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Study on the Effect of Laser Pulse Energy on the Geometric Quality of the Laser Machined Parts

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The direct write laser-machining process is based on CNC technology and therefore it is assumed that the laser beam focal spot scans the workpiece surface in conformance with the predetermined tool path. However, laser-machining experiments indicate that the geometric quality of the machined part is not only defined by the pre-determined tool path but is also largely influenced by the dynamics of the laser-material interactions. The geometry and surface profile of the machined part is the result of a combined effect of the complex dynamic processes accompanying the machining process. All laser-machining systems have unique dynamic characteristics, represented by random variations of process parameters, *e.g.*, pulse energy, travel speed, *etc*. Thus, accurate prediction of part quality becomes very difficult, requiring a systematic experimental study for each specific material and the laser-machining system. The objective of this work is to experimentally investigate the effect of variations in laser pulse energy on the geometric quality of the machined parts in terms of accuracy, precision, and surface quality.

The laser micromachining process involves a large number of variables, which mutually interact affecting the final geometric quality of the machined part. However, in this investigation only the pulse energy was used as a control parameter. Shallow craters were created in copper foil and in silicon wafer by applying a single pulse to one location and then moving the part to a new position for the subsequent pulse. The craters were machined in a matrix pattern, where each row corresponds to the specific pulse energy, E, within the range of [48…662] μJ. For each pulse energy fifty-one craters were machined to obtain sufficient statistical data of the crater geometry. The results of the experimental study were based on the dimensional geometry and the surface topology of the machined craters. The crater shape can be approximated by a circular paraboloid with a height (crater depth), h, and diameter, d. The crater depth and the diameter are important parameters to determine machining accuracy and precision. Both these parameters are directly related to the pulse energy, and the beam characteristics and ultimately determine the shape and surface finish of the machined part.

Effect of pulse energy on the crater diameter, depth and volume of material removed was studied individually. Observations of the craters reveal that each of the geometric parameters has a random component due to variations around the mean value. The sources of these variations are the deviations in the pulse energy, changes in mode fluctuation, and instabilities in the laser-material interaction. In this study, a pattern recognition analysis is used to evaluate the random properties of the geometric parameters that represent "statistical machinability" of the analyzed material. Pattern recognition analysis based on Bayesian classifiers, linear discriminants, and variance analysis can be used as a tool that supports a proper selection of the process parameters to achieve desired geometric quality.

The crater becomes wider and deeper with increasing pulse energy. For example, in the case of machining of silicon wafer, a change in the pulse energy from 44 μJ to 533 μJ (12.12 times) increases the mean value of the crater depth from 7.09 μm to 17.52 μm (2.47 times) and concurrently, the crater diameter increases from 7.81 μm to 12.64 μm (1.62 times). However, the pulse with lesser energy provides: (a) a much smoother surface of the crater, and (b) a smaller heat-affected area around the crater, leading to a better quality machining. The crater diameter is one of the important parameters, which contributes significantly to the formation of the part geometry and its surface topology. By varying the pulse energies, the power density distribution within the laser focal spot was modified to provide a change in the crater diameter. Figure 1 illustrates the evolution of the crater diameter with respect to pulse energy, $d(E)$. A large number of experiments showed that the random behavior of the parameters in the formation of the crater geometry is primarily due to an initial variation in the pulse energy and the nonlinear dynamics of the laser-material interaction. The mean value of the crater diameter increases with an increase in the pulse energy. This fundamental rule is correct only in a statistical sense, but is incorrect for some particular craters due to the instabilities within the laser-material interaction zone. Therefore, the variance, $var(d(E))$, is used to statistically estimate the random properties of $d(E)$. It is important to note that $var(d(E))$ is not a constant for different pulse energies. The value of $var(d(E))$ also provides an estimation of the quality of the machining process, i.e., smaller $var(d(E))$ means lesser deviations in the shape geometry which corresponds to better geometric quality of the machined part. Second parameter, the crater depth is an integrated component of the part geometry and surface topology. Therefore, if the crater depth is known for a specified pulse energy and material, the final surface profile can be predicted. This approach is normally used for depth-controlled laser machining, in which case the number of machined layers, an added parameter, determines the final part geometry. Figure 2 shows the evolution of crater depth with respect to pulse energy, $h(E)$. The variance of the crater depth, $var(h(E))$, can be used to estimate the quality of the surface profile, which can be either achieved or predicted as an integrated value of variations around the mean value.

For high-precision laser micromachining, the combination of geometric parameters, such as crater depth and diameter, plays a significant role in the determination of the final machined quality primarily because the crater geometry and the surface topology are usually understood as projections of the laser beam energy profile onto the workpiece surface. Experimental results confirm that the machined crater inherits the beam profile; however, the crater geometry is not an exact map of the beam profile onto the workpiece surface. The dynamics of the laser-material interactions correspondingly changes the crater surface profile. The volume removed from the material depends on the wavefront of the focused laser beam profile, beam mode characteristics, surface reflectivity of the workpiece material, and its original surface profile, which includes the surface irregularities at each point of that local area that had been impinged by the wavefront of the laser beam. Subsequent impingement of wavefronts within the single pulse defines the conformed shape of the crater. This phenomenon results in the chaos in material removal process inside the crater once the crater starts to deepen; and this behavior of the laser-material interaction is one of the sources of the random components of the crater depth and diameter data. It is also necessary to note that the crater depth and diameter are interrelated, and cannot be controlled separately. Hence, the selection of proper process parameters based on experimental study induces a need for significant attention to a combination of crater depth and diameter. One of the possible ways to take this fact into consideration is to use pattern recognition analysis, which provides a mathematically correct separation of the experimentally obtained data into unique clusters, which correspond to specific pulse energies.

Figure 3 shows the classification of crater geometry parameters (diameter and depth) with respect to the pulse energy. It also lays the foundation for the proper selection of machining parameters, i.e., the pulse energy. There are two typical situations where machining parameters are selected with respect to the geometric quality of the machined part. The first situation occurs when the part accuracy and precision are known and machining parameters are selected to achieve the desired geometric quality. The second situation is more widely used in practice, especially for laser machining, where applying a "trial-and-error" approach, the "optimal" process and machining parameters are selected. Therefore it is necessary to know what degree of accuracy and precision will be achieved. The approach suggested below serves both situations. Each cluster for a particular pulse energy has a certain data spread around the cluster center. Therefore, selecting a certain pulse energy as a process parameter, the prediction of the best accuracy and precision that can be achieved during machining for the specific part material becomes more accurate. The evolution of the crater diameter and depth with respect to the pulse energy also indicates that the depth varies more than twice as much as the diameter. For example, in the case of machining of copper foil, an increase in the pulse energy from 48 μJ to 547 μm (11.4 times) provides an increase in the crater diameter from 13.72 μm to 25.37 μm (1.85 times), and an increase in the crater depth from 4.23 μm to 17.35 μm (4.1 times). This fact is also an important factor in the proper selection of the machining parameters.

From the manufacturing perspective, there is always a trade-off between productivity and quality. This dilemma exists in laser micromachining as well. The productivity of the laser-machining process is based on the material removal rate, which increases with pulse energy, but the geometric quality of the machined parts in terms of accuracy and precision decreases. Machining with lower pulse energy will produce parts with better accuracy but at a lower productivity. In order to examine this issue, circular features with outer diameter of 100 μm were machined. Figure 4 shows the circles, machined with pulse energies of 547 μJ, 240 μJ, and 48 μJ. As a result, the corresponding variations of the outer diameter are $\pm$ 5.1 μm, $\pm$ 3.9 μm, and $\pm$ 2.1 μm. An increase in the precision by 2.5 times is achieved by decreasing the pulse energy from 547 μJ to 48 μJ.

The following conclusions can be drawn from this study:

1. The results obtained from the geometric parameters of the machined craters, indicate that the measured data on crater diameter and depth contain random components. The statistical properties of these components depend on the pulse energy.
2. The use of pattern recognition analysis as a statistical tool can provide proper selection of the process parameters to optimize the machining process with respect to productivity and/or part geometric quality.
3. The crater depth is primarily affected by the pulse energy; therefore, the proper selection of pulse energy could precisely control the depth of laser machining.
4. The use of lower pulse energy significantly improves the final accuracy and precision of machined parts, and reduces the heat-affected area, burrs, and damage to the surrounding material.
5. The method is applicable to study and analyse a wide variety of materials and laser machining parameters to improve the geometric quality of the machined parts.

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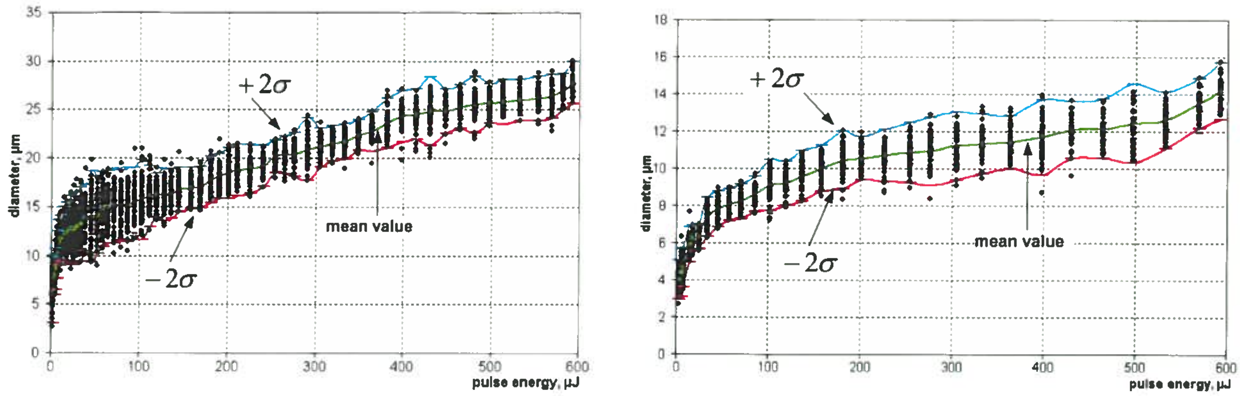

Figure 1. Evolution of the crater diameter with respect to pulse energy (left – copper, right – silicon).

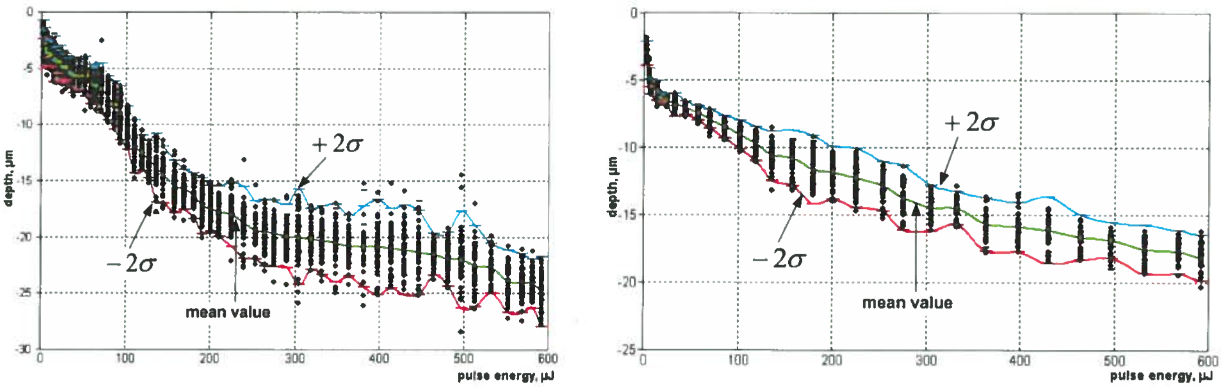

Figure 2. Evolution of the crater depth with respect to the pulse energy (left – copper, right – silicon).

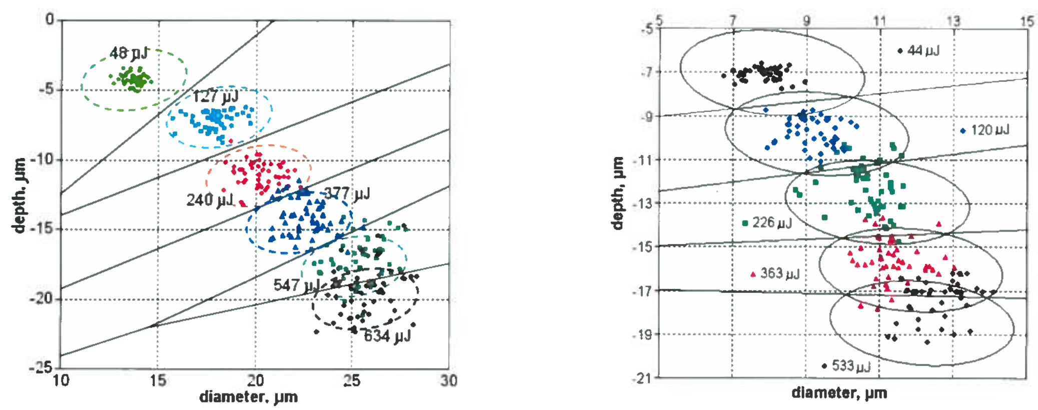

Figure 3 Classification based on crater diameter and depth with respect to pulse energy (left– copper, right– silicon).

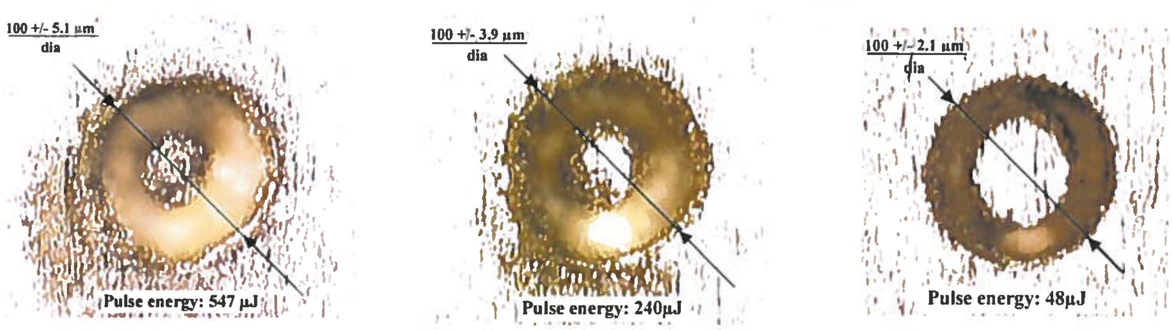

Figure 4. Circles in copper foil with an outer diameter of 100 µm machined with different pulse energies.