects on the laser-matter interaction processes provides crucial information for the manufacturing and response of the solid targets in inertial confinement fusion [16].

2. Experimental methodology

In this work an Al-6061 orthogonal part of 9 mm thickness is selected as the laser irradiated target of our study, due to its overall thermomechanical behavior and well-known physical properties. The 10 × 3 × 0.9 cm sized Al workpiece was dry milled with spindle rotation frequency of \( n = 1910 \) rpm and a feed rate of \( f = 2292 \) mm/min (feed per tooth \( f_z = 0.4 \) mm/z). The chosen tool-tip radius was \( r = 0.8 \) mm. The resulting rough periodic surface profile of the Al target is presented in figure 1b. The part of the surface studied under the present conditions of laser irradiation, shown in the next figures, covers the region from about 1200 \( \mu \)m to 1800 \( \mu \)m (mirrored on y-axis) along the x axis on figure 1b.

The optical geometry for the present experiments is shown in detail in figure 1a: The laser source used for the interaction with the Al samples is a pulsed laser source (6 ns pulse duration) emitting radiation of 0.5 to 1.2 mJ per pulse, at 532 nm. The output of the laser system is guided through metallic mirrors to a converging lens (\( f = 100 \) cm) and the beam is then focused onto the target surface. The Al targets, which are produced with a specific surface roughness, are hit with a single pulse of energy > 0.5 mJ; this value constitutes a threshold below which no detectable effect was induced by the laser on the target surface.

The profilometry set-up is presented in figure 1a. It is incorporated in the optical arrangement and is used for the characterization of the samples before and after they have been irradiated with the laser pulse. The profilometry configuration is based on a Michelson white light interferometer, described in detail in [4]. Briefly, a beam splitter separates the white light from the source, generating the reference and object beams, the latter being reflected by the sample surface. A metallic mirror placed on a linear piezoelectric actuator is used for altering the optical path of the reference beam. The two beams are recombined on a CCD camera and a series of acquired interferograms for the different positions of the moving metallic mirror allows for the determination of the surface topology [4]. Using a roughness meter (Roughness gauge TESA Rugosurf 20) the same results for \( R_t \) were indicated, as shown for validity in figure 1d.
3. Finite element modelling

The LS-DYNA software is used for the development of the FEM model [17]. A 3D coupled thermal and mechanical analysis is performed. The temperature distribution is found by solving the heat conduction equation:

\[
\rho(T)C_p(T) \frac{\partial T(x,y,z,t)}{\partial t} - \nabla[k(T)\nabla T(x,y,z,t)] = Q(x,y,z,t) - L_i
\]

(1)

where \( x, y \) and \( z \) are the space coordinates while \( \rho, C_p, k \) are the mass density, specific heat at constant pressure and the thermal conductivity of the target material, respectively. The source term, \( Q \), represents the laser energy absorbed by the sample, while \( L_i \) is the latent heat of melting and is equal to zero in the thermoelastic regime.

The conservative equations of mass, momentum and energy are also solved:

\[
\frac{\partial \rho}{\partial t} + \rho \nabla \mathbf{v} = 0
\]

(2)

\[
\rho \frac{\partial^2 U_i}{\partial t^2} = \mu \frac{\partial^2 U_i}{\partial k^2} + (\lambda + \mu) \frac{\partial}{\partial i} \left( \frac{\partial U_k}{\partial k} \right) - (3\lambda + 2\mu) \alpha T \frac{\partial T}{\partial i}
\]

(3)
The source term \( Q(x, y, z, t) \), has an elliptic spatial form and represents the absorbed laser energy per unit volume per unit time by the sample:

\[
Q(x, y, z, t) = I_o (1 - R) e^{-\frac{4\ln2(x/a_o)^2}{r_0} e^{-[(x/r_a)^2+(y/r_b)^2]} a_\theta e^{-a_b z}}
\]

where \( I_o \) is the incident laser intensity on target, \( R \) is the optical reflectivity of the sample, \( a_\theta \) is the optical absorption coefficient, \( r_0 \) is the laser pulse duration at full width at half maximum (FWHM), \( r_a \) the semi-major axis and \( r_b \) semi-minor axis of the laser spot, \( x_o, y_o \) the centre coordinates, and \( \theta \) the rotation angle.

The 3D FEM model simulates the transient structural response of a homogeneous isotropic Al target. The dimensions of the solid target are \( 1.5 \times 1.5 \times 0.012 \text{ mm} \). A hexahedral, 3D-solid eight-node element is adopted for the transient analysis. A total of approximately 4.8 million elements is used for the model where surface roughness is not considered (model), while a total of approximately 4.2 million elements is used when surface roughness is modelled (R-model). Moreover, the beam spot has an elliptic shape. The major and minor axes of the elliptical laser spot are 160 \( \mu \text{m} \) and 75 \( \mu \text{m} \) long as indicated in the experiment. Since the laser spot defines the area of interest in our study, the sub-model of size \( 1.5 \times 0.6 \text{ mm} \) is considered, as shown in figure 3a (top-right) for the FEM models. A total of 960000 and of 840000 elements, were used for the FEM model \( (z = 12 \mu \text{m}, 0 \leq y \leq 600) \) and the R-model \( (z = 12 \mu \text{m}, 0 \leq y \leq 400 \text{ and } z = 9 \mu \text{m}, 400 \leq y \leq 600) \) simulations, respectively. The hydrodynamic and deviatoric behavior of the metallic target is considered by using simultaneously the analytical Grüneisen EOS coupled with the Johnson-Cook (J-C) strength material model, that considers plastic and fracture effects [18]. The temperature dependent thermomechanical properties and the J-C material model and failure parameters, as well as the Grüneisen EOS coefficient properties of the workpiece, are taken from literature [19-21].

4. Results and discussion

The laser fluence threshold for transition from the elastoelastic to the melting phase is computed to be 1.5 J/cm\(^2\), a value that has been also validated by the experiments. The effect of the laser pulse on the surface roughness of the workpiece is demonstrated in figure 2 for the pulse energy of 0.7 mJ and a fluence of 2 J/cm\(^2\), which is above the melting threshold of Al. Full and appropriately cropped images, tight around the elliptical shaped laser spot, are shown in figure 2. The corresponding 3D surface plots and lineouts of the Al target, prior and after the laser pulse hits the surface, are also demonstrated. To follow the experimental measurements alignment and the presentation of the results, the direction of the roughness pattern shown in figures 2 and 3 is mirrored on the y axis (compared to figure 1).
Figure 2. **Top three rows:** 3D surface plots and lineout graphs of the Al surface before (left) and after (middle) irradiation and of the subtracted images (right). **Bottom three rows:** same as before of the cropped images, demonstrating the vicinity of where the elliptical laser spot hits the surface of the workpiece.

The full and cropped images and the 3D and lineout images apart from the area clearly affected by the laser pulse, also reveal details on the height/depth of the affected peaks. According to the subtracted images (prior and after the laser pulse) some resulting laser-affected roughness peaks show a difference reaching up to 4 μm in height/depth, for one spike even up to 6 μm. Such spikes exist also outside the laser-affected region of the sample and are considered as artefacts (measurements noise). Most peaks inside the laser-affected region, influenced by the laser pulse, show differences in height/depth below 1 μm.

To model the surface roughness, a rough step-like linear approximation is carried out, as shown via the profile data from the original Al image in figure 3a. On the top-right is also presented the 3D full model by considering the step-like approximation of the roughness periodic profile. On the bottom of figure 3a the meshed sub-model of roughness (R-model) is shown. The FEM results of temperature,
Von Mises stresses and the plastic strain of the FEM model and the R-model are presented in figure 3b for 10 ns and 20 ns and for laser fluence of 2 J/cm².

Furthermore, the final nodal positions after the laser beam irradiation are presented in the graph on the bottom-right of the figure. At 10 ns the heated target is in the elastic regime, at 13 ns plastic effects are initiated and at 16 ns the surface temperature exceeds the melting point. At 20 ns the heated material is in the melting regime. The total fractured volume for the R-model is computed to be ∼172 μm³, while this value becomes ∼163 μm³ for the model without roughness. The maximum depth due to material fracture is 0.1 μm for both models. This value along with the maximum computed temperature of 850 °C, indicates that ablation phenomena do not take place for this laser fluence.

Figure 3. a) Top left: Image processing of the roughness profile data (figure 1c) in MATLAB (red) filtered using Gaussian smoothing (green). A rough linear approximation (black) is used to define the preliminary roughness FEM R-model (top right). The meshed sub-model of the R-model is presented at the bottom. b) FEM results of temperature, Von Mises stress and plastic strain distribution for the FEM model and the R-model at 10 ns and 20 ns for laser fluence of 2 J/cm² and the nodal positions after laser irradiation (bottom right).
5. Summary
The surface roughness and the effect of a single laser pulse on an Al 6061 workpiece is investigated via numerical simulations and experimental measurements. A single pulse of 6 ns duration an 0.7 mJ of energy (fluence of 2 J/cm², plastic regime) is used to hit the Al target and induce changes in the surface roughness, which are visualized by a white-light profilometry set up with sub-micrometer resolution. A FEM thermal-structural model is used to model the laser irradiated rough surface, with dimensions using a step-like linear approximation of the experimentally obtained periodic surface profile. The experimental and computational outcomes agree well. Combining the numerical models with the experimental techniques presented in this study constitutes a promising tool for an in-depth analysis of the influence of heat parameters on the surface roughness of different materials, below the ablation threshold, and can be further extended to various laser machining and micromachining applications. Future temperature measurement experiments are expected to provide additional insight on these issues. Higher spatial modelling of the micro-roughness characteristics will be further included in the models that will be developed for our future studies.

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