Improving the surface quality through a laser scan and machining strategy combining powder bed fusion and machining processes

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Abstract
This paper focuses on the unconventional laser powder bed fusion (LPBF) technique in which the LPBF and machining processes were executed alternately to fabricate higher quality parts compared to those obtained using subtractive machining processes. The additional machining process changed the stress distribution inside the built part, resulting in the deformation of the surface morphology in the final part. The phenomenon pertaining to the combined LPBF and machining process based fabrication was investigated, and the influence of the process parameters on the formation of the surplus part and deformation of the machined surface was evaluated. In addition, a laser scan and machining strategy was formulated to improve the surface quality of the built part. The surplus buildup at the edge of the fabricated part occurred owing to the difference in the thermal properties between the solidified part and deposited metal powder. The laser-irradiated position at the first layer buildup and energy density were the principal factors affecting the formation of the surplus part, and the surplus buildup could be reduced using the laser scan strategy, in which the laser-irradiated position was shifted inward. The peripheral face of the built part formed periodical steps, owing to the deformation induced by the change in the thermal distribution inside the built part. These steps could be reduced using the machining strategy combining the rough machining process with a finishing allowance and stepwise finishing process.

Keywords: Hybrid additive manufacturing, Powder bed fusion, Surface machining, Surface quality, Laser scan strategy, Machining strategy

1. Introduction
Laser powder bed fusion (LPBF) with metal materials is one of an additive manufacturing (AM) technique and is in the process of reaching to the position as maturing technologies. The AM technique was firstly proposed by Kodama as a new method to build a three-dimensional part automatically using a resin [1]. At that time, the mechanical and physical property of built part was inferior comparing to the conventional subtractive machining processes due to the limitation of usable materials and the dimensional accuracy induced by building processes, so that this technology was named rapid prototyping [2]. The subsequent development of various materials such as polymer, ceramic and metal powder enabled the application to the end-use products, and the name of this technique was turned into rapid manufacturing (RM) or rapid tooling (RT) although the dimensional accuracy was still developing [3]. Currently, this technique was standardized as the AM by the definition in the International Committee of the American Society for Testing Materials (ASTM) as a “process of joining materials to make objects from three-dimensional model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” [4]. Many industries are now seeking the suitable application by using the additive processes in order to gain the advantage while reducing the number of parts that was applied to the functional parts. The maturation of topology optimization theory and the enhancement of commercial integrated three-dimensional (3D) computer-aided design (CAD) system also contributes to the manufacturing of weight saving and highly functionality parts owing to the capacity of AM processes [5].

LPBF processes have many advantages over subtractive machining processes; however, in many cases, LPBF processes are limited to manufacture high quality parts. A key limitation of the LPBF technique is the low surface quality of the built parts, owing to the use of powder materials, and many post-processing methods have been proposed to enhance the quality of the built parts. AlMangour and Yan investigated the effect of the shot-peening treatment on the improvement of the surface quality and concluded that the severe plastic deformation enhanced the hardness, compressive yield strength, and wear resistance of the built parts owing to the interaction of the fine surface layer formation and work-hardening effect [6]. AlMangour et
al. also reported that the hot isostatic pressing (HIP) post treatment could help reduce defects such as cracks and pores, and that maintaining a high temperature for a large duration could lead to severe plastic deformation and recrystallization of the materials [7]. Fatemi et al. indicated that the residual stress could be relaxed by annealing the built part, which helped increase the torsional fatigue life owing to the increase in the local ductility at the pores [8]. In addition, they noted that performing the surface finishing of the built part could extend the torsion fatigue life by removing the stress concentration fields. Popovich et al. examined the influence of the heat treatment and HIP treatment on the built parts and noted that these treatments could enhance the mechanical properties of the built parts by miniaturizing the microstructure, and, in fact, built parts with a tailored microstructure could be obtained [9]. Morgano et al. investigated the feasibility of laser shock peening in improving the surface quality of the built parts and noted that implementing this technique could help change the strain distribution in the built part in a non-destructive manner and optimize the buildup parameters to obtain the required mechanical properties [10]. Pyka et al. formulated an experimental design to improve the surface quality in the post treatment phase and obtained the optimal process parameters based on the predefined surface roughness and morphological characteristics to build 3D porous structures [11]. Mireles et al. visualized the defects inside a built structure by using an infrared imaging apparatus and demonstrated the possibility of in situ monitoring to correct the defects by applying an automatic closed-loop feedback control system [12]. Dong et al. proposed the application of electrochemical post-processing to improve the surface quality of built parts [13]. They observed that the etching process helped reduce the surface roughness on the internal and external surface of the built parts. Moreover, it was noted that the initial surface roughness was a key parameter influencing the etching characteristics and that the etching processes could be optimized to achieve a uniform surface without excessive material removal.

To improve the surface quality of the built parts, a subtractive machining process can be introduced to obtain a smooth surface with a high dimensional accuracy. Many methods combining the AM process with other techniques have been proposed to develop hybrid AM equipment. Jeng and Lin developed a hybrid manufacturing system, in which the directed energy deposition and milling processes were combined to smooth the top surface of the built parts and control the powder supply [14]. The proposed hybrid manufacturing system was noted to be effective in modifying and repairing molds. Song and Park combined the wire-arc AM (WAAM) and milling processes [15]. Specifically, the layer buildup and face milling operations were performed alternately to obtain a smooth surface, and it was noted that this approach could be used to build large parts while reducing the manufacturing time and thermal warpage. Karunakaran et al. proposed the addition of an arc welding unit to any existing computerized numerical control machine as a low cost process [16]. Abe et al. developed a hybrid system pairing the LPBF process with surface machining through end-milling and demonstrated that this approach be used to manufacture an injection molding die with a reduced production time and manufacturing cost [17]. Xiong et al. proposed a hybrid plasma deposition and milling (HPDM) system, in which the surface of the built parts was smoothed by depositing the metal powder via a plasma torch and machining the top surface through end-milling [18]. It was demonstrated that the HPDM process could enable the direct manufacturing of metal prototypes and tools.

In particular, introducing machining processes involving cutting tools to LPBF processes can help achieve a smooth surface on a built part. However, the morphology of the built part varies according to the thermal behavior and stress distribution on the built part when the machining processes are performed. Considering this aspect, the focus of this study was a hybrid AM system in which the LPBF and machining processes were executed alternately to build high quality parts comparable to those obtained using subtractive machining processes. Specifically, the buildup phenomena corresponding to the combination of the LPBF and machining processes were investigated experimentally, and the influence of the process parameters on the surplus buildup formation and machined surface deformation was evaluated. Moreover, a laser scan and machining strategy to improve the surface quality of the built parts was formulated.

2. Experimental method

2.1 Hybrid AM equipment combining the LPBF and machining processes

The process of building parts by using a hybrid AM equipment combining a machining process with an end mill is illustrated in Fig. 1. When the metal powders are deposited on the substrate, a laser beam is selectively irradiated to the powder surface to build a layer in accordance with the programmed NC data. The standard thickness of the metal powder layer is 50 μm, and the metal powder is deposited on the substrate by the action of gravity alone. Subsequently, the scan direction of the laser beam is varied by 90° to prevent anisotropy in any layer. After building multiple layers by repeating the metal powder supply and selective laser melting processes, the edge of the unfinished built part is machined through contour milling by the end mill. In some cases, the top surface is also smoothed via machining because the height of the built part is different than the desired height. To obtain the final parts, the LPBF and machining processes are
performed alternately until the top layer is built. In general, the surface of the built part obtained using a simple LPBF process involves a partially melted and solidified area on the fully solidified structure owing to the non-uniform energy input by the laser beam irradiation [19]. Introducing a machining process can help remove these non-uniform surfaces and build parts with a high density and dimensional accuracy.

2.2 Experimental conditions

The experimental conditions to build a part by using the hybrid AM equipment are listed in Table 1. The system developed in this work was a customized hybrid AM equipment, and the process chamber was filled with an inert gas to prevent the oxidization of the metal powder during the LPBF and machining processes. A pulsed wave CO2 laser beam (Coherent Inc.: K500) with a wavelength of 10.6 μm was used to irradiate the building platform by using a galvanometer scanner (GSI Group Inc.: M3ST). The beam diameter was 0.2 mm, implemented by using a dynamic focus lens, and the laser scan velocity was varied from 110 to 480 mm/s. The hatching distance for a layer buildup was 0.2 mm. The hybrid AM equipment involved a mounted spindle with a maximum spindle rotation of 50,000 rpm (KaVo: Type4041), and the machining process was performed under dry conditions. The cutting tool was a ball end mill made of solid carbide, with a diameter of 0.6 mm. The axial depth of cut was determined to be 60 μm, taking into account the requirements for the hybrid buildup processes. The metal powder was a mixture of 70% alloy steel powder (ISO: 42CrMo4), 20% copper phosphorous alloy powder (ASTM: C52100) and 10% nickel powder in weight, and its average particle size was 25 μm. A molding die built using these mixture powders has been reported to have sufficient mechanical strength and hardness [20]. The metal powder was deposited on the substrate, and its surface was sandblasted by white alumina with an average particle size of 300 μm to improve the wettability of the metal powder. The deposited height was maintained at a constant value of 50 μm by using a recoating blade. The metal powder was deposited under the action of gravity alone. The built size area was 10×10 mm, and the built height was varied from 1-6 mm.

To evaluate the influence of peripheral machining on the buildup behavior, the surface morphology of the built part was examined. The built surface and cross-section in the vertical direction were observed using a scanning electron microscope (SEM), and the adhered length and height were measured through the recorded images. The built part was cut off through electrical discharge machining and examined to evaluate the buildup characteristics and performance of the hybrid process. In addition, the influence of the process parameters on the surface morphology was evaluated by considering the energy density, calculated using the laser power, laser scan velocity, beam diameter, and layer thickness. The results were used to formulate a laser scan and machining strategy to improve the surface quality of the built parts.

3. Result and discussions

3.1 Observation of the built parts at the LPBF and machining processed positions

Figure 2 shows the SEM images of the built parts at the boundary of the LPBF and machining processes when 20 layers were built on the substrate, and the peripheral face from the 1st to the 10th layers was machined, corresponding to one cycle of alternate buildup via the LPBF and
machining processes. The zoomed in images of the LPBF processed position and the boundary of the LPBF processed and machining positions are also presented. Fig. 2(a) shows that a smooth surface was obtained at the position in which the peripheral machining was performed, and defects such as pores and cracks were not observed on the machined surface. In contrast, the position in which the LPBF processes were performed exhibited a rough surface owing to the adhesion of the partially melted powder or unmelted powder, as shown in Fig. 2(b). In addition, the width of the built part on the LPBF processed block was larger than that of the designed 3D model, owing to the enlargement of the built part in accordance with the radius of the irradiated laser beam. However, the machined surface had a smooth surface without defects, similar to the designed 3D model shape. These results indicated the ability of the machining processes in improving the surface morphology and dimensional accuracy.

Figure 3 shows the cross-sectional image of the built part, with the part shown in Fig. 2 cut off for the evaluation. The part buildup achieved using the hybrid AM equipment was unique. After the machining processes were performed to smooth the peripheral face, LPBF processes were performed on the machined surface. The width of the built part was narrow owing to the machining of the peripheral face, and consequently, a LPBF process was performed around the edge of the built part to deposit the metal powder. As a result, the solidified metal powder outside the built part sank to the machined peripheral face owing to the laser irradiation on the deposited metal powder outside the built part. The width of the overhang position and sunk depth from the machined surface were defined as illustrated in Fig. 3, and the influence of the process parameters on the surplus width and sunk depth was investigated.

3.2 Influence of process parameters on the formation of the surplus buildup

Figure 4 shows the variation of the surplus width and sunk depth with the number of layers in the LPBF process when the beam diameter was 0.5 mm and the energy density on the powdered surface was 80 J/mm³. The surplus width and sunk depth did not exhibit a considerable change with the increase in the number of layers in the LPBF processes, and the average surplus width and sunk depth were 0.33 mm and 0.19 mm, respectively. In addition, the sunk depth was lower than the layered height (0.5 mm). These results suggested that the surplus width and sunk depth were influenced by the characteristics of the first layer built when the LPBF processes were performed after the machining processes. The surplus buildup occurred owing to the difference in
the thermal conductivity of the built part (9 W/m·K) and deposited metal powder (0.14 W/m·K) [21]. The laser beam irradiation around the edge of the built part in the first-layer buildup was performed at the position in which the built part and deposited metal powder were mixed, and the conduction of the input energy varied with the thermal conductivity of the different materials. Specifically, the deposited metal powder melted owing to its low thermal conductivity, resulting in the formation of the surplus buildup. Moreover, the subsequent layers were built up on the built part, the thermal conductivity of which was higher than that of the deposited metal powder, and the surplus buildup was not enlarged, owing to the conduction of the input energy to the built part. In addition, the laser-irradiated position in each layer building process was constant, and the additional energy input to build the following layer did not affect the surplus width and sunk depth.

Figure 5 shows the variation in the surplus width and sunk depth of the built part with the laser scan velocity in the LPBF process when the beam diameter was 0.5 mm and the energy density on the powdered surface varied from 25 to 110 J/mm³. The surplus width and sunk depth were influenced by the laser scan velocity, and they increased in proportion with the increase in the energy density, although the sunk depths were lower than the layered height during the block building process. Moreover, many pores could be observed inside the built part at an energy density of 30 J/mm³. The energy density was the principal parameter affecting the formation of the pores inside the built parts, and the melt pool behavior was influenced by the energy density [22]. However, the energy density was not attributed in the formation of surplus region. These results indicated that the surplus region buildup was influenced by the laser-irradiated position and the energy density. In addition, the machining processes could be modified according to the laser-irradiated position in the first layer buildup and its energy density, although the peripheral face machined in the previous processes was required to be remachined to obtain a smooth peripheral face of the built part.

3.3 Laser scan strategy to reduce the surplus buildup

As mentioned in the previous section, the laser-irradiated position was one of the principal factors affecting the surplus buildup formation at the edge of the built part. Therefore, a laser scan strategy to vary the laser-irradiated position in each layer buildup was evaluated. Figure 7 illustrates the principle of the laser scan strategy to reduce the surplus width at the edge of the built part. When the first layer was built immediately after the machining of the built part, the laser-irradiated position was shifted inward against the edge of the 3D CAD model. The offset amount pertaining to the first layer buildup was 0.2 mm, and the offset amount was decreased by 0.02 mm in each subsequent buildup. The energy density was maintained at 80 J/mm³ at a laser diameter of 0.5 mm.

Figure 8 shows the effect of the laser-irradiated position offset on the surplus buildup. The sunk depth at the edge of the built part when using the proposed laser scan strategy was 0.1 mm, which was 47% lower than that in the case of conventional processes. In addition, the pores

![Figure 5](image1.png)

**Fig. 5** Variation in the surplus width and sunk depth with the laser scan velocity

![Figure 6](image2.png)

**Fig. 6** Comparison of the cross-sectional images at energy densities of (a) 30 J/mm³ and (b) 80 J/mm³
induced by the adhesion of the partially melted powder were not observed around the edge of the built part. However, the excessive offset at the laser-irradiated position worsened the peripheral face quality owing to the presence of the partially melted powder at the position in which the machining processes were performed. These results suggested that the machining processes after the layer buildup could be improved by controlling the laser scan strategy, thereby reducing the manufacturing time owing to the reduction in the surplus buildup.

3.4 Observation of the peripheral face subjected to alternate LPBF and machining processes

Figure 9 shows the SEM images of the peripheral face subjected to the conduction of alternating LPBF and machining processes. The buildup conditions involved a laser power of 300 W, energy density of 80 J/mm³, and height of 10 layer builds. As shown in the images, periodical steps were formed on the peripheral face. The profile of the peripheral face was measured via optical microscopy, as shown in Fig. 10. Specifically, the figure shows the base line obtained from the designed 3D CAD model, and the initial position refers to the top surface of the built part. The machined position around the top surface coincided well with the designed base line; however, the peripheral face at the lower positions shifted inward. The profile of the peripheral face was periodic, and the interval of each step was 0.5 mm, which coincided with the machined height. These steps were formed owing to the variation of the thermal distribution inside the built part, owing to the varied machining of the peripheral face. It is well known that a sheet metal can be deformed through the temperature gradient mechanism (TGM), buckling mechanism, and upsetting mechanism [23]. The formation of the steps on the peripheral face corresponded to the TGM. When the laser beam was irradiated to the deposited metal powder after the machining processes were performed, the machined surface below the deposited metal powder heated and cooled according to the laser-irradiated position, resulting in the deformation of the previously machined peripheral face. Positions below the top surface did not deform, owing to the rigidity of the built part. In addition, the variation in the residual stress inside the built part affected the deformation of the machined peripheral face. The built part obtained using the AM equipment possessed an internal tensile residual stress, and the magnitude of the stress varied with the morphology and process parameters [24]. Moreover, the
re-irradiation of the laser beam during the layer buildup reduced the residual stress [25]. The peripheral face was deformed by the TGM and the release of the residual stress during the LPBF processes, resulting in a maximum deformation of 22 μm.

3.5 Influence of the process parameters on the periodic deformation on the machined peripheral face

Figure 11 shows the variation in the deformation width on peripheral face with the energy density during the LPBF processes. The built height, after the LPBF and machining processes were performed 20 times, was 10 mm, and the deformation width during the processes was evaluated by calculating the average deformed width. Under an energy density less than 40 J/mm³, the deformation width increased with an increase in the energy density, although its values became nearly constant at energy densities beyond 40 J/mm³. The maximum deformation width was 15 μm, and the threshold coincided with the energy density at which pores formed inside the built part. Subsequently, the influence of the number of layers in one cycle of the LPBF processes on the deformation width was examined. Fig. 12 shows the variation in the deformation width on the peripheral face with the number of layers in the LPBF process. The built size was 10×10×10 mm, and the built height in each LPBF process was varied according to the number of layers, as the peripheral face was machined after each LPBF process. The axial depth of cut in the peripheral face machining was constant at 70 μm, and the machined height was varied according to the layered height in each LPBF process. The deformation width increased with the increase in the number of layers, and its values were nearly constant at 25 μm after more than 30 layers were built. These results suggested that the energy density and number of layers were the principal factors affecting the deformation behavior of the peripheral face during the machining process. In general, the large number of process parameters in the LPBF makes it challenging to determine the optimal conditions. However, it is expected that the optimal conditions to minimize the deformation behavior of the peripheral face can be easily determined by taking into account the energy density and number of layers.

3.6 Machining strategy to improve the peripheral face quality

Figure 13 shows the proposed approach to improve the peripheral face quality by changing the machining strategy. As mentioned in the previous section, the deformation behavior was influenced by the laser energy and the number of layers in the LPBF processes, and it could be controlled by taking into account the process parameters. In the proposed method, the machining process was performed in two steps, involving a rough machining of the peripheral face with a finishing allowance, and finishing the most recent LPBF processed position after the following LPBF processes were performed. After the peripheral face of the built part was realized, it was machined with a finishing allowance, as shown in Fig. 13(a). After the following LPBF processes were performed, and the next block was built on the face, as indicated in Fig. 13(b), the peripheral face of the previous block was finished, and that of the current block was roughly machined, as depicted in Fig. 13(c). In this machining process, the ball end mill with a neck relief was used to prevent any interference between the built part and cutting tool.

Figure 14 compares the SEM image of the peripheral face on the built part machined using the proposed and conventional machining processes. The peripheral face
obtained using the proposed machining process was smooth, and no periodical steps were observed. The surface roughness in this case was $R_z=5.4\ \mu m$, which was 60% lower than that achieved using the conventional process.

4. Conclusions

In this study, a hybrid AM equipment combining the LPBF and machining processes was developed to build a part, and the influence of the process parameters of the LPBF and machining processes on the building quality was investigated experimentally. The unique problems induced by this type of hybrid machining were highlighted, and a laser scan strategy and machining strategy to improve the surface quality were formulated. The following conclusions were derived:

1. The LPBF processes at the edge of the built part after the machining processes were performed on the deposited metal powders, and consequently, the metal powder solidified outside the built part during the LPBF process sank to the machined peripheral face owing to the difference in the thermal properties of the solidified part and deposited metal powder.

2. The surplus width and sunk depth at the edge of the built part were determined considering the characteristics of the first layer buildup, taking into account the difference in the thermal properties of the solidified part and deposited metal powder. The principal factors affecting the formation of the surplus buildup were the laser-irradiated position and energy density.

3. The surplus region at the edge of the built part could be reduced using the laser scan strategy, in which the laser-irradiated position was shifted inward. However, the excessive offset of the laser-irradiated position worsened the surface quality owing to the formation of the partially melted powder at the position in which the machining processes were performed.

4. The peripheral face of the built part exhibited periodical steps induced by the combination of the LPBF and machining processes. Specifically, the periodical step was formed owing to the variation in the thermal distribution according to the machining of the peripheral face and the release of the residual stress inside the built part.

5. The energy density and number of layers were the key factors affecting the deformation behavior of the peripheral face during the machining process. This deformation could be reduced using a two-step machining strategy involving a rough machining of the peripheral face with a finishing allowance, and realizing the finishing of the most recent LPBF processed position after the following LPBF processes were performed.

5. Declarations

5.1 Funding
   Not applicable.

5.2 Conflicts of interest
   Not applicable.

5.3 Availability of data and material
   Not applicable.

5.4 Code availability
   Not applicable.

5.5 Authors' contributions
   Furumoto T: Conducted the LPBF experiments, evaluated the obtained data, organized all data and wrote the manuscript. Abe S: Proposed the laser scan and machining strategy for the improvement of the surface quality of built parts by combining LPBF and machining processes, conducted the machining experiments and evaluated the obtained data. Yamaguchi M: Evaluated the surface of built part by SEM. Hosokawa A: Supervision of all research.

5.6 Ethics approval

Fig. 14 Comparison of the SEM images of the peripheral face (a) proposed (b) conventional machining processes

![Image](image_url)
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