A STRATEGY FOR FABRICATING COMPLEX STRUCTURES VIA A HYBRID MANUFACTURING PROCESS

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Abstract

The purpose of this paper is to introduce a strategy for fabricating complex structures via a hybrid manufacturing process. The Laser Aided Manufacturing Process (LAMP) lab at Missouri S&T has developed a hybrid process combining both a direct metal deposition process and a five-axis CNC milling. Accessibility is a difficulty when finish machining internal features. The concept is to pause the deposition process to finish machine an internal feature while it is still visible is one possible solution to this issue. However, this must be done in a manner that will not be spoiled when the deposition process continues. This paper discusses processing strategy, tool selection, and experimental validation of a technique to build complex structures via mid-process machining with an undercutting mill.

Keywords: rapid prototyping, laser deposition, milling process.

1 Introduction & Background

The Direct Metal Deposition (DMD) is a unique technique which can be used to manufacture near net shape components. However, the surface finish of parts made using DMD may not be suitable for some end-use components. This limits DMD to certain applications unless a finish machining operation is done as a post-deposition step [2]. In contrast, the resulting geometries of direct laser deposited components do not require rough machining, due to the additive nature of the process. As a result, the Hybrid Laser Deposition and Milling (HLDM) technique, capable of both DMD and finish machining, will reduce total processing time and/or tooling and material consumption for a given part geometry.

Recently, research work on hybrid process has been done in different areas. Selective laser cladding (SLC) and milling processes were combined [4]. Plasma deposition was combined as additive with NC milling process as subtractive to fabricate metal vase [6]. Similarly, the combination of wire welding technology using a CO2 laser with milling was carried out [1]. A rapid pattern manufacturing system was developed for the sand casting involving both additive and subtractive techniques [5].

Funded by the National Science Foundation and Air Force Research Laboratory, the University of Missouri-Rolla (UMR) has developed the Laser Aided Manufacturing Process (LAMP). The (LAMP) has done some works related to hybrid process. CNC machining and layered deposition processes were integrated to realize the automatic hybrid manufacturing process without human interference [8]. An adaptive slicing algorithm for the five-axis Laser

Aided Manufacturing Process was developed at Missouri S&T. The newly developed algorithm implemented in process planning helps the hybrid system build parts more efficiently [9].

Machining conditions in HLDM are very harsh. The optics required for the DMD portion of the process precludes the usage of cutting fluids in the milling portion of the process. This issue is compounded for deep cavities and small features because they require a tool with a high length to diameter ratio. The purpose of the experimental investigation is to enhance a new technique of HLDM for machining deep or external features. This technique is based on sequential additive and subtractive operations that take advantage of specialized milling tools that can produce an undercut. Geometry such as thin features, deep cavities and internal features which are impossible to machine by conventional methods can be manufactured by HLDM.

2 Solutions for Production of Internal Features

The HLDM concept is to deposit material using the laser deposition technique, layer by layer, which are subsequently machined to a specified geometry. They can be machined using small diameter and short tools to obtain required dimensions accuracy and surface finish quality as shown in figure (1).

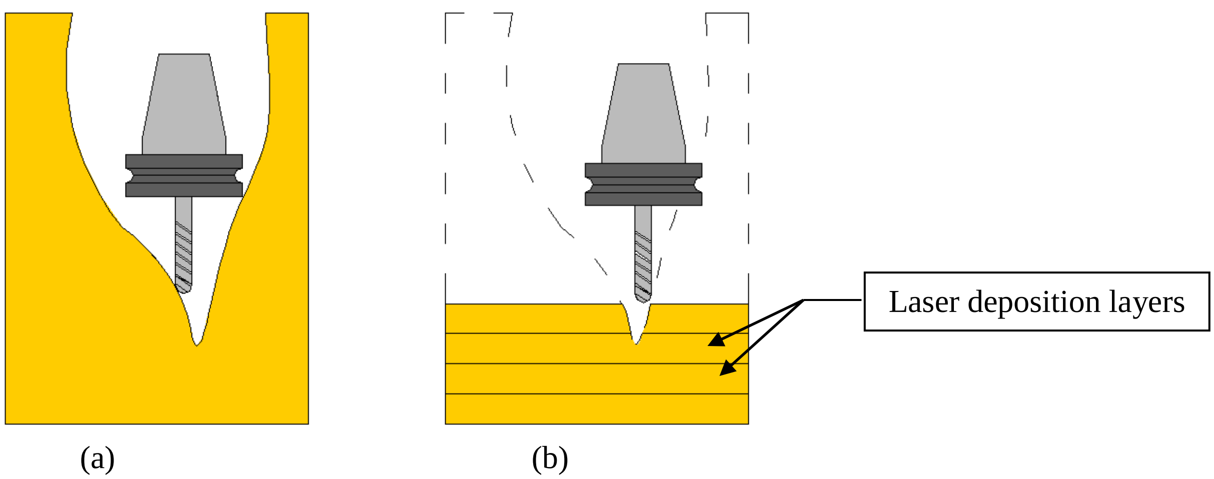


Figure (1): machining feasibility (a) machining whole part by conventional technique causes collision, (b) machining layer by layer.

There are two possible routes to achieve the desired part geometry. The simplest solution, shown in Figure (1a), is to deposit the entire geometry and then machine it. This solution works well as long as the machining tool has accessibility to all the features that need to be machined. However, this can lead to a collision, so it is not a general-purpose solution. The second possibility is to machine the part periodically during the build process, as illustrated in Figure (1b). Periodic machining also allows the use of shorter tools, which allows access to smaller diameter tools. This solves the collision problem, but introduces two new issues:

1. Planning: When is it necessary to stop the deposition process and machine? Switching from the deposition process to the machining process takes time. To make the best use of the machine's capabilities, the number of process switches should be minimized.
2. Fidelity: How can the machined areas be protected from the laser during subsequent deposition? Without some kind of protection, the machined surfaces will have altered surface finish or, at worst, deformed geometry from melting, as illustrated in figure (4).

2.1 Undercut Milling

The concept presented in this paper uses a tool capable of producing an undercut, a T-slot cutter in this instance, to partially machine the deposited material, leaving some material to act as a base for subsequent deposition [6]. Once the first layer laser deposition is done, the certain shielding height (***h***) and tool offset (***w***) must be maintained to avoid spoiling the machined surfaces, as shown in Figure (2).The factors ***h*** and ***w*** are investigated in Section 3.2, below.

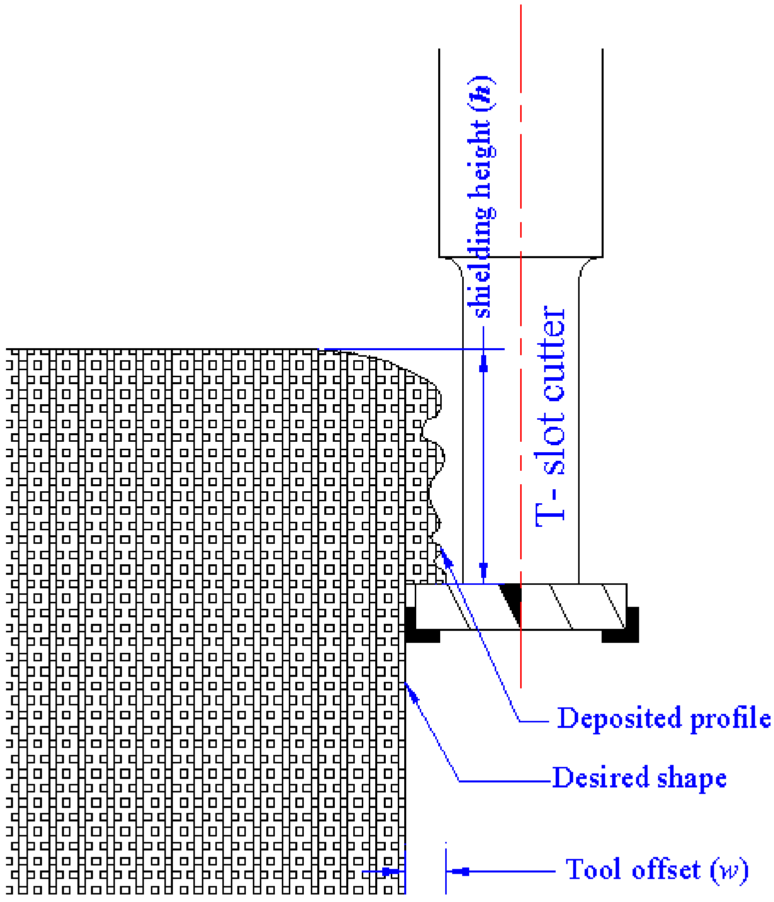


Figure (2): principle of milling machining using T-slot cutter

All experiments were carried out on a 5 axis FADAL CNC milling machine with an integrated laser cladding nozzle, as shown below in figure (3). Laser deposition is used to deposit a thin wall. When a thin wall is deposited, the vertical surface profile is machined using T-slot cutters to attain fine surface state of the near-net shape metal part.

Figure (3): Integrated 5-axis FADAL CNC and Laser Deposition Head

Experiments details:

This work investigates the shielding height (***h***) and tool offset (***w***) dimensions needed to obtain the best dimensions. The goal of the experiment was to minimize ***w*** and ***h*** to reduce the machining time and cost, yet still provide shielding for the machined surface, as shown in figure (4). The system parameters used in the experiment are enumerated below:

Laser deposition parameters:

- Laser power 1000 w
- Powder feed rate 8.0 g/min
- Feed rate 375 mm/min

Milling machining parameters:

- The milling machining was done by using Cobalt T-slot milling cutter (cutter diameter 16.6 mm, 8 teeth) and the milling parameters are used in this work are [7] as following:
- Feed rate 50
- Spindle speed 250 rpm
- Radial depths of cut are (0.4, 0.8 and 1.8 mm).
- Axial depth of cut is 4 mm.

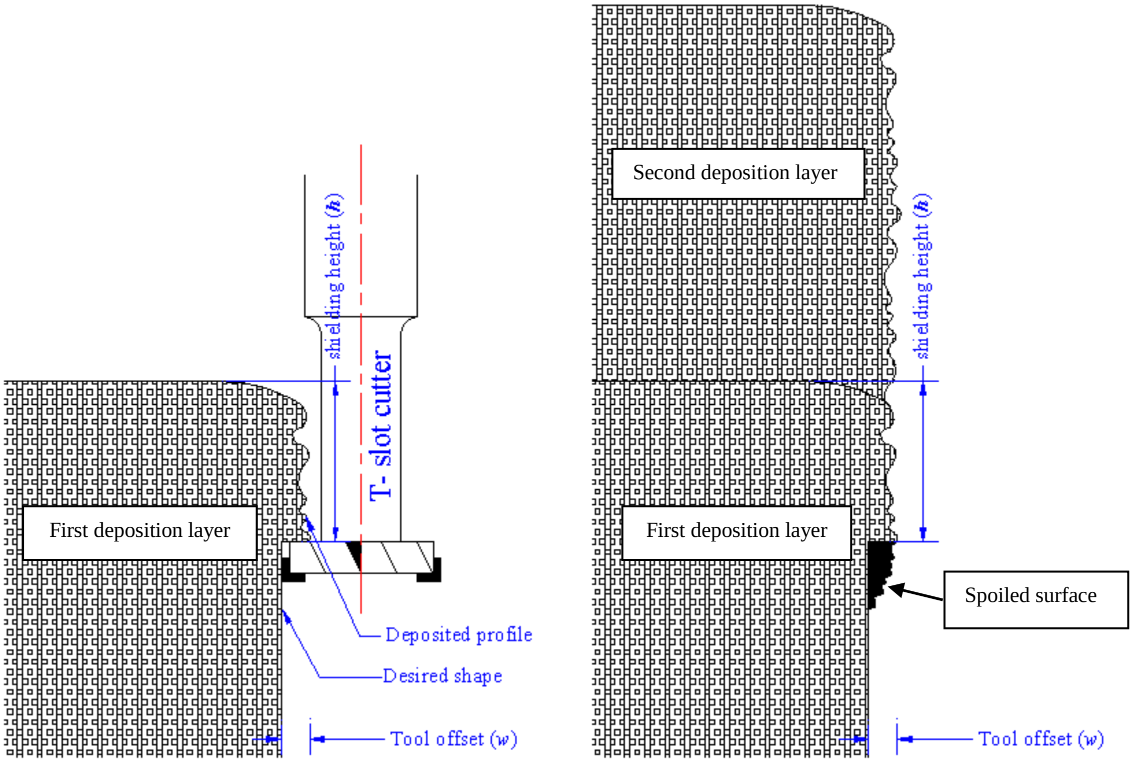
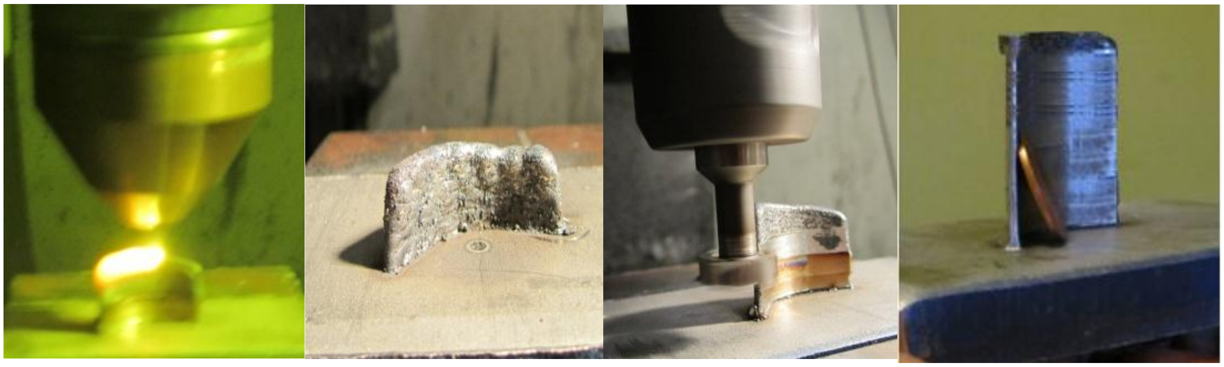


Figure (4): undercut milling machining to reduce spreading of molten pool at the following deposition process

3 Proof of Concept

3.1 Manufacturing

A turbine blade was fabricated by hybrid process combining both a direct metal deposition process and a five-axis CNC milling. It is roughly 30 mm length, 1 mm thick and 50 mm height as shown in figure (5).



(a) (b) (c) (d)

Figure (5): fabricate processes of a turbine blade. (a) laser deposition scene; (b) first layer of laser deposition process;(c) milling process scene; (d) fabricated sample

3.2 Analysis:

The specific problem addressed in this paper is choosing and optimizing the tool offset distance (***w***) and the shielding height distance (***h***) to avoid spreading of molten at the subsequent laser deposition process and to reduce the spoiled surface distance of the previous machined surface profile layer, as shown in figure (4). The spoiled surface distance happen attribute to melt some amount of this overhang which is formed from (***w***) and (***h***). This spoiled surface distance is inversely proportional to (***w***) and (***h***) distances.

In order to maximize the deposition layer thickness "H" to reduce the switching between laser deposition and milling machining processes, there are some conditions should be considered which is listed below:

Conditions of the process:

d_1 : tool diameter
d_2: shank diameter
TL: tool length
h_1: tool width
H: layer deposition thickness
h: shielding height
w : tool offset
$h_1 \leq H - h$
$d_1 - d_2 > w$, illustrated in figure (6).

H_{min}: minimum deposition layer thickness depends on tool width" h_1" .

$$H_{min} \geq h_1 + h$$

H_{max}: maximum deposition layer thickness depends on tool length "TL".

$$H_{max} < h_1 + TL$$

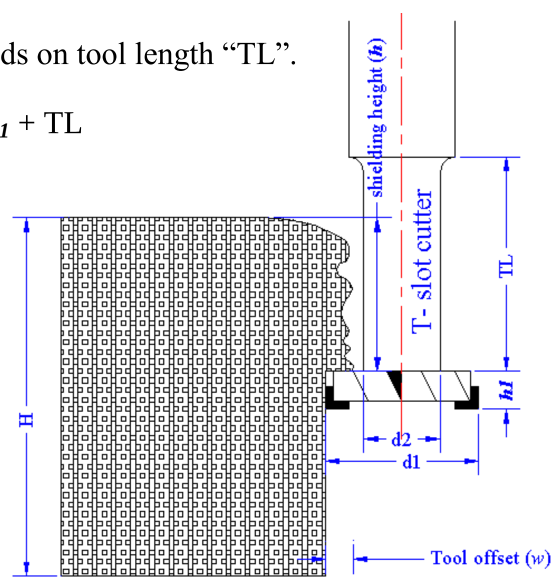


Figure (6): Tool dimensions condition of the process

There are two independent factors: shielding height (***h***) with three levels (1.00, 1.50 and 2.5 mm), and the second independent factor is tool offset (***w***) with three levels (0.40, 0.80 and 1.20 mm). There is one dependent variable which is a non-spoiled machined surface profile height..

Independent variables

Factor A: shielding height (***h***)

Factor A levels (1.00, 1.50 and 2.5 mm)

Factor B: tool offset (***w***)

Factor B levels (0.40, 0.80 and 1.20 mm)

These levels of both factors were selected depend on previous experiments.

Dependent variable: Non-spoiled machined surface profile layer (mm), and it is measured by digital caliper.

The experiments parameters were investigated which are significantly affect the performance characteristics by the ANOVA and the F test (standard analysis) as shown in table (1) and (2).

Table (1): Dependent Variable: non spoiled machined surface

Source	DF	Squares	Mean Square	F Value	Pr > F
Model	8	3.86766667	0.48345833	52.55	<.0001
Error		18		0.16560000	0.00920000
Corrected Total		26		4.03326667	

Table (2):

Source	DF	Squares	Mean Square	F Value	Pr > F
Tool offset	2	1.12186667	0.56093333	60.97	<.0001
Shielding	2	2.66746667	1.33373333	144.97	<.0001
Tool offset*Shielding	4	0.07833333	0.01958333	2.13	0.1191

Both of two factors shielding height (***h***) and tool offset (***w***) are significantly effect on the experiment. With a p-value of 0.1191, the combine if the treatment is not significant as shown in table (2), therefore, the regression model is linear as shown in SAS output in table (3).

Table (3): Parameter Estimate(Parameter Standard)

Variable	DF	Estimate	Error	t Value	Pr > |t|
Intercept	1	9.06111	0.08245	109.90	<.0001
Tool offset	1	0.24667	0.02801	8.81	<.0001
Shielding height	1	0.38000	0.02801	13.57	<.0001

So, our regression model is:

$$Y = \beta_0 + \beta_1 X + \beta_2 X \quad (1)$$

$$Y = 9.061 + 0.246 X_1 + 0.38 X_2 \quad (2)$$

Where, $\beta_{0:}$ intercept of the line. Effects plots, with the regression line, are shown in figure (7).

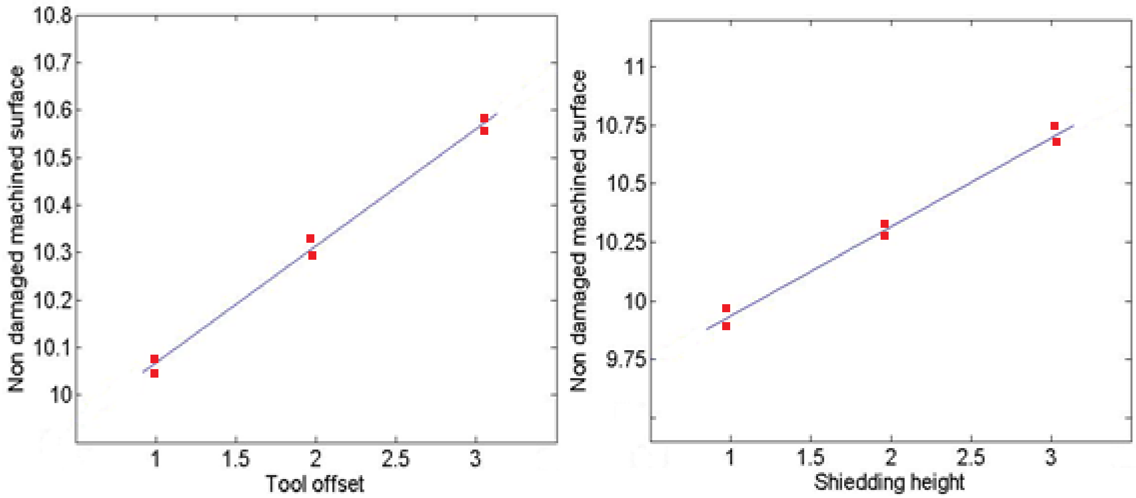


Figure (7): SAS output plot of regression model

With this model the response variable which is non-spoiled machined surface distance (mm) can be estimated clearly.

4 Results and Discussion

The optimization of minimum of both shielding height (***h***) and tool offset (***w***) distances requires the maximum non spoiled machined surface distance is attained. The regression model of experiment is obtained by using SAS software

This work on the development of the DMD process using Hybrid Laser Deposition and Milling (HLDM) technique taking advantage of undercut machining using T-slot cutter to machine laser deposition components to improve surface roughness and dimensions accuracy

To be an efficient solution, both shielding height (*h*) and tool offset (*w*) distances were minimized such that the machined surface was not damaged by subsequent laser metal deposition steps. For the 316L stainless steel used in this experiment, the minimum acceptable value of (*h)* and (*w)* were found to be 1.5 mm and 0.8 mm, respectively, when using 1000 W, 375 mm/min, and 8.0 g/min as the laser deposition parameters. A turbine blade was manufactured using these parameters.

5 Conclusions

Metal Direct Prototyping is unique method among current RP techniques. Hybrid Laser Deposition and Milling (HLDM) can machine complicate shapes that traditional ways cannot do it taking advantage of additive and subtractive technique. Moreover, it is more economy than traditional machining when will be deal with expensive material attribute to some amount of removal material to get the desired shape.

Using this technique, the processing time wasted due to switching between additive and subtractive methods can be minimized. The optimization parameters used here ensure that a minimum amount of material is wasted in the subtractive step. Finally, this method allows for unsupported undercut features to be fabricated via the hybrid process using only 3 axes.

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