Effect of Laser Frequency and Focal Length on Copper Surface Temperature During Laser Heating

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Abstract. Laser heating is a process that uses laser as a heat source. In this paper, the copper surface temperature during the laser heating process was studied by controlling the laser frequency and focal length. The laser heating experiment was conducted using a fiber laser marking machine and irradiated with a constant 27Watt laser power within a duration of 51 seconds. The laser frequency and focal length were varied from 100 kHz to 300 kHz and -3 cm to +3 cm, respectively. Meanwhile, laser surface modification (LSM) was performed on the copper rod surface to enhance the laser energy absorption. Furthermore, the defocusing modes for laser heating were used to analyze the variation of temperature. The focus point of the focal length for this experiment was set up at 18.4 cm from the focal plane and denoted as 0. Laser frequency and focal length were found to play an important role in increasing the surface temperature during laser heating since it affects the heat input delivered to the materials. It was found that the surface temperature reaches a higher degree, 879.2 ^{0}C with the combination of 200 kHz laser frequency at focal length 0.

Keywords: Laser Heating, Surface Temperature, Focal length, Laser Frequency.

1 Introduction

In recent years, lasers are regarded as advanced material processing tools that bridge the gap in advanced manufacturing systems because of their accuracy, low cost, localized processing and high speed of operation. In material processing, the use of lasers is an appealing option for high-tech production [1]. The laser beam is used as a heat source to heat, melt or to fuse exactly the energy of the surface and the inner part stays unchanged [2]. Since the arrangements of the optical setting for the laser beam are very precise, the localized heating can be controlled easily [3]. However, the applications of lasers in an industry require knowledge of the interaction mechanism between the laser beam and the workpiece [4].

Laser heating is found to be one of the effective methods that use a laser beam to heat the surface of materials or workpiece and accomplish it by conduction. It is a consistent and precise method for small areas that helps to accomplish the heating process by localized heat input. The efficiency of the laser heating process is determined by the absorption of the radiation by the irradiated material [5]. Laser absorption in a metal depends on several different parameters, both involving the laser and the metal itself. The application of laser technology in material heating takes advantage of heat energy from the laser beam.

In laser heating, the energy that is needed to increase the temperature of the material is all dependent on the laser-material interaction. Due to the nature of the reflectivity of the laser beam on metal, it could limit the laser energy absorption [6]. Besides, there are a few laser parameters that influence the absorption which are laser power, laser frequency, spot diameter, speed, focal length and many more. However, laser frequency and focal length affect the temperature increase apart from laser power.

The laser frequency is crucial because the materials may respond differently at different frequencies. On the other hand, it will be influencing the material properties and appearance because it affects the heat input delivered to the materials [7]. The optimal frequency would lead to better heating of the metal. Subsequently, focal length also plays a major role in temperature rise. In laser processing, the position of the focus (focal plane) of the laser beam focusing and the relative position of the workpiece to be processed mainly have a certain relationship. There are three cases of defocusing that can occur which are negative defocus, positive defocus and zero defocus. Defocuses have a relationship with the beam spot size and have a direct impact on temperature [8]. It was found that laser defocusing affects the temperature increase [9].

However, to the best of our knowledge, there are no comprehensive studies that relate laser heating parameters. The problem of laser heating process and thermal properties investigation and complex materials are still increasing [2]. This work aims to study the effect of laser frequency and focal length on the surface temperature. These parameters and their interaction have a strong influence on the laser heating process. The study helps to find a better parameter range setting to improve the temperature distribution.

2 Experimental Setup

The raw materials of the copper rod with a purity of 99.99% and 6 mm of diameter were cut sectioned by using a precision cut-off machine into 6 mm × 6 mm samples. Table 1 shows the properties of pure copper. Prior to the process, all the samples were ground progressively using SiC sandpaper, and then cleaned with acetone solution for a second to remove any contaminant layer that adhered to the samples' surfaces.

Table 1. Thermo- physical properties of copper.

Properties	
Density	8.96 g/ cm^3
Specific heat capacity	0.386 J/ g °C
Thermal conductivity	401 W. m^{-1}. K^{-1}
Melting point	1083°C

The copper rod surface is then treated with laser surface modification (LSM) process to enhance the surface roughness and increase the laser energy absorption during the laser heating [10,11,12]. The surface roughness value, Ra before treated with LSM was 0.433 µm. Roughness has a significant impact on absorptivity due to multiple reflections in the undulations [13]. It marked the surface within the diameter of 6 mm. The process is consistent throughout all the samples. The sample is once again cleaned with the acetone solution prior to the laser heating process.

After the LSM process, the material will be set up for the laser heating process. The experimental setup is shown in Figure 1. The laser heating was performed at an ambient temperature using a fiber laser machine. A ceramic board was placed under a copper rod to reduce the heat conductivity. The diameter of the laser beam irradiated on the copper rod surface was set as 3 mm. Each experiment was conducted at a constant power, and duration as shown in Table 2. Meanwhile, laser frequency and focal length were set as a variable parameter. Focal length at 18.4 cm means that the laser beam is at focus position which is denoted as 0.

An infrared thermometer, Micro-Epsilon CTL2MHSF300- C3, whose temperature measuring range is 385°C- 1600°C was used to measure the surface temperature in the irradiated spot on the sample, as shown in Figure 1. During the laser heating process, the beam from the infrared thermometer and laser were set side by side on the modified copper rod surface to get the maximum temperature without involving any material damage. However, since the beam size of the infrared thermometer is bigger than the laser beam, it will overlap with each other and influence the increase in temperature value. In this case, when the laser energy is emitted to the copper rod surface, it will heat up and subsequently increase the surface temperature as seen in Figure 2.

Table 2. Range of laser heating parameters.

Parameters	
Power	27 Watt
Duration	51 s
Laser frequency	100 kHz, 200 kHz, 300 kHz
Focal length offset	18.4 cm; (-3, -2, -1, 0, +1, +2, +3) cm

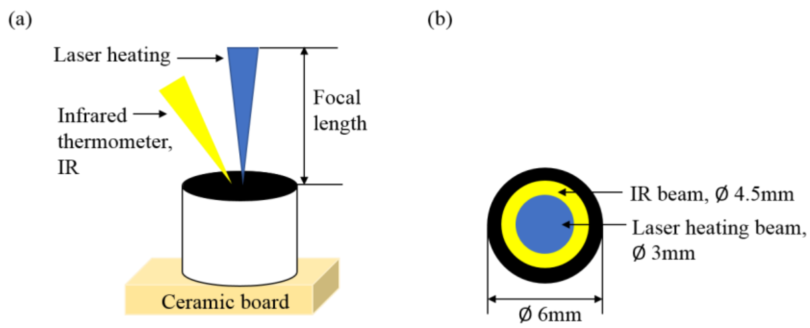

Fig. 1. Schematic diagram of laser heating process setup (a) front view and (b) top view.

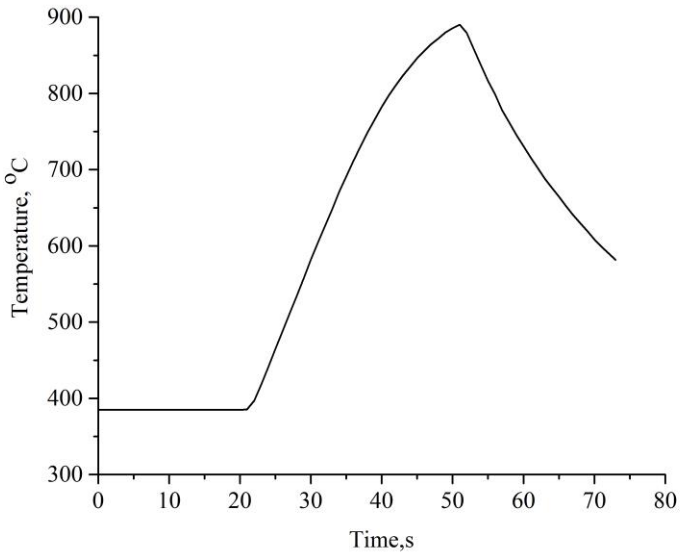

Fig.2. The temperature profile of the laser heating.

3 Results and Discussion

Table 3 shows the obtained temperature with different laser frequency and focal length offset within 51 s of laser heating. The first measure performed was the effect of laser frequency on surface temperature and followed by the focal length offset. Each focal length offset was repeated three times and the average value was measured. In addition, the standard deviation is calculated and it shows a low standard deviation, indicating that the values of the three sets of each parameter tend to be close to the mean.

Following that, the value of the coefficient of variation was determined to show that a lower standard deviation does not necessarily imply less varied data. However, the rise and fall of the measured temperature, which is likely because of the limitations of the infrared thermometer temperature measurement, are still in close agreement which is acceptable.

Table 3. Temperature data of focal length offset at different laser frequency.

Laser frequency, kHz		Temperature, °C						
	Focal length offset, cm	-3	-2	-1	0	+1	+2	+3
100	Sample 1	522.5	673.2	790.3	806.5	785.9	740.4	599.3
	Sample 2	502.0	678.3	782.0	809.1	777.5	734.6	757.1
	Sample 3	522.0	674.9	788.8	801.5	759.5	711.2	568.8
	Average	515.5	675.5	787.0	805.7	774.3	728.7	581.1
	S. Deviation	11.69	2.60	4.42	3.86	13.49	15.46	16.10
	CV, %	2.27	0.38	0.56	0.48	1.74	2.12	2.77
200	Sample 1	607.3	640.8	751.9	869.8	810.2	694.3	616.7
	Sample 2	614.3	647.9	752.9	890.1	802.6	686.7	612.5
	Sample 3	614.1	644.6	748.5	877.8	814.4	701.0	618.1
	Average	611.9	644.4	751.1	879.2	809.1	694.0	615.8
	S. Deviation	3.98	3.55	2.31	10.23	5.98	7.15	2.91
	CV, %	0.65	0.55	0.31	1.16	0.74	1.03	0.47
300	Sample 1	624.6	627.1	716.3	726.1	678.0	616.6	591.7
	Sample 2	631.5	646.2	719.6	748.2	676.8	616.9	581.6
	Sample 3	622.0	622.6	714.6	723.4	672.3	630.4	589.1
	Average	626.0	632.0	716.8	732.6	675.7	621.3	587.5
	S. Deviation	4.91	12.53	2.54	13.61	3.00	7.88	5.24
	CV, %	0.78	1.98	0.35	1.89	0.44	1.27	0.89

Figure 3 shows the variation of temperature with laser frequency. It clearly indicates that when the laser frequency increases, the temperature decreases. The highest temperature obtained is at a laser frequency of 200 kHz while the lowest temperature is at a laser frequency of 300 kHz. As the laser frequency rises, there is just a slight temperature difference. This is because the heating effect on the surface will be more intense at a lower laser frequency.

However, when the focal length is shifted, the differences of temperature become more obvious for all the laser frequency. And in this instance, the focal length seems to be more significant than the laser frequency. Generally, the laser frequency is inversely proportional to laser power. However, in this study, the laser power was kept constant at 27 Watt throughout all the samples. When the laser frequency is too high, the laser power may not be efficient for the process which explains why most of the 300 kHz of laser frequency produces the lowest temperature.

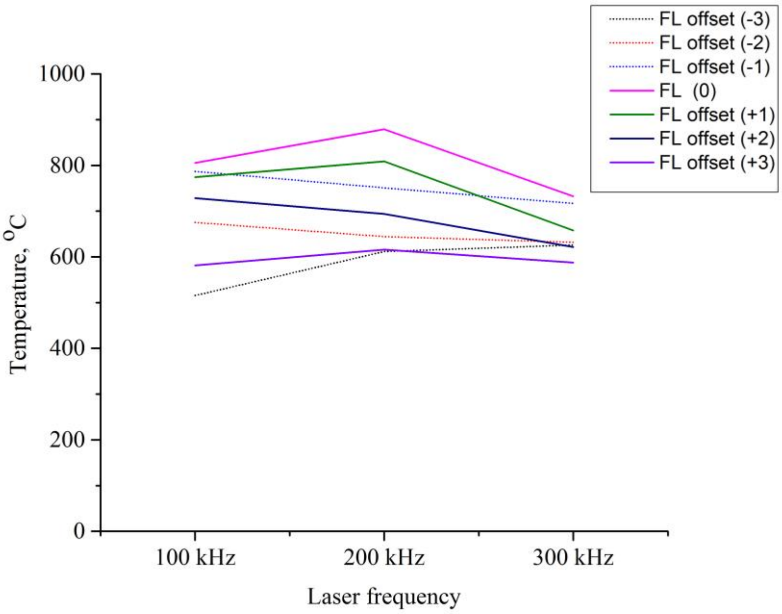

Fig. 3. Graph of temperature against laser frequency.

From the tabulated data, the results of varying the levels of focal length, starting with a fully focused beam are shown in Figure 4 with various laser frequency settings. The graph illustrates that when the focal length offset of each laser frequency is varied, the temperature changes dramatically from -3 to +3 cm. Besides, at focal length 0, the temperature drops as the laser frequency changed. The temperature achieves a higher degree (879.2^{0}C) when the laser beam is pointed at a focal length, 0 and laser frequency of 200 kHz compared to other defocused positions. This is because when the laser defocus approaches focal length 0, the beam spot diameter becomes smaller, leading the copper surface temperature to rise.

The lowest temperature is at focal length offset -3 cm and 100 kHz which is 515.5^{0}C. According to the findings, when the laser beam becomes less unfocused, the temperature decreases and vice versa. This is due to the laser beam's energy being scattered over a broader surface, which reduces the intensity of the heat supplied on the surface. The lower intensity prevents the heat from penetrating deeper into the material [14].

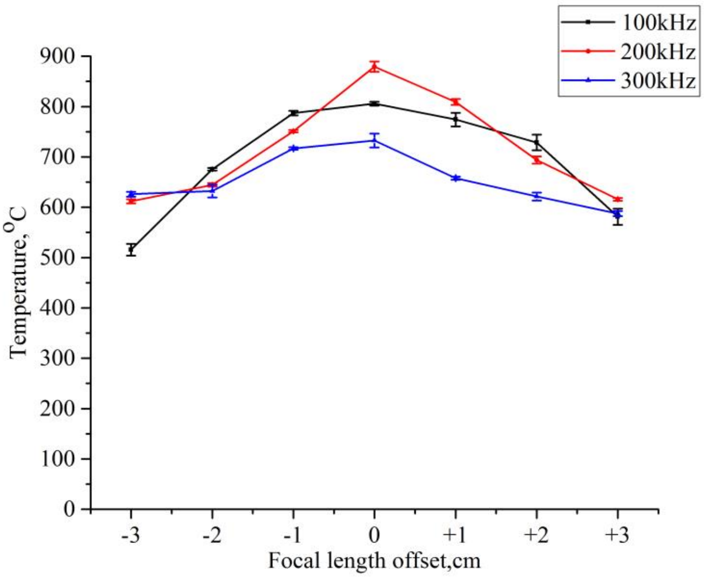

Fig. 4. Graph of temperature against focal length offset.

To sum up, the variation of the focal length offset setting is as shown in Figure 5. It has been studied by Jianli Liu et. al., the effect of the three kinds of focus modes (negative defocus, focus, and positive defocus) [15]. The laser beam is said to be fully focused when it is located at the focal point of the focusing lens. In focused beam laser heating, the beam converges to its minimum radius value so that the size of the area irradiated by the beam is minimized.

The optimum focal length offset was the second focus condition, Figure 5. (b) because the surface has the highest laser energy absorption due to the smallest laser beam. It was discovered that, at focus point distance, where the diameter of the laser beam becomes smallest, the photon can produce enough laser energy [6] to supply the heat onto the surface. Thus, increase the temperature. And it is vice versa with negative and positive defocus conditions. After all, the laser beam focal position was found to have a significant influence on the surface temperature.

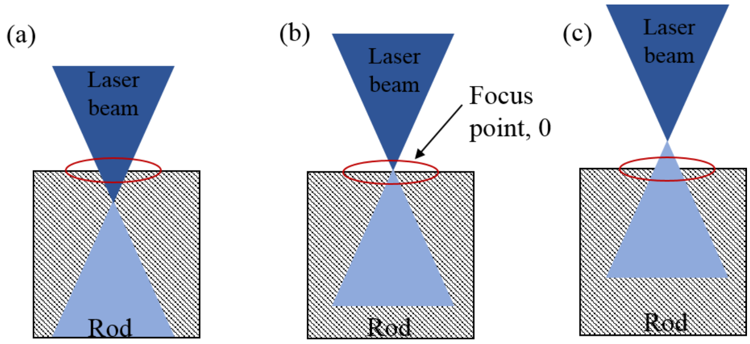

Fig. 5. Schematic of the laser beam at (a) negative defocus, (b) focus and (c) positive defocus plane.

4 Conclusions

The purpose of this study is parameter control towards the copper surface temperature of the laser heating process. To summarize, laser frequency and focal length are two parameters that need emphasis, since it has a significant impact on the surface temperature distribution during the laser heating process. The surface temperature mostly achieves the highest degree at a laser frequency of 200 kHz. Increasing or decreasing the laser frequency range, the surface temperature will drop. At focal length 0, the highest temperature, 879.2^{0}C is obtained compared to other defocused positions. It is because when the laser beam becomes more focused, the temperature increases and vice versa.

The combination parameter of 200 kHz of laser frequency and focal length at 0 defocused, was an optimum range where the copper surface absorbs more laser beam's energy and thus, surface temperature increases.

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