

Assessment of Guidelines for Conducting Round Robin Studies in Additive Manufacturing

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INTRODUCTION

There is strong demand in the additive manufacturing (AM) community for guidance in conducting round robin studies. This topic was one of the consensus-based priority action items identified in the Measurement Science Roadmap for Metals-Based Additive Manufacturing for accelerating widespread use of AM [1]. Further, ASTM International Committee F42 on Additive Manufacturing and the International Organization for Standardization (ISO) Technical Committee 261 on Additive Manufacturing identified in their Joint Plan for AM Standards Development the need for high-level round robin standards broadly impacting AM [2].

The desire for round robin studies likely stems from the need for qualification and certification of parts used in critical applications. Qualification and certification of aerospace metallic materials is well defined and very rigorous, often requiring thousands of tests, millions of dollars, and five to fifteen years to complete [3]. Many in the AM community see round robin testing as a way to distribute the burden of qualification by having multiple institutions contribute to the process. However, accomplishing this requires some guidance on conducting the round robin studies as well as an examination of round robin tests themselves.

EXISTING STANDARDS

Round robin, or interlaboratory, studies involve multiple institutions each performing a defined task following an established procedure, and returning the result of that task. This type of examination is very common in evaluating measurement methods. In fact, both ASTM and ISO have standards detailing how to conduct interlaboratory studies to evaluate measurement methods [4,5], as well as documents summarizing these standards [6, 7]. All of these documents emphasize that the purpose of the round robin study is to evaluate the “precision”

of the measurement method by calculating repeatability and reproducibility statistics.

The fact that a round robin study is primarily an investigation of reproducibility is important because many in the AM community may want round robins to provide more. A round robin study is not intended to investigate the sensitivity of an output with process variables; this is better accomplished in a factorial design of experiments or a ruggedness test [8]. A round robin study is not necessarily a method to collect part performance data for qualification and design allowables. The study must be completed and acceptable reproducibility demonstrated before anyone knows if the gathered data is appropriate for these purposes. Also, a round robin study is not intended as a benchmarking study to determine which machine or system performs best.

While most of the space in ASTM E691 and ISO 5725-2 is devoted to the statistics involved in evaluating the various measurement results, there is important guidance in each about how to conduct the round robin study. For example, both standards discuss the study membership (study coordinator, statistician, participants), the design of experiment, the preparation of materials, etc. The control in these experiments (i.e., what is sent to all the laboratories in the study) is always the material. The focus of the experiments (i.e., what is being evaluated) is the measurement method. The outcome of the each test (i.e., what is returned to the study coordinator) is the measurement result.

ANALOGY TO AM

It is possible to draw an analogy between round robin studies for evaluating measurement methods and round robin studies for AM. In an AM round robin, the control would be the design of the part to be built. The outcome would be the fabricated part. The focus of the experiment,

however, is not necessarily as clear. An initial inclination might be to say it is the AM process that is being investigated. However, there are many more variables involved in producing an AM part than only the AM process (e.g., properties of the raw input material), and it is certainly conceivable to conduct a round robin study where participating laboratories build parts with multiple AM processes. It is likely more accurate to say the focus of an AM round robin is to evaluate the manufacturing plan.

THE MANUFACTURING PLAN

The manufacturing plan is a set of instructions on how to build a part. ASTM standard specifications for AM materials require the need for a manufacturing plan and suggest that the plan include the machine(s) to be used, the properties of the raw material, pre-determined process parameters (i.e., machine settings), traceable digital files, process steps, post-processing procedures, and more [9]. However, there is still no definitive or minimum set of variables that should be specified in the manufacturing plan.

ASTM E691 states that a valid, well-written measurement method (the analog to a manufacturing plan) should exist prior to initiating the round robin study and that the measurement method should have been subjected to a ruggedness test. A ruggedness test is essentially a full factorial design of experiments investigating effects of various factors on the outcome [8]. The idea is that the ruggedness test would reveal what level of control should be placed on the individual variables. However, the number of factors or variables in a single AM process is extremely large and the types of processes are diverse. While there is certainly literature on the sensitivity of density, residual stress, mechanical properties, etc. to several process parameters, a complete test is impractical.

In the absence of a complete ruggedness test, manufacturing plans in AM round robin studies that NIST has participated in have either been extremely prescriptive or extremely unregulated. The more prescriptive manufacturing plans have had sections prescribing the part geometry and build orientation, machine requirements, raw material (including chemistry, particle size and distribution, recycling of powder, and powder handling), process setup and machine parameters (including recommended

calibrations, building platform requirements, beam settings and beam path strategies, and build chamber environment), in-process requirements and recording, process completion requirements, post-processing, and reporting. These studies not only specified the raw material required to build the parts, but also supplied the virgin powder to each participant. The more unregulated study asked participants to procure their own powder (stating only that the material should be appropriate for the participant's chosen system) and asked participants to develop their own machine parameter set. However, both manufacturing plans are perfectly acceptable and appropriate for round robin study. The more unregulated plans encompass many machines and machine types that have differing requirements and capabilities. The more prescriptive plans govern only one machine type. Unfortunately the results of these studies are not yet available.

Since the manufacturing plan will apply to all participants in the round robin study, the procedures and instructions must be applicable and accessible to each and every participant. Many users make tweaks and improvements to their systems and procedures that help make higher quality products more consistently. If other members of the participants list have not made those same tweaks and improvements, the results of the round robin will likely be skewed. Some users might see these tweaks and improvements as a competitive advantage and may not be willing to share them with the entire group. Others in the group may not be able to make the tweaks and improvements because of various system limitations. The consequence is that the common procedure followed by all participants will be dictated by the capabilities of the least flexible or experienced participant.

DIFFERENCES IN AM STUDIES

While there is a good analogy between round robins for measurement methods and for AM, there are some key differences due to the uniqueness of AM that warrant examination. One obvious difference is in the outcomes of the round robins. The statistics that characterize the measurement method are calculated directly from the measurement results returned from each laboratory. In AM, each participating laboratory returns the physical parts; further measurement must be performed before any statistics can be calculated (i.e., there is an

additional step). A difficulty with this is that there are a large number of measurements that can be performed on the returned parts, from dimensional measurement to mechanical testing to metallography, and more. As such, the results of one round robin with a scope limited to a small number of measurements cannot fully describe the “precision” of a manufacturing plan.

Post-processing presents an interesting challenge to characterizing additive manufacturing systems. Very few AM parts, especially metal parts, are used directly out of the machine. Most parts require post-processing, whether that be machining to achieve a certain geometric tolerance or surface roughness, or heat treatment to relieve residual stress and attain a desired mechanical strength. However, if the post-processing is part of the manufacturing plan and is conducted at (or by) each laboratory, then the round robin study encompasses more than just additive manufacturing. On the other hand, if parts are tested directly out of the machine, their performance data may not be truly indicative of parts used in actual applications. This latter case is problematic for qualification. A likely compromise is to have participants return parts right out of the machine and allow the study coordinator to arrange post processing of all parts by a reputable vendor.

The control in AM round robins (the design file) is also not as simple as one might originally think. Nearly all AM systems work with the stereolithography (.STL) file format, but these STL files are often generated from computer aided design (CAD) solid models. One should keep in mind that there may be some loss in fidelity when converting from the native CAD file to the STL file. This loss may be of high importance in a round robin examining the part geometry. Further, some AM systems require support structures. Whether the controlled design contains support structures or the process of placing support structures is specified, it is a necessary consideration when designing the round robin study. One should also keep in mind that removing the support structures may affect the final properties (especially geometry) of the part and will likely require specification within the manufacturing plan.

CONCLUSIONS

The uniqueness of AM makes it necessary to develop specific guidance on conducting round robin studies. The existing standards on round robin studies for measurement methods provide excellent starting points for guidance on conducting AM round robins. While differences will surely exist between AM round robins and round robins for measurement methods, the resulting information is likely to be similar. Specifically, the primary result of a round robin study is a measurement of repeatability and reproducibility. This is important for the AM community to keep in mind because by itself, guidance on conducting a round robin is not necessarily the same as ensuring good repeatability and reproducibility. Data showing excellent repeatability and reproducibility will be vital for process qualification. However, repeatability and reproducibility that are acceptable for qualification are likely the products of a rigorous manufacturing plan. Similarly to ASTM E691 recommending that the test method be completed by one laboratory before round robin testing [4], the development of a manufacturing plan should be completed before conducting the round robin and is likely better done within one institution. Without knowing which factors or variables most affect the performance properties of the final part, the results of the round robin studies are extremely specific. Tightening or loosening control of one variable, or changing the value of the variable, may significantly alter the results and therefore require a new round robin and complete re-qualification. Yet, a well-conducted round robin study, especially one focusing on part geometry, can go a long way toward demonstrating that AM parts can be built to meet a required tolerance.

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