Design and application of laser scanning strategy for machining deep surface grooves with a continuous-wave fiber laser

Si Qing Liu
Sang Wook Han
Tae Woo Hwang
Daniyal Abolhasani
Young Hoon Moon (✉ yhmoon@pusan.ac.kr)

Pusan National University https://orcid.org/0000-0001-9766-9891

Research Article

Keywords: Surface grooving, Laser scanning strategy, Continuous-wave fiber laser, Metal–plastic hybrid, Joining strength

Posted Date: February 22nd, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2580507/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License
Design and application of laser scanning strategy for machining deep surface grooves with a continuous-wave fiber laser

Si Qing Liu¹, Sang Wook Han², Tae Woo Hwang³, Daniyal Abolhasani¹, Young Hoon Moon¹※

¹School of Mechanical Engineering, Pusan National University, 30 Jangjeon-dong, Geumjeong-gu, Busan 46241, Republic of Korea.

²Research & Development Integrated Center, Hyundai-Steel, 1480, Bukbusaneop-ro, Songak-eup, Dangjin-si, Chungcheongnam-do, 31719, Republic of Korea

³Department of Joining Technology, Korea Institute of Materials Science, 797 Changwon-daero, Changwon, Gyeongnam, 51508, Republic of Korea

※Corresponding Author: Young Hoon Moon

School of Mechanical Engineering, Pusan National University, 30 Jangjeon-dong, Geumjeong-gu, Busan 46241, Republic of Korea.

Tel: 82-51-510-2472, Fax: 82-51-512-1722, Email: yhmoon@pusan.ac.kr
Abstract

A laser scanning strategy for fabricating deep surface grooves using a continuous-wave fiber laser was investigated in this study. Because the low productivity of short-pulsed-wave lasers limits their application to a small scale, a continuous-wave (CW) fiber laser that can provide a high power density was used for rapid fabrication of deep grooves. An innovative tailored laser-scanning strategy of fabricating patterned deep grooves was analytically designed based on the power density and interaction time. Considering the thermophysical properties of the material, controlled laser processing parameters were determined for fabricating surface grooves with rectangular and chevron cross-sectional patterns. To confirm the usefulness of the research results, the scanning strategy obtained in this study was applied for achieving high-quality joining between injection-molded metal-plastic hybrids (MPHs). A deep-surface-grooved A5052 aluminum alloy sheet was bonded to two plastics, polyamide and polypropylene, via injection molding. Lap shear tensile tests of the MPHs revealed their significantly enhanced joining strength owing to a better mechanical interlocking of the groove. The developed laser scanning strategy using a CW fiber laser can be widely applied in the fabrication of deep grooves of various cross-sections with high reliability.

Keywords: Surface grooving; Laser scanning strategy; Continuous-wave fiber laser; Metal–plastic hybrid; Joining strength
Nomenclature

\( a \) thermal diffusivity, \( \text{m}^2\text{s}^{-1} \)

\( A_m \) grooved cross-sectional area in the scanning direction, \( \text{mm}^2 \)

\( C_p(l) \) specific heat capacity of a liquid phase at constant pressure, \( \text{J/kg K} \)

\( C_p(s) \) specific heat capacity of a solid phase at constant pressure, \( \text{J/kg K} \)

\( E \) power density, \( \text{W/mm}^2 \)

\( E_a \) absorbed power density from a laser source, \( \text{W/mm}^2 \)

\( E_m \) unit energy for the grooving, \( \text{J/mm}^3 \)

\( E_n \) net heat energy, \( \text{J} \)

\( dE_n/dt \) rate of heat energy delivered, \( \text{J/s or W} \)

\( E_p \) analytically required power density for grooving, \( \text{W/mm}^2 \)

\( L_m \) heat of fusion, \( \text{kJ/kg} \)

\( L_v \) heat of vaporization, \( \text{kJ/kg} \)

\( P \) laser power, \( \text{J/s or W} \)

\( r_B \) beam radius, \( \text{mm} \)

\( T_m \) melting temperature, \( \text{K} \)

\( T_o \) room temperature, \( \text{K} \)

\( T_p \) peak temperature, \( \text{K} \)

\( T_v \) vaporization temperature, \( \text{K} \)

\( V \) removed volume, \( \text{mm}^3 \)

\( v \) laser beam moving rate, \( \text{mm/s} \)

\( dV/dt \) removal volume rate, \( \text{mm}^3/\text{s} \)

- Greek symbols

\( \alpha \) linear expansion coefficient, \( \text{K}^{-1} \)

\( \eta \) grooving efficiency

\( \lambda \) thermal conductivity, \( \text{Js}^{-1}\text{m}^{-1}\text{K}^{-1} \)

\( \rho \) density, \( \text{kg/m}^3 \)

\( \tau \) beam interaction time, \( \text{s} \)
1. Introduction

Laser grooves or patterns that affect material surface properties, such as adhesiveness, friction coefficient, wettability, and appearance [1-4], have many attractive applications. Lasers with short pulses in nanosecond range have been widely used for creating surface micro-patterns. The productivity of short-pulse lasers can be changed by controlling laser parameters, such as wavelength, pulse width, pulse duration, repetition rate, and scanning velocity [5]. However, the relatively low productivity of short-pulsed laser processing limits its application to a small scale [6]. Another limitation of short-pulsed lasers is the uncontrolled melting of the processed area at an average power. In this context, ultrashort pulse technology has been applied for achieving a high ablation rate and excellent quality; however, fine tuning of the operating parameters is required for minimizing the thermal load on the target material [5].

The recent development of ultrashort pulse laser systems that supply high average power has significantly increased the micromachining productivity [7,8]. This permits upscaling of ablation rates and large-area processing, promoting the applicability of ultrashort pulse laser technology to a variety of industrial processes. However, their high cost limits their widespread commercialization. In general, the average power level of short-pulsed lasers is still insufficient for deep grooving, owing to their small pulse energy or low pulse repetition rate.

In contrast, continuous-wave (CW) lasers can provide high power density at a reasonable cost [9,10]. This power density can be efficiently used in generating deep surface grooves by controlling laser processing parameters. In addition, a single-mode laser can be focused down to several tens of micrometers in diameter, resulting in a high power density of more than 10 MW/cm², even at an average power of the order of 100 W. This power density is sufficient for generating a keyhole, and deep grooves can be formed by controlling melting, evaporation, and resolidification, on the metal surface [11]. Groove formation by a pulsed laser is an ablative process, whereas melting is the primary mechanism of CW laser processing. Consequently, the groove depth and width were demonstrated to be unstable during CW laser processing. As stabilization of the groove shape is required for industrial applications,
multi-pass scanning is beneficial for generating deeper grooves [10]. Therefore, a multi-pass scanning strategy of fabricating deep surface grooves using a CW fiber laser was investigated in this study.

Laser surface grooving is essentially thermal laser machining, which is based on the conventional mechanisms of laser beam heating, including melting and vaporization [12]. Fig. 1 illustrates the principle of laser surface grooving, wherein a high-energy laser beam produces grooves on the surface of a substrate by vaporizing the workpiece material. In this process, high thermal energy is transferred to the surface of the workpiece. The heat energy absorbed by the surface melts and vaporizes the workpiece material [13,14].

![Fig. 1 Principles of laser surface grooving](image)

The principal process variables during laser beam movement on a material surface are listed in Table 1.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser beam characteristics</td>
<td>Power, temporal mode, spatial mode, wavelength, raw beam diameter, polarization</td>
</tr>
<tr>
<td>Material properties</td>
<td>Thickness, density, roughness, composition, transformation temperature, absorptivity, thermal conductivity, specific heat capacity, thermal expansion coefficient, latent heat</td>
</tr>
<tr>
<td>Laser processing parameters</td>
<td>Focal depth, projected spot size, position of focal plane, scanning speed, shield gases, environmental temperature</td>
</tr>
</tbody>
</table>

As a large number of variables influence the interaction between a laser beam and material, an analytical study is expected to provide better insights into the laser grooving process [15]. The laser
power density and interaction time are essential variables for surface grooving because they determine the peak surface temperature. Therefore, in this study, the principal processing variables, such as power density and interaction time, were identified using an analytical heat model based on the temperature fields around a moving energy source. Based on the above analysis, a scanning strategy for obtaining surface grooves with chevron and rectangular shapes was designed and applied to the laser-grooving process.

To confirm the usefulness of the research results, the scanning strategy obtained in this study was applied for achieving high-quality joining between injection-molded metal-plastic hybrids (MPHs).

The hybrid structure consisting of dissimilar materials, mainly metal-to-metal, metal-to-ceramic, and metal-to-plastic, is a promising alternative for achieving specific performance with reduced weight [16-18]. In terms of technical benefits, MPH structures are superior in terms of freedom of design and shape because of the formability of plastics [19,20]. The integrated structure can minimize the use of raw materials and exploit each material to create cost-effective structures in the required space.

However, the differences between metals and plastics, specifically their physical and chemical properties, can lead to problems that cannot be solved without special processing methods. MPHs have been joined using mechanical interlocking, chemical adhesives, and hybrid welding to achieve the required connection strengths.

Recently, a direct joining technique called injection-molded direct joining (IMDJ) was investigated for obtaining hybrid joints [21,22]. However, the IMDJ requires three-dimensional geometric patterns on the metal surface to achieve a sufficient joining strength. The injected molten plastic fills the groove on the metal surface to form mechanical interlocking. Thus, laser-assisted patterning or grooving, which leads to material removal in the irradiated section, can significantly improve the joint strength of MPHs.

Previous studies have confirmed the substantial influence of laser patterning on the joining strength of MPHs [23-25]. However, as described above, previous studies on MPHs have mainly focused on micro- and nanoscale surface grooving or patterning. A deep surface groove formed on the metal surface
by multiple scanning of a CW laser could improve the bonding strength of MPH owing to their anchoring effect [26].

Therefore, as a new approach of significantly increasing the joining strength of MPHs, deep surface grooving by multiple scanning with a CW laser was implemented in this study.

To evaluate the bonding quality in an MPH, an A5052 aluminum alloy sheet was bonded with two plastics, polyamide (PA) and polypropylene (PP), via injection molding. The molten plastic infiltrated the surface grooves on a metal workpiece that was initially placed in a mold. Two different groove patterns were fabricated for investigating the joining effectiveness. The characteristics of the MPH joints with two different groove patterns were investigated using an optical microscope, and the strength of the MPH joints was measured via a tensile shear.

2. Process design for laser grooving

2.1 Analytical analysis of the laser grooving process

The power density ($E$) is the principal process variable for surface grooving because it determines the peak surface temperature and is given as follows:

$$E = \frac{P}{\pi r_B^2} \quad (1)$$

Power density controls the principal mechanism of thermal processes, such as heating, melting, and vaporization. For surface grooving, the power density must be sufficiently high to vaporize the substrate in the affected region. When considering the surface grooving process, in which a laser beam moves at a rate of $v$, the local temperature field changes with time owing to transient heat flow. Therefore, the beam interaction time must be considered together with the power density [12].

The beam interaction time, $\tau$ is given as follows:

$$\tau = \frac{2r_B}{v} \quad (2)$$
Therefore, in this study, the principal processing variables, $E$ and $\tau$ were identified from the analytic heat model to analyze the temperature fields around a moving energy source and control the processing mechanism.

The quantity of heat required to remove a given volume of the substrate material depends on (1) the heat required to raise the temperature of the substrate to its melting point, $C_p(s) (T_m - T_o)$, (2) the heat of fusion to transform a solid phase into a liquid phase at the melting point, $L_m$, (3) the heat required to raise the temperature of the substrate from its melting point to the vaporization temperature, $C_p(l) (T_v - T_m)$, and (4) the heat of vaporization to transform a liquid phase into vapor at the vaporization point, $L_v$.

Therefore, the unit energy required for grooving (vaporization) is given as follows:

$$E_m = \rho [C_p(s) (T_m - T_o) + L_m + C_p(l) (T_v - T_m) + L_v]$$  \hspace{1cm} (3)

From Eq. (3), the analytically required power density for grooving $E_p$ can be obtained as follows:

$$E_p = E_m v = \rho v [C_p(s) (T_m - T_o) + L_m + C_p(l) (T_v - T_m) + L_v]$$  \hspace{1cm} (4)

To investigate the relationship between the absorbed power density and interaction time during laser processing, a basic mathematical model of the heat flow was used in this study.

Fig. 2 shows the temperature profile corresponding to the distance from the laser source.
When the surface temperature increases to $T_p$ in a semi-infinite body, the temperature field around the heat source can be expressed as a basic mathematical model of heat flow [27–29]. The relationship between the absorbed power density, $E_a$, and interaction time, $\tau$, can be expressed as follows:

$$\log E_a = \log(T_p - T_0) + \log \left( \frac{\pi \alpha}{2 \lambda} \right) - \frac{1}{2} \log \tau$$

(5)

Because the feasibility of Eq. (5) has been experimentally confirmed in previous studies [12,30], it was used to design the laser processing parameters for the laser grooving.

For laser grooving, the absorbed power density, $E_a$, obtained from Eq. (5), must exceed the analytically required power density for grooving, $E_p$, obtained from Eq. (4). Based on this principle, the optimal processing parameters were deduced. The thermal properties of the aluminum used in this study are listed in Table 2.

**Table 2** Thermal properties of aluminum

<table>
<thead>
<tr>
<th>$\rho$ (Kg m$^{-3}$)</th>
<th>$\lambda$ (JS m$^{-1}$K$^{-1}$)</th>
<th>$C_p$ (s) (Jkg$^{-1}$K$^{-1}$)</th>
<th>$C_p$ (l) (Jkg$^{-1}$K$^{-1}$)</th>
<th>$a \times 10^8$ m$^2$s$^{-1}$</th>
<th>$T_m$ (K)</th>
<th>$T_v$ (K)</th>
<th>$L_m$ (kJkg$^{-1}$)</th>
<th>$L_v$ (MJkg$^{-1}$)</th>
<th>$\alpha \times 10^8$ K$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2704</td>
<td>238</td>
<td>1000</td>
<td>1180</td>
<td>88</td>
<td>932</td>
<td>2740</td>
<td>388</td>
<td>10.79</td>
<td>23</td>
</tr>
</tbody>
</table>

Fig. 2 Temperature profile corresponding to the distance from the laser source. (HAZ: heat affected zone)
Fig. 3 compares $E_a$ and $E_p$ for different interaction times. According to the $E_a$ and $E_p$ plotted in the framework of power density vs. interaction time, the relative positions of $E_a$ and $E_p$ with respect to the axes can provide feasible processing conditions for laser grooving. From a metallurgical perspective, melting the substrate using less energy is desirable. Therefore, a higher power density and shorter interaction time are required for accelerating the vaporizing process. Thus, a beam interaction time of $10^{-4}$ s at the intersection zone of $E_a$ and $E_p$ was selected as the feasible region for laser grooving.

Therefore, a laser-scanning speed of 200 mm/s was obtained using following:

$$v = \frac{2r_B}{\tau} = \frac{2 \times 0.01}{10^{-4}} = 200\text{mm/s}$$

(6)

---

2.2 Laser power for the grooving process

The optimal laser power must be determined for surface grooving. Two different groove patterns, as shown in Fig. 4, were used for investigating the effectiveness of the joining. A chevron-shaped groove...
is shown in Fig. 4(a); its depth was set to 0.9 mm for producing deeper grooves and avoiding distortion of the metal substrate. In addition, a rectangular groove with the same cross-sectional area as that of the chevron groove was investigated for comparison, as shown in Fig. 4(b).

![Fig. 4 Schematic of laser grooving: (a) chevron and (b) rectangular patterns](image)

Laser grooving is a thermal process with relatively low energy efficiency because the material removal mechanism is mostly based on three phases: heating, melting, and vaporization. The grooving efficiency is the fraction of power used for grooving with respect to the power absorbed from the incident power, which cannot be represented by equation. Based on the literature, the efficiency values for melting and vaporization at a given laser power were empirically determined [12,29]. To evaluate grooving efficiency, laser grooving experiments were performed at laser powers of 30, 40, 50, and 60 W.

Fig. 5 represents the one-layer laser scanning strategy of creating a groove with 1.2 mm width and a certain depth. In this study, one-layer scanning implies 60 scans in the Y-direction, with a hatch spacing of 20 µm.

![Fig. 5 Schematic of one-layer scanning](image)
Considering the actual operational conditions, multilayer scanning, such as six-, eight-, and 10-layer repetitive scanning, was performed. Fig. 6 shows the cross-sectional view of the grooves after eight repetitive scans at a laser scanning speed of 200 mm/s. As shown in Fig. 6, rectangular grooves with 1.2 mm width and respective depth were successfully obtained at various laser powers. The depth of the groove increased with increasing power, but the edges were rounded at laser powers above 50 W, as shown in Figs. 6(c) and (d).

![Cross-sectional view after eight repetitive scans at 200 mm/s: (a) 30, (b) 40, (c) 50, (d) 60 W](image)

**Fig. 6** Cross-sectional view after eight repetitive scans at 200 mm/s: (a) 30, (b) 40, (c) 50, (d) 60 W

Fig. 7(a) and (b) show the variation in the groove depth with the number of scans and average groove depth per scan at various laser powers, respectively. Although a higher power can expedite the grooving process, 40 W was selected as the optimal power for obtaining better sharpness at edges, in this study.
Fig. 7 (a) Variation of groove depth with scanning times at various laser powers, (b) average groove depth per scan at various laser powers

2.3 Efficiency analysis for the laser grooving process

Laser grooving is a thermal process with relatively low energy efficiency because the material removal mechanism is simultaneously based on heating, melting, and vaporization. Not all the energy generated by the laser is used for grooving the substrate. Laser light impinging on the surface cannot be fully absorbed owing to reflection, transmission, or reradiation. Conduction heat is dissipated from the molten pool throughout the substrate. The evaporation efficiency of the molten pool also changes with the temperature field and resulting spatially varying material response. Considering these three phases, the grooving efficiency $\eta$ must be used for characterizing the grooving process.

The net heat energy, $E_n$, required for achieving laser grooving can be obtained from $E_m$ as expressed by Eq. (3). The balanced equation can be expressed as follows:

$$E_n = E_m \cdot V$$

(7)
Because the laser grooving operation is a time-dependent process, \( E_n \) is delivered at a given rate, and evaporation occurs at a certain speed. Therefore, Eq. (7) can be expressed using the following rate-balance equation:

\[
\frac{dE_n}{dt} = E_m \frac{dV}{dt},
\]

(8)

where \( dE_n/dt \) and \( dV/dt \) are the heat energy delivery and volume removal rates, respectively.

The volume removal rate in the laser grooving process can be expressed by the cross-sectional area of the removed substrate and scan speed, as follows:

\[
\frac{dV}{dt} = A_m \cdot v
\]

(9)

By substituting these terms into Eq. (9), the rate-balance equation can be obtained as follows:

\[
\frac{dE_n}{dt} = P = E_m \cdot A_m \cdot v
\]

(10)

The grooving efficiency \( \eta \) is the fraction of power used for grooving with respect to the power absorbed from the incident power, which cannot be represented by a simple equation. Referring to Ion [12] and Klemens [29], the efficiency values for melting and vaporization at a given laser power were empirically determined.

Including the grooving efficiency \( \eta \) in Eq. (10), the equation for the laser power can be expressed as follows:

\[
P = \frac{E_m \cdot A_m \cdot v}{\eta}
\]

(11)

Rearranging Eq. (11) with respect to \( \eta \), we obtain Eq. (12) as follows:

\[
\eta = \frac{E_m \cdot A_m \cdot v}{P}
\]

(12)

From the experimental data shown in Fig. 14, \( \eta \) can be determined using Eq. (12).
At 40 W, $E_{m}$ can be calculated using Eq. (3) and the data listed in Table 3.

$$E_{m} = \rho \left[ C_p(s)(T_m - T_o) + L_m + C_p(l)(T_v - T_m) + L_v \right] = 37.707 \text{ J/mm}^3$$  \hspace{1cm} (13)

Therefore, $\eta$ can be calculated from Eq. (12).

$$\eta = \frac{E_m \cdot A_m \cdot v}{P} = 0.0321$$  \hspace{1cm} (14)

Fig. 8 shows the grooving efficiencies at various laser powers obtained using Eq. (12).

![Graph showing grooving efficiencies at various laser powers](image)

**Fig. 8** Variation of grooving efficiencies at various laser powers

As shown in Fig. 8, the grooving efficiency is 2–8% under the given conditions. The $\eta$ values obtained in this study were similar to the efficiency of the laser removal process presented by Apostolos et al. [31]. In terms of laser power, the grooving efficiency increases with an increase in the laser power.

At higher laser power values, the heating time is minimized as more energy enters the processing area and the thermal attack on the workpiece is more intense. Therefore, the volume of the removed material is larger at higher laser power.

The grooved cross-sectional area in the scanning direction can be assessed using following:
\[ A_m = \frac{\eta \cdot P}{E_m v} \]  

(15)

The present study can be used for designing and gaining insight into optimum processing parameters in terms of energy efficiency.

### 2.4 Laser scanning strategy

The scanning strategies used for obtaining the target grooves were determined as shown in Fig. 9 and 10. Bidirectional path reversal between the +Y and -Y directions was performed in this study for enhancing groove flatness and uniformity. During laser grooving, the workpiece on the build platform must be gradually lifted as grooving progresses. In this study, the build platform was lifted at interval of 0.1 mm. After completing grooving of 0.1 mm depth via programmed multilayered scanning at a fixed build-platform position, the workpiece was lifted by 0.1 mm and the programmed multilayered scanning was repeated. As shown in Fig. 15(b), the average depth after the one-layer scanning at 40 W was 0.0085 mm. This implies that 12 (0.1 mm/0.0085 mm) successive layer scans were required for obtaining a groove depth of 0.1 mm. Therefore, in this study, a bidirectional successive 12-layer scan to obtain 0.1 mm groove depth at a fixed build-platform position is defined as a “unit scan.”

The laser scanning strategy used to form a rectangular groove is shown in Fig. 9(a). To obtain 0.9 mm groove depth, the unit scan (i.e., 60 linear scans bidirectionally repeated 12 times) was repeated nine times, lifting the build platform by 0.1 mm between repetitions, as shown in Fig. 9(b).

Fig. 10(a) shows the formation of chevron grooves through multilayered scanning. As described previously, a bidirectional successive 12-layer scan for obtaining a 0.1 mm grooving depth at a fixed build-platform position is defined as a “unit scan.”
Fig. 9 Schematic of the rectangular groove formation:
(a) planar scanning path, (b) repetition of unit scan with lifting of build platform

Fig. 10 Schematic of the forming of chevron grooving:
(a) planar scanning path, (b) repetition of unit scan with lifting of build-platform
For chevron grooving, the unit scan (i.e., 47 linear scans bidirectionally repeated 12 times) was repeated 12 times at a clockwise incident angle of 39° and nine times at an anticlockwise incident angle of 39°, as shown in Fig. 10(b).

3. Experimental validation of laser scanning strategy

3.1 Laser grooving

Groove formation characteristics were experimentally examined using a 1.5 mm thick Al5052 sheet. Al5052 is an aluminum alloy with high strength and low thermal expansion coefficient.

The laser grooving system is illustrated in Fig. 11. An nLight quasi-continuous-wave 500 W fiber laser (nLight-QCW) was used as the laser source. Experiments were conducted using specially designed setups for tailored scanning.

![Fig. 11 Schematic of laser system](image)

The laser processing parameters used for the laser grooving are summarized in Table 3. The scanning path was controlled using a scanning system to irradiate specific parts of the metal surface.

<table>
<thead>
<tr>
<th>Table 3 Laser system specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>Value</td>
</tr>
</tbody>
</table>
The laser beam was designed to scan the selected region by controlling the irradiation angle. The laser irradiation angle was controlled by rotating the horizontally mounted workpiece on the jig of the rotating holder, as shown in Fig. 12. The Z-axis was perpendicular to the surface of the workpiece. The incident angle was changed by rotating the workpiece with respect to the Z-axis.

![Image](image1.png)

**Fig. 12** Metal positioning for laser grooving

The hatch spacing significantly influenced the heat distribution and pattern morphology [32]. A repetitive scanning path with a hatch spacing of 20 µm, which was the same as the spot diameter, was adopted in this study.

Argon gas was flowed at a speed of 20 L/min to assist laser grooving and prevent oxidation of the metal groove during the scanning process.
To obtain the target groove shape using the laser grooving process, the grooving characteristics of three raster scanning patterns, the X-direction, 45° direction to the X-axis, and Y-direction, were studied, as shown in Fig. 13.

![Diagram of laser scanning patterns](image)

**Fig. 13** Direction of raster laser scanning patterns: (a) X-direction, (b) 45° direction to the X-axis, (c) Y-direction

Fig. 14 shows the cross-sections of the obtained laser grooves. As shown in Fig. 14, the laser scanning direction significantly affected the groove shape.

![Cross-sections of laser grooves](image)

**Fig. 14** Cross-section of obtained laser grooves: (a) X-direction, (b) 45° direction to the X-axis, (c) Y-direction

Laser scanning along the X-axis formed a deeper groove in the scanning direction as shown in Fig. 14(a). The 45° direction to the X-axis formed a slightly shallower groove in the scanning direction, as
shown in Fig. 14(b). Laser scanning along the Y-direction formed a flat and smooth rectangular cross section along the direction of width, as shown in Fig. 14(c). The flow and thermal behavior of molten metal strongly depend on the heat density distribution of the irradiated beam. As grooving began by creating an initial kerf, more heat was absorbed by the kerf. This quickly vaporized the material in the kerf. This rapid vaporization created high-pressure vapor that further eroded the walls of the kerf while ejecting material from the groove [33]. As the absorptivity of metals can be well approximated by an increasing relationship with temperature [12], the concentrated heat density in the kerf owing to the higher absorptivity also intensified the biased groove shapes. Fig. 15 represents the erosion front during grooving.

![Fig. 15 Erosion front during grooving via moving laser source](image)

### 3.2 Features of laser grooving

Two different groove patterns with rectangular and chevron shapes were fabricated. The scanning duration per unit scan were 201.0 and 157.9 s for the rectangular and chevron grooves, respectively. Fig. 16 shows the shapes and cross-sectional images of the fabricated grooves. Because the dimensional differences of the grooves are negligible, the volume of molten plastic flowing into the groove can be regarded as the same for all MPHs.
4. Application of deep grooved metal to enhance joining strength of MPH

To confirm the usefulness of deep macro-grooves on joining strength, the results obtained in this study were applied for achieving high-quality joining between injection-molded MPHs.

4.1 Materials

PA and PP are widely used pellet materials in the industry for injection molding. Al5052 workpieces with surface grooves fabricated as described in Section 3 were used as the metal part. Both the metal and plastic workpieces used in this study had the same dimensions of 80 mm × 25 mm × 1 mm, and the bonding contact surface was set to 15 mm × 25 mm for investigating the joining characteristics of the MPH as shown in Fig. 17. The metal pieces were cleaned using ethyl alcohol and an ultrasonic cleaner. The plastic pellets used for injection molding were dried at 80 °C for 2 h for removing the excess moisture.
4.2 Joining of the MPH by injection molding

To evaluate the joint strength of the MPH with macro-groove patterns, the metal workpiece was bonded with plastic via injection molding, conditions of which are listed in Table 4.

Table 4 Injection molding conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Nozzle temperature</th>
<th>Injection speed</th>
<th>Injection time</th>
<th>Mold temperature</th>
<th>Cooling time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nozzle temperature</td>
<td>240 °C</td>
<td>15 mm/s</td>
<td>3 s</td>
<td>20 °C</td>
<td>20 s</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 18 shows a schematic of an injection machine containing an injection system and steel mold with a cavity. A surface-grooved aluminum workpiece was placed in the cavity prior to injection. As shown in Fig. 18(a)–(c), molten plastic passes through the barrel and fills the metal workpiece in the mold during injection joining. The MPH pieces were obtained after bonding, cooling, and clamp opening, as shown in Fig. 18(d).
Fig. 18 Schematic of injection process: (a) plastification, (b) packing/cooling, (c) injection, (d) demolding

Tensile shear tests were performed at a speed of 10 mm/min for measuring the joint strength of the MPH. Fig. 19 shows the tensile system with a mounted workpiece.

Fig. 19 (a) Schematic of tensile test machine, (b) tensile shear test

4.3 Joining strength of the MPH by injection molding

PP and PA plastics were joined to grooved metal workpieces for evaluating the joining performance of the MPHs with surface grooves.

Fig. 20 illustrates the fabricated MPH workpieces made of Al5052 and PA. As shown in the figure, the Al–PA MPH with rectangular and chevron grooves was successfully joined under the molding conditions listed in Table 3. The Al-PP MPHs were also fabricated under the same molding conditions.
For comparison, self-bonded plastic workpieces PA–PA and PP–PP were also fabricated. Plastic workpieces of the same size as the aluminum workpieces were manufactured separately and joined by injection molding with the same plastic. PA–PA joined workpiece is shown in Fig. 21.

The strength of the aluminum–plastic joints was measured using a tensile shear test. Fig. 22 shows the test results for the self-bonded plastic workpieces. The force–displacement curves for the PA–PA- and PP–PP-joined workpieces exhibited different plastic flow behaviors. The load and displacement of PA–PA exhibited limited ductility, and fractures occurred at the bonded surface. Therefore, the tensile force sharply increased to the peak force, and the bonded joint broke without further elongation. PP–PP
exhibited a high ductility, as shown in Fig. 22. The curve exhibits a less steep elastic slope than that of PA–PA but undergoes a long period of plastic deformation. These differences in the flow characteristics between the PA and PP plastics significantly influence the resultant bonding strengths of the MPHs.

![Force–displacement curves for PA–PA and PP–PP joined workpieces](image)

**Fig. 22** Force–displacement curves for PA–PA and PP–PP joined workpieces

Fig. 23(a) shows the tensile shear test results of the MPHs fabricated in this study. Clearly, the force–displacement curves of the MPHs strongly depend on the flow characteristics of the plastic materials. The load and displacement of the Al–PA MPH showed a sharp increase in the peak force with less elongation than that of the Al–PP MPH. In both the Al–PA and Al–PP MPH, the strengths of the MPHs with the chevron groove were higher than those with the rectangular groove. More importantly, the bonding strength of the Al–PA MPH was 1.8–2.0 times higher than that of the PA–PA self-bonded plastic. However, the bonding strength of the Al–PP MPH was similar to or lower than that of the PP–PP self-bonded plastic.

Fig. 23(b) compares the maximum tensile forces for the respective tensile tests. As shown in the figure, the peak tensile strengths of PA–PA and PP–PP are similar; however, when these plastics are joined to the metal in an MPH, the MPH bonding strengths are significantly influenced by the plastic flow behavior. The highest value of force of 1890 N was obtained for the Al–PA MPH with the chevron groove. The least value of force was obtained for the Al–PP MPH joint with a rectangular pattern. The
results indicate that the highest bonding strength can be achieved when the groove has a powerful mechanical interlocking ability, and the rigid plastic prevents separation from the groove owing to the limited deformation. As shown above, the innovative laser-scanning strategy obtained in this study was successfully applied for fabricating deep grooves to improve the joining strength of MPHs.

Fig. 23 Results of tensile shear test: (a) force–displacement, (b) maximum force of MPHs
5. Conclusion

A laser scanning strategy for fabricating deep surface grooves using a CW fiber laser was investigated in this study. The conclusions of this study are as follows:

(1) Multipath scanning using a CW fiber laser is feasible for fabricating deeper grooves with various cross-sectional patterns.

(3) Analytic modeling based on the power density and interaction time is valuable in process designing, particularly in the selection of processing parameters and scanning sequence scheduling.

(2) An innovative laser scanning strategy was successfully applied to fabricate deep grooves to improve the joining strength of the MPHs.

(4) The joining strength of an MPH joined via injection molding mainly depends on the interlocking ability of the groove patterns and rigidity of the plastic under the applied load. Chevron-shaped grooving with rigid polyamide (PA) achieved superior joining strength in this study.

(5) The laser scanning strategy using a CW fiber laser can be widely applied in the rapid fabrication of deep grooves with various cross-sections.

Acknowledgment

This work was supported by a Korea Basic Science Institute (National Research Facilities and Equipment Center) grant, funded by the Ministry of Education. (Grant No. 2021R1A6C101A449).

Declaration of interest

The authors have no relevant financial or non-financial interests to disclose.

Contributions

SQ Liu: investigation, writing—original draft, SW Han: investigation, methodology, TW Hwang:
investigation, data curation, D Abolhasani: validation. YH Moon: supervision, project administration, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

References


