Hybridization of Commercial Directed Energy Deposition System for In-Situ Repair of Parts

Juan Pablo Garcia Chavira[1 2], Angel Bravo[1 2], Jason McCleary[1 2], Kurtis Watanabe[1 2], Dr. Francisco Medina[1 2]

[1]The University of Texas at El Paso, El Paso, Texas, USA

[2]W. M. Keck Center of 3D Innovation, El Paso Texas, USA

Abstract

Metal additive manufacturing (MAM) processes have matured since their inception. Still, limitations regarding the scalability and high energy and material cost for the process have limited it to the fabrication of specialized complex parts. Even then, due to MAM's proneness to thermal gradients, rough surface finish, and need for support structures, some type of post-processing using traditional manufacturing is required. Combining both additive and subtractive technologies into a hybrid system provides the opportunity to mitigate the limitations of individual technologies and enhance their advantages. Of the additive manufacturing (AM) technologies, directed energy deposition (DED) has gained interest for hybridization due to its flexibility compared with other AM processes. Hybrid DED has proven successful in reducing material usage and manufacturing time over pure DED and even subtractive processes. In particular, the repair of existing parts to extend their lifetime has become a field in which hybrid DED excels. Most hybrid DED processes are built by adding an additive component to an existing subtractive system, such as CNC, thereby placing an emphasis on the subtractive process. But this can result in a reduction in print quality due to the need for an inert environment for DED processes. By emphasizing the AM process by integrating a subtractive system into a commercial DED system, such as RPM Innovations 222XR, an increment in the availability of quality hybrid DED systems can be achieved. To prove this, the quality of the end-product must be ensured. Thus, a gage repeatability and reproducibility (GR&R) study was performed on parts fabricated on the hybrid system that was developed.

Introduction

Metal additive manufacturing (MAM) has gained interest in research due to its ability to produce complex parts in a single process. Ahn et al. mentions that "MAM technologies can directly fabricate a metallic part with a complex shape without an additional manufacturing process" [1]. While Eisenbarth et al. say "AM is often said to provide 'complexity for free', which means that resource consumption in terms of time, energy, and material is the same for the fabrication of a simple or complex structure, as resource consumption depends mostly on the total built volume" [2]. But MAM technologies have significant limitations that keep them from becoming mainstream, large-scale manufacturing processes. Important limitations are the high cost and low throughput, which keep MAM suitable as a single manufacturing process mainly for applications requiring highly specialized parts with high geometric complexity [3], [4]. Other considerable shortcomings regarding these technologies are scalability, dimensional accuracy, warping and surface finish which necessitates the implementation of additional post-processing, consisting mainly of heat treatment and subtractive manufacturing processes, to achieve a final part [1], [3], [4], [5], [6], [7], [8], [9], [10].

Most MAM parts, to be adequate for end use, require postprocessing often in the form of an additional subtractive process [7], [9]. Thus, combining the additive process and the subtractive post-process in a single system has become an increasingly common approach [4]. This type of approach is known as hybrid additive manufacturing. Not all MAM technologies are being hybridized at the same rate, with the most common technology to hybridize being directed energy deposition (DED) [4]. The reason for this predominance is mainly not requiring a powder bed, capacity for localized material deposition, and rapid building of complex geometries [11]. The most common way to hybridize DED technologies is equipping a subtractive CNC machine with an additive head [7], [10]. This approach is simple and cheap without requiring heavy programming or modifications of the functionality of the original CNC machine. Another approach for hybridization is to either combine a CNC machine with a six-axis robot arm equipped with an additive head or use two six-axis robot arms, one with additive and subtractive capabilities respectively [7]. These approaches have advantages such as increasing complexity in fabrication and deeper customization but making hybridization more complex and expensive. One important obstacle for all prominent hybridization methods is the need for an inert environment. Most hybrid AM systems tackle this obstacle by using localized shielding gas on the melt pool, thus preventing oxidation, which may be less effective than an inert enclosure [7].

A new approach was developed with the intention of providing an alternative to equipping a subtractive system, with additive technologies. Instead, in this project, it was proposed to equip an additive machine with an additional subtractive gantry for hybridization (Figure 1). This prioritizes the additive process leveraging a commercially available additive system with an inert enclosure. A custom subtractive CNC gantry was built from scratch and mounted inside the commercial DED machine. Since the subtractive system was built from scratch, it was important to ensure reliability in its operation before fully implementation in the repair of a part using both the additive and subtractive process. Thus, a GR&R study was performed on parts built with the subtractive gantry.

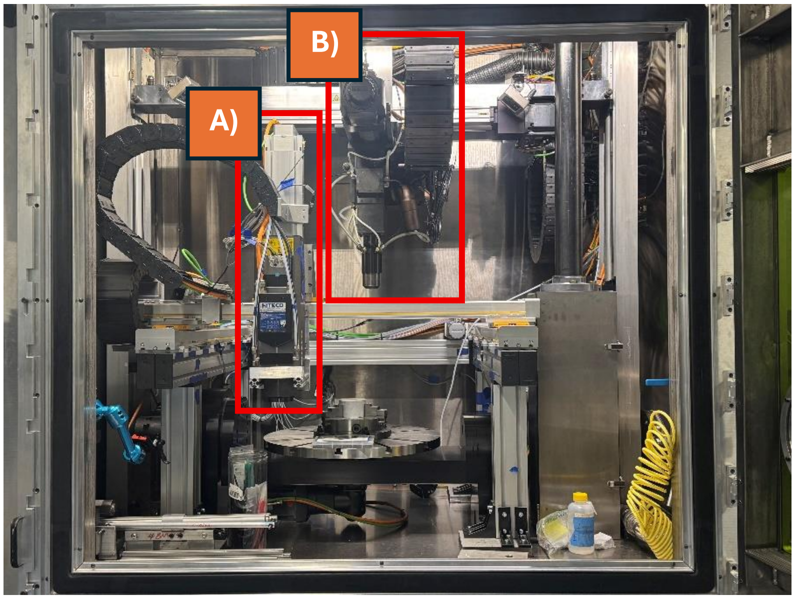

Figure 1: Subtractive gantry mounted on the additive machine a) indicates the subtractive gantry, while b) indicates the additive gantry

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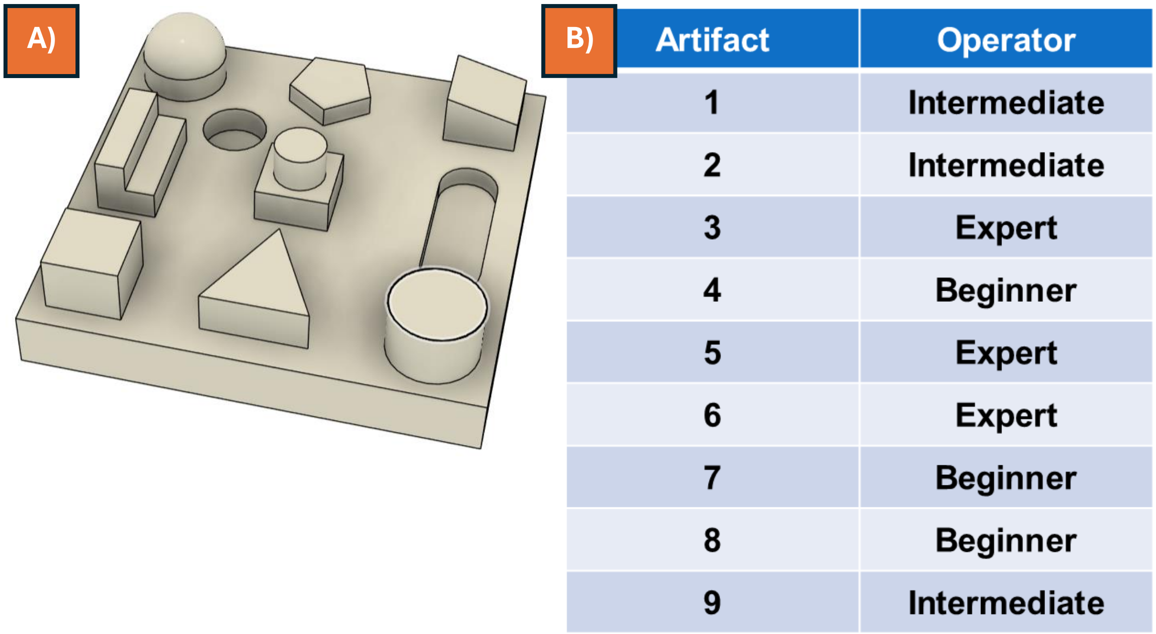
Methodology

This study employed a rigorous Gauge Repeatability and Reproducibility (GR&R) analysis to assess and quantify variability within our manufacturing and measurement processes [12], [13]. The primary goal was to determine how much variability different operators introduced and to validate the reliability of the measurement system. Three operators with varying experience levels participated in the study using a predesigned artifact (Figure 2a) that incorporated all critical features and dimensions essential to product quality [14]. Each operator machined the artifact three times, and the trial order was randomized to minimize bias (Figure 2b) [13].



Artifact	Operator
1	Intermediate
2	Intermediate
3	Expert
4	Beginner
5	Expert
6	Expert
7	Beginner
8	Beginner
9	Intermediate

Figure 2: a) GR&R artifact design, b) manufacturing operator sequence

Operators began by generating the G-code using a standardized postprocessor tool, since variability in toolpath selection or feed rate at this stage could propagate downstream [15]. The generated G-code was then uploaded to the CNC gantry, where machining was executed under a well-defined procedure; all machine setup parameters and any adjustments were meticulously documented [13]. After machining, parts were inspected using a high-precision optical, laser, and probe measurement system Keyence LM-X100TL; the LM-X had been calibrated prior to the study to ensure consistent measurement conditions [14] .

A comprehensive data collection protocol was implemented to ensure traceability. For each trial, part identifier, operator ID, trial number, and timestamp were recorded, along with all critical dimension measurements and any observational notes on machining or inspection deviations [12]. An ANOVA-based GR&R analysis then partitioned total process variability into repeatability (intra-operator) and reproducibility (inter-operator) components [13]. Measurement system performance was quantified such that a GR&R contribution below 10% was deemed excellent, between 10% and 30% acceptable, and above 30% unacceptable, requiring corrective action [15].

This methodological approach thoroughly evaluated both machining and measurement systems and yielded actionable insights for process optimization and quality assurance. The rigorous and transparent process ensured that final products consistently met defined quality standards [14].

Results & Discussion

The machine parts were cleaned and taken to the LM-X so the measuring sequence could be performed, then the data was collected, cleaned and stitched together. The ANOVA-based GR&R analysis was conducted using Minitab. As seen in Figure 3 each artifact had 9 geometries to measure with around 3 – 9 features or measurement items per geometry. Measurement items consisted of diameters, side measurements, heights and depths which made comparing the total measurements from artifact-to-artifact difficult. Instead, the GR&R percentage was determined on a geometry-to-geometry basis, considering the repeatability of the geometries. The GR&R percentage was then calculated to be 0.08% well below the 10% mark needed to deem the manufacturing operation as excellent (Table 1).

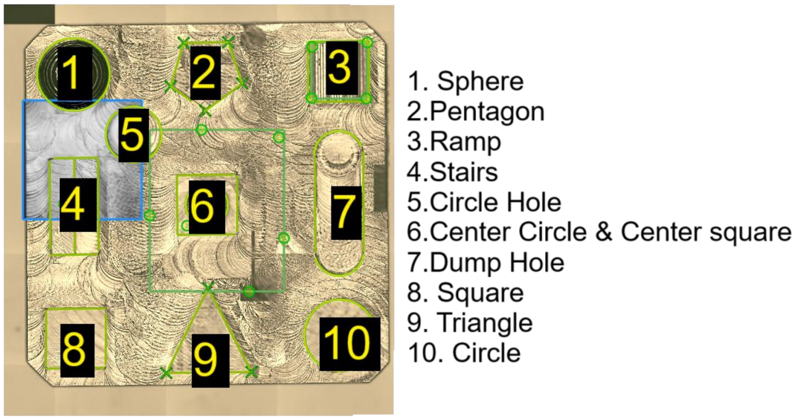
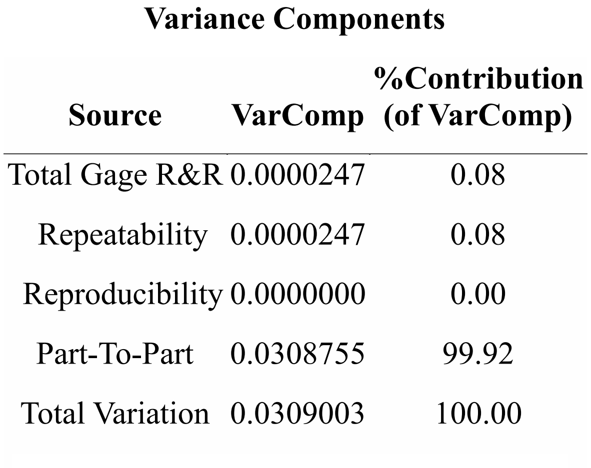


Figure 3: GR&R artifact with the geometries considered for the measurements



Variance Components

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0000247	0.08
Repeatability	0.0000247	0.08
Reproducibility	0.0000000	0.00
Part-To-Part	0.0308755	99.92
Total Variation	0.0309003	100.00

Table 1: Result of the GR&R study

Additionally, a one-way ANOVA was done for each of the nine geometries and their measurement items. This was done to assess the contribution of the user expertise on each of the relevant dimensions of the artifact. Essentially the null hypothesis H_0 states that all means are equal while H_1 indicated that all means are not equal. The significance level was $\alpha = 0.05$ from which all p values were above that ranging from 0.4 to 0.9, except the vertical sides of the center square (Figure 4) which had a p value of 0.011. Thus, the null hypothesis could not be rejected for most of the cases, validating the findings of the GR&R. This means that it cannot be said, statistically, that user expertise was the main source of variation for the machining process.

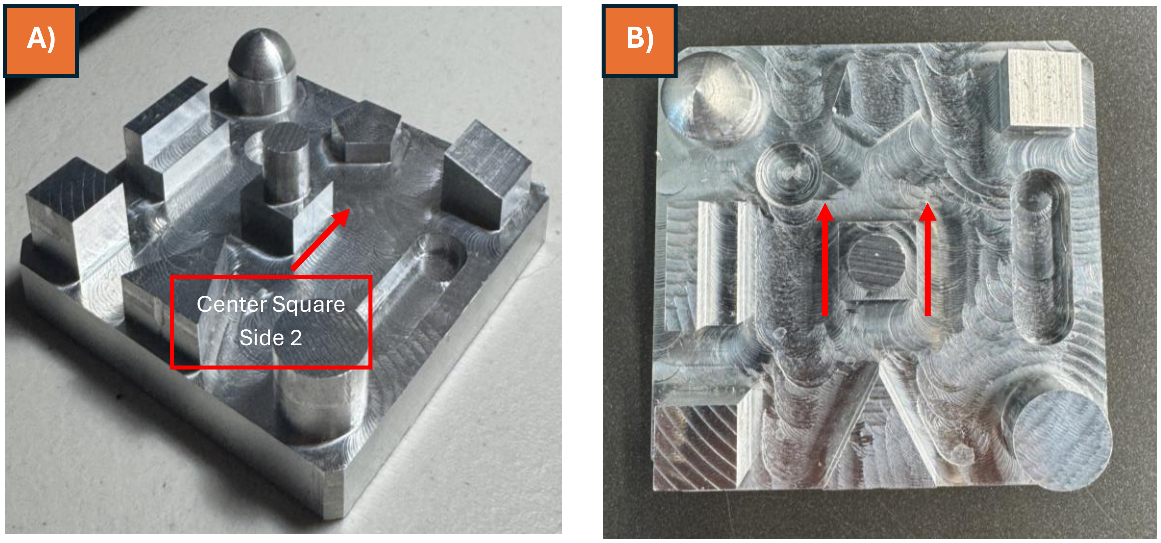


Figure 4: Artifact indicating the only measurement for which the null hypothesis was rejected a) isometric view and b) top-down view

Conclusion

There was variation across artifacts for which for most of the geometries the impact of the user cannot be statistically assured. This may be indication that the subtractive process of the system is sufficiently automated for the experience level of the operator to not be of sufficient impact to change the outcome of the operation. Since the objective of the complete system is the repair of components, achieving tolerance is of importance as criteria for the success of the system. The GR&R cannot ensure the ability for the system to achieve tolerance, but it can give assurance that the system is sufficiently reliable not to change with user expertise. Future studies need to explore other sources of variation to ensure the repeatability of the process. As part of future work to test both the additive and subtractive system in conjunction, a case study for the repair of a part and measure the extension of its life cycle and dimensions to ensure adequate tolerances must be done.

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