

Comparative Assessment of the Transient Temperature Response during Single-discharge Machining by Micro-EDM and LIP-MM Processes

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Abstract: The micro-EDM is a well-established subtractive type of micro-manufacturing process and has been at the center of research for the last 15 years. The laser induced plasma micro-machining (LIP-MM) is a novel multi-material and tool-less micro-machining process that also removes material through plasma. Since, both processes remove material through melting and vaporization, machining is always accompanied with heat affected zone. Since different materials have different thermo-physical properties, the plasma discharge energy level for minimal HAZ is material-dependent. The plasma discharge energy level corresponding to minimal HAZ can be experimentally determined by examining the dependence of the spatial distribution of the transient temperature response near the machined zone on the energy level. This paper, for the first time, presents an experimental investigation on real time measurement of the transient temperature response during single discharge machining at different pulse energy levels by the micro-EDM and the LIP-MM processes. The experimental data establishes a relationship between the pulse energy level and the transient temperature response and thus can be used for identifying the conditions for minimal HAZ in the two processes.

Keywords: Micromachining, Laser Induced Plasma, Micro-EDM, Transient Temperature Response

1.0 Introduction

The micro-EDM is a well-established subtractive type of micro-manufacturing process and has been at the center of research for the last 15 years. In micro-EDM, material removal is facilitated through electro-thermal mechanisms induced by the plasma that is created when the electric field generated by the voltage applied between the tool and the conductive workpiece exceeds the threshold value for dielectric breakdown.

The laser induced plasma micro-machining (LIP-MM) is a novel multi-material and tool-less micro-machining process that also removes material through plasma [1-7]. The plasma is generated in a transparent dielectric medium through laser induced dielectric breakdown. It has similar material removal mechanism and material is removed in both processes through vaporization and melting. However, differences in their respective modes of plasma generation and plasma characteristic properties such as its size, repetition rate, energy and discharge duration result in differences in their

machining capabilities, especially the heat affected zone (HAZ), machining tolerance, and geometric accuracy. Since different materials have different thermo-physical properties, the plasma discharge energy level for minimal HAZ is material-dependent. The plasma discharge energy level corresponding to minimal HAZ can be experimentally determined by examining the dependence of the spatial distribution of the transient temperature response near the machined zone on the energy level.

This paper, for the first time, presents an experimental investigation on real time measurement of the transient temperature response during single discharge machining at different pulse energy levels by the micro-EDM and the LIP-MM processes. The experimental data establishes a relationship between the pulse energy level and the transient temperature response and thus can be used for identifying the conditions for minimal HAZ in the two processes. Nickel was used as the workpiece material. Based on the experimental results, the paper also presents a comparative assessment of the transient temperature

response at equal pulse energy levels for the two processes.

2.0 Experimental Determination of the Transient Temperature Response:

Various non-contact and contact-based conventional experimental techniques have been developed to measure the real time transient temperature response within the workpiece during conventional machining applications such as welding, machining, etc. . However, in the case of micro-EDM and LIP-MM processes, several constraints such as limited access to the measuring point, extremely small area to be measured ($\sim\mu\text{m}$), high temporal and spatial gradients in a very small area ($\sim 10^3\text{ }^\circ\text{C} / \sim 10^2\text{ }\mu\text{m}$), presence of a dielectric liquid, and plasma interference render the conventional experimental techniques difficult to use.

In recent years C-type micro-thin film thermocouples (C-type micro-TFTC) have been developed that address the above-mentioned constraints . They have been used with significant success in measurement of the real time transient temperature response on workpiece surfaces in ns-pulsed laser ablation [8]. The recently developed C-type thin film thermocouples were also used for the measurement of the transient temperature response in the present study. The following section describes the characteristics of C-type micro-TFTCs, and the Ni workpiece with C-type micro-TFTCs deposited on its surface.

2.1 Development of the Ni Workpiece with C-type Micro-TFTCs¹

The C-type micro-TFTCs (W-5% -Re vs. W-26% - Re) developed are characterized by a very small node size ($2\text{ }\mu\text{m} \times 2\text{ }\mu\text{m}$), fast response time that is approximately $\sim 120\text{ ns}$ and is many orders of magnitude faster than the conventional contact and non-contact based techniques (ns vs. $\sim\text{ms}$ and μs), and high working temperature (up to $2,760\text{ }^\circ\text{C}$) . They can be deposited through photo-lithography on the workpiece surface near the point of interest. They are capable of functioning even within a dielectric medium and in the presence of plasma interference. These unique characteristics make them the most suitable technique to measure the transient temperature

¹ The development of the Ni workpiece was largely accomplished by Prof. Xiaochun Li and his students at the Mechanical Engineering Department, University of Wisconsin – Madison at their micro-fabrication facility. The author gratefully acknowledges their help.

response in the very close proximity from the plasma-matter interaction spot during micro-ED machining and LIP-MM

A mask of a 2D array of 16 micro-TFTCs was designed in AutoCAD in an area of approximately $50 \times 50\text{ mm}^2$ [8]. Figure 1 shows the layout of the 2D array and a close-up view of the thermocouple nodes. As shown, 4 micro-TFTC sensor nodes were placed in each quarter with an inter-node gap of $20\text{ }\mu\text{m}$. The quarters surrounded the micro-machining zone, where single-discharge machining by micro-ED milling and LIP-MM would occur.

The micro-TFTCs are only $1\text{ }\mu\text{m}$ thick and have a very small node size. In order to successfully deposit the thermocouple nodes through photolithography, the workpiece should be free of any contaminants and should have very low surface roughness. A Ni workpiece of microelectronic-grade surface roughness was prepared through a novel technique that involved electroplating and etching on a silicon wafer [8, 9]. Ni was selected because it could be easily deposited on the silicon wafer through sputtering and electroplating.

Figure 2 shows the various steps involved in the preparation of the Ni substrate of micro-electronic grade surface roughness. As shown in the figure, a thin layer of silicon nitride was deposited on the wafer as the dielectric material followed by Ti through sputtering to promote adhesion of the seed layer of Ni. Ni of micro-electronic grade roughness was then subsequently deposited through electroplating on the seed layer. Silicon was removed through wet etching, thereby leaving the Ni substrate with Ti and silicon nitride as the dielectric material.

The 2D array of micro-TFTCs was then subsequently deposited on the dielectric layer of the Ni substrate through photo-lithography [9]. Figure 3 illustrates the various steps involved in the development of the workpiece. As illustrated, after deposition, the dielectric layer of silicon nitride and Ti were removed through dry and wet etching, respectively to expose the Ni in the center between the sensor nodes where micro-machining will take place. A detailed step-by-step description of the processes involved in the development of the Ni workpiece with the micro-TFTCs including the preparation of the Ni workpiece, design, fabrication, and calibration of the C-type micro-TFTCs is discussed in detail in the earlier work performed by Choi et al. [8].

Figure 4 presents a microscopic image of the workpiece with deposited C-type micro-TFTCs. As the

figure suggests, the nodes were approximately $2 \times 2 \mu\text{m}$, and were deposited at a distance of about $26 \mu\text{m}$ from the edges of the micro-machining zone. The pads of the 16 micro-TFTCs were bonded to the C-type thermocouple extension wires (EXGG-C-24, Omega) with a high temperature silver paste (Pyro-Duct 597-A, Aremc). In order to ensure sufficient rigidity, the extension wires were further attached to the fixture holding the workpiece through kapton tape. The workpiece was attached to the fixture through a double sided high shear strength solvent resistant polyester tape. Figure 5 shows the image as obtained by an ordinary digital camera of the sensor array after extension wire bonding with the high temperature silver paste.

The micro-TFTCs were subsequently examined and characterized for their functionality and sensitivity. The sensitivity was characterized from room temperature to $1,091 \text{ }^\circ\text{C}$ in a temperature

controlled vacuum furnace. The temperature of the vacuum furnace was not increased beyond $1,091 \text{ }^\circ\text{C}$ due to temperature limitations imposed by the silver paste. However, the silver paste would not experience high-temperatures of this range during micro-machining and further higher temperatures could be recorded by the C-type micro-TFTCs. The thermocouples exhibited a linear response to temperature changes with a $18.6 \mu\text{V}/^\circ\text{C}$ sensitivity [9].

Subsequent to characterization, the workpieces were used for measurement of the transient temperature responses during single discharge machining by the micro-EDM and the LIP-MM processes, respectively. The following sections, describe the experimental setup, procedure, and experimental results for the two processes. Micro-EDM is discussed first followed by the LIP-MM process.

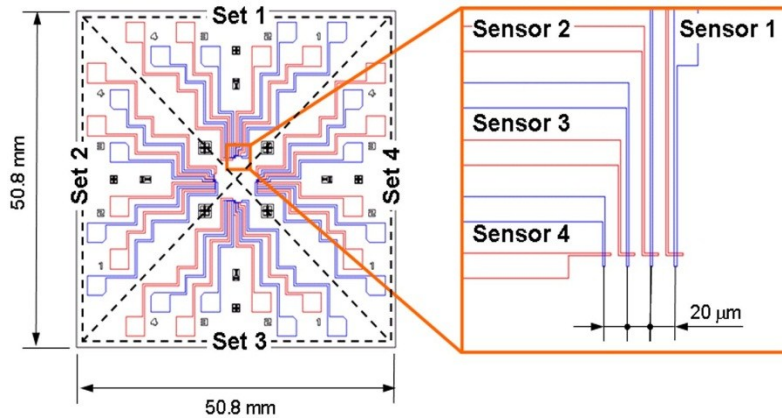
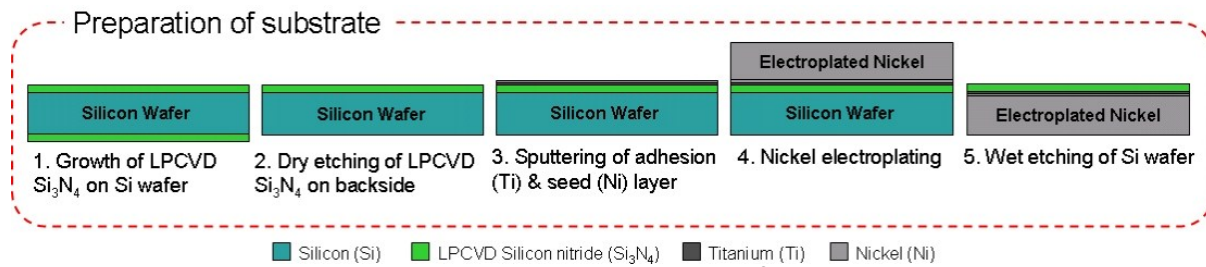


Figure 1: Design layout of the 2D array of micro-TFTCs and close-up view of the thermocouple junctions



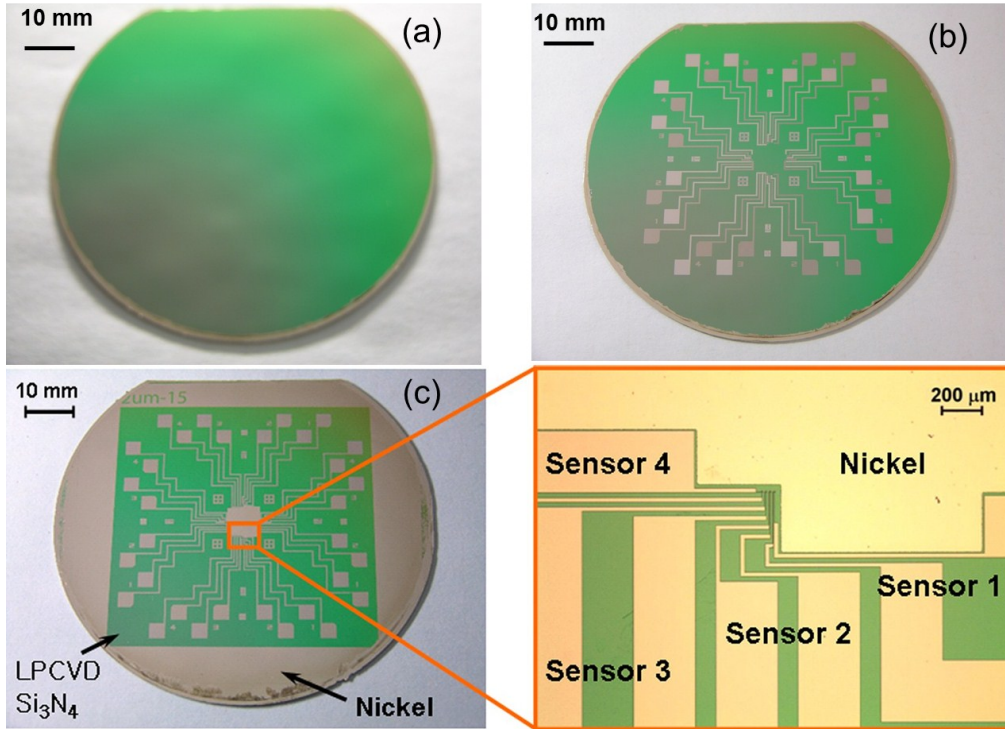


Figure 3: Steps in the development of the workpiece: (a) preparation of the Ni substrate of micro-electronic grade surface roughness and silicon nitride as the dielectric layer, (b) deposition of the micro-TFTCs through photolithography on the substrate, (c) etching of the dielectric layer to expose Ni in the micro-machining zone

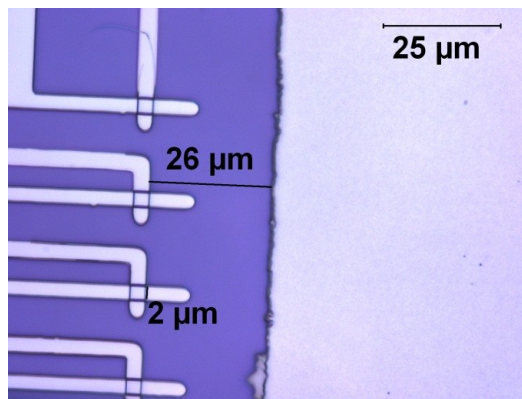


Figure 4: Microscopic image of an array of four thermocouple nodes placed at a distance of 26 μm from the micro-machining zone

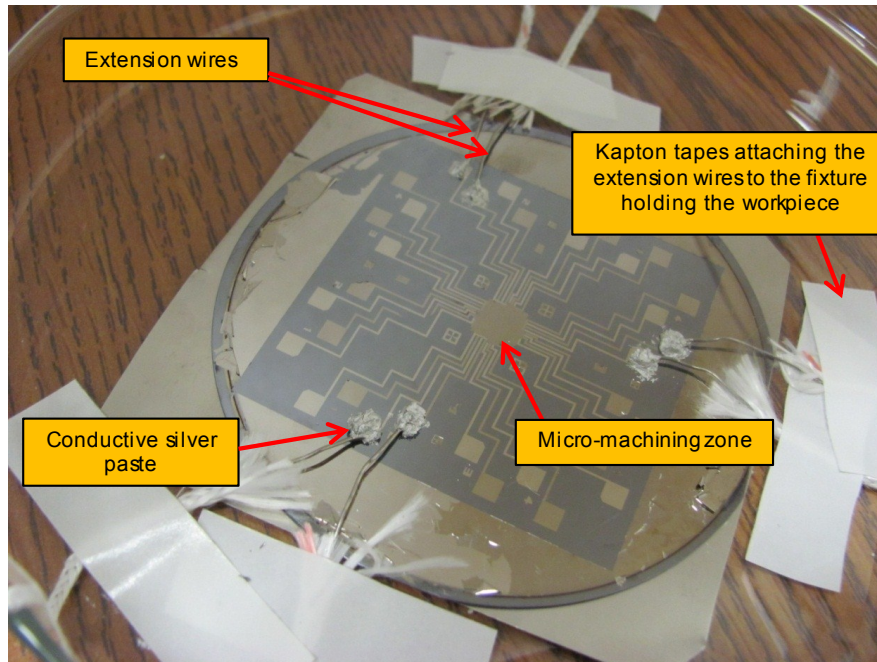


Figure 5: Image of the C-type micro-TFTC sensor array after wire bonding with conductive silver paste

3.0 Experimental Results:

To focus on fundamental issues, only single-discharge machining at equal pulse energy levels was used to study the transient temperature response on the surface of the Ni workpiece. Craters were machined by the micro-EDM and LIP-MM processes at varying radial distances from the micro-TFTC nodes. Figure 6 shows typical craters machined at varying distance from thermocouple nodes by the LIP-MM process.

Single discharge machining was performed in the micro-machining zone by micro-EDM and LIP-MM processes at three pulse energy levels of 9.52, 7.68, and 5.94 μJ . The voltage signal from the micro-TFTCs was captured by the high speed oscilloscope at 2.5 Giga Samples/Sec. The micro-TFTC has a constant and linear sensitivity of 18.6 $\mu\text{V}/^\circ\text{C}$ throughout its working temperature range. Hence, the magnitude of the voltage signal obtained through the thermocouple has a direct and linear correlation with the transient temperature as measured at varying radial distances, while its duration represents the duration of the transient temperature response. Figure 7 exhibits a typical post-processed signal showing the temporal distribution of the transient temperature response during single discharge machining by the micro-EDM process.

Figure 7 exhibits a typical post-processed signal showing the temporal distribution of the transient temperature response during single discharge machining by the micro-EDM process.

3.1 Comparative Assessment of the Transient Temperature Responses

Figures 8 and 9 illustrate the spatial distribution of the transient temperature responses during single-discharge machining by the Micro-EDM and the LIP-MM processes at the three pulse energy levels of 9.52, 7.78, and 6.07 μJ . The spatial distribution of the transient temperature response was observed to be different in the two processes. Even when machined at equal pulse energy levels, the transient temperature response measured during the LIP-MM process was found to exhibit a higher spatial gradient than the micro-EDM process. It decreased sharply from the maximal recorded temperature of approximately 1,800 $^\circ\text{C}$ at 20 μm nodal distance to 800 $^\circ\text{C}$ at 50 μm from the edge of the crater. Similar drop in temperature (2,250 $^\circ\text{C}$ to 800 $^\circ\text{C}$) was observed in micro-EDM at an order of magnitude higher nodal distance of 500 μm from the edge of the crater. Thus the plasma-matter interaction in LIP-MM results in more localized heat deposition on the workpiece surface than in the micro-EDM process.

The difference in the spatial gradient can be primarily attributed to differences in plasma characteristics that are plasma size and discharge duration in the two processes. The plasma discharge duration in LIP-MM as measured by the high speed camera was observed to be typically 30 ps and 22 ps at pulse energy levels of 9.63 and 6.07 μJ , respectively [3]. The plasma discharge duration in micro-EDM is typically on the order of μs [10]. Therefore, at equal pulse energy levels, the plasma

discharge duration in LIP-MM is 10^{-6} (ps vs. μ s) smaller than that in the micro-EDM process. Hence, the resulting time for heat transfer through conduction is also 10^{-6} shorter for the LIP-MM process. This coupled with the fact that the plasma size is smaller in LIP-MM ($10\ \mu\text{m}$ vs. $\approx 30\ \mu\text{m}$ in micro-EDM), the plasma-matter interaction results in more localized heat deposition in the workpiece at higher spatial gradient than in the micro-EDM process. This results in vaporization of the workpiece material with negligible heat transfer to the adjoining areas, minimal melting and formation of HAZ.

In the case of micro-EDM, plasma-matter interaction results in melting and vaporization of the workpiece material accompanied with heat transfer to the adjoining areas that lead to the formation of HAZ and recast layer. Since, the plasma-matter interaction in LIP-MM results in more localized heat deposition on the workpiece surface, leading to vaporization of the workpiece material at the plasma-matter interaction spot and minimal HAZ in close proximity to the machined zone, it offers many advantages over the micro-EDM in high precision machining of thermally conductive materials.

4.0 Conclusion

This paper, for the first time, presents an experimental investigation on the real time measurement of the transient temperature response during single discharge machining at different pulse energy levels by the micro-EDM and the LIP-MM processes. The paper also proves the feasibility of using C-type micro-TFTCs for real time measurement of the transient temperature response for the two processes.

The experimental data establishes a relationship between the pulse energy level and the transient temperature response during machining by the two processes. It was experimentally observed that the transient temperature response in LIP-MM had a higher spatial gradient than in the micro-EDM process, primarily due to shorter discharge duration and plasma size. The differences in the spatial gradient of the transient temperature response during single-discharge machining by the two processes explains the differences in machining characteristics especially in the formation of HAZ near the machined at equal pulse energy levels.

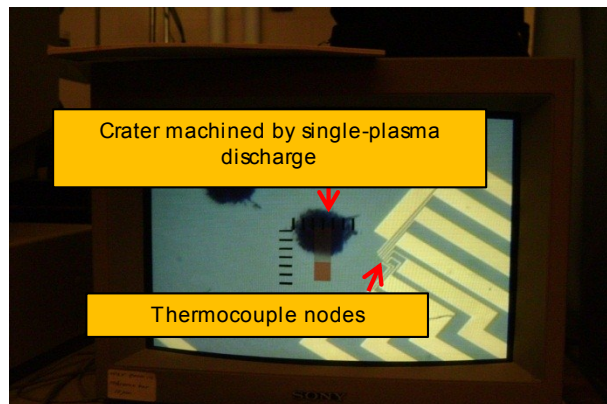


Figure 6: Image obtained by a CCD camera of craters machined near the thermocouple nodes by the LIP-MM process in a typical Si workpiece

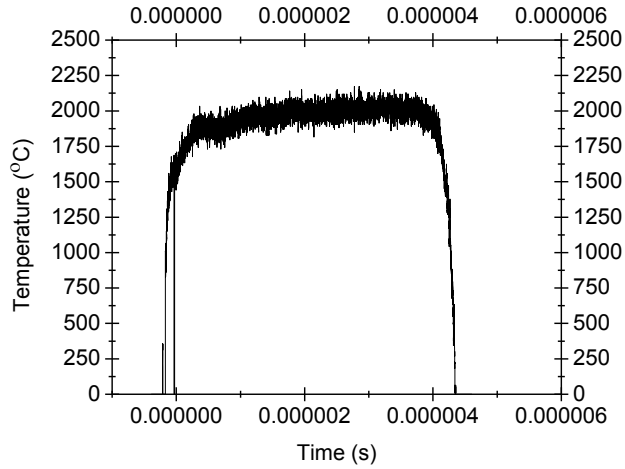


Figure 7: Typical post-processed transient temperature response obtained by the high-speed oscilloscope during single-discharge machining by the micro-EDM process

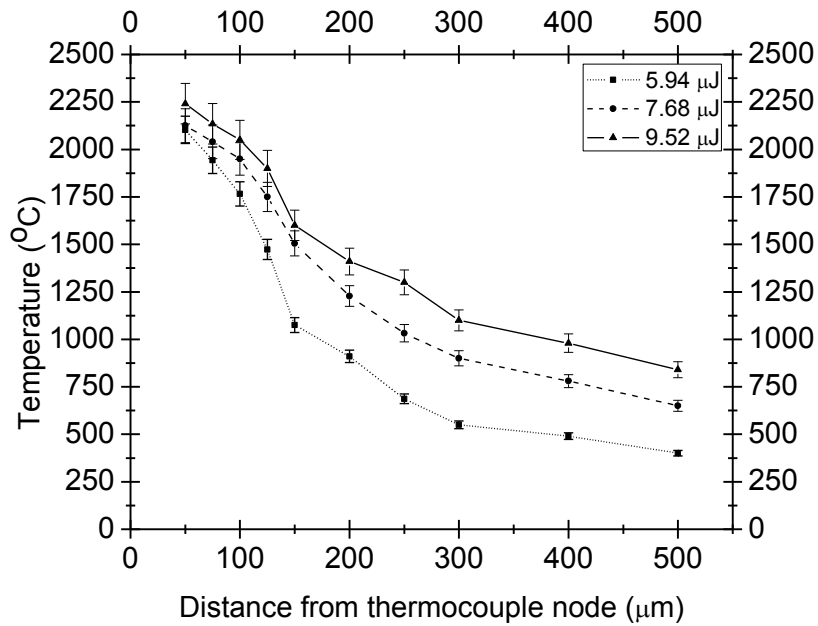


Figure 8: Spatial distribution of the transient temperature response at the three pulse energy levels

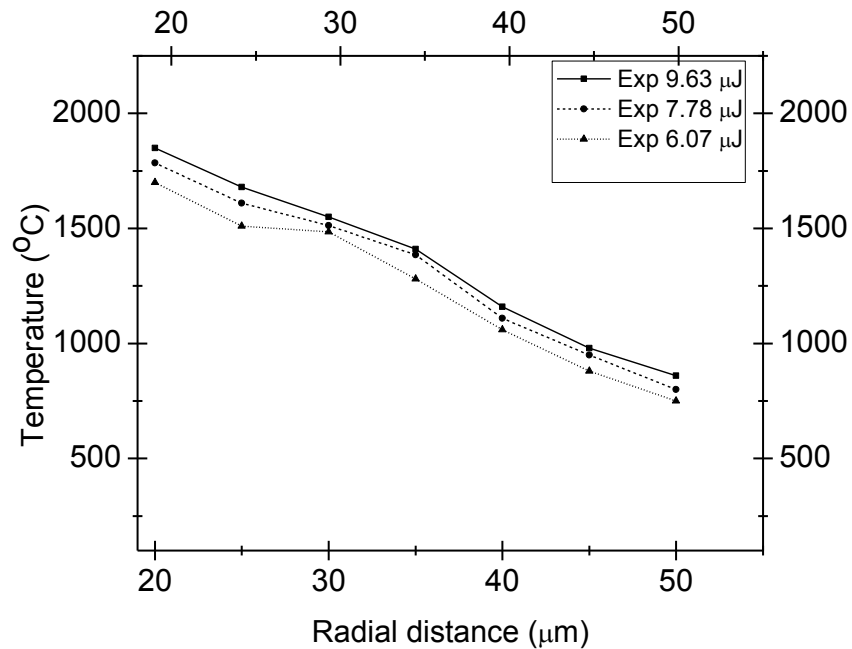


Figure 7: Spatial distribution of the transient temperature response at the three pulse energy levels by the LIP-MM process

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