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Temperature Prediction Model for Laser Polishing on Aluminum and a Measurement of Polishing Effect

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ABSTRACT

Laser polishing involves the local melting of a product's surface using a laser beam, thereby improving its surface roughness. Processing parameters such as laser power, feed rate, frequency, and tool path affect laser polishing. The surface temperature changes depending on these parameters, and determines the completeness of the polishing. For example, when a specimen is irradiated using a high-energy laser beam, its temperature increases excessively, leading to extensive melting. In contrast, a low-energy laser beam results in incomplete polishing. Therefore, it is important to be able to predict the surface temperature that can be easily changed by various parameters before conducting the actual experiment. In this study, a temperature prediction model is established to predict the time evolution of the surface temperature of an aluminum specimen irradiated using a laser beam. Furthermore, the feasibility of the prediction model is verified via comparisons with simulation results.

1. Introduction

Surface roughness is one of the main factors during the manufacturing process that affect a product's quality and performance. Consequently, a good polishing process is essential to ensure an appropriate level of surface roughness. There are several polishing methods, including chemical, electrolytic, and belt polishing, as well as magnetorheological finishing, and the product's surface roughness can be improved and made to glister using these methods. Laser polishing is a thermal process given its use of a laser beam. It is possible to polish local areas on a micro-scale because of the laser's small concentration area. A product can be polished regardless of the rigidity or hardness of the material owing to the non-contact process used by laser polishing[1-3]. Furthermore, it has the advantage that machining error due to torsion of the material and tool wear and/or noise resulting from thermal shock do not occur.

With respect to laser polishing, many related studies have been conducted. A thermal model was established to determine how the temperature is distributed when the laser is irradiated onto several metallic materials in powder form. The optimal parameter conditions for various materials during laser sintering can be found using this model[4]. In the case of laser polishing, simulations and experiments predict the heat-affected zone and measured melting range of a specimen when irradiated by a pulse laser[5,6]. With regard to studies on forming parameters, it was found that surface roughness levels

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after laser polishing are related to the melted materials, and the establishment of a thermal model and related experiments demonstrated the feasibility of this finding[7]. It was also found by a commercial finite element analysis program and performing experiments that different initial temperatures of the base material affected the polishing outcome[8,9]. In addition, the laser's power, feed rate, beam diameter, and frequency when using a pulsed laser can influence the laser polishing process[10-14].

It is important to predict changes in the surface temperature of a specimen when irradiated by a laser. The surface temperature differs depending on the laser's power, the velocity of the glass rod used, and the defocusing level during the irradiation process with a moving glass rod. A numerical model was established to determine how the temperature changes because of changes in theses parameters[15]. The properties of the specimen can be altered by its temperature. The degree of viscosity, stock removal, and the tension of the material are influenced by the surface temperature during the polishing process[16]. Moreover, if the irradiated region does not receive sufficient laser energy and reach the melting point of the material, the desired polishing level may not be reached. In contrast, with an excessive amount of laser energy and excessive material melting, a poor surface roughness result is common. Therefore, finding the optimal processing parameters through a temperature prediction model makes it possible to avoid the situations described above while performing a laser polishing process.

In this research, we investigated how the temperature changes with time at specific points in the specimen caused by the laser heat source is irradiated. For this purpose, a prediction model is established, and it predicts the temperature change over time at an arbitrary point when the heat source moves along a specified tool path. In addition, computer-aided engineering (CAE) processes under conditions identical to the model are examined to assess the degree of agreement between the prediction model and the CAE results.

The area below the time-temperature graph derived from the established model is then calculated. Using this value, it is possible to determine whether the specimen is sufficiently molten for a comparison with the actual laser polishing experimental result under identical conditions. In this manner, it can be determined whether the specimen received an adequate, excessive, or insufficient amount of energy by comparing the areas under the graph at different processing conditions or at different specific positions.

2. Laser Polishing

2.1 Laser polishing

Laser polishing is a forming process in which the laser source initially irradiates the surface of a workpiece, with the surface temperature then rising and melting locally, after which the surface becomes smooth because of re-solidification. In other words, if a workpiece that has an initially rough surface is irradiated, relatively prominent parts are melted locally. These molten materials then flow into grooved parts and become solidified. The laser-applied region then has better surface roughness than the initial state. These processes are illustrated in Fig. 1.

2.2 Zig-zag tool path for laser polishing

In this study, the temperature prediction model is applied to a case where the laser is irradiated along the tool path in zig-zag shape with an aluminum specimen. In addition to the power and feed rate of the laser, the path length and path interval can also affect the polishing degree when the laser irradiates in a zig-zag shape. These two parameters, the path length and path interval, are shown in Fig. 2.

First, with a long path length, the time for the heat source to return becomes longer from the viewpoint of any fixed point. In other words, the cooling time for it becomes longer. In contrast, with a short path length, the heat source is reached quickly and the cooling time then becomes shorter relative to that with a long path length. Hence, a different path length

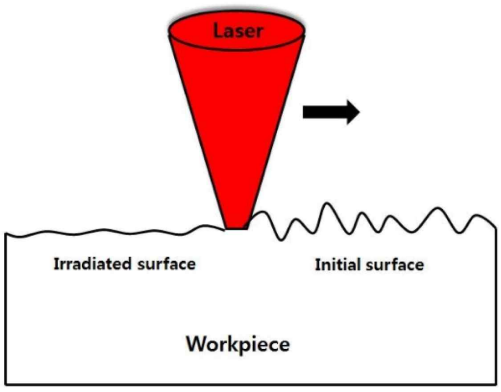


Fig. 1 Process of laser polishing

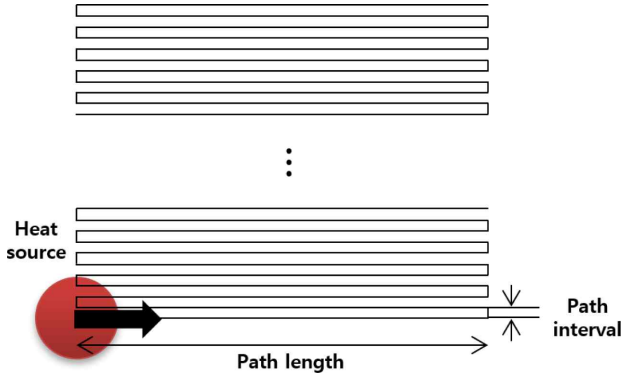


Fig. 2 Zig-zag tool path for laser polishing process

leads to a difference in the amount of energy presented at any point but with the same amount of time, causing the surface temperature to differ from case to case despite identical forming parameters.

Second, with a short path interval, the frequency of the heat source applied to any specific point is increased because of the laser's large spot size relative to the path interval. The amount of energy that any point has received is then rapidly increased, with a high surface temperature occurring as a result. However, a long path interval has a lower frequency of irradiation of the laser heat source and relatively less energy during the same polishing process time.

3. Surface Temperature Prediction Model

Before establishing the temperature prediction model, several assumptions apply during the polishing process. First, the change in the temperature in the thickness direction may be ignored because of the establishment of a model for a thin aluminum sheet. Second, only the increase and decrease in the temperature caused by conduction in the aluminum sheet are considered, and heat transfer by convection with air and radiation in three dimensions is ignored. Third, the density of the energy irradiated by the laser heat source on the surface is regarded as homogeneous for convenience of the calculation. To establish the surface temperature prediction model considering a zig-zag shape of the tool path, laser power is fixed at a value of 100 W. The laser spot diameter is fixed at 0.2 mm. The feed rate, path length, and path interval are considered as changeable parameters. A flow chart of the establishing model is shown in Fig. 3.

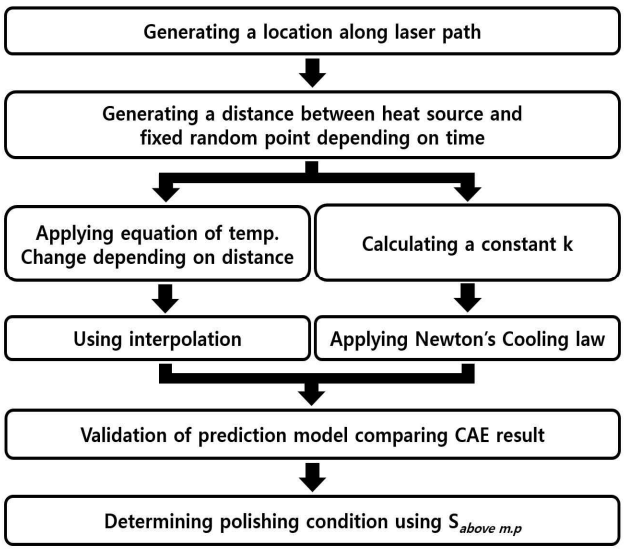


Fig. 3 Flow chart for establishing surface temperature prediction model

3.1 Generating a location along the laser path and distance between the heat source and a random point depending on the time

How the distance between a moving heat source and a fixed random point changes with respect to time should be known in order to develop the prediction model. With a zig-zag-shaped tool path, the heat source and fixed point become closer and farther apart again, and this process is repeated as the heat source is moved along the tool path. To determine the associated values accurately, the two-dimensional location information of the moving heat source for a specific feed rate, path length, and path interval are calculated according to the time interval. The distance between the heat source and the fixed point is also calculated to determine the temperature change. This provides information about how the distance between the heat source and the fixed point changes with respect to time. A section undergoing a temperature increase for which the distance from two points has decreased and a section undergoing a temperature decrease for which the distance has increased are easily distinguished using this information. The above process is applicable as an example at a feed rate of 200 mm/s, a path length of 5 mm, and a path interval of 0.02 mm. These results are shown in Fig. 4.

3.2 Section undergoing a temperature increase

As noted in the paragraph above, it is possible to define which section undergoes a temperature increase and which undergoes a temperature decrease according to the distance

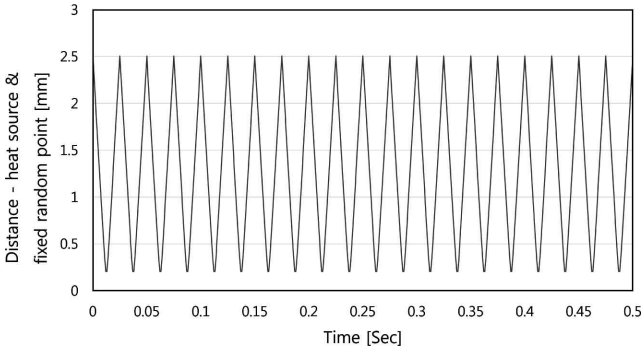


Fig. 4 Distance between heat source and fixed random point depending on time

between the heat source and fixed point. In this paragraph, the method used to predict the change in the surface temperature for sections which the temperature increases is explained. For such sections, it was confirmed that the surface temperature varies in accordance with the distance when any fixed point is irradiated continuously by the laser heat source. ANSYS Fluent CAE was used to confirm this result. The resulting graph is illustrated in Fig. 5. A shorter distance between the heat source and the fixed point leads to greater increases in the temperature. A longer distance results in a temperature that approximates room temperature. It was also noted that the temperature change depending on time follows a power function, expressed as Equation (1).

$$T = at^{b} + 300 \tag{1}$$

The equation of the temperature change with a change in the distance from 10 mm to 0 mm is expressed as follows.

$$\begin{cases} T = 139t^{1.147} + 300;\ d = 10\ mm \\ T = 181.9t^{0.9396} + 300;\ d = 8\ mm \\ T = 377.6t^{0.5548} + 300;\ d = 4\ mm \\ \vdots \\ T = 1244t^{0.1462} + 300;\ d = 0.2\ mm \\ T = 1392t^{0.1284} + 300;\ d = 0\ mm \end{cases} \tag{2}$$

The power function coefficient a of Equation (1) increases as an exponential function and index b decreases linearly. Therefore, the coefficient a and index b can be represented

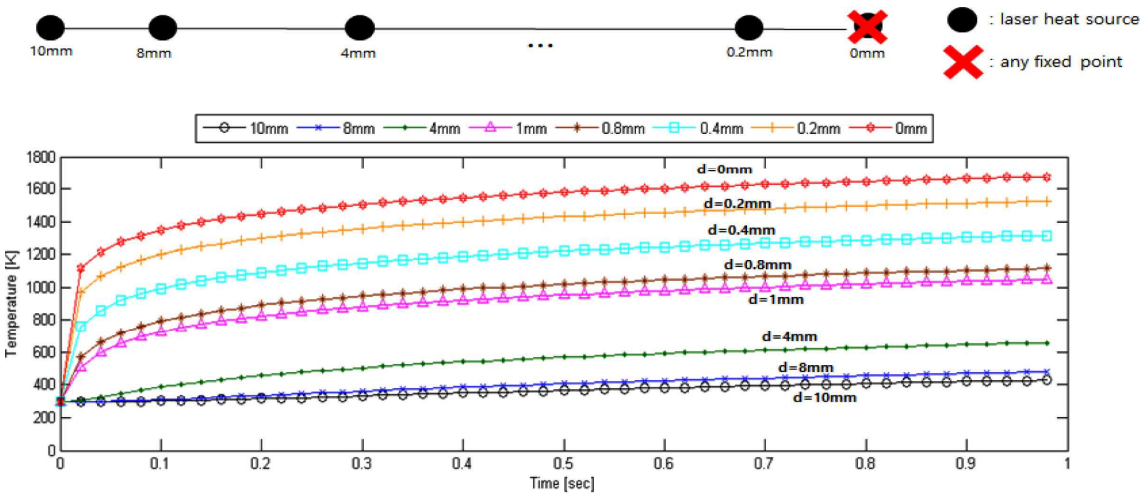


Fig. 5 Temperature Change according to Distance between Laser Heat Source and Any Fixed Point

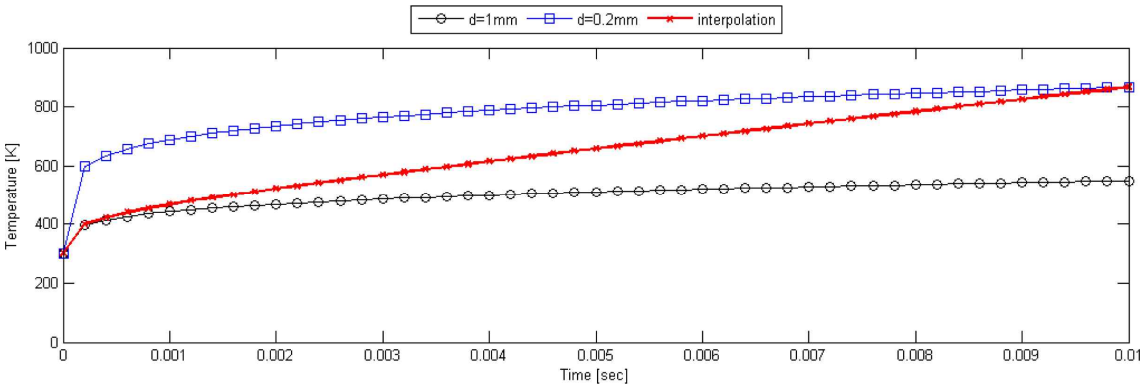


Fig. 6 Interpolating two adjacent temperature profile

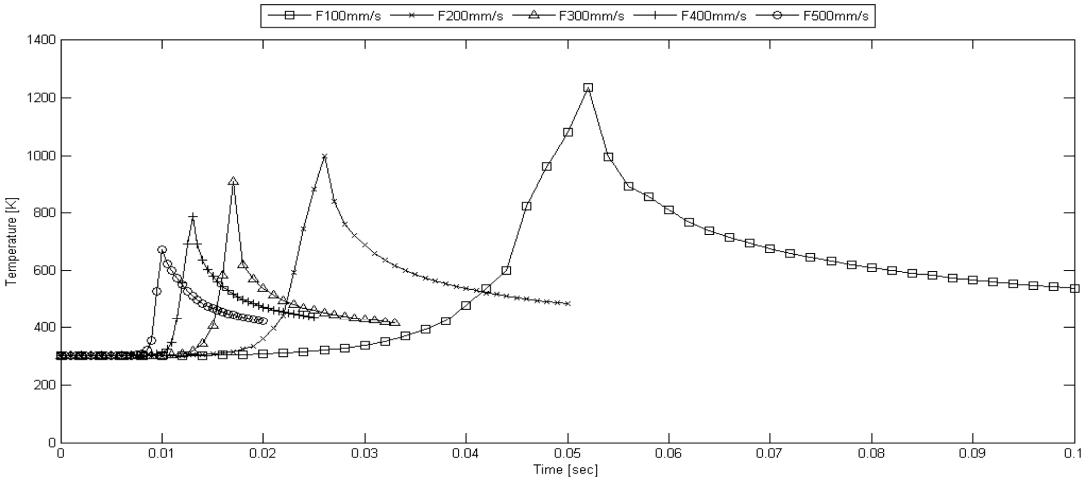


Fig. 7 Temperature change profile based on different feed rate of laser source

as a function of the distance d between the heat source and the fixed point. These are expressed as follows.

$$a = 640.6\exp(-1.65d) + 769.3\exp(-0.1766d) \quad (3)$$

$$b = 0.1008d + 0.1434 \quad (4)$$

Accordingly, substituting Equations (3) and (4) for Equation (1) derives the temperature change equation for the section undergoing a temperature increase, as follows.

$$T = [640.6\exp(-1.65d) + 769.3\exp(-0.1766d)] \times t^{0.101d+0.1434} + 300 \quad (5)$$

The surface temperature change depending on time for a specific distance can be determined through Equation (5).

This equation can be used to predict sections that will undergo a temperature increase. For example, it assumes that the laser heat source is positioned at a distance of 1mm from a fixed point. The laser heat source moves closer to a fixed point and the distance then becomes 0.2 mm. In this situation, the movement of the laser heat source from d = 1 mm to d = 0.2 mm can be considered as the occurrence of a pulse at d = 1 mm, with the next pulse occurring at d = 0.2 mm in a very short time. The surface temperature changes for the occurrences of the two pulses can be determined using Equation (5); the situation in which the laser comes closer to the fixed point is then represented using an interpolation. This is shown in Fig. 6 and Equation (6).

$$T_{1\ 0.2mm} = (1-u)\,T_{d=1mm} + u\,T_{d=0.2mm} \quad (0 < u < 1) \quad (6)$$

Hence, if the section for which the temperature increase is determined from Fig. 4, it becomes possible to predict the surface temperature by means of interpolation for these sections.

3.3 Section undergoing a temperature decrease

The method used to predict the surface temperature for a section is described.

$$\frac{dT}{dt} = -k(T - T_r) \quad (7)$$

T_r: room Temperature, k: cooling rate, constant (k>0)

Integrating Equation (7) with the initial value results in the following equation.

$$T = T_{r+(}T_0 - T_r)e^{-kt} \quad (8)$$

T_0: initial Temperature

The positive constant k denotes the cooling rate, and a higher k indicates that the temperature will decrease more quickly in the same amount of time. The slope from the section undergoing a temperature decrease was used to determine the constant k. The slope is the distance between two points per unit of times, and a large slope means that the heat source passes the fixed point quickly. This causes a large value of k.

The laser was moved the same distance but at several different feed rates to determine the value of k. Fig. 7 shows how the slope of the temperature changes with feed rate of laser source. This made it possible to determine the slope of the section for which the temperature decreased and the temperature change according to different feed rates with the

Table 1 Cooling rate k according to temperature decrease slope

Feed rate [mm/s]	100	200	300	400	500
Slope	99.4	198.8	298.9	397.5	496.6
k	16.1	40.3	71.2	127.2	164.5

Table 2 Material properties of aluminum

Thermal conductivity (k)	202.4 W/mK
Density (ρ)	2719 kg/m^3
Specific heat (c_p)	871 J/kgK

CAE program and then to formulate the relationship between k and the slope of the section for which the temperature decreased.

From the results shown in Table 1, a rapid feed rate creates a large slope for the section undergoing a temperature decrease while also increasing the value of k because of the well-cooled condition. Here, k is expressed as a function of the slope of the section for which the temperature is decreasing. It is written as follows.

$$\sqrt{k} = 0.02277(slope) + 1.847 \tag{9}$$

Only the information of the slope of such a section is needed to calculate k for any other random tool path using Equation (9).

3.4 Validation of the prediction model compared with the results from CAE

CAE was utilized to verify the feasibility of the prediction model for the surface temperature change of the aluminum specimen when undergoing laser irradiation with the zig-zag shaped tool path. This was done with the ANSYS Fluent software. The material properties of aluminum provided by the Fluent database were applied. These values shown in Table 2.

A simulation was conducted of the irradiation by a laser of a two-dimensional aluminum plate. The specimen had a width of 120 mm and a height of 65 mm; the mesh size was 0.15 mm squared, and the time step used was 0.0001 s. The laser power was 100 W and the spot size had a diameter of 0.2 mm. The feed rate, path length, and path interval were controllable parameters. CAE results for various conditions and a comparison of the prediction model and results of the CAE simulation are illustrated in Figs. 8, 9, and 10, where

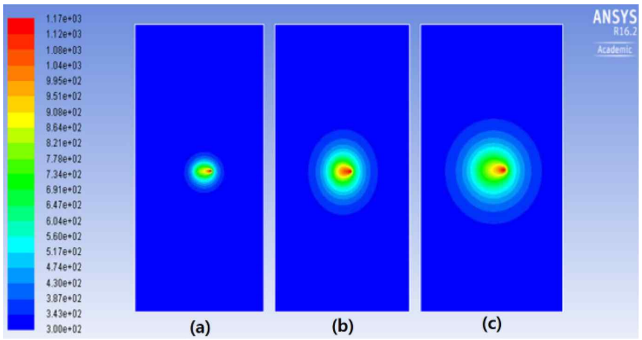


Fig. 8 ANSYS fluent CAE simulation for cases: (a) F = 400 mm/s, p.l(path length) = 2 mm, p.i(path interval) = 0.04 mm, (b) F = 200 mm/s, p.l = 5 mm, p.i = 0.02 mm, and (c) F = 100 mm/s, p.l = 4 mm, p.i = 0.05 mm

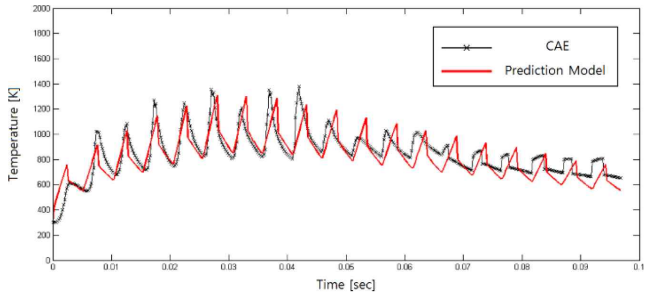


Fig. 9 Comparison of prediction model and CAE data on condition of F = 400 mm/s, p.l = 2 mm, and p.i = 0.04 mm

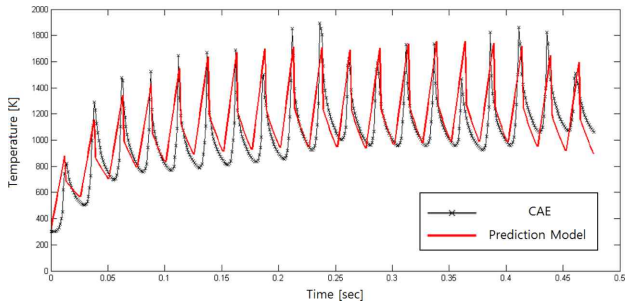
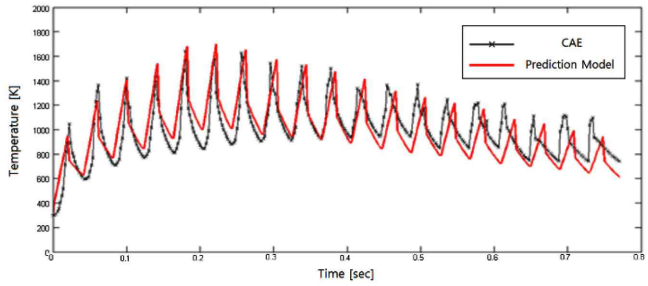


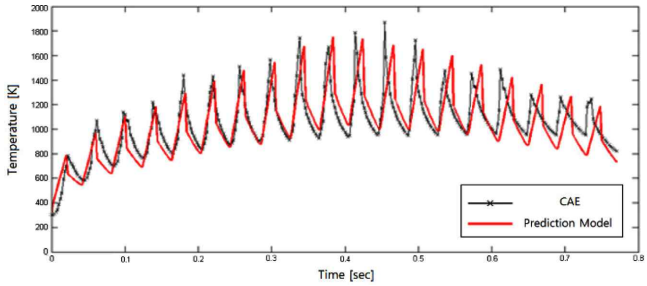
Fig. 10 Comparison of prediction model and CAE data on condition of F = 200 mm/s, p.l = 5 mm, and p.i = 0.02 mm

F is federate, p.i is the path length and p.l is the path length, respectively.

It was found that a different random point leads to different temperature changes but with an identical set of parameters. The prediction model results were compared with the CAE results for two other points to ensure the feasibility of the prediction model for this setup. The forming parameters of the two cases are as follows: a 100 mm/s feed rate, a 4 mm path length, and a 0.05 mm path interval. Given the laser heat source's position of (0,0) at first, (2,0.18) point and (2,0.45)



(a)



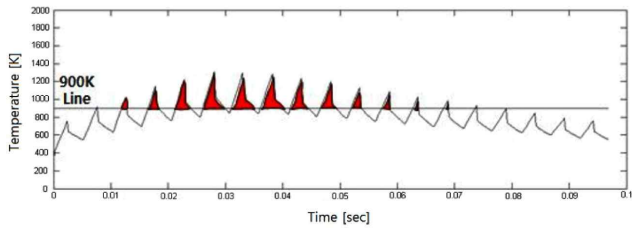
(b)

Fig. 11 Comparison of prediction model and CAE data under identical condition of F = 100 mm/s, p.l = 4 mm, and p.i = 0.05 mm at different position when the starting point of the laser source is (0,0): (a) at (2,0.18), and (b) at (2,0.45)

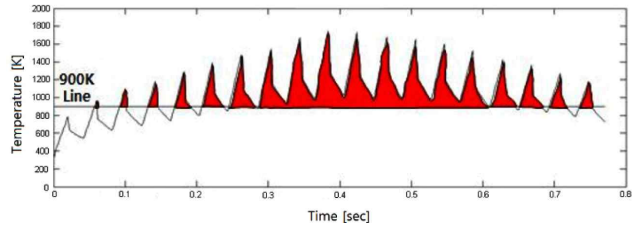
point are set as fixed points. Through the temperature prediction process and CAE, the prediction model and CAE results were obtained, as shown in Figs. 11(a) and (b).

4. Determining the Polishing Condition Using $S_{above\ m.p}$ Compared to an Actual Experiment

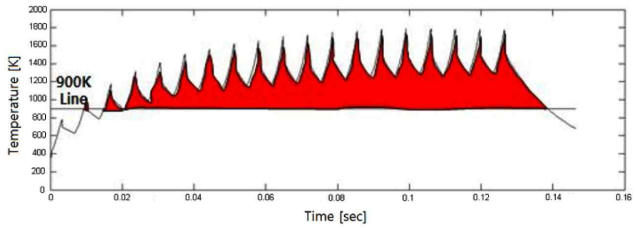
The established prediction model was validated by a comparison with the CAE output, and in this paragraph a comparison is made with the results of an experiment. The value of $S_{above\ m.p}$ is defined, corresponding to the area of the graph from the temperature change prediction model that contains more than the melting points. In particular, this area is related to the fact that aluminum has a melting point of approximately 900 K, as illustrated in Fig. 12. The physical meaning of $S_{above\ m.p}$ is also explained. A large value of $S_{above\ m.p}$ indicates that the specimen receives a considerable amount of energy to hold the temperature at 900 K or more, while also receiving more energy for temperatures higher than 900K at the same time. In contrast, a small value of $S_{above\ m.p}$ indicates that the specimen does not receive enough energy, leading to insufficient laser polishing. This can be expressed by the following equation on the basis of



(a)



(b)



(c)

Fig. 12 Defining $S_{above\ m.p}$: (a) Deficient material melting, (b) Sufficient material melting (c) Excessive material melting for laser polishing

the factors discussed above.

$$S_{above\ m.p} \propto Energy\ irradiated\ by\ laser \tag{10}$$

It was determined whether the specimen had sufficient energy, insufficient energy, or excessive energy for polishing using the value of $S_{above\ m.p}$. For example, as shown in Fig. 12(a) through (c), the value of $S_{above\ m.p}$ is relatively small in the Fig. 12(a) case, providing evidence that the specimen does not receive enough energy. However, the $S_{above\ m.p}$ value for the case in Fig. 12(c) is relatively large. Thus, the specimen receives enough energy to cause over-melting. Hence, the reference point of the polishing degree through $S_{above\ m.p}$ as obtained for several conditions can determined whether the polishing was suitable. Laser polishing experiments were conducted to determine the reference point for $S_{above\ m.p}$, and criteria for upper and lower limit values of $S_{above\ m.p}$ are suggested through a comparison of $S_{above\ m.p}$ with the surface roughness R_a.

4.1 Experimental set-up

Experiments were conducted under various conditions

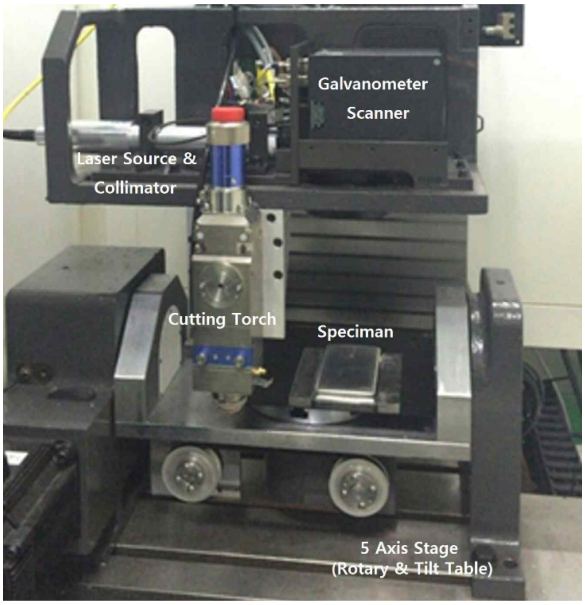


Fig. 13 Experimental device for laser polishing

Fig. 14 DektakXT surface profiler for measuring a specimen's surface roughness

using a laser machining device that was capable of five-axis control. The processing conditions are summarized in Table 2. A two-dimensional computer-aided design (CAD) model was created for the desired pattern, the laser path was created using a computer program, and the extracted path data were transferred to the laser machining device using NC code to perform the laser polishing process. The specimen was aluminum 5052 and is 112 mm × 65 mm in size and 1 mm thick. The laser machining process used is shown in Fig. 13. Enlarged images of the polished specimen results were captured with a Dino-lite camera, and the surface roughness was measured using a Dektak XT surface profiler, as shown in Fig. 14. The surface roughness was measured three times under identical conditions and the average value was used.

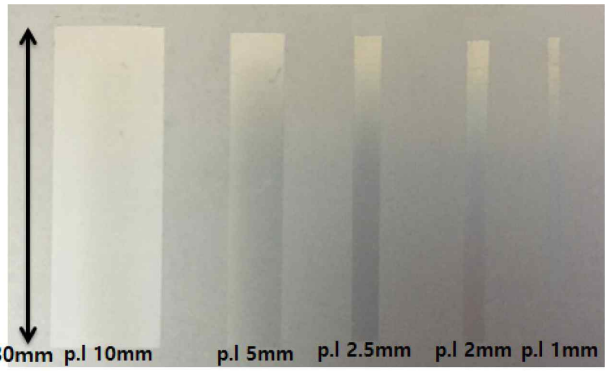


Fig. 15 Laser polishing experiment results for several different path lengths under identical conditions of F = 300 mm/s, p.i = 0.01 mm

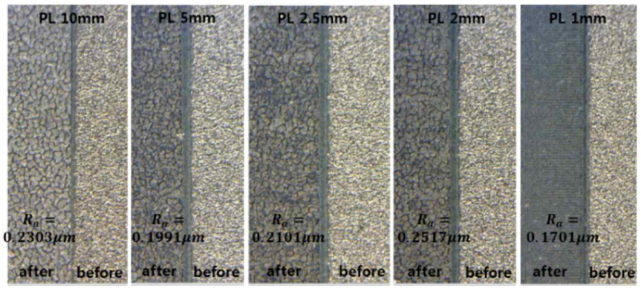


Fig. 16 Experimental results of ×200 initial R_a = 0.5273 μm

4.2 Criterion of the polishing condition in terms of $S_{above\ m.p}$ and the surface roughness

Experiments were conducted while varying the path length with a feed rate of 300 mm/s, a path interval of 0.01 mm, and a forming length of 30 mm. Five different path lengths were assessed: 10 mm, 5 mm, 2.5 mm, 2 mm, and 1 mm. The polished specimens under the five conditions are shown in Fig. 15, and enlarged images showing the measured surface roughness outcomes are shown in Fig. 16.

In Figs. 15 and 16, the laser polishing result with a path length of 10mm showed that the initial surface and polished surface differ from each other, but neither was glossy, indicating that the surface does not receive sufficient energy for polishing. Although the roughness was 0.5273 μm, it remains larger than the results with other path lengths. At a path length of 2.5 mm, glossiness was visually noted, and the surface roughness was also decreased by approximately 60.2% compared with the initial value. With a path length of 2mm, the irradiated energy easily became concentrated, allowing the black patterns known as dendrites to be generated on the surface of the specimen because of the excessive energy. For this reason, glossiness did not appear and the surface roughness was greater.

Table 3 Forming conditions for laser polishing experiment

Laser Irradiation Type	Pulsed
Frequency	200 kHz
Power	100 W
Spot Size	0.2 mm
Feed Rate [mm/s]	100, 300
Path Length [mm]	10, 5, 2.5, 2, 1, 0.5

With the path length of 1 mm, However, a short length and adequate irradiation time were noted. Therefore, an appropriate amount of energy for polishing was received. Hence, the specimen became polished and the surface roughness was found to have the lowest value.

The temperature change on surface of the specimen and the $S_{above\ m.p}$ values obtained from the prediction model are shown in Fig. 15 and Table 3 under conditions identical to those used in the experiments. It was shown that if the specimen receives insufficient energy with a large surface roughness value, $S_{above\ m.p}$ in such a case has a low value. This was the case when the path length is 10 mm in the experiment discussed above when the $S_{above\ m.p}$ value is approximately 21. In contrast, if the surface roughness was large because of the excessive energy, the $S_{above\ m.p}$ value was large. The experiment with a path length of 2 mm corresponded to this case, and the surface roughness was reduced compared to the initial surface, and $S_{above\ m.p}$ value is close to 185. In the other three cases, the surface roughness values were sufficiently reduced, and the $S_{above\ m.p}$ values in these cases were located between the above two values. The surface roughness values are used as criteria for a good polishing condition, and the $S_{above\ m.p}$ values for these cases were within specific upper and lower limits. From this result, the lower limit of $S_{above\ m.p}$ and the upper limit of $S_{above\ m.p}$ for effective laser polishing can be defined as 21 and 185, respectively. These defined limit values can be used to determine the polishing condition in various setups.

5. Application of $S_{above\ m.p}$ values to the polishing condition compared with an experiment

In this section, the polishing condition under different process parameters is determined based on the upper and lower limit values of $S_{above\ m.p}$ defined above. To do this,

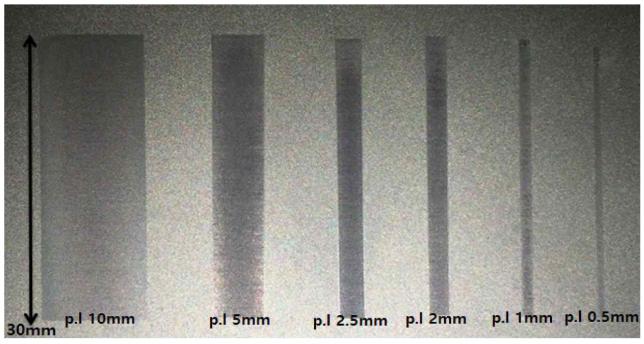


Fig. 17 Laser polishing experimental results for several different path

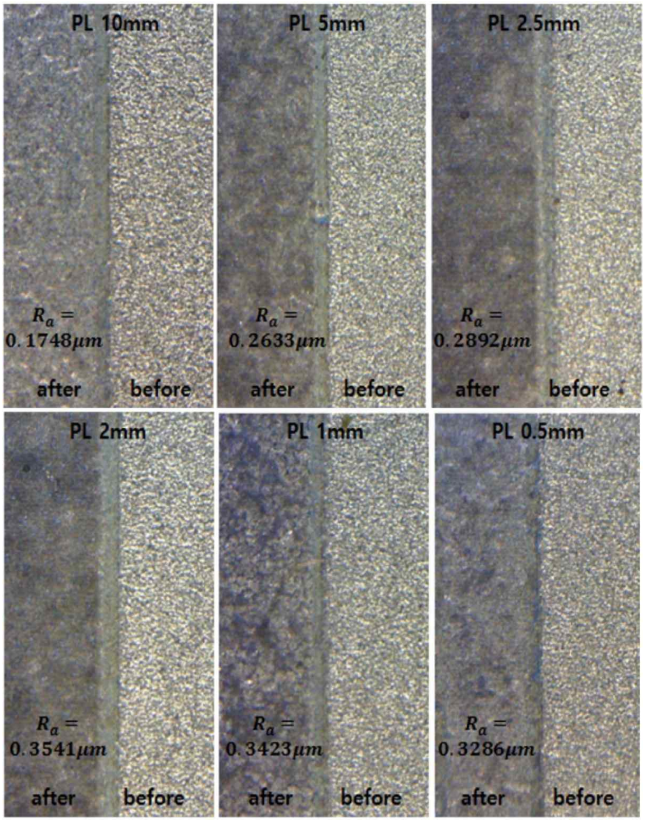


Fig. 18 Experimental results of ×200 initial R_a=0.5183 μm

polishing experiments were performed. The fixed process parameters were a power of 100 W, a feed rate of 100 mm/s, a path interval of 0.01 mm, and a forming length of 30 mm. The path length was also used as a variable parameter with values of 10 mm, 5 mm, 2.5 mm, 2 mm, 1 mm, and 0.5 mm. The polished specimens and surface roughness outcomes for each case are shown in Fig. 17 and 18, respectively. The surface roughness was measured three times under identical conditions and the average value was used. As shown in Fig. 17, when the path length is 10 mm, the surface of the specimen is glossy and the $S_{above\ m.p}$ value is found to be

within the upper and lower limits.

The temperature change and the $S_{above\ m.p}$ value according to the prediction model for each cases are described in Fig. 19 and Table 4, respectively.

Additionally, the surface roughness is relatively low compared to those in other cases, indicating that the laser polishing process is properly performed. However, for the other cases, because the path length is short, the period of energy received becomes short such that specimen receives excessive energy. For this reason, it was possible to confirm dendrite patterns on the surfaces. In addition, the $S_{above\ m.p}$ values of the five cases exceeded the upper limit, and the measured surface roughness values were lower than the initial value but nonetheless relatively large. Over-melting occurred under the conditions described below.

The $S_{above\ m.p}$ value was highest when the path length was

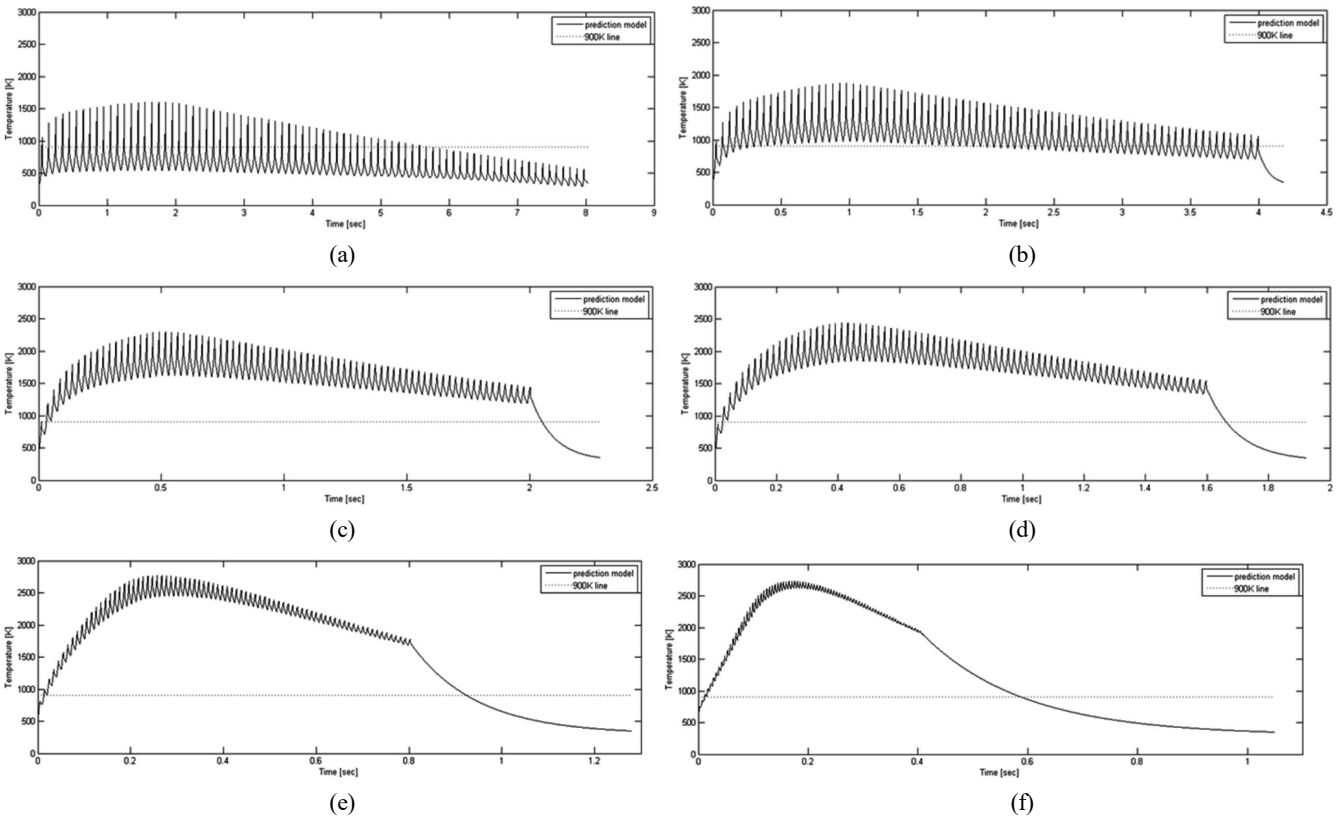


Fig. 19 Temperature change according to time for different path length under same conditions of power = 100 W, F = 100 mm/s, p.i = 0.01 mm: (a) p.l = 10 mm, (b) p.l = 5 mm, (c) p.l = 2.5 mm, (d) p.l = 2 mm, (e) p.l = 1 mm, (f) p.l = 0.5 mm

Table 4 $S_{above\ m.p}$ values obtained from prediction model and polishing condition associated with different path length under identical conditions of power = 100 W, F = 300 mm/s, and p.i = 0.01 mm

Path length	(a) 10 mm	(b) 5 mm	(c) 2.5 mm	(d) 2 mm	(e) 1 mm	(f) 0.5 mm
$S_{above\ m.p}$	108.55	598.81	1354.13	1358.75	1032.8	601.08
Polishing condition	sufficient	excessive	excessive	excessive	excessive	excessive

Table 5 $S_{above\ m.p}$ values obtained from prediction model and polishing condition associated with different path length under identical conditions of power = 100 W, F = 300 mm/s, and p.i = 0.01 mm

Path length	(a): 10 mm	(b): 5 mm	(c): 2.5 mm	(d): 2 mm	(e): 1 mm
$S_{above\ m.p}$	20.57	30.55	136.97	184.63	167.56
Polishing condition	poor	sufficient	sufficient	excessive	sufficient

2 mm, and the surface was also the roughest. As the path length become shorter than 2 mm, the $S_{above\ m.p}$ value and the surface roughness decreased. This is identical to the outcome described in the paragraph above. Because the path length was short despite the identical feed rate, the time was not sufficient to apply the proper amount of energy, resulting in a reduced $S_{above\ m.p}$ value and less surface roughness. However, $S_{above\ m.p}$ showed a value that exceeds the upper because of the low feed rate, and excessive melting occurred.

6. Conclusion

In this research, we investigated how the temperature changes with time at specific points in the specimen caused by the laser heat source is irradiated. In particular, a time-dependent temperature-change prediction model was established for a specific arbitrary point to be observed when the laser heat source moved along a zig-zag processing path. To validate the model, the temperature change results were obtained through a CAE simulation under identical conditions. It was confirmed that the temperature change according to the prediction model is in good agreement with the CAE results. Specifically, it showed that the temperature change differs depending on the position of the point to be observed even under identical forming conditions. The $S_{above\ m.p}$ value was defined as the area over 900 K, the melting temperature of aluminum, in the temperature change graph resulting from the established model. The upper and lower limits for the polishing condition were defined through this value. A comparison between the experiments and the value of $S_{above\ m.p}$ determined whether effective polishing or excessive melting occurred.

A considerable amount of time is required to obtain results through the CAE program. However, using the established model, it is possible to obtain results in a short period of time without undertaking CAE, and it is efficient as the calculation is simplified because only the coordinate for the position to be measured must be changed. In addition, it is intuitively confirmed from $S_{above\ m.p}$ that the specimen is at a temperature higher than its melting point or at a very high temperature caused by excessive energy through the temperature change graph at a specific position. This makes it easy to predict the optimal conditions for laser polishing through various parameter settings.

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