NISTIR 8100

Supplementary information for an interlaboratory study of additively manufactured nickel alloy (IN625) tensile specimens

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National Institute of Standards and Technology
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Penny Pritzker, Secretary

National Institute of Standards and Technology
Willie May, Under Secretary of Commerce for Standards and Technology and Director

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1. INTRODUCTION

In fiscal year 2014, National Institute of Standards and Technology (NIST) conducted a round robin study to investigate the variation of mechanical properties of nickel alloy (IN 625) tensile specimens fabricated on six different laser-based powder bed fusion (LPBF) machines from the same machine vendor by six different institutions. The study results were summarized in a journal paper [1]. This report provides the supplementary information generated during planning and execution of the study. This supplementary information includes: (1) the manufacturing plan and blank process control document sent to the participants, (2) a description of the build programs sent to the participants, (3) engineering drawings with build instructions, (4) powder size distribution analysis of the powder sent to the participants, and (5) results obtained from a different LPBF machine. Copies of the process control documents received from the participants are provided in the Appendix.

During this study, the round robin coordinator identified a willing participant who had a LPBF machine from a different vendor. To obtain an additional data point for future comparative studies, this participant was invited to fabricate tensile specimens using the same powder and manufacturing plan with the process settings provided to the other participants. This participant was also sent the same individual tessellated and slice files to duplicate the process and fabricate the tensile bars. Upon receiving the build platform with the tensile specimens attached, NIST followed the same post processing procedures to heat treat them, extract the specimens, and prepare the specimens for the tension tests. This report[1] also provides a comparison of tension test results and fracture analysis

[1] Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

between the results obtained from the main group of participants and the participant with a different LPBF machine (section 6).

2. MANUFACTURING PLAN AND BLANK PROCESS CONTROL DOCUMENT SENT TO PARTICIPANTS

NIST sent the following manufacturing plan and blank Process Control Document (PCD) to each participant before fabricating the specimens. The manufacturing plan consists of a detailed list of steps for each participant to follow in order to fabricate the build. NIST requested that the participants track the machine parameters used for the build in the Process Control Document (PCD). Participants returned the completed process control document back to NIST.

Manufacturing Plan, NIST IN625 RR

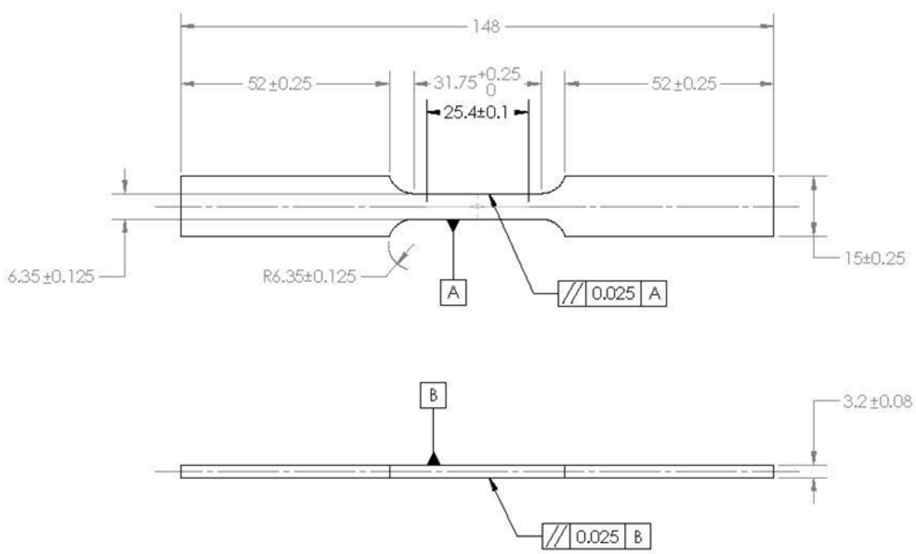
The Manufacturing Plan defines the requirements to complete the desired work that is agreed upon by the supplier and purchaser. The Process Control Document is a procedure to ensure the requirements of the Manufacturing Plan are met. Together, the Manufacturing Plan and PCD tightly control and fully document the fabrication of test coupons for generating material property data.

0. Scope and Purpose of Study
   Starting in May of 2014, NIST will conduct a round robin test to 1) further refine test protocols and analysis methods that will be used in future, more extensive round robin tests that will result in certification of AM materials, and 2) assess the variability in the tensile properties of additively made nickel alloy (Inconel 625) tension specimens from different institutions. The focus will be the Direct Metal Laser Sintering (DMLS) EOS M270/M280 process.

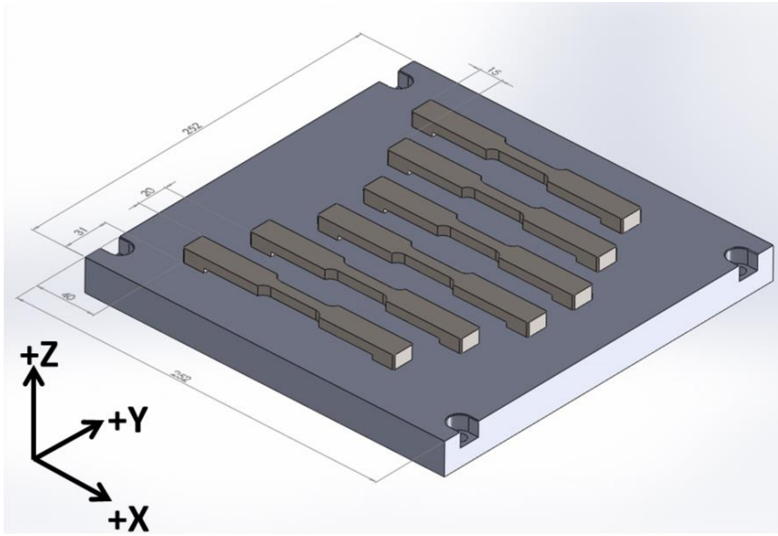
   NIST will distribute virgin nickel chrome (IN625) powder and build plates for the participants. Before distribution, NIST will sample the various powder lots for subsequent powder analysis. Each participant will follow a NIST-provided manufacturing plan to make one single build of eight (8) tensile bars, using a NIST-provided build file. (In the cases where the NIST-provided EOS job file is not compatible, NIST will provide the necessary information for the participant to construct the job file.) . Inability to comply with the manufacturing plan should be raised by the participant and approved by the study coordinator.

Each participant will send the tensile bars, still on the NIST-provided build plate, to NIST. NIST will coordinate the heat treatment, removal from the build plates, and testing the bars. NIST statistical experts will then perform the data analysis and make recommendations for test protocols and analysis methods for future round robins that lead to certification of AM materials. All results will be shared with the participants and may be published as well. The specific results from individual participants will not be publically attributed. All participants may keep any unused powder for their own future use.

1. Part Description
    1.1. Engineering Drawing (the final geometry of the tensile specimen conforms to ASTM E8/E8M [2], dimensions are in mm's) :



Please note – the following revised drawing sent to the participants by email within the build files reflects the actual build design in the study. The original image in the manufacturing plan was an earlier version of the build design which was modified slightly. Dimensions are in mm's.



1.2. STL file: to be sent by email from study coordinator
1.3. EOSJOB file: to be sent by email from study coordinator

2. Machine Requirements
    2.1. System
        2.1.1. Process: Laser Powder Bed Fusion
        2.1.2. Manufacturer: EOS
        2.1.3. Model: EOSINT M270
        2.1.4. Laser System: 200 W maximum power, 1060 nm - 1100 nm wavelength (preferred IPG YLR-SM-200)
    2.2. Software: EOS M270 Operating Software Version: PSW 3.5 rev 71 or newer preferred, not required.
    2.3. Maintenance: All maintenance of the system must be current and documented. Preventative maintenance must have been completed within 6 months of building the test specimens.
    2.4. System Calibrations: All system calibrations shall be current and documented. Some of these calibrations should be completed as part of regular preventative maintenance (e.g., laser power, skywriting, etc.). Others should be performed by the individual users (e.g., beam offset, x and y scaling).

3. Powder Requirements
    3.1. Powder shall be supplied to the participants by the study coordinator for use in this study. The subsections below document the powder as procured by the study coordinator. Samples have been extracted from each powder container for further evaluation.
    3.2. Chemistry (mass fraction):
        Ni (balance ≥ 58.00 wt - %)
        Cr (20.00 - 23.00 wt - %)

Mo (8.00 - 10.00 wt - %)
Nb (3.15 - 4.15 wt - %)
Fe (≤ 5.00 wt - %)
Ti (≤ 0.40 wt - %)
Al (≤ 0.40 wt - %)
Co (≤ 1.0 wt - %)
C (≤ 0.10 wt - %)
Ta (≤ 0.05 wt - %)
Si, Mn (each ≤ 0.50 wt - %)
P, S (each ≤ 0.015 wt - %)

3.3. Powder Size and Distribution: mean diameter = 37.8 µm ± 12.4 µm. D(0.7) = 40 µm.

3.4. Recycling of Powder: Only virgin (per ASTM 2924) powder may be used to produce the components.

4. Process Set-Up Requirements

4.1. Platform: Build platforms can be provided to participants upon request. If a participant would prefer to use their own build platform, it should conform to the specifications below. An individual participant's build plate will be returned upon completion of the study.

4.1.1. Material: Platform must be AISI 1045 steel.

4.1.2. Thickness: Platform must be 20 mm ± 2 mm thick.

4.1.3. Condition: Platform should be ground flat to a roughness of R_z = 10 µm or better. The platform demagnetized after grinding. The platform shall be thoroughly cleaned of machining lubricants prior to installation into the system. Once installed, the build platform surface shall be cleaned with alcohol using a lint free cloth and gloved hands.

4.1.4. Preheat: Platform shall be preheated to a temperature of 80 °C.

4.2. Recoater Blade: The blade shall be ceramic (EOS part HSS 2200-4073) and within the manufacturers specified useful lifetime and or original specification. The blade shall be maintained and cleaned according to manufacturer's guidelines.

4.3. Process Parameters: The study coordinator will provide, via email, an EOSJOB file with process parameters preset. Participants should check and document correct settings of all process parameters. All process parameters below are to be explicitly followed and reported. The process parameters are to be defined in the default job file and held constant throughout all builds unless otherwise agreed upon. Any changes in the default parameter set from build to build must be documented and carried forward in all reporting. All parameter sets are to be disclosed. Each job file will be saved and archived upon completion of the build for each and every build. All parameters that are unique to each system and that are not saved in the job file shall also be documented. A list of all process parameters shall be created and reported. The process parameter list shall include all key parameters, system settings and machine conditions including but not limited to:

4.3.1.Base Parameter Set: The EOS MP1 (Cobalt-Chrome) parameter set for an EOS M270 with 200W laser machine using the layer thickness in 4.3.2 shall be used.

4.3.2.Layer Thickness: 20 µm layers

4.3.3.Material Specific Settings

4.3.3.1. Material Dependent Scaling Factors (to be set at each machine for each machine). Scaling Factors may be determined from the EOS certification part and fine tuning spreadsheet

X	Y	Z(0)	Z(200)
TBD by participant	TBD by participant	TBD by participant	TBD by participant

4.3.3.2. Beam Offset (mm): May be determined from EOS certification part

4.3.3.3. Beam Expander Setting: 1

4.3.4.Adjust Tab

4.3.4.1. Groups: All individual parts shall be contained in their own group with the same exposure setting (4.3.5). The position and rotation of the group shall not be modified from 2.1.

4.3.4.2. Sorting: Sorting of parts by X/Y/Z by smallest point.

4.3.5. Exposure Parameters

4.3.5.1. Pre exposure type: PreContour

4.3.5.1.1. First Contour

	Standard	OnPart	Downskin
Speed (mm/s):	900.0	800.0	1600.0
Power (W):	100.0	100.0	100.0

Beam Offset (mm):	0.000		Contour	Yes (checked)
Thickness (mm):	0.040		Post Contour	No (unchecked)
Corridor (mm):	0.040			

4.3.5.1.2. Second Contour (Turned Off)

	Standard	OnPart	Downskin
Speed (mm/s):	-	-	-
Power (W):	-	-	-

Beam Offset (mm):	-		Contour	No (unchecked)
Thickness (mm):	-		Post Contour	No (unchecked)

Corridor (mm):	-			

4.3.5.1.3. Edges (Turned Off)

Edge factor	-		Edges	No (unchecked)
Threshold:	-		Post Edge	No (unchecked)
Minimum radius factor:	-			
Beam offset (mm):	-			
Speed (mm/s):	-			
Power (W):	-			

4.3.5.2. Skin exposure type: OuterSkin

4.3.5.2.1. Stripes

Distance (mm):	0.10		Stripe width (mm):	4.00
Speed (mm/s):	800.0		Stripes overlap (mm):	0.10
Power (W):	195.0		Skywriting:	Yes (checked)
Beam offset (mm)	0.030		Offset:	Yes (checked)
Hatching, X	Yes (checked)		Alternating:	Yes (checked)
Hatching, Y	Yes (checked)		Rotating:	Yes (checked)
			Rotated Angle	67°*

*may not be available for specification

4.3.5.2.2. UpDown

	Upskin	Downskin			
Distance (mm):	0.05	0.05		Overlap with inskin (mm):	0.10
Speed (mm/s):	800.0	3000.0		Min. length (mm):	2.00
Power (W):	195.0	195.0			
Thickness (mm):	0.00	0.04			
X:	Yes (checked)	Yes (checked)			
Y:	Yes (checked)	Yes (checked)			
Alternating	No (unchecked)	No (unchecked)		Skywriting	Yes (checked)

4.3.5.2.3. Skip layer

Skipped layers:	0
Offset layers:	0
Expose first layer:	Yes (checked)

4.3.5.3. Core exposure type: InnerSkin

4.3.5.3.1. Chess

	Squares	Gap			
Distance (mm):	0.10	0.10		Square width (mm):	8.00
Speed (mm/s):	800.0	800.0		Gap width (mm):	0.00
Power (W):	195.0	195.0		Overlap (mm):	0.08
Beam offset:	-0.050			Alternating:	Yes (checked)
Hatching:	X = Yes (checked)	Y = Yes (checked)		Rotated:	Yes (checked)
Skywriting:	No (unchecked)			Offset:	Yes (checked)

4.3.5.3.2. Skip layer

Skipped layers:	0
Offset layers:	0
Expose first layer:	Yes (checked)

4.3.5.4. Post exposure type: Postcontour

4.3.5.4.1. First Contour

	Standard	OnPart	Downskin
Speed (mm/s):	900.0	800.0	1600.0
Power (W):	120.0	120.0	120.0

Beam Offset (mm):	0.015		Contour	Yes (checked)
Thickness (mm):	0.040		Post Contour	Yes (checked)
Corridor (mm):	0.040			

4.3.5.4.2. Second Contour (Turned Off)

	Standard	OnPart	Downskin
Speed (mm/s):	-	-	-
Power (W):	-	-	-

Beam Offset (mm):	-		Contour	No (unchecked)
Thickness (mm):	-		Post Contour	No (unchecked)
Corridor (mm):	-			

4.3.5.4.3. Edges

Edge factor	2.00		Edges	Yes (checked)
Threshold:	3.0		Post Edge	Yes (checked)
Minimum radius factor:	0.00			
Beam offset (mm):	0.000			
Speed (mm/s):	900.0			
Power (W):	100.0			

4.3.5.5. Skin Thickness (x/y): 3.00 mm

4.3.5.6. Skin Thickness (z): 3.00 mm

4.3.5.7. Base radius: 0.00 mm

4.3.5.8. Core open to platform: No (unchecked)

4.3.5.9. Skin/Core: Yes (checked)

4.3.6.Setting

4.3.6.1. Part Specific Scaling: 0% in X and Y

4.3.6.2. Material Dependent Scaling 0% in X and Y

4.3.6.3. Part Specific Undersize/Oversize: 0 mm

4.3.7.Building

4.3.7.1. Start Height: 0.02mm

4.3.7.2. Final Height: *the height of the tallest part in 1.2* (4.18 mm)

4.3.7.3. Layer Thickness: See 4.3.2

4.3.8.DMLS

4.3.8.1. DMLS: DMLS shall be unchecked

4.3.8.2. Pre-exposure: Pre-exposure shall be set to 0.06 mm (3 layers).

4.3.9.Recoating.

4.3.9.1. Minimum charge amount: 150 %

4.3.9.2. Maximum charge amount: 200 %

4.3.9.3. Dosing boost amount: 300 %

4.3.9.4. Recoater speed 1: 500 mm/s

4.3.9.5. Recoater speed 2: 80 mm/s

4.3.9.6. Lower dispenser platform: 1.00 mm

4.3.9.7. Contact-free outward travel: yes (checked)

4.3.10. Scanner Settings

4.3.10.1. Automatic Calibration: Yes, every 2 layers

4.4. Build Chamber Environment

4.4.1. Purge Gas: For the purpose of this study, nitrogen will be used as the inert gas within the process chamber. Nitrogen 'sourced' from a nitrogen generator, bottle, or dewar is allowable. If the Nitrogen is from a bottle or dewar, user should report the nominal gas purity.

4.4.2. Flow Rates: Flow rates set within manufacturers' specification.

4.4.2.1. Flow Meters set on the front of the machine (5 meters)

4.4.2.2. Flow meter set (voltage) on the filtration unit

4.4.3. Filtration: Filtration must be enabled. Filter maintenance must be current per manufacturer guidelines

4.4.4. Oxygen Level: Oxygen level must be less than 1.3 % oxygen (15000 ppm) maximum.

4.5. Required Quality Control Checks at Build Start

The following Quality Control Checks are required to be performed sequentially before beginning the build.

4.5.1. System Maintenance and Cleaning: All system maintenance must be performed and the interior of the chamber, including optical components, powder hoppers, recoater blade, shall be cleaned per manufacturer guidelines.

4.5.2. Laser Power: The laser power shall be measured (if possible) using a laser power meter within calibration at all power levels prescribed in 4.3 and fall within 10 % of the prescribed value. Each measurement is to be reported as setpoint, displayed and measured value. If any value is outside the prescribed value, the individual measurement shall be repeated and if the average of 3 measurements exceeds the power range, corrective action should be taken which includes laser maintenance and adjusting the setpoint value to achieve the desired delivered laser power.

4.5.3. Installation of Platform: Platform may be installed after completion requirements in 4.5.1 and 4.5.2. The build platform shall be parallel to the recoating blade and recoating arm motion to within 50 µm. Preferred method of levelling to recoating blade uses feeler gage/ shims between build platform and recoating blade. Preferred method of levelling to recoating arm motion uses dial indicator mounted to recoating arm. After installation and levelling of the platform, it shall be cleaned in a manner described in 4.1.3.

4.5.4. Powder Loading: New powder, directly from containers, must be loaded into the dispenser per manufacturer guidelines (sieving not necessary). Sufficient quantities shall be loaded to achieve a complete build without the need to refill. Any devices used to stab, pack or tamp the powder must be stainless steel and cleaned using acetone and wiped with a lint free cloth prior to inserting into the powder.

4.5.5. First layer: Once the build platform is leveled and the powder is loaded, railed, packed and smoothed, the first layer shall be created. The recoating arm should be past the dispenser platform. The build platform should be brought up to the level of the recoating blade, then lowered by the distance equal to one layer thickness. The dispenser platform shall be raised to a height to expose enough powder to deposit one layer as well as fill any gaps, holes, crevices, etc. between the dispenser platform and the collector bin. The recoating arm shall then be moved across the dispenser platform and build platform (to the home position) at the speed described in 4.3.9.5.

4.5.6. Platform Temperature: The platform temperature must be within 5 °C of the value prescribed in 4.1.4. Record the platform temperature at the start of the build.

4.5.7. Oxygen Level: The oxygen level must be less than the level prescribed in 4.4.4. Record the oxygen level at the start of the build process.

5. In Process Requirements

5.1. Limits

5.1.1. Environment: If during processing the oxygen level in the build chamber exceeds the level prescribed in 4.4.4, the build shall be stopped.

5.2. Build Pause/Interruption

5.2.1. No planned interruption of the build is required.

5.2.2. Any interruption to the continuous build cycle must be recorded with a description of the reason for the interruption and corrective action.

5.2.3. Prior to opening the build chamber, the oxygen level and platform temperature must be recorded.

5.2.4. Upon continuation of the build, the requirements of 4.5.6 and 4.5.7 must be met and preferably be within 10 % of the values recorded in 5.2.3.

6. Process Completion Requirements

6.1. Removal from System

6.1.1. The build shall be allowed to cool inside the build chamber submerged in powder under protective environment until the temperature drops below 30 °C.

6.1.2. The temperature and oxygen level shall be recorded prior to opening the build chamber.

6.1.3. The build and platform shall be removed from the chamber and cleaned of loose powder using a non-metallic brush.

6.1.4. The build and platform may be further cleaned by using a metallic brush or other means to remove partially sintered powder particles.

6.1.5. Laser Power: The laser power shall be measured (if possible) using a laser power meter within calibration at all power levels prescribed in 4.3. Each measurement is to be reported as setpoint, displayed and measured value.

6.1.6. Cleaning: The system may be cleaned at this point following manufacturer guidelines.

6.2. Powder Recovery

6.2.1. Excess, loose powder removed from the build platform through the completion of 6.1.3 shall be collected and stored in appropriately marked containers indicating that it is USED.

6.2.2. Any partially sintered material is not allowable for reuse and should be disposed of properly.

6.2.3. Participants may keep any unused powder for their own use.

7. Post Process Requirements
    7.1. Heat treat
    7.2. Machine samples
        7.2.1. Mill top surface
        7.2.2. Remove samples by electric discharge machining (EDM)
        7.2.3. EDM gage section
        7.2.4. Grind remaining surfaces

8. Reporting
    8.1. Part Technical Data
    8.2. Machine Technical Data
    8.3. Powder Technical Data
    8.4. Process Setup Technical Data
    8.5. In Process Technical Data
    8.6. Process Completion Technical Data
    8.7. Post Process Technical Data
    8.8. Testing Technical Data

Process Control Document

Technical Data *(section numbers refer to Manufacturing Plan)*

Part Manufacturing Technical Data

Completed by the part manufacturer

	Value	**Requirement Section**	**Approval**
Job Number			
Build File Name:		1.2	
Process		2.1.1	
Equipment Manufacturer and Model:		2.1.2	
Equipment Serial Number:			
Laser Manufacturer and Model:		2.1.4	
Laser Serial Number:			
Software Version:		2.2	

Date of last preventative maintenance		2.3	
System Calibration Current		2.4	
Material Requirements			
Verify Powder Heat/Lot Loaded Matches Feedstock Technical Data			
Material Condition (Virgin/Recycled)		3.4	
Process Setup Requirements			
Build Platform Material		4.1.1	
Build Platform Thickness		4.1.2	
Build Platform Condition		4.1.3	
Build Platform Preheat, °C		4.1.4	
Recoater Blade Material/Part Number		4.2	
Process Parameter Settings			
Base Parameter Set		4.3.1	
Base Parameter Filename			
Layer Thickness, µm		4.3.2	
Sort Parts Method:		4.3.4.2	
Exposure Parameters	Complete Exposure Parameters Table Below	4.3.5	
Pre Contour Type		4.3.5.1	
Skin Exposure Type		4.3.5.2	
Core Exposure Type		4.3.5.3	
Post Contour Type		4.3.5.4	
Skin Thickness (x/y), mm		4.3.5.5	
Skin Thickness (z), mm		4.3.5.6	
Base Radius:		4.3.5.7	
Core open to platform?:		4.3.5.8	
Skin/Core:		4.3.5.9	
Scaling and Offset			

Material Specific Scaling	X, %					Y, %
Part Specific Undersize/Oversize Beam Offset, mm		4.3.6.3			4.3.6.1	
					4.3.6.2	
Building Screen						
Start Height (mm):					4.3.7.1	
Final Height (mm):					4.3.7.2	
Layer Thickness					4.3.2	
DMLS Settings						
DMLS	Off					Range, (mm)
Pre-exposure	On					Range, (mm)
					4.3.8.1	
					4.3.8.2	
Recoating Screen						
Minimum Charge, %						
Maximum Charge, %						
Dosing Boost, %						
Recoating Speeds (mm/s)	Recoating Speed 1				Recoating Speed 2	4.3.9.4, 4.3.9.5
Dosing Boost, %						
Lower Dispenser Platform			4.3.9.6			
Contact-free outward travel			4.3.9.7			
Build Time Estimation						
Build Chamber Environment					4.4	
Purge Gas Used					4.4.1	
Purge Gas Source					4.4.1	
Flow Rates					4.4.2	
Filtration					4.4.3	
Oxygen Set Point					4.4.4	
Quality Control Checks at Build Start						
System Maintenance and Cleaning Performed					4.5.1	
Pre Build Laser Power Measurement	Setpoint				Display	Measured
Pre Contour						
Stripes					4.5.2	
Up Skin						

Down Skin					
Post Contour					
Edges					
Build Platform Leveling Complete		4.5.3			
Platform Temperature				4.5.6	
Platform Level					
Oxygen Level				4.5.7	
In Process Requirements					
Limits	Max Limit			Min Limit	Max Measured
Build Start Time					
Build Interruptions (If Yes, Attach Documentation per 5.2)				5.2	
Process Completion					
Platform Temperature at Time of Chamber Opening				6.1.1,6.1.2	
Chamber Oxygen Prior to Opening				6.1.2	
Recovered Powder Labeling				6.2	
Post Build Laser Power Measurement	Setpoint			Display	Measured
Pre Contour					
Stripes				6.1.5	
Up Skin					
Down Skin					
Post Contour					
Edges					

Exposure Parameters

Completed by the part manufacturer

	Value	**Requirement Section**	**Approval**

Job Number						
Build File Name:						
Pre Exposure						
Pre Exposure Type					4.3.5.1	
First Contour		Standard	OnPart	Downskin	4.3.5.1.1	
	Speed (mm/s):					
	Power (W):					
	Beam Offset (mm):		Contour			
	Thickness (mm):		Post Contour			
	Corridor (mm):					
Second Contour		Standard	OnPart	Downskin	4.3.5.1.2	
	Speed (mm/s):					
	Power (W):					
	Beam Offset (mm):		Contour			
	Thickness (mm):		Post Contour			
	Corridor (mm):					
Edges	Edge factor		Edges		4.3.5.1.3	
	Threshold:		Post Edge			
	Minimum radius factor:					
	Beam offset (mm):					
	Speed (mm/s):					
	Power (W):					
Skin Exposure						
Skin Exposure Type					4.3.5.2	
Stripes	Distance (mm):		Stripe width (mm):		4.3.5.2.1	

	Speed (mm/s):		Stripes overlap (mm):			
	Power (W):		Skywriting:			
	Beam offset (mm)		Offset:			
	Hatching, X		Alternating:			
	Hatching, Y		Rotating:			
UpDown		Upskin	Downskin		4.3.5.2.2	
	Distance (mm):					
	Speed (mm):					
	Power (W):					
	Thickness (mm):					
	X:					
	Y:					
	Alternating:		Overlap with inskin(mm):			
	Skywriting:		Min. length (mm)			
Skip Layer	Skipped Layers				4.3.5.2.3	
	Offset layers:					
	Expose first layer:					
Core Exposure						
Core Exposure Type					4.3.5.3	
Chess		Squares	Gap			
	Distance (mm):					
	Speed (mm/s):					
	Power (W):					
	Width (mm):					
	Beam offset (mm)		Overlap:			
	Hatching, X:		Alternating:			

	Hatching, Y:		Rotating:			
	Skywriting:		Rotated Angle:			
	Offset:					
Post Exposure						
Post Exposure Type					4.3.5.4	
First Contour		Standard	OnPart	Downskin	4.3.5.4.1	
	Speed (mm/s):					
	Power (W):					
	Beam Offset (mm):		Contour			
	Thickness (mm):		Post Contour			
	Corridor (mm):					
Second Contour		Standard	OnPart	Downskin	4.3.5.4.2	
	Speed (mm/s):					
	Power (W):					
	Beam Offset (mm):		Contour			
	Thickness (mm):		Post Contour			
	Corridor (mm):					
Edges	Edge factor		Edges		4.3.5.4.3	
	Threshold:		Post Edge			
	Minimum radius factor:					
	Beam offset (mm):					
	Speed (mm/s):					
	Power (W):					

3. BUILD FILES SENT TO THE PARTICIPANTS

Figure 1 shows a block diagram of the process of developing build files from the initial computer solid models using various software modules. NIST sent the computer files to all the participants.

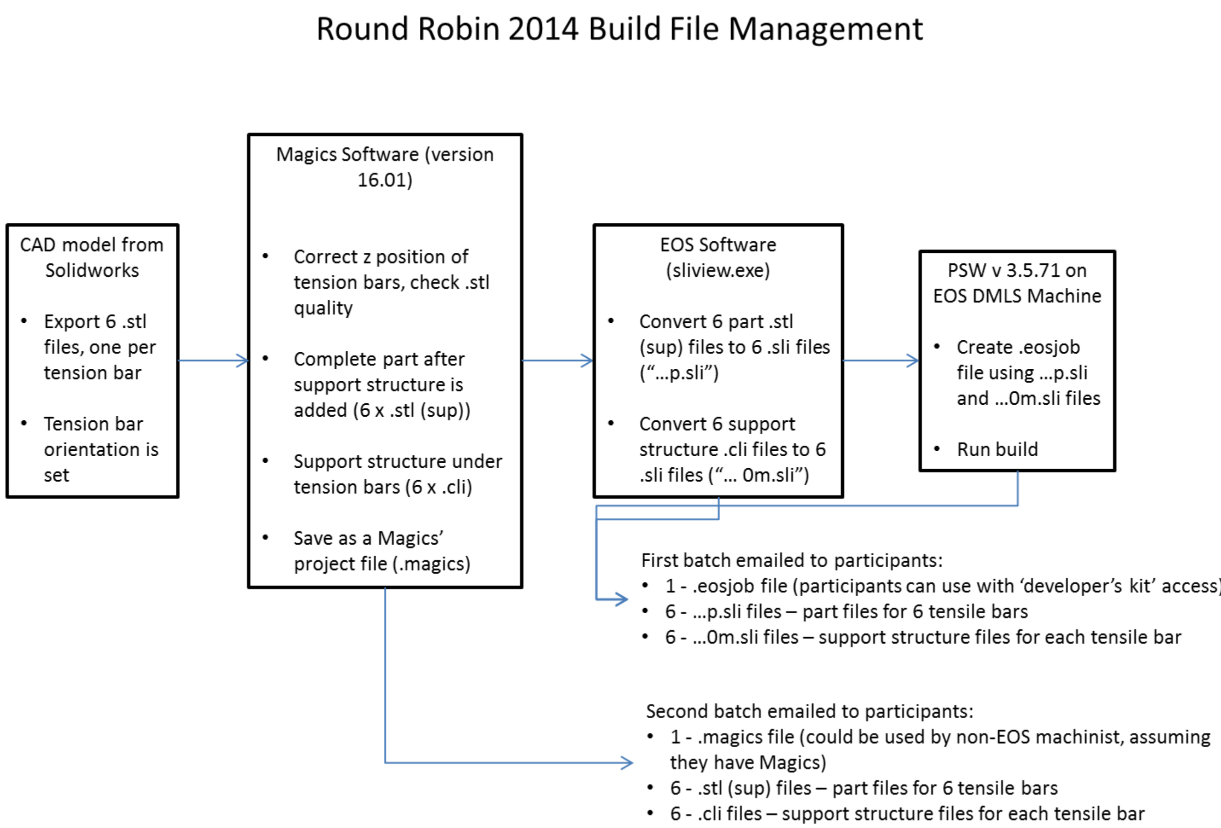


Figure 1. Block diagram of the process of developing the build files.

Material setting: "MP1_020_100_Surface" (default)

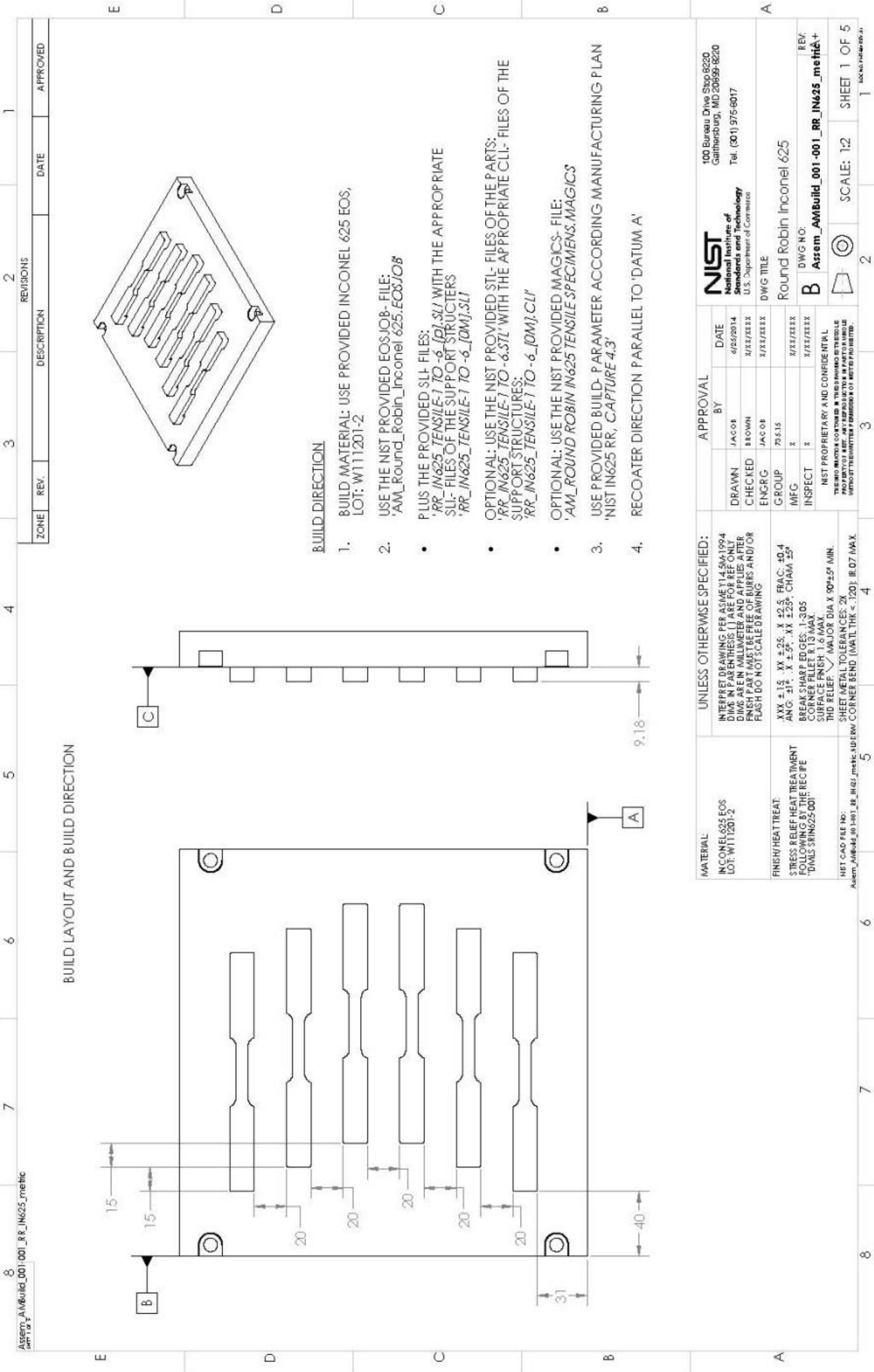
NIST generated the following build files and distributed them to the participants:

- Six STL files, named: "RR_IN625_tensile_x.stl" where x = 1 to 6 for each of the 6 tensile bars
- Six CLI support structure related files, named: RR_IN625_tensile_x_0m. cli where x = 1 to 6
- One Magics file, named: "AM_Round Robin IN625_tensile specimens.magics"
- six part related slice files named: "RR_IN625_tensile_x_p.sli" where x = 1 to 6

- six support structure related slice files named: "RR_IN625_tensile_x_0m.sli" where x = 1 to 6 for each of the 6 tensile bars
- One EOS build file, named: "AM_Round Robin_Inconel 625.eosjob"

4. ENGINEERING DRAWINGS WITH BUILD INSTRUCTIONS SENT TO PARTICIPANTS

Engineering drawings of the build with post processing directions.



Assem_AMBuild_001-001_RR_IN625_metric

POST PROCESS DIRECTIONS (A)

1. DRY RUN BUILD: REMOVE ONE TEST CUBE

- REMOVE ONE OF THE TEST CUBES FROM THE BUILD PLATE BY USING A HEXSAW AND KEEP IT AS A WITHNESS PIECE FOR THE 'AS MANUFACTURE' CONDITION OF THE MATERIAL

2. ALL BUILDS: STRESS RELIEF HEAT TREATMENT

- ACCORDING TO THE TEMPERATURE-TIME- RECIPE "DMLS SRIN625-001" FOR IN625

3. DRY RUN BUILD: REMOVE ONE TEST CUBE

- REMOVE THE LAST REMAINING TEST CUBES FROM THE BUILD PLATE BY USING A HEXSAW AND KEEP IT AS A WITHNESS PIECE FOR THE 'HEAT TREATED' CONDITION OF THE MATERIAL

4. ALL BUILDS: REMOVE AND TENSILE TEST SPECIMENS

- SEE DRAWING "..." AND COMPARE THIS WITH THE ACTUAL CONDITIONS OF THE SPECIMENS AND WITH THE BUILD PLATE. IF THE PARTS AND THE BUILD PLATE ARE IN APPROPRIATE SHAPE, THEN PLEASE CONTINUE WITH THE FOLLOWING STEPS:

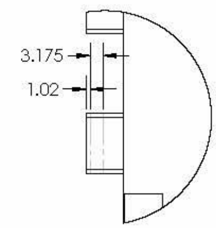
OPTION A: WIRE- EDM AND GRINDING COMBINED

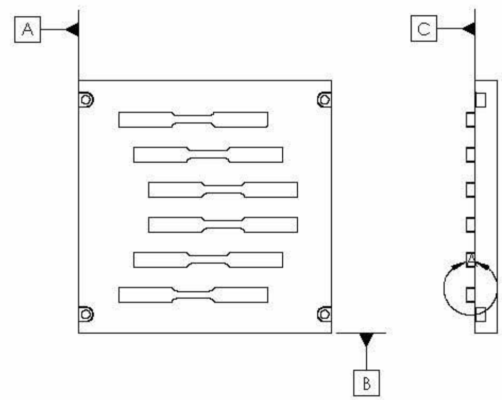
- 1'ST BURN CUT SHOULD BE 0.5MM FROM THE UPPER SIDE OF THE TENSILE SPECIMENS TO REMOVE THE UPPER MATERIAL OFFSET
- 2'ND BURN CUT SHOULD BE 6.35MM FROM THE UPPER SIDE (AFTER THE 1'ST CUT) OF THE TENSILE SPECIMENS TO REMOVE THESE FROM THE BUILD PLATE
- 3'RD + X BURN CUTS TO SKIM THE SPECIMENS ON BOTH SIDES TO ACHIEVE THE REQUIREMENTS ON THICKNESS, FLATNESS, AND PARALLELISM ACCORDING TO THE DRAWING "AMEDM_E8_025x0125X1". LET THE SPECIMENS APPROXIMATELY 0.01" OVERSIZED ON EACH SIDE FOR THE FINAL GRINDING STEP.
- 4'TH BURN CUT SHOULD BE ON BOTH REDUCED SIDES AT THE GAUGE SECTION TO ACHIEVE THE REQUIREMENTS ON WIDTH, STRAIGTHNESS, AND PARALLELISM ACCORDING TO THE DRAWING "AMEDM_E8_025x0125X1"
- GRIND THE SPECIMENS DOWN TO THE REQUIERED THICKNESS. (SEE DRAWING: "AMEDM_E8_025X0125X1")

5. FINISHING OF THE BUILD PLATE

- MILLING OR GRINDING OFF THE REMAIN DEBRIS FROM THE BUILD PLATE

DETAIL A
SCALE 1 : 1





MATERIAL:
INCONEL 625 EOS
LOT: W111201-2

FINISH/HEAT TREAT:
stress relief heat treated parts and build plate combined according to the recipe: DMLS SRIN625-001

NIST CAD FILE NO:
Assem_AMBuild_001-001_RR_IN625_metric.SLDDRW

UNLESS OTHERWISE SPECIFIED:
INTERPRET DRAWING PER ASME Y14.5M-1994
DIMS IN PARENTHESIS ( ) ARE FOR REF ONLY
DIMS ARE IN MILLIMETER AND APPLIES AFTER FINISH
PART MUST BE FREE OF BURRS AND/OR FLASH
DO NOT SCALE DRAWING

.XXX ±.125; .XX ±.25; .X ±2.5; FRAC: ±1/64
ANG: ±1°; .X ±.5°; .XX ±.25°; CHAM ±5°

BREAK SHARP EDGES: .004-.012
CORNER FILLET: R.125 MAX.
SURFACE FINISH: 1.6 MAX.
THD RELIEF: ✓ MAJOR DIA X 90°±5° MIN.
SHEET METAL TOLERANCES: 2X
CORNER BEND (MATL THK < .120): R.07 MAX.

APPROVAL	BY	DATE
DRAWN	JACOB	11/04/2014
CHECKED	BROWN / FALVEY	X/XX/XXXX
ENGRG	JACOB	X/XX/XXXX
GROUP	735.15	
MFG	X	X/XX/XXXX
INSPECT	X	X/XX/XXXX

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DWG TITLE
Round Robin Income 625

B Assem_AMBuild_001-001_RR_IN625_metric REV: A+

SCALE: 1:4 SHEET 2 OF 5

Assem_AMBuild_001-001_RR_IN625_metric

POST PROCESS DIRECTIONS (B)

1. DRY RUN BUILD: REMOVE ONE TEST CUBE
- REMOVE ONE OF THE TEST CUBES FROM THE BUILD PLATE BY USING A HEXSAW AND KEEP IT AS A WITHNESS PIECE FOR THE 'AS MANUFACTURE' CONDITION OF THE MATERIAL

2. ALL BUILDS: STRESS RELIEF HEAT TREATMENT
- ACCORDING TO THE TEMPERATURE-TIME- RECIPE "DMLS SRIN625-001" FOR IN625

3. DRY RUN BUILD: REMOVE ONE TEST CUBE
- REMOVE THE LAST REMAINING TEST CUBES FROM THE BUILD PLATE BY USING A HEXSAW AND KEEP IT AS A WITHNESS PIECE FOR THE 'HEAT TREATED' CONDITION OF THE MATERIAL

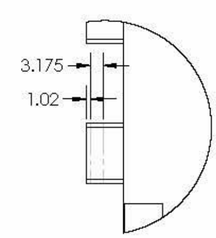
4. ALL BUILDS: REMOVE AND TENSILE TEST SPECIMENS
- SEE DRAWING "..." AND COMPARE THIS WITH THE ACTUAL CONDITIONS OF THE SPECIMENS AND WITH THE BUILD PLATE. IF THE PARTS AND THE BUILD PLATE ARE IN APPROPRIATE SHAPE, THEN PLEASE CONTINUE WITH THE FOLLOWING STEPS:

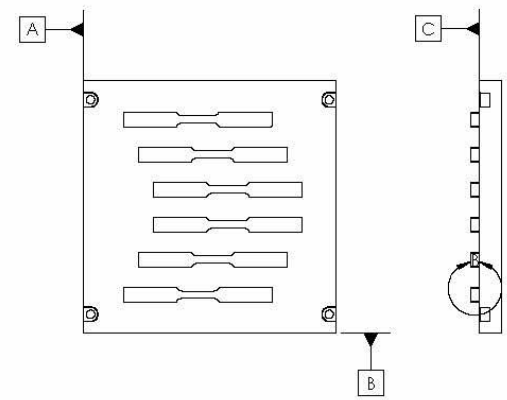
OPTION B: WIRE- EDM

- 1'ST BURN CUT SHOULD BE 0.5MM FROM THE UPPER SIDE OF THE TENSILE SPECIMENS TO REMOVE THE UPPER MATERIAL OFFSET
- 2'ND BURN CUT SHOULD BE 6.35MM FROM THE UPPER SIDE (AFTER THE 1'ST CUT) OF THE TENSILE SPECIMENS TO REMOVE THESE FROM THE BUILD PLATE
- 3'RD + X BURN CUTS TO SKIM THE SPECIMENS ON BOTH SIDES TO ACHIEVE THE REQUIREMENTS ON THICKNESS, FLATNESS, AND PARALLELISM ACCORDING TO THE DRAWING "AMEDM_E8_025x0125X1". LET THE SPECIMENS APPROXIMATELY 0.01" OVERSIZED ON EACH SIDE FOR THE NEXT PRECISE CUT.
- 4'TH + X BURN CUTS JUST ALONG THE GAUGE SECTION PLUS 5 MM ON EACH GRIP SIDE TO ACHIEVE THE REQUIREMENTS ON ROUGHNESS, THICKNESS, FLATNESS, AND PARALLELISM ACCORDING TO THE DRAWING "AMEDM_E8_025x0125X1"
- 5'TH BURN CUT SHOULD BE ON BOTH REDUCED SIDES AT THE GAUGE SECTION TO ACHIEVE THE REQUIREMENTS ON WIDTH, STRAIGHTNESS, AND PARALLELISM ACCORDING TO THE DRAWING "AMEDM_E8_025x0125X1"

5. FINISHING OF THE BUILD PLATE
- MILLING OR GRINDING OFF THE REMAIN DEBRIS FROM THE BUILD PLATE

DETAIL B
SCALE 1 : 1





MATERIAL: INCONEL 625 EOS LOT W111201-2	UNLESS OTHERWISE SPECIFIED: INTERPRET DRAWING PER ASME Y14.5M-1994; DIMS IN PARENTHESIS ( ) ARE FOR REF ONLY; DIMS ARE IN MILLIMETER AND APPLIES AFTER FINISH; PART MUST BE FREE OF BURRS AND/OR FLASH; DO NOT SCALE DRAWING	APPROVAL	BY	DATE
		DRAWN	JACOB	11/04/2014
		CHECKED	BROWN / FALVEY	X/XX/XXXX
		ENGRG	JACOB	X/XX/XXXX
FINISH/HEAT TREAT: stress relief heat treated parts and build plate combined according to the recipe: DMLS SRIN625-001	.XXX ±.125; .XX ±.25; .X ±2.5; FRAC: ±1/64; ANG: ±1°; .X ±.5°; .XX ±.25°; CHAM ±5°; BREAK SHARP EDGES: .1-.25; CORNER FILLET: R.255 MAX.; SURFACE FINISH: 1.6 MAX.; THD RELIEF: MAJOR DIA X 90°±5° MIN.	GROUP	735.15	
		MFG	X	X/XX/XXXX
		INSPECT	X	X/XX/XXXX
NIST CAD FILE No: Assem_AMBuild_001-001_RR_IN625_metric.SLDDRW	SHEET METAL TOLERANCES: 2X; CORNER BEND (MATL THK < .120): IR.07 MAX.	NIST PROPRIETARY AND CONFIDENTIAL		

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DWG TITLE: Round Robin Incone 625

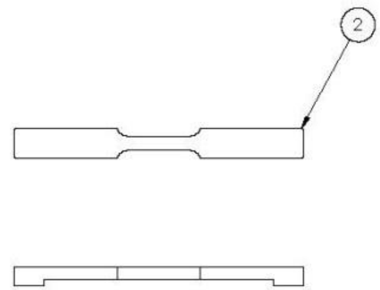
B | Assem_AMBuild_001-001_RR_IN625_metric | REV: A+

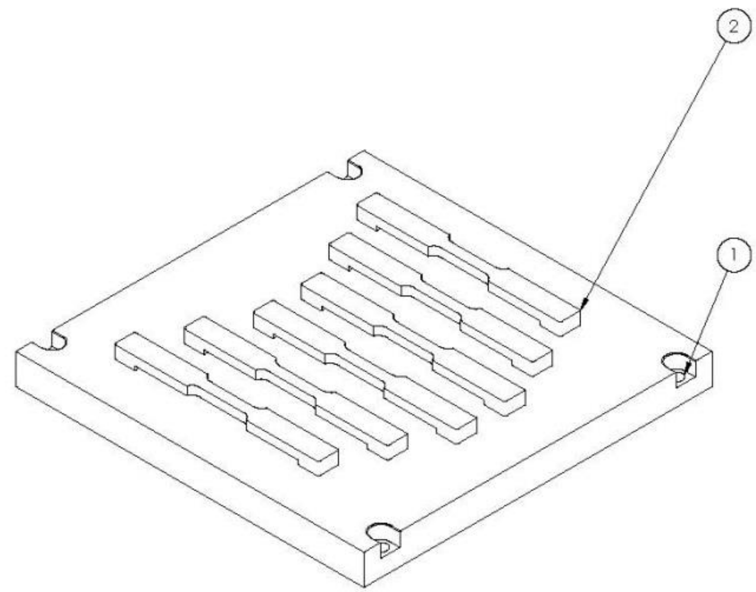
SCALE: 1:4 | SHEET 3 OF 5

Assem_AMBuild_001-001_RR_IN625_metric

BILL OF MATERIALS

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Build_Plate_noEDM-Holes_2014	PLATE, EOS BUILD WITH HOLES	1
2	AMBUILD_I_001-001	tensile samples: netshape	6
3	Part1^Assem_AMBuild_001-001_RR_IN625		1
4	AMBuild_cylinder_10		10





MATERIAL:
INCONEL625 EOS
LOT: W111201-2

FINISH/HEAT TREAT:
stress relief heat treated parts and build plate combined according to the recipe: DMLS SR IN625-001

NIST CAD FILE No:
Assem_AMBuild_001-001_RR_IN625_metric.SLDDRW

UNLESS OTHERWISE SPECIFIED:
INTERPRET DRAWING PER ASME Y14.5M-1994
DIMS IN PARENTHESIS ( ) ARE FOR REF ONLY
DIMS ARE IN MILLIMETER AND APPLIES AFTER FINISH
PART MUST BE FREE OF BURRS AND/OR FLASH
DO NOT SCALE DRAWING
.XXX ±.15 .XX ±.25; .X ±2.5; FRAC: ±0.4
ANG: ±1°; .X ±.5°; .XX ±.25°; CHAM ±5°
BREAK SHARP EDGES: .1-3.05
CORNER FILLET: R.13 MAX.
SURFACE FINISH: 1.6 MAX.
THD RELIEF: MAJOR DIA X 90°±5° MIN.
SHEET METAL TOLERANCES: 2X
CORNER BEND (MATL THK < .120): IR.07 MAX.

APPROVAL	BY	DATE
DRAWN	JACOB	6/27/2014
CHECKED	BROWN	X/XX/XXXX
ENGRG	X	X/XX/XXXX
GROUP	735.15	
MFG	X	X/XX/XXXX
INSPECT	X	X/XX/XXXX

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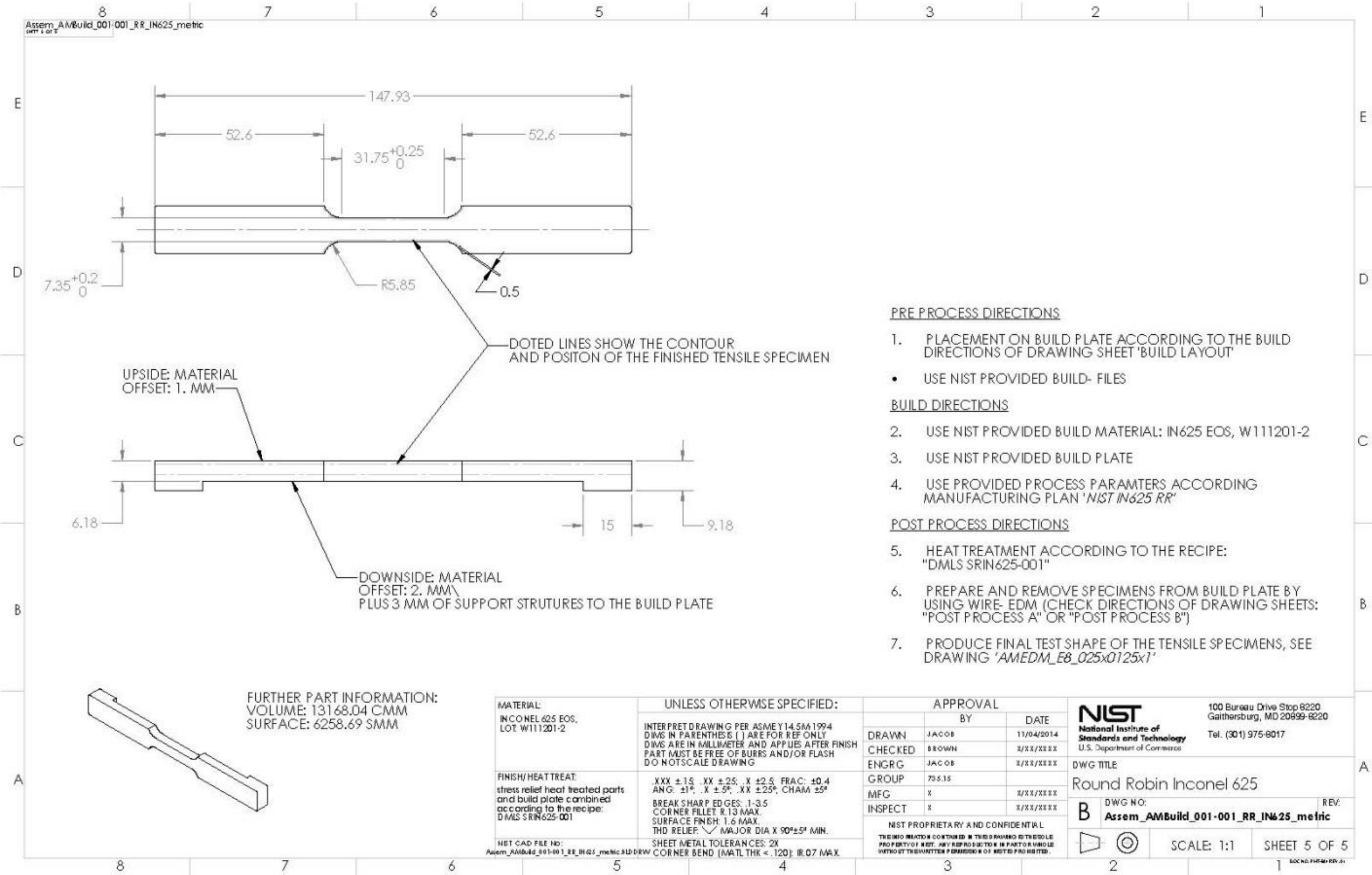
DWG TITLE:
Round Robin Inconel 625

B DWG NO: Assem_AMBuild_001-001_RR_IN625_metric REV:

SCALE: 1:4 SHEET 4 OF 5



Assem_AMBuild_001-001_RR_IN625_metric
147.93
52.6
31.75 +0.25 0
52.6
7.35 +0.2 0
R5.85
0.5
DOTED LINES SHOW THE CONTOUR
AND POSITON OF THE FINISHED TENSILE SPECIMEN
UPSIDE: MATERIAL
OFFSET: 1. MM
6.18
15
9.18
DOWNSIDE: MATERIAL
OFFSET: 2. MM\
PLUS 3 MM OF SUPPORT STRUTURES TO THE BUILD PLATE
FURTHER PART INFORMATION:
VOLUME: 13168.04 CMM
SURFACE: 6258.69 SMM
PRE PROCESS DIRECTIONS
1. PLACEMENT ON BUILD PLATE ACCORDING TO THE BUILD DIRECTIONS OF DRAWING SHEET 'BUILD LAYOUT'
• USE NIST PROVIDED BUILD- FILES
BUILD DIRECTIONS
2. USE NIST PROVIDED BUILD MATERIAL: IN625 EOS, W111201-2
3. USE NIST PROVIDED BUILD PLATE
4. USE PROVIDED PROCESS PARAMTERS ACCORDING MANUFACTURING PLAN 'NIST IN625 RR'
POST PROCESS DIRECTIONS
5. HEAT TREATMENT ACCORDING TO THE RECIPE: "DMLS SRIN625-001"
6. PREPARE AND REMOVE SPECIMENS FROM BUILD PLATE BY USING WIRE- EDM (CHECK DIRECTIONS OF DRAWING SHEETS: "POST PROCESS A" OR "POST PROCESS B")
7. PRODUCE FINAL TEST SHAPE OF THE TENSILE SPECIMENS, SEE DRAWING 'AMEDM_E8_025x0125x1'
MATERIAL:
INCONEL 625 EOS,
LOT W111201-2
FINISH/HEAT TREAT:
stress relief heat treated parts and build plate combined according to the recipe: DMLS SRIN625-001
NIST CAD FILE No:
Assem_AMBuild_001-001_RR_IN625_metric.SLDDRW
UNLESS OTHERWISE SPECIFIED:
INTERPRET DRAWING PER ASME Y14.5M 1994
DIMS IN PARENTHESIS ( ) ARE FOR REF ONLY
DIMS ARE IN MILLIMETER AND APPLIES AFTER FINISH
PART MUST BE FREE OF BURRS AND/OR FLASH
DO NOT SCALE DRAWING
.XXX ±.15; .XX ±.25; .X ±2.5; FRAC: ±0.4
ANG: ±1°; .X ±.5°; .XX ±.25°; CHAM ±5°
BREAK SHARP EDGES: .1-3.5
CORNER FILLET: R.13 MAX.
SURFACE FINISH: 1.6 MAX.
THD RELIEF: MAJOR DIA X 90°±5° MIN.
SHEET METAL TOLERANCES: 2X
CORNER BEND (MATL THK < .120): IR.07 MAX.
APPROVAL
BY
DATE
DRAWN JACOB 11/04/2014
CHECKED BROWN X/XX/XXXX
ENGRG JACOB X/XX/XXXX
GROUP 735.15
MFG X X/XX/XXXX
INSPECT X X/XX/XXXX
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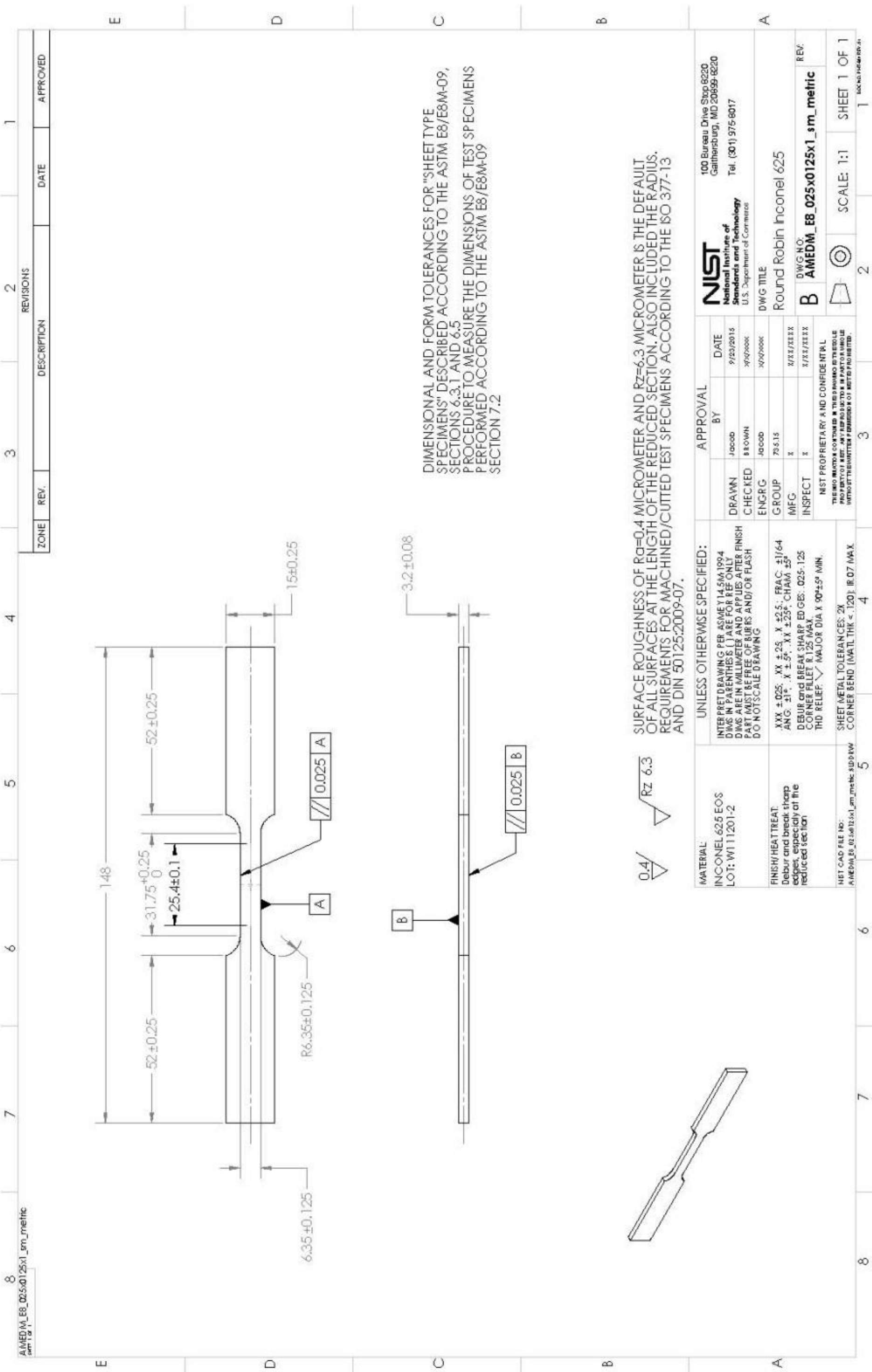
Tel. (301) 975-8017
DWG TITLE
Round Robin Inconel 625
B
DWG NO:
Assem_AMBuild_001-001_RR_IN625_metric
REV:
SCALE: 1:1
SHEET 5 OF 5

Engineering drawing of the final tensile specimens:



5. ANALYSIS OF PARTICLE SIZE DISTRIBUTION OF THE POWDERS SENT TO PARTICIPANTS

IN625 powder size distribution as determined using sieves

ASTM B214 [3] was followed to perform the sieve analysis for each of the 15 buckets of IN625 powder sent to the participants. Originally two buckets were distributed to each of the 7 participants; however, one bucket was misplaced and therefore a fifteenth, replacement bucket, was issued. All 15 buckets were from the same manufacturing lot (M111201). Seven sieves were chosen based on the expected maximum size of the powder. The chosen US Standard sieve sizes were: 230 (75 μm > 63 μm), 270 (63 μm > 53 μm), 325 (53 μm > 45 μm), 400 (45 μm > 38 μm), 450 (38 μm > 32 μm), 500 (32 μm > 25 μm), 635 (25 μm > 20 μm), and pan (> 20 μm). According to the powder's mill certificate, 98 % of the powder was expected to be 53 μm or smaller, therefore one sieve size larger than 53 μm was used, sieve 230 (US Standard size).

The powder in each sieve was determined using a mass balance and the cumulative mass percent was calculated for each sieve. Figure 2 is an example plot from one of the powder samples. The data was used to approximate the powder diameter at cumulating mass percentages of 10 % (D10), 50 % (D50), and 90 % (D90). In other words, the D50 for a given powder as determined by sieving indicates 50% of the powder mass has this diameter size or smaller.

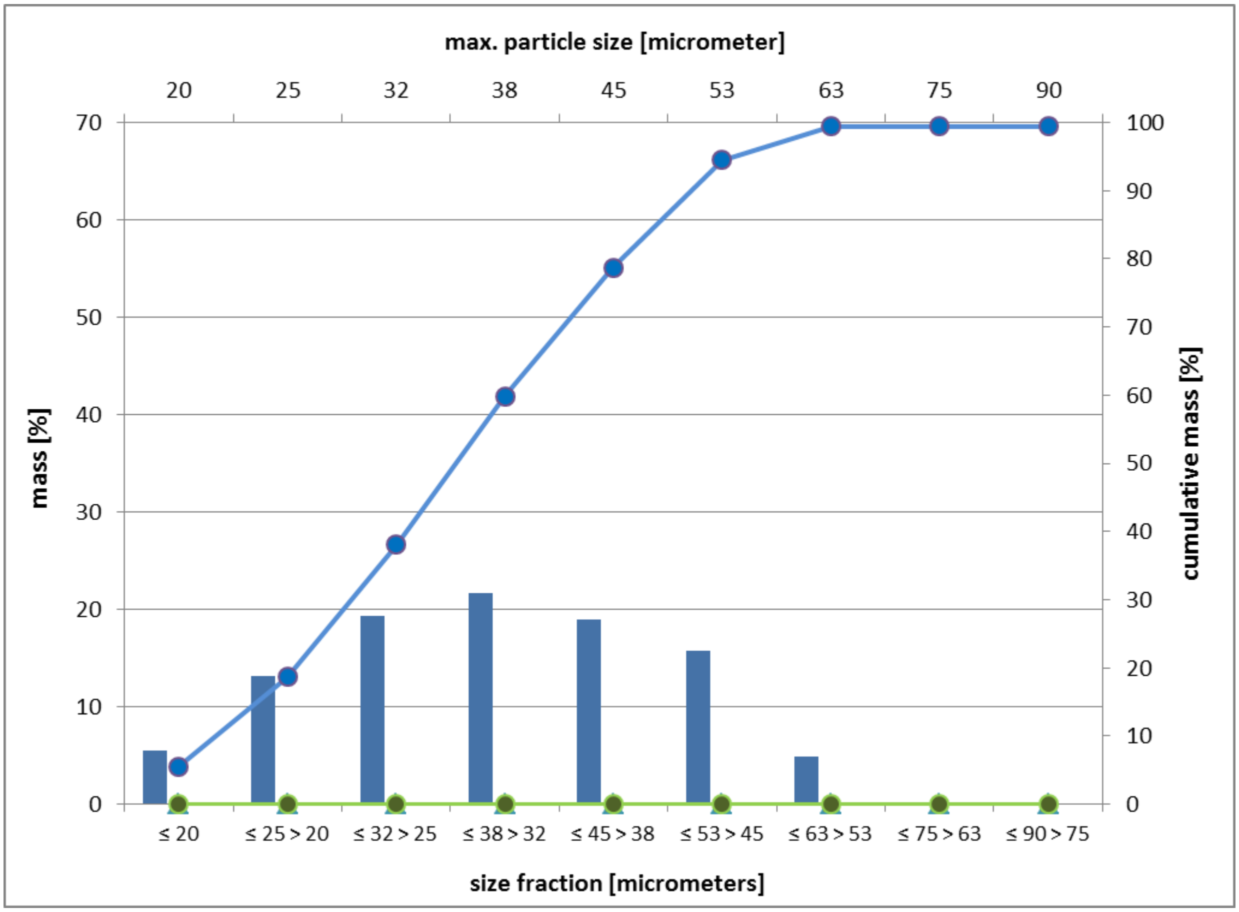


Figure 2. Cumulative mass (%) versus powder size (μm) versus for one of the IN625 powder samples. The data in this plot was used to approximate the powder diameter at the cumulative mass percentages of 10 %, 50 %, and 90 % for each powder bucket (see ASTM E11 for sieve variation [4]).

A line was chosen to connect the data points however it is possible that the actual powder size distribution between the sieves does not follow a straight line. To report the diameter at the cumulative mass percent at 10 %, 50 %, and 90 %, linear interpolation was chosen to approximate the powder diameter at these percentages. Thus the D50 for the distribution in Figure 2 is 35 μm, or in other words, 50% of the powder mass has a diameter of 35 μm or smaller. Table 1 lists the powder diameter for each bucket as determined by sieving.

Table 1. The powder diameter determined by sieving for each of the 15 participant buckets of IN625. The 10 %, 50 %, and 90 % cumulative mass percentages are shown along with the average and standard deviation.

Bucket #	**D10**	**D50**	**D90**
1	20.32	34.85	50.54
2	14.59	34.68	49.82
3	10.59	30.84	48.3
4	22.28	35.4	50.36
5	21.03	36.36	51.5
6	22.15	36.41	51.18
7	16.68	33.29	48.88
8	19.65	33.98	49.33
9	21.14	34.37	49.66
10	14.08	32.28	48.89
11	21.95	36.57	51.48
12	16.12	33.22	48.79
13	13.99	31.79	48.86
14	20.67	35.47	50.98
15	21.69	35.29	50.72
Average =	18.46	34.32	49.95
St D =	3.77	1.74	1.08

IN625 powder size distribution as determined using laser diffraction

Table 2 lists the particle size distribution measured using laser diffraction of the 15 buckets of IN625 that were distributed to the participants. The technique involves using isopropanol (IPA) to suspend the powder. The D10, D50, and D90 values are based on a cumulative volume percentage, rather than a cumulative mass percent as is used for sieve analysis. In other words, the D50 for a given powder as determined by laser diffraction indicates 50 % of the powder volume has this diameter size or smaller. The average powder diameter (μm) for D10, D50, and D90 are shown at the bottom along with the corresponding standard deviation.

Table 2. Powder distribution as determined using laser diffraction for each of the 15 participant buckets of IN625. The diameter at the 10 %, 50 % and 90 % cumulative volume percentages are shown for each bucket along with the average and standard deviation.

IN625 Bucket #	**Label**	**D10**	**D50**	**D90**
1	A	16.122	28.293	49.243
2	B	14.609	24.723	42.127
3	C	15.752	26.51	44.861
4	D	14.645	25.224	43.875
5	E	14.895	24.908	41.779
6	F	15.321	25.972	43.797
7	G	15.696	27.623	48.657
8	H	15.362	26.554	45.823
9	I	15.642	26.605	45.047
10	J	15.561	27.962	50.103
11	K	17.389	28.396	45.749
12	L	15.39	26.589	45.748
13	M	15.251	26.063	44.773
14	N	15.065	26.152	45.634
15	P	15.336	26.009	44.718
	Average	15.469	26.506	45.462
	St Dev	0.671	1.146	2.359

Figure 3 shows the volume percent versus particle size (μm) as determined by laser diffraction for all 15 powder samples.

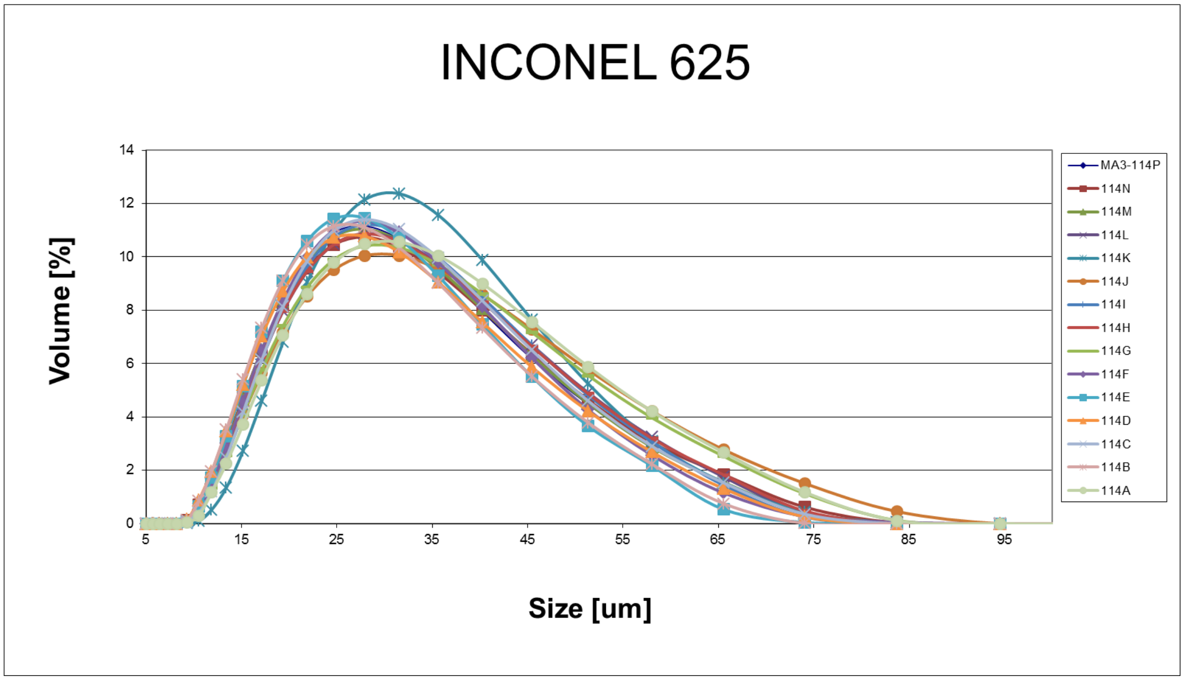


Figure 3. Volume percent versus powder diameter for all 15 samples of IN625 powder. The legend shows a different symbol for each of the 15 buckets.

Comments on the size distribution results

Although the main goal of this study was not comparing the results of different size distribution techniques, we did want to understand the size distribution of our powder used by the participants. The vendor powder specification reported 98 % of the powder mass should have a diameter of 53 μm or smaller. Our sieve results showed that 98 % of the powder mass had a diameter of 58.02 μm ± 2.72 μm or smaller.

6. TENSION SPECIMENS FABRICATED ON A DIFFERENT LPBF MACHINE

During this study, the round robin coordinator identified a willing participant who had a LPBF machine from a different vendor. NIST sent this participant the same powder and the same individual tessellated and slice files to fabricate the parts as sent to the other participants. This participant used the manufacturing plan and the files to duplicate the process parameters in their machine. Upon receiving the build platform with the tensile specimens attached, NIST followed the same post processing procedures to heat treat, extract the specimens, and prepare the specimens for the tension tests. The statistical analysis was conducted on the tension test results, including the specimens from the different LPBF machine.

Statistical analysis

The yield strength (YS), ultimate tensile strength (UTS), elongation after fracture (A), and Young's modulus (E), were measured for 6 test specimens produced by each participant. Figure 4 shows summaries of these results, in the form of boxplots. Each rectangular box comprises the middlemost 50 % of the data, the thick horizontal line within the box marks the median, and the whiskers, if present, extend to the extreme data points. Circles indicate potential outliers: values that lie farther than 1.5 times the inter-quartile range from either the top or bottom sides of a box. As seen in these plots, the tensile properties of the specimens from the last participant (with a different LPBF machine) are clearly different than the properties obtained from the specimens fabricated on the other participants' machines. Therefore, the results from participant #7 were not included in the following statistical analysis.

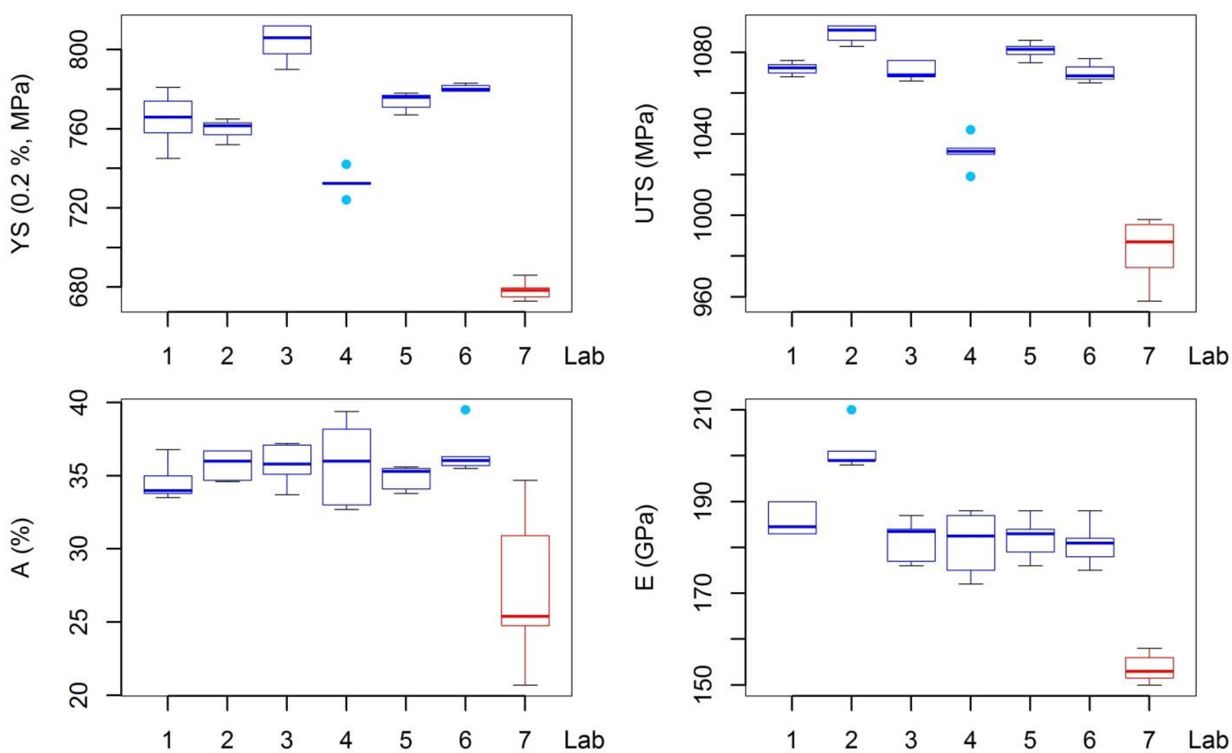


Figure 4. Boxplots of tension test results of the specimens received from all participants. Box plots of measured mechanical properties from all participants including Lab 7. The data from Labs 1 through 6 were used in the statistical analysis. Results from the additional participant, Lab 7, that used a different LPBF machine, are also shown.

Values of the following covariates were also reported by almost all participants: energy density, volume rate, layer thickness, and skin power. However, these attributes had only two or three different values, and their values varied between some of the laboratories, but never within a laboratory.

The statistical model for the value $x_{i,j}$ of each of the four measurands (YS, UTS, A, and E) measured on test coupon i produced by laboratory j expresses it as an additive superposition of three different effects, $x_{i,j} = \mu + \alpha + b_j + e_{i,j}$. This is called a *mixed effects model* [5] because μ and α are treated as fixed effects, and the b_j and $e_{i,j}$ are treated as random effects. For YS, for example, μ denotes the true value of the yield strength for this material that results from this manufacturing process, α is the effect of a particular covariate (for example, energy density), b_j is the effect of laboratory j, and $e_{i,j}$ is the effect of this particular coupon, all for $j = 1, \ldots, n$, with $n = 6$ participants, and $i = 1, \ldots, m_j$, where $m_j = 6$ denotes the number of coupons from participant j that were used in the analysis.

The fact that the covariates take constant values within laboratories, and that often they take the same values also between laboratories, prevents studying their effects other than one at a time. This is an important weakness of the study that should be avoided in future studies.

The $\{b_j\}$ are modeled as independent, Gaussian random variables with mean of 0 and standard deviation τ, which characterizes the between-laboratory dispersion of values; and the $\{e_{1,j}, \ldots, e_{mj,j}\}$ are modeled as independent, Gaussian random variables with mean of 0 and standard deviation σ_j, which characterizes the dispersion of values within laboratory j, and may vary between laboratories. These models were fitted using function `lme` from the package `nlme` for the R environment for statistical computing and graphics [6, 7]. Their fit to the data was evaluated via graphical examination of the corresponding estimates of the laboratory and coupon effects. The heterogeneity of the results from the different laboratories may be evaluated in greater detail by applying Cochran's Q-test to determine whether the standard deviation of the laboratory effects τ is zero [8].

Table 3 summarizes the results that may be relevant to the design of future, more ambitious interlaboratory studies of additive manufacturing. The between-laboratory range of values, expressed relative to the estimate of the measurand, listed in the column labeled $\hat{\tau}/\hat{\mu}$ (%), is a modest 1.3 % to 4.1 %. The between-laboratory variability is substantially (up to 4 times) larger than the typical within-laboratory variability, listed in the column labeled $\hat{\tau}/\mathrm{median}(\{\hat{\sigma}_j\})$, for all measurands except for elongation, whose values are surprisingly uniform across laboratories.

Considered one at a time, none of the four covariates (energy density, volume rate, layer thickness, and skin power) had effects significantly different from zero, once the differences between laboratories were taken into account. An analysis based on summary data (averages and standard errors of these averages), where the same mixed effects model was fitted using a different statistical procedure [9], implemented in function *rma* defined in R package *meta* for Viechtbauer [10] revealed the following:

- For yield strength (YS), ultimate tensile strength (UTS), and Young's modulus (E), there is significant between-lab heterogeneity (that is, the standard deviation τ of the laboratory effects is significantly greater than 0), but not for elongation after fracture (A), as judged by Cochran's *Q*-test.
- Only for yield strength is there a slight indication of possible significance of energy density upon mechanical performance, with higher values of the energy density (coefficient of corresponding effect is positive, 0.66, with associated standard uncertainty 0.28) tending to produce greater yield strength.

Table 3. Selected results from fitting mixed effects models to the experimental data. The values in the last two columns are the same for all the covariates (to within the number of significant digits quoted) because the variability in the covariates was insufficient to impact the variability of the measured values of the mechanical properties.

	Estimate	Effect	$\hat{\tau}/\hat{\mu}$ (%)	$\hat{\tau}$/median ($\{\hat{\sigma}_j\}$)
Energy Density				
Yield Strength (MPa)	701	0.66	2.4	3.2
Ultimate Tensile Strength (MPa)	1044	0.25	2.0	4.9
Elongation (%)	36.3	-0.01	1.3	0.4
Young's Modulus (GPa)	203	-0.17	3.3	1.5
Volume Rate				
Yield Strength (MPa)	802	-13	2.1	3.2
Ultimate Tensile Strength (MPa)	1081	-5	1.9	4.9
Elongation (%)	35.1	0.15	1.4	0.4
Young's Modulus (GPa)	177	3.4	3.8	1.5
Layer Thickness				
Yield Strength (MPa)	816	-1.7	2.1	3.2
Ultimate Tensile Strength (MPa)	1086	-0.64	1.9	4.9
Elongation (%)	35	0.02	1.4	0.4
Young's Modulus (GPa)	174	0.44	3.9	1.5
Skin Power				
Yield Strength (MPa)	852	-0.36	2.0	3.2
Ultimate Tensile Strength (MPa)	1100	-0.14	1.9	4.9
Elongation (%)	34.6	0.00	1.4	0.4
Young's Modulus (GPa)	164	0.09	4.1	1.5

Fractography analysis

Fractography analysis of these specimens was also carried out to understand the differences seen in the tensile test results. A series of scanning electron micrographs were taken of the fracture surface from tensile bar 5 from participant 7. The tensile bar in the following images was stress-relief heat-treated following the same heat treatment followed for the other 6 participants [1]. The build platform was heated to 840 °C in 6 h and temperature held at 840 °C for 1 h. For comparison purposes, micrographs from a specimen made on the LPBF machine of the other 6 participants are included at the end of this section (Figure 22 to Figure 27).

The nature of the fracture surface morphology in the following images showed significant differences compared to a specimen made on the LPBF machine of the other 6 participants [1] (Figure 22 to Figure 27). The surface shows several secondary cracks, some quite large, that appear to be the result of the variability in the LPBF process. The small secondary cracks appear to have initiated near an unmelted powder particle (or other microstructural anomaly) and propagated a short distance into the bulk of the sample (i.e., perpendicular to the primary fracture plane) and arrested. These cracks may be the result of translating a manufacturing plan developed for one LPBF machine for use on a different vendor's LPBF machine. The translation of the manufacturing plan may have resulted in the sub-optimum build producing lower mechanical properties and the observed fracture surface.

Figure 5 is a low-magnification view of the surface showing a large flaw in the lower left corner of the tensile specimen cross-section. This flaw appears to be a pore caused by trapped gas and is the most likely initiation point of the primary fracture. At higher magnification (Figure 6 and Figure 7), this area shows that the pore may have originated during the solidification process as unmelted and partially melted powder are clearly observable within.

The fracture surface has a number of large secondary cracks aligned in the build direction (Figure 5). During the build, the powder was applied in layers in a horizontal plane. The horizontal secondary cracks may have initiated as interlayer cracks that pulled apart during the tensile loading. However since these cracks appear to be open, it may suggest that they are build related rather than the result of loading. Higher magnification images also show smaller secondary cracks that are in various directions along the surface as well (Figure 8 and Figure 13).

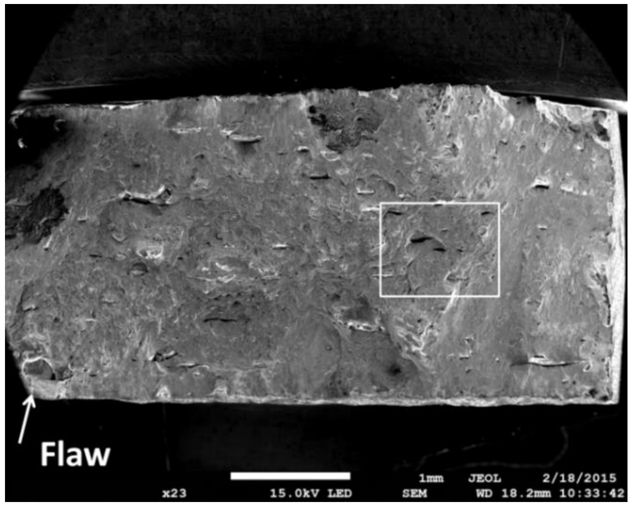
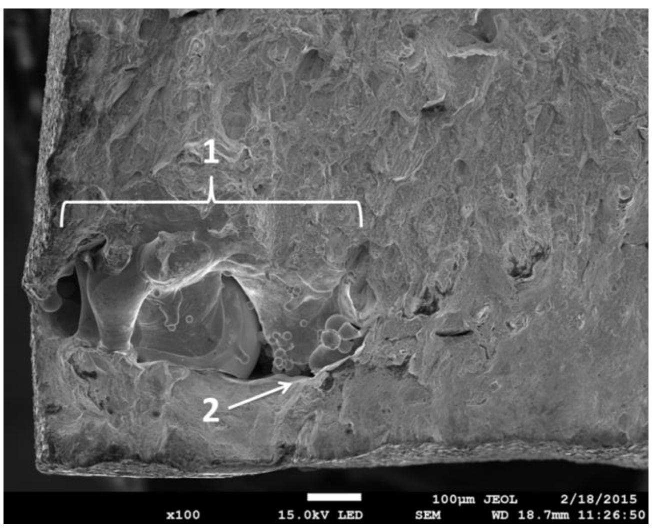


Figure 5. Overview of the fracture surface (x23) showing a large flaw in the lower left corner of the specimen and large secondary cracks parallel to build layers. The white box is the region magnified in Figure 8.



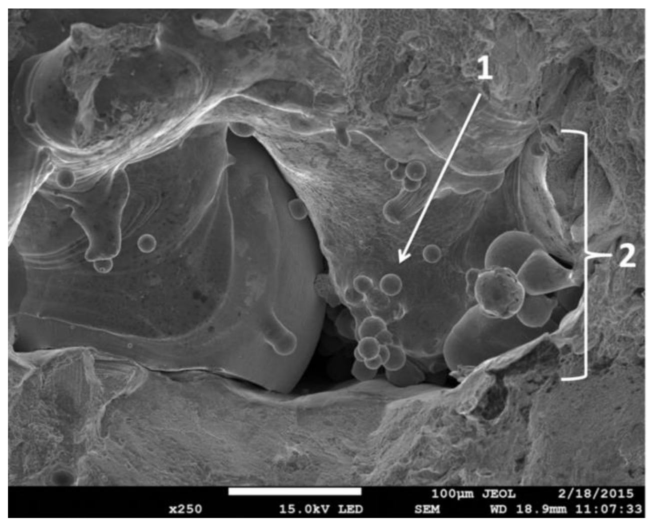


Figure 6. A low magnification view (x100) of the lower left corner of the specimen showing the flaw (1) and what appears to be a short crack that initiated to the right of a large particle (2).

Figure 7. A higher magnification image (x250) showing unmelted and partially melted particles (1) of various sizes trapped within the flaw (2).

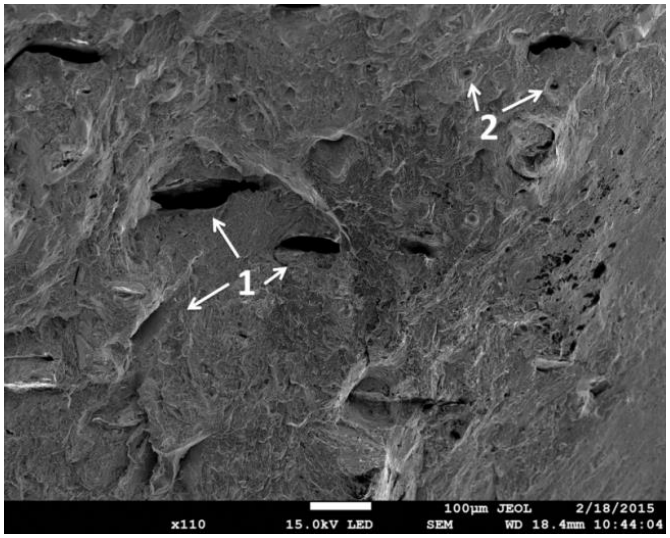


Figure 8. Higher magnification (x110) of the white box in Figure 5 with secondary cracks (1) and dimple-like microvoids (2). Some cracks are aligned in the build direction while others are not.

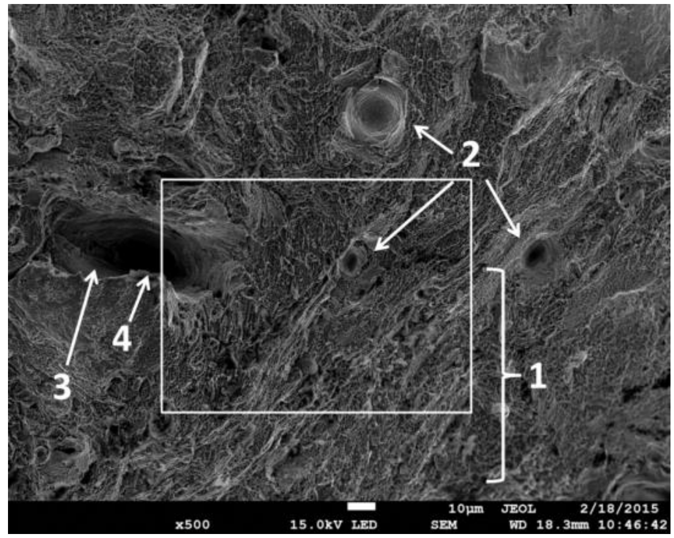
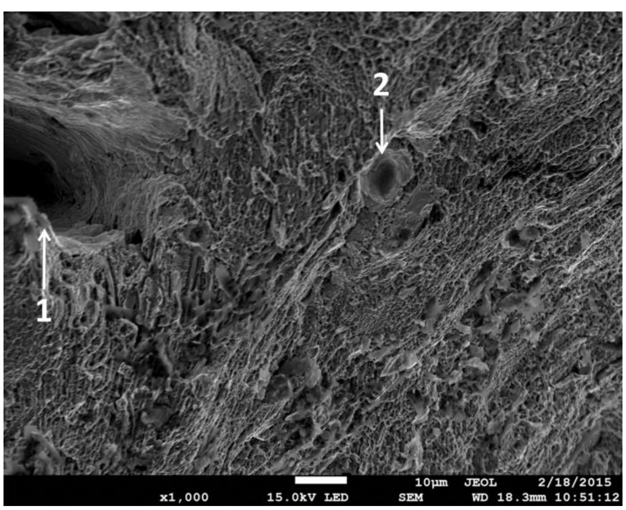


Figure 9. Higher magnification (x500) of Figure 8 showing similar features to Figure 13. Fine dendritic segregation (1), microvoids (2), a small secondary crack (3), and an unmelted powder particle within the crack (4). The white box is the region magnified in Figure 10.



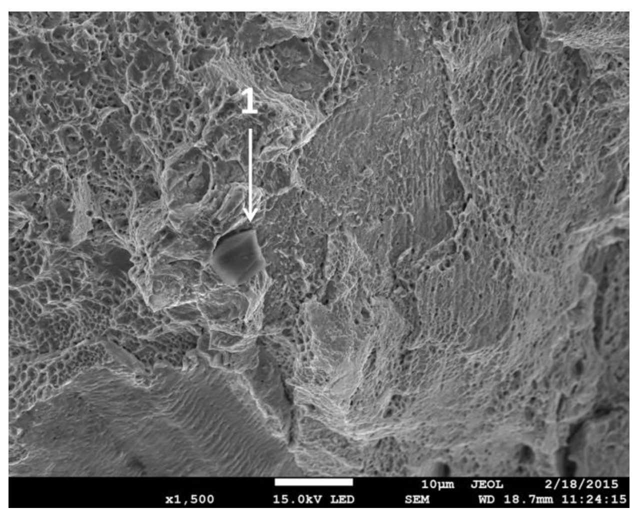


Figure 10. Higher magnification (x1000) of Figure 9 showing a portion of the small crack (1) (labeled 3 in Figure 9) and a microvoid (2) from Figure 9. The fine scaled dendrites can easily be seen across the surface.

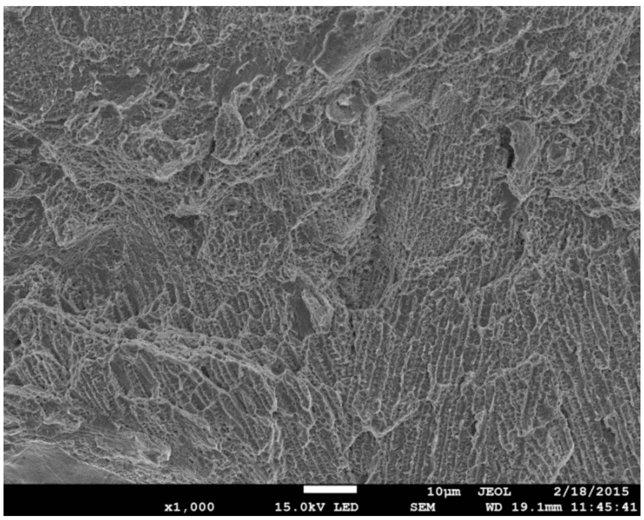


Figure 12. This area of the fracture surface shows areas of very consistent dendrite orientation.

Figure 11. Another high magnification image (x1500) of the fracture surface showing dendrites. In the center of this image there is a cube shaped formation (1) that appears to be a different nature then the surrounding material and could be crystallographic.

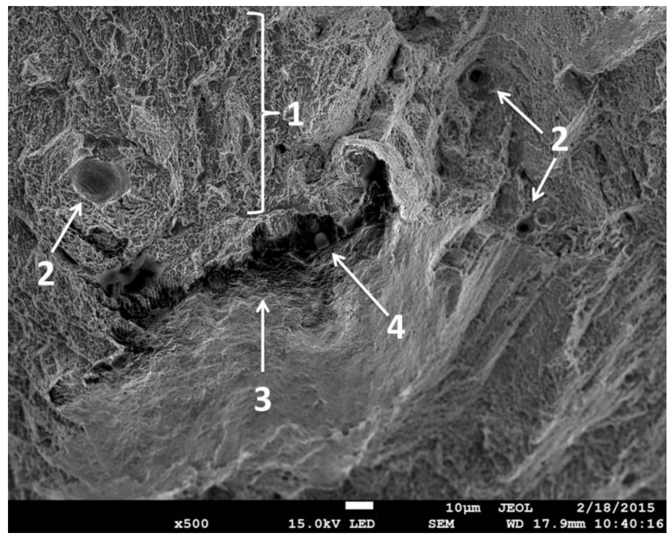


Figure 13. A small secondary crack (3) is surrounded by fine dendritic segregation (1) and microvoids (2). An unmelted particle is within the crack (4). While the microvoids reflect the ductility observed in the mechanical data, the crack may have contributed to lower overall ductility in this specimen as compared to the specimen representing the other 6 participants.

Fine-scaled dendrites, resulting from micro-segregation during the solidification process, are exhibited at region 1 in Figure 13 and these are the most prevalent features on the fracture surface overall. Microvoids, or dimple-like features, are also visible on the surface and they are noted in Figure 13 as region 2. Numerous voids were observed and they ranged in size from extremely fine to quite large. Since many of the observed microvoids are smaller than the diameter of an unmelted powder particle, it is possible these formed around an unmelted powder or contaminate particle during solidification. Microvoids typically form during final fracture (i.e., after necking has initiated in the sample) and indicate ductile failure, which is consistent with the mechanical test data for this specimen. While lower than the results from the other 6 participants, this specimen did demonstrate significant ductility prior to failure.

Figure 13 also shows a small secondary crack (region 3). Several secondary cracks, also ranging in size were observed on the fracture surface of this specimen. Most exhibited small, unmelted powder particles near the mouth of the crack, which can be seen in Figure 13 (region 4). These cracks were most likely produced by local variability in the layered solidification process and may have contributed to the reduced strength. Another example of a secondary crack is shown in Figure 14 through Figure 17.

The powder particles were examined further and Figure 18 and Figure 20 are high magnification images of partially melted powder from Figure 17. Some evidence of decohesion can be seen between the unmelted powder particle and the surrounding matrix (decohesion at region 2 in Figure 18), which is also consistent with the reduced mechanical properties for this specimen. The particle morphology was relatively spherical. Some evidence of grain structure and fine-scale dendrites is also observable at extremely high magnification (Figure 19 and Figure 21).

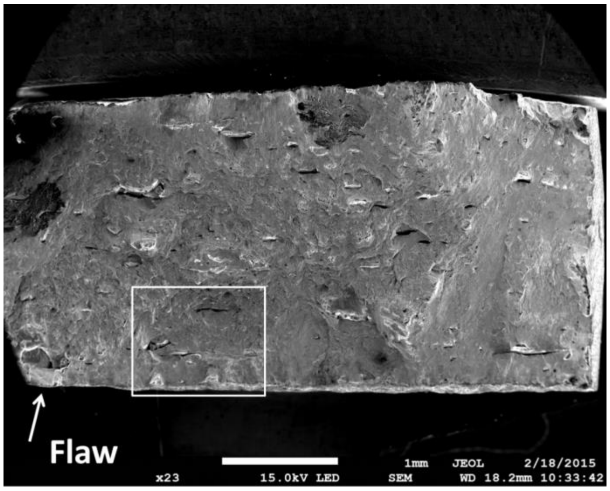


Figure 14. Figure 5, a low magnification overview (x23) of the fracture surface. The white box is the region magnified in Figure 15. Note the area for Figure 15 with relation to the flaw.

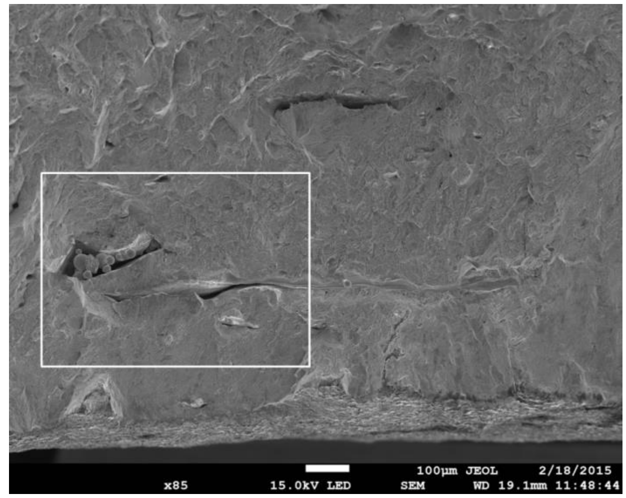


Figure 15. Higher magnification (x85) of Figure 14 showing secondary cracks, one with unmelted or partially melted powder particles trapped inside. Note the thin horizontal crack passing through the white box extends from the flaw across most of this image. The white box is the region magnified in Figure 16.

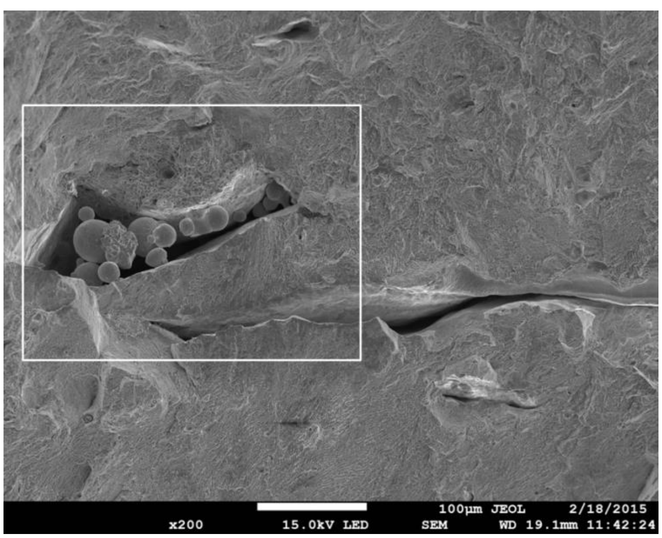


Figure 16. Higher magnification (x200) of Figure 15 showing secondary cracks with unmelted or partially

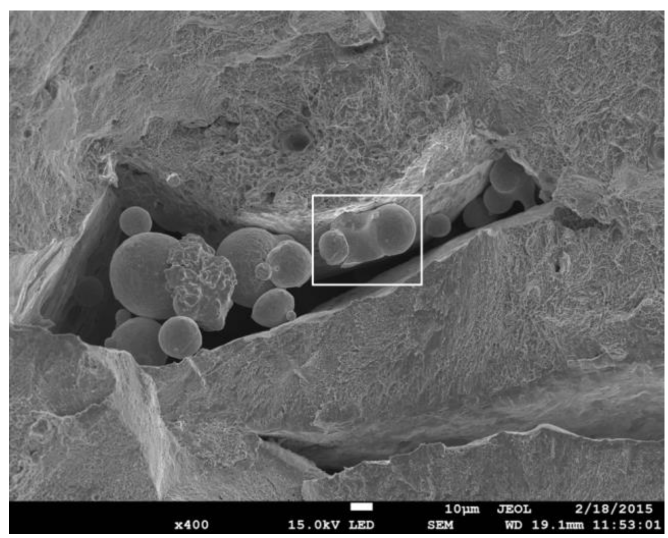


Figure 17. A higher magnification view (x400) of the mouth of a secondary crack showing unmelted or

melted powder trapped in the mouth of the crack. The thin horizontal crack noted in Figure 15 that extends from the flaw is easier to see. The white box is the region magnified for Figure 17.

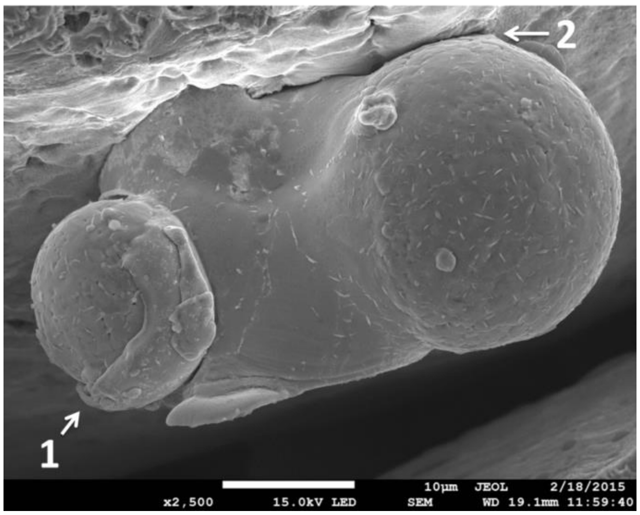


Figure 18. Partially melted powder at a higher magnification (x2500) from Figure 17. The rough texture on the particle surfaces is produced by rapid solidification during the atomization process (1). There is evidence of decohesion between the unmelted powder particle and the surrounding matrix (2).

partially melted powder particles trapped inside. The white box is the region magnified for Figure 18.

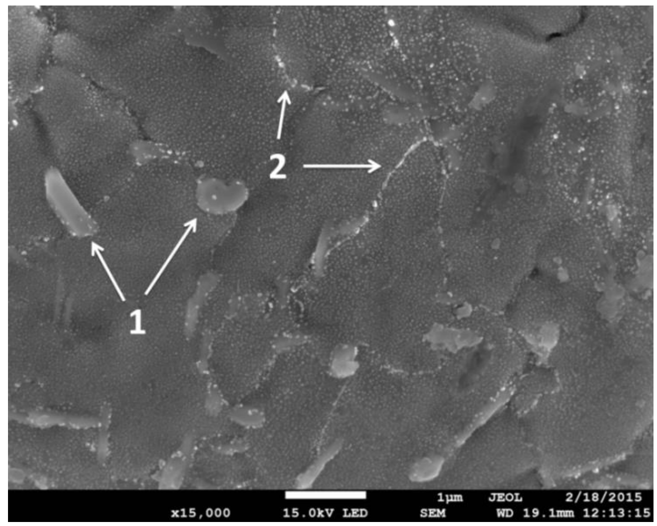


Figure 19. A high magnification image (x15000) of Figure 18 showing the surface of an unmelted powder particle. The brighter regions are likely second phase precipitates (1) decorating extremely fine grain boundaries (2).

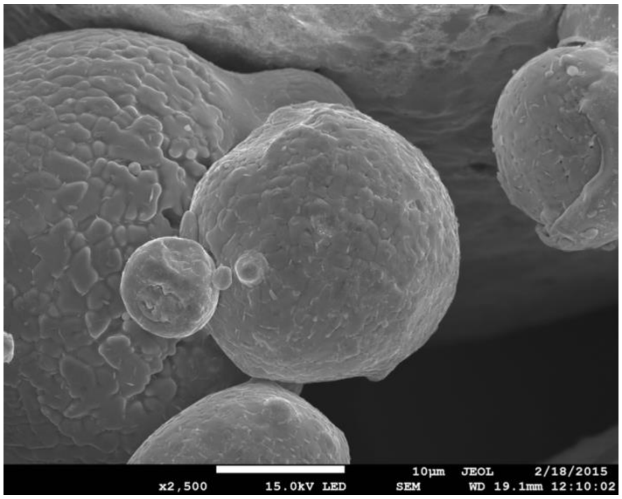


Figure 20. Partially melted powder within the secondary crack at a high magnification (x2500) from Figure 17. The rough texture on the particles surface is produced by rapid solidification during the atomization process.

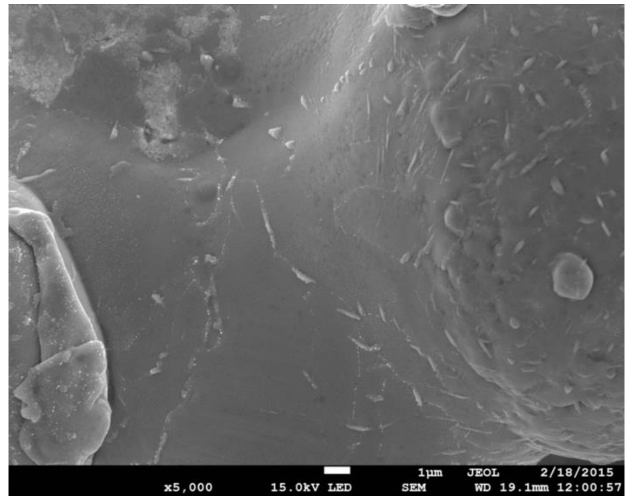


Figure 21. The melted region between two partially melted powder particles (x5000) shown in Figure 18. The brighter regions are likely second phase participates decorating extremely fine grain boundaries.

The above images represent the microstructure and associated fracture patterns of a specimen fabricated on a different LPBF machine then the other 6 participants. The nature of the fracture surface morphology in these images showed significant differences compared to a specimen made on the LPBF machine of the other 6 participants [1]. The difference in the facture pattern may be the result of translating a manufacturing plan developed for one LPBF machine for use on a different vendor's LPBF machine. The translation of the manufacturing plan may have resulted in the sub-optimum build results exhibited in the above images and in the lower mechanical properties. Figure 22 through Figure 27 show the fractography results from a specimen made using the LPBF machine of the 6 participants.

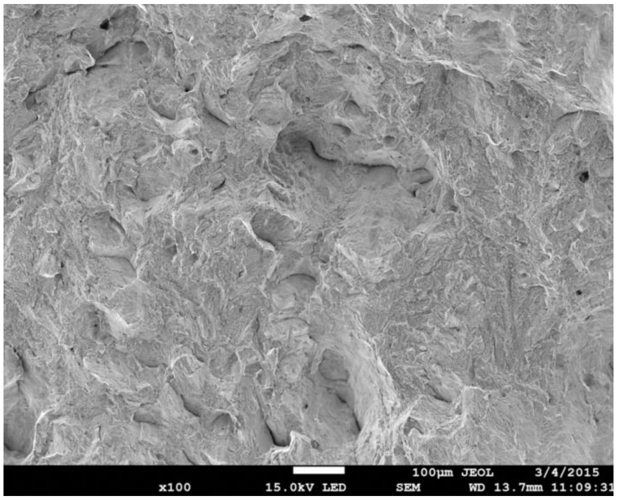


Figure 22. A region of fracture zone (x100) that does not appear to have horizontal secondary cracks related to the build layer but rather localized transgranular cracking in various directions.

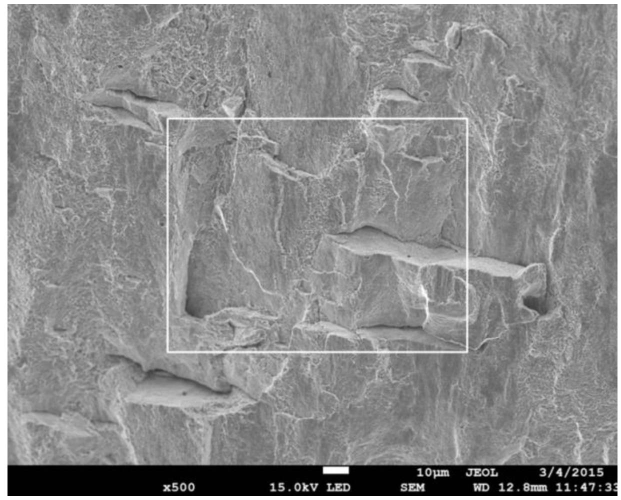


Figure 23. A group of facets (x500). The white box is the region magnified in Figure 24. These step-like cracks appear to be aligned in the build direction, however they do not appear to be as open as seen with the other specimen (Figure 8 and Figure 17).

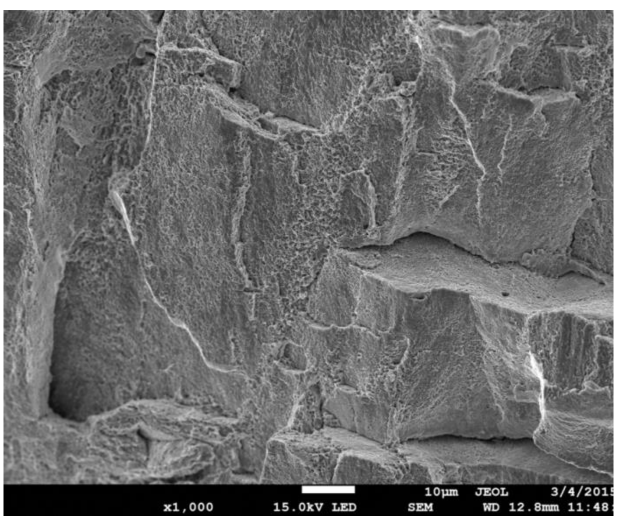


Figure 24. Several transgranular cleave-like (TCL) facets on the fracture surface (x1000).

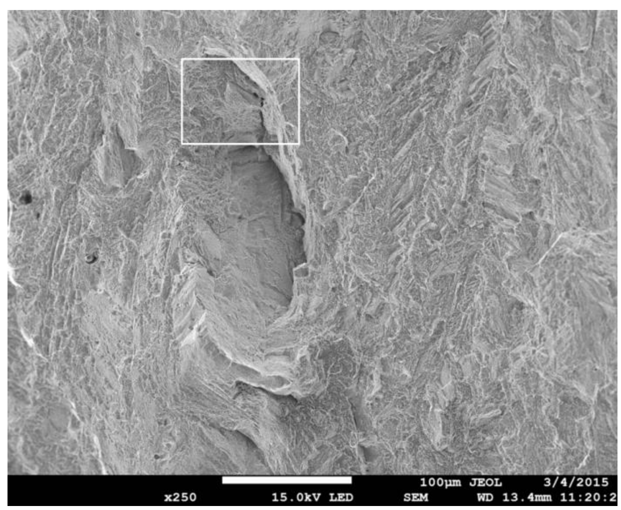


Figure 25. A different area of the fracture surface (x250). Large TCL facet is in the middle of the

image and the top of the facet was chosen to magnify in Figure 26.

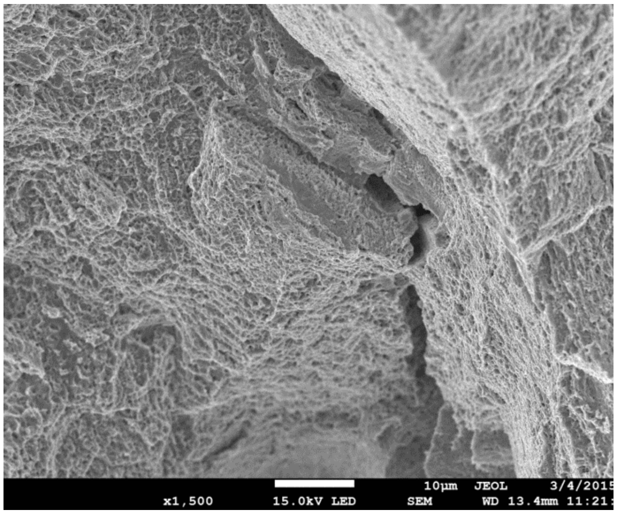


Figure 26. Dendrites are evident around a secondary crack (x1500).

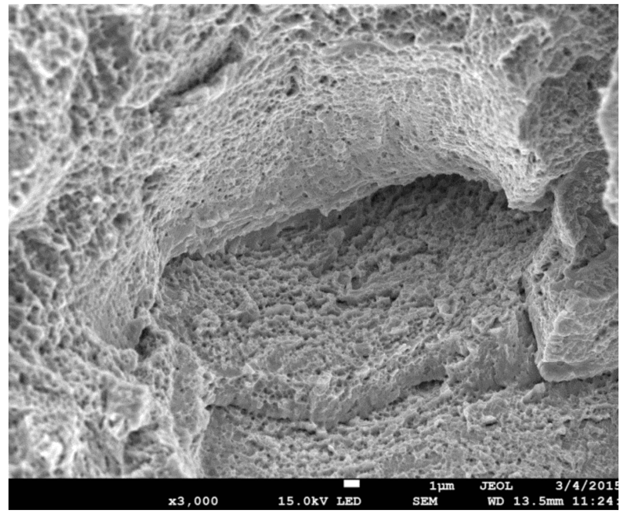


Figure 27. A high magnification image (x3000) of the fracture surface shows primarily dendrites with a transgranular cleavage-like feature.

7. SUMMARY

Conducting a round robin study involving a large number of variables requires significant effort to identify and control most, if not all, of these variables. Additive manufacturing processes are examples of such processes with very large, on the order of hundred, number of variable process parameters. Therefore, careful planning is needed to determine the manufacturing plan and collect all necessary information to be able to draw conclusions from the resulting tests.

This report presented all the information and documentation shared between the study coordinator (NIST) and each participant during execution of this study. This report also provided an example of using some fixed process parameters on different LPBF machines, which are not intended to necessarily use the same parameters. The test results from the specimens fabricated on a different vendor's LPBF machine showed significant differences both in mechanical properties as well as fracture and microstructure characteristics. These differences are most likely the result of translating a manufacturing plan developed for one LPBF machine for use on a different vendor's machine. The translation of the manufacturing plan may have resulted in the sub-optimum build results. Future studies will take these results into account when setting and applying fixed parameters on different AM platforms.

The results indicate that differences between laboratories, even between those that have used the very same parent material and manufacturing process (the only ones considered in the analyses that produced the results summarized in Table 3), generally are considerably more important than differences between coupons manufactured in the same laboratory. This fact suggests that there is more to be gained by increasing the number of participating laboratories, than by increasing the number of coupons manufactured by each laboratory.

Future experiments will be designed to enable investigation of the effects that process variables (the covariates considered above and others) have upon the mechanical properties of the resulting parts. To achieve this goal, settings of key process variables should be varied deliberately, over practically significant ranges, both within laboratories and between laboratories, in a suitably designed experiment. For example, one may choose at a minimum two different values for the energy density, but then ensure that the two levels are used in different runs in each laboratory.

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- Arizona Commerce Authority: Dan Franklin
- University of Louisville: Tim Gornet, Brent Stucker, Gary Graf, Matt Taylor
- Western Illinois University-Quad City Manufacturing Lab: Eric Faierson
- Picatinny Arsenal: Stacey Kerwien, Elias Jelis, Matthew Clemente, Dave Dekmar, Sr.
- Aberdeen Proving Ground: Rick Moore, Lester Hitch

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APPENDIX

COPY OF THE 7 PROCESS CONTROL DOCUMENTS RETURNED BY THE PARTICIPANTS

Participant 1 PCD

Process Control Document

Technical Data

Part Manufacturing Technical Data

Completed by the part manufacturer

	Value	Requirement Section	Approval
Job Number			
Build File Name:	AM_Round Robin_Inconel 625	1.2	
Process	Laser Powder Bed Fusion	2.1.1	
Equipment Manufacturer and Model:	EOS EOSINT M270D	2.1.2	
Equipment Serial Number:	SI978		
Laser Manufacturer and Model:	H0911286	2.1.4	
Laser Serial Number:	1212-0163		
Software Version:	PSW Version 3.5 (Build 64)	2.2	
Date of last preventative maintenance	02/04/14	2.3	
System Calibration Current	yes	2.4	
Material Requirements			
Verify Powder Heat/Lot Loaded Matches Feedstock Technical Data	Containers #2 and #15		
Material Condition (Virgin/Recycled)	Virgin	3.4	
Process Setup Requirements			
Build Platform Material	New Plate PN: 2200-4372	4.1.1	

Build Platform Thickness	22.15 mm				4.1.2	
Build Platform Condition	New Plate Cleaned				4.1.3	
Build Platform Preheat, °C	80 C				4.1.4	
Recoater Blade Material/Part Number	Ceramic, PN: 2200-3013				4.2	
Process Parameter Settings						
Base Parameter Set	EOS MP1				4.3.1	
Base Parameter Filename	MP1_Surface_101					
Layer Thickness, µm	20				4.3.2	
Sort Parts Method:	-				4.3.4.2	
Exposure Parameters	Complete Exposure Parameters Table Below				4.3.5	
Pre Contour Type	NIST_RR_IN625_PreContour				4.3.5.1	
Skin Exposure Type	NIST_RR_IN625_OuterSkin				4.3.5.2	
Core Exposure Type	NIST_RR_IN625_InnerSkin				4.3.5.3	
Post Contour Type	NIST_RR_IN625_Postcontour				4.3.5.4	
Skin Thickness (x/y), mm	3.00				4.3.5.5	
Skin Thickness (z), mm	3.00				4.3.5.6	
Base Radius:	0.00				4.3.5.7	
Core open to platform?:	No (unchecked)				4.3.5.8	
Skin/Core:	Yes (checked)				4.3.5.9	
Scaling and Offset						
Material Specific Scaling	X, %					Y, %
Part Specific Undersize/Oversize Beam Offset, mm	0	4.3.6.3	0	0	4.3.6.1	
			0	0	4.3.6.2	
Building Screen						
Start Height (mm):	0.02				4.3.7.1	
Final Height (mm):	9.180				4.3.7.2	
Layer Thickness	0.020 mm				4.3.2	
DMLS Settings						
DMLS	Off					Range, (mm)
Pre-exposure	On				0.06	Range, (mm)
					4.3.8.1	
					4.3.8.2	

Recoating Screen			
Minimum Charge, %	150		
Maximum Charge, %	200		
Dosing Boost, %	300		
Recoating Speeds (mm/s)	Recoating Speed 1	Recoating Speed 2	4.3.9.4, 4.3.9.5
Dosing Boost, %	500 mm/s	80 mm/s	
Lower Dispenser Platform Contact-free outward travel	1.00 mm | 4.3.9.6 Yes, (checked) | 4.3.9.7		
Build Time Estimation	18:42:36		
Build Chamber Environment		0	
Purge Gas Used	Nitrogen	4.4.1	
Purge Gas Source	Nitrogen Generator	4.4.1	
Flow Rates	5.48 bar, 1.50 V	4.4.2	
Filtration	Enabled	4.4.3	
Oxygen Set Point	1.3%	4.4.4	
Quality Control Checks at Build Start			
System Maintenance and Cleaning Performed	Cleaned	4.5.1	
Pre Build Laser Power Measurement	Setpoint	Display	Measure d
Pre Contour			
Stripes		4.5.2	
Up Skin			
Down Skin			
Post Contour			
Edges			
Build Platform Leveling Complete	Yes | 4.5.3		
Platform Temperature	80.0 C	4.5.6	
Platform Level	Build Platform Z = 1.190 mm		
Oxygen Level	0.88%	4.5.7	
In Process Requirements			
Limits	Max Limit	Min Limit	Max Measure d
Build Start Time	08 | 04 | 14 | 14:30		
Build Interruptions	None	5.2	

(If Yes, Attach Documentation per 5.2)					
Process Completion					
Platform Temperature at Time of Chamber Opening	28.0 C			6.1.1,6.1.2	
Chamber Oxygen Prior to Opening	2.00%			6.1.2	
Recovered Powder Labeling	Yes			6.2	
Post Build Laser Power Measurement	Setpoint			Display	Measure d
Pre Contour					
Stripes				6.1.5	
Up Skin					
Down Skin					
Post Contour					
Edges					

Exposure Parameters

Completed by the part manufacturer

	Value				**Requirement Section**	**Approval**
Job Number						
Build File Name:	AM_Round Robin_Inconel 625					
Pre Exposure						
Pre Exposure Type	NIST_RR_IN625_PreContour				4.3.5.1	
First Contour		Standard	OnPart	Downskin	4.3.5.1.1	
	Speed (mm/s):	900.0	800.0	1600.0		
	Power (W):	100.0	100.0	100.0		
	Beam Offset (mm):	0.000	Contour	Yes (checked)		

	Thickness (mm):	0.040	Post Contour	No (unchecked)		
	Corridor (mm):	0.040				
Second Contour		Standard	OnPart	Downskin	4.3.5.1.2	
	Speed (mm/s):	-	-	-		
	Power (W):	-	-	-		
	Beam Offset (mm):	-	Contour	No (unchecked)		
	Thickness (mm):	-	Post Contour	No (unchecked)		
	Corridor (mm):	-				
Edges	Edge factor	-	Edges	No(unchecked)	4.3.5.1.3	
	Threshold:	-	Post Edge	No(unchecked)		
	Minimum radius factor:	-				
	Beam offset (mm):	-				
	Speed (mm/s):	-				
	Power (W):	-				
Skin Exposure						
Skin Exposure Type	NIST_RR_IN625_OuterSkin				4.3.5.2	
Stripes	Distance (mm):	0.10	Stripe width (mm):	4.00	4.3.5.2.1	
	Speed (mm/s):	800.0	Stripes overlap (mm):	0.10		
	Power (W):	195.0	Skywriting:	Yes(checked)		
	Beam offset (mm)	0.030	Offset:	Yes(checked)		
	Hatching, X	Yes(checked)	Alternating:	Yes(checked)		
	Hatching, Y	Yes(checked)	Rotating:	Yes(checked)		
UpDown		Upskin	Downskin		4.3.5.2.2	
	Distance (mm):	0.05	0.05			
	Speed (mm):	800.0	3000.0			

	Power (W):	195.0	195.0			
	Thickness (mm):	0.00	0.04			
	X:	Yes(checked)	Yes(checked)			
	Y:	Yes(checked)	Yes(checked)			
	Alternating:	No (unchecked)	Overlap with inskin(mm):	0.10		
	Skywriting:	Yes (checked)	Min. length (mm)	2.00		
Skip Layer	Skipped Layers	0			4.3.5.2.3	
	Offset layers:	0				
	Expose first layer:	Yes (checked)				
Core Exposure						
Core Exposure Type	NIST_RR_IN625_InnerSkin				4.3.5.3	
Chess		Squares	Gap			
	Distance (mm):	0.10	0.10			
	Speed (mm/s):	800.0	800.0			
	Power (W):	195.0	195.0			
	Width (mm):	8.00	0.00			
	Beam offset (mm)	-0.050	Overlap:	0.08		
	Hatching, X:	Yes (checked)	Alternating:	Yes (checked)		
	Hatching, Y:	Yes (checked)	Rotating:	Yes (checked)		
	Skywriting:	No (unchecked)	Rotated Angle:	-		
	Offset:	Yes(checked)				
Post Exposure						
Post Exposure Type	NIST_RR_IN625_Postcontour				4.3.5.4	
First Contour		Standard	OnPart	Downskin	4.3.5.4.1	
	Speed (mm/s):	900.0	800.0	1600.0		
	Power (W):	120.0	120.0	120.0		

	Beam Offset (mm):	0.015	Contour	Yes (checked)		
	Thickness (mm):	0.040	Post Contour	Yes (checked)		
	Corridor (mm):	0.040				
Second Contour		Standard	OnPart	Downskin	4.3.5.4.2	
	Speed (mm/s):	-	-	-		
	Power (W):	-	-	-		
	Beam Offset (mm):	-	Contour	No (unchecked)		
	Thickness (mm):	-	Post Contour	No (unchecked)		
	Corridor (mm):	-				
Edges	Edge factor	2.00	Edges	Yes(checked)	4.3.5.4.3	
	Threshold:	3.0	Post Edge	Yes(checked)		
	Minimum radius factor:	0.00				
	Beam offset (mm):	0.000				
	Speed (mm/s):	900.0				
	Power (W):	100.0				

Participant 2 PCD

Process Control Document

Technical Data

Part Manufacturing Technical Data

Completed by the part manufacturer

	Value	Requirement Section	Approval
Job Number			
Build File Name:	NIST Plate	1.2	BB
Process	DMLS	2.1.1	BB
Equipment Manufacturer and Model:	EOS M280	2.1.2	BB
Equipment Serial Number:	SI 1469		BB
Laser Manufacturer and Model:	IPG YLR-400-SM	2.1.4	BB
Laser Serial Number:	can not find		BB
Software Version:	3.6 Build 32	0	BB
Date of last preventative maintenance	6/24/2014	2.3	BB
System Calibration Current	Yes - checked on 6/24/2014	2.4	BB
Material Requirements			
Verify Powder Heat/Lot Loaded Matches Feedstock Technical Data	Cans 3 + 11 lot M1112012		BB
Material Condition (Virgin/Recycled)	Virgin	3.4	BB
Process Setup Requirements			
Build Platform Material	Steel - Provided	4.1.1	BB
Build Platform Thickness	~~[illegible]~~ As provided	4.1.2	BB
Build Platform Condition	Machined - Cleaned w/ IPA	4.1.3	BB
Build Platform Preheat, °C	80	4.1.4	BB
Recoater Blade	Ceramic	0	BB

Material/Part Number	IN 625		BB
Process Parameter Settings			
Base Parameter Set	MPI_040_101 Performance	4.3.1	BB
Base Parameter Filename	same ↑		BB
Layer Thickness, µm	40	4.3.2	BB
Sort Parts Method:		4.3.4.2	
Exposure Parameters	Complete Exposure Parameters Table Below	4.3.5	
Pre Contour Type	No exposure	4.3.5.1	
Skin Exposure Type	_Default_outerskin_DirectPart	4.3.5.2	
Core Exposure Type	No exposure	4.3.5.3	
Post Contour Type	_Default_Postcontours	4.3.5.4	
Skin Thickness (x/y), mm	200.00 mm	4.3.5.5	
Skin Thickness (z), mm	200.00 mm	4.3.5.6	
Base Radius:	0.00 mm	4.3.5.7	
Core open to platform?:	NO	4.3.5.8	
Skin/Core:	Yes	4.3.5.9	
Scaling and Offset	0.000 % for both X, Y		
Material Specific Scaling	X, % 0.122% X, 0.153 % Y		Y, %
Part Specific Undersize/Oversize Beam Offset, mm	4.3.6.3 0.000 mm	4.3.6.1	
		4.3.6.2	
Building Screen			
Start Height (mm):	0.020	4.3.7.1	
Final Height (mm):	9.200	4.3.7.2	
Layer Thickness	0.040 mm (40 µm)	4.3.2	
DMLS Settings			
DMLS	Off ✓ BB	0.00	Range, (mm)
Pre-exposure	On ✓ BB	0.04	Range, (mm)
		4.3.8.1	
		4.3.8.2	
Recoating Screen			
Minimum Charge, %	150 %	BB	
Maximum Charge, %	200 %	BB	
Dosing Boost, %	300 %	BB	
Recoating Speeds (mm/s)	Recoating Speed 1 ~~[illegible]~~	Recoating Speed 2	4.3.9.4, 4.3.9.5
~~Dosing Boost, %~~	500 mm/s	150 mm/s	

Lower Dispenser Platform	1.0 mm	4.3.9.6	
Contact-free outward travel	Checked Yes	4.3.9.7 BB	
Build Time Estimation			
Build Chamber Environment	Nitrogen	0	BB
Purge Gas Used	Nitrogen	4.4.1	BB
Purge Gas Source	Nitrogen Generator	4.4.1	BB
Flow Rates		4.4.2	
Filtration	Clean air	4.4.3	BB
Oxygen Set Point	1.30 %	4.4.4	BB
Quality Control Checks at Build Start			
System Maintenance and Cleaning Performed	Yes	4.5.1	BB
Pre Build Laser Power Measurement	Setpoint	Display	Measured
Pre Contour			
Stripes		4.5.2	
Up Skin			
Down Skin			
Post Contour			
Edges			
Build Platform Leveling Complete	4.5.3		
Platform Temperature	80°C	4.5.6	BB
Platform Level	Yes		BB
Oxygen Level		4.5.7	
In Process Requirements			
Limits	Max Limit	Min Limit	Max Measured
Build Start Time	8/19/2014		BB
Build Interruptions (If Yes, Attach Documentation per 5.2)	None	5.2	BB
Process Completion			
Platform Temperature at Time of Chamber Opening	23.0°C	6.1.1,6.1.2	BB

Did not perform (handwritten beside the Pre Build Laser Power Measurement through Edges rows) during build, the O_2 amount was approx. 0.023 % O_2

Chamber Oxygen Prior to Opening	unknown - did not record			6.1.2	BB
Recovered Powder Labeling	Virgin + Used			6.2	BB
Post Build Laser Power Measurement	Setpoint			Display	Measured
Pre Contour					
Stripes				6.1.5	
Up Skin					
Down Skin					
Post Contour					
Edges					

Did not perform

Exposure Parameters

Completed by the part manufacturer

	Value				Requirement Section	Approval
Job Number						
Build File Name:	NIST Plates					
Pre Exposure						
Pre Exposure Type	NO EXPOSURE				4.3.5.1	
First Contour		Standard	OnPart	Downskin	4.3.5.1.1	
	Speed (mm/s):					
	Power (W):					
	Beam Offset (mm):		Contour			
	Thickness (mm):		Post Contour			
	Corridor (mm):					
Second Contour		Standard	OnPart	Downskin	4.3.5.1.2	
	Speed (mm/s):					
	Power (W):					
	Beam Offset (mm):		Contour			

	Thickness (mm):		Post Contour			
	Corridor (mm):					
Edges	Edge factor		Edges		4.3.5.1.3	
	Threshold:		Post Edge			
	Minimum radius factor:					
	Beam offset (mm):					
	Speed (mm/s):					
	Power (W):					
Skin Exposure						
Skin Exposure Type	_DEfault_Outerskin_Direct Part				4.3.5.2	BB
Stripes	Distance (mm):	0.11	Stripe width (mm):	7.0	4.3.5.2.1	BB
	Speed (mm/s):	950.0	Stripes overlap (mm):	0.08		
	Power (W):	290.0	Skywriting:	✓		
	Beam offset (mm)	0.030	Offset:	✓		
	Hatching, X	✓	Alternating:	✓		
	Hatching, Y	✓	Rotating:	✓		
UpDown		Upskin	Downskin		4.3.5.2.2	
	Distance (mm):	0.09	0.05			
	Speed (mm):	650.0	2400.0			
	Power (W):	140.0	140.0			
	Thickness (mm):	0.12	0.16			
	X:	✓	✓			
	Y:	✓	✓			
	Alternating:	NO	Overlap with inskin(mm):	0.10		
	Skywriting:	✓	Min. length (mm)	0.10		
Skip Layer	Skipped	0			4.3.5.2.3	

	Layers	0				
	Offset layers:	0				
	Expose first layer:	✓				
Core Exposure						
Core Exposure Type	NO - Exposure				4.3.5.3	BB
Chess		Squares	Gap			
	Distance (mm):					
	Speed (mm/s):					
	Power (W):					
	Width (mm):					
	Beam offset (mm)		Overlap:			
	Hatching, X:		Alternating:			
	Hatching, Y:		Rotating:			
	Skywriting:		Rotated Angle:			
	Offset:					
Post Exposure						
Post Exposure Type	- Default - Post contours				4.3.5.4	BB
First Contour		Standard	OnPart	Downskin	4.3.5.4.1	
	Speed (mm/s):	400.0	400.0	2400.0		
	Power (W):	190.0	190.0	120.0		
	Beam Offset (mm):	0.015	Contour	✓		
	Thickness (mm):	0.080	Post Contour	✓		
	Corridor (mm):	0.100				
Second Contour		Standard	OnPart	Downskin	4.3.5.4.2	
	Speed (mm/s):	1000.0	1000.0	1000.0		
	Power (W):	0.0	0.0	0.0		
	Beam Offset (mm):	0.000	Contour	No check		

	Thickness (mm):	0.040	Post Contour	No check		
	Corridor (mm):	0.100				
Edges	Edge factor	2.00	Edges	✓	4.3.5.4.3	
	Threshold:	3.0	Post Edge	✓		
	Minimum radius factor:	0.00				
	Beam offset (mm):	0.000				
	Speed (mm/s):	600.0				
	Power (W):	100.0				

Results from Finetuning job:

X scaling: 6.122 %

Y scaling: 0.153 %

New Beam offset: 0.027

BB

Participant 3 PCD:

Process Control Document

Technical Data

Part Manufacturing Technical Data

Completed by the part manufacturer

	Value	Requirement Section	Approval
Job Number			
Build File Name:	NIST_In625	1.2	
Process		2.1.1	
Equipment Manufacturer and Model:	EOSINT M270	2.1.2	
Equipment Serial Number:			
Laser Manufacturer and Model:	IPG YLR-200-SM	2.1.4	
Laser Serial Number:	11102522		
Software Version:	PSW 3.4	0	
Date of last preventative maintenance	6-5-14	2.3	
System Calibration Current		2.4	
Material Requirements			
Verify Powder Heat/Lot Loaded Matches Feedstock Technical Data	In625 Containers 7+13 M1112012		
Material Condition (Virgin/Recycled)	Virgin	3.4	
Process Setup Requirements			
Build Platform Material	NIST provided EOS plate Charge-Nr: 26 2200-4372	4.1.1	
Build Platform Thickness	22.13mm	4.1.2	
Build Platform Condition	New	4.1.3	
Build Platform Preheat, °C	80	4.1.4	
Recoater Blade		0	

Material/Part Number	Steel					
Process Parameter Settings						
Base Parameter Set	CoCr MP1				4.3.1	
Base Parameter Filename	IN718_020_CoCr_MP1_Q<ML					
Layer Thickness, µm	.020mm				4.3.2	
Sort Parts Method:					4.3.4.2	
Exposure Parameters	Complete Exposure Parameters Table Below				4.3.5	
Pre Contour Type	_PreContours_CoCR_MP1				4.3.5.1	
Skin Exposure Type	_outerSkin_CoCr_MP1				4.3.5.2	
Core Exposure Type	_InnerSkin_CoCr_MP1				4.3.5.3	
Post Contour Type	_PostContours_CoCr_MP1				4.3.5.4	
Skin Thickness (x/y), mm	3.0				4.3.5.5	
Skin Thickness (z), mm	3.0				4.3.5.6	
Base Radius:	0				4.3.5.7	
Core open to platform?:	no				4.3.5.8	
Skin/Core:	Yes				4.3.5.9	
Scaling and Offset						
Material Specific Scaling	.1% X, % .1% Y					Y, %
Part Specific Undersize/Oversize Beam Offset, mm		4.3.6.3			4.3.6.1	.040mm
					4.3.6.2	
Building Screen						
Start Height (mm):	0.04				4.3.7.1	
Final Height (mm):	9.18				4.3.7.2	
Layer Thickness	0.020				4.3.2	
DMLS Settings						
DMLS	Off				0	Range, (mm)
Pre-exposure	On				0.06	Range, (mm)
					4.3.8.1	
					4.3.8.2	
Recoating Screen						
Minimum Charge, %	120					
Maximum Charge, %	180					
Dosing Boost, %	300					
Recoating Speeds (mm/s)	Recoating Speed 1				Recoating Speed 2	4.3.9.4, 4.3.9.5
Dosing Boost, %	500				80	

Lower Dispenser	1,0		4.3.9.6			
Platform Contact-free outward travel	Yes		4.3.9.7			
Build Time Estimation	19[illegible]:15:59					
Build Chamber Environment					0	
Purge Gas Used	Nitrogen				4.4.1	
Purge Gas Source					4.4.1	
Flow Rates					4.4.2	
Filtration					4.4.3	
Oxygen Set Point					4.4.4	
Quality Control Checks at Build Start						
System Maintenance and Cleaning Performed					4.5.1	
Pre Build Laser Power Measurement	Setpoint				Display	Measured
Pre Contour						
Stripes					4.5.2	
Up Skin						
Down Skin						
Post Contour						
Edges						
Build Platform Leveling Complete	Yes	4.5.3				
Platform Temperature	80°C				4.5.6	
Platform Level						
Oxygen Level	0.04%				4.5.7	
In Process Requirements						
Limits	Max Limit				Min Limit	Max Measured
Build Start Time	3:49pm					
Build Interruptions (If Yes, Attach Documentation per 5.2)	no				5.2	
Process Completion						
Platform Temperature at Time of Chamber Opening	26°				6.1.1,6.1.2	

Chamber Oxygen Prior to Opening	0,03%			6.1.2	
Recovered Powder Labeling				6.2	
Post Build Laser Power Measurement	Setpoint			Display	Measured
Pre Contour					
Stripes				6.1.5	
Up Skin					
Down Skin					
Post Contour					
Edges					

Exposure Parameters

Completed by the part manufacturer

	Value				Requirement Section	Approval
Job Number						
Build File Name:						
Pre Exposure						
Pre Exposure Type					4.3.5.1	
First Contour		Standard	OnPart	Downskin	4.3.5.1.1	
	Speed (mm/s):	900	800	1600		
	Power (W):	100	100	100		
	Beam Offset (mm):	0	Contour	yes		
	Thickness (mm):	0,040	Post Contour	no		
	Corridor (mm):	0,040				
Second Contour		Standard	OnPart	Downskin	4.3.5.1.2	
	Speed (mm/s):	—	—	—		
	Power (W):	—	—	—		
	Beam Offset (mm):	—	Contour	off		

	Thickness (mm):	—	Post Contour	off		
	Corridor (mm):	—				
Edges	Edge factor	—	Edges	No	4.3.5.1.3	
	Threshold:	—	Post Edge	No		
	Minimum radius factor:	—				
	Beam offset (mm):	—				
	Speed (mm/s):	—				
	Power (W):	—				
Skin Exposure						
Skin Exposure Type					4.3.5.2	
Stripes	Distance (mm):	0,1	Stripe width (mm):	4,0	4.3.5.2.1	
	Speed (mm/s):	800	Stripes overlap (mm):	0.1		
	Power (W):	195	Skywriting:	yes		
	Beam offset (mm)	0,03	Offset:	yes		
	Hatching, X	yes	Alternating:	yes		
	Hatching, Y	yes	Rotating:	yes		
UpDown		Upskin	Downskin		4.3.5.2.2	
	Distance (mm):	0,05	0.05			
	Speed (mm):	800	3000			
	Power (W):	195	195			
	Thickness (mm):	0	0.04			
	X:	yes	yes			
	Y:	yes	yes			
	Alternating:	no	Overlap with inskin(mm):	0,1		
	Skywriting:	yes	Min. length (mm)	2.0		
Skip Layer	Skipped	0			4.3.5.2.3	

	Layers					
	Offset layers:	0				
	Expose first layer:	yes				
Core Exposure						
Core Exposure Type					4.3.5.3	
Chess		Squares	Gap			
	Distance (mm):	0.1	0,1			
	Speed (mm/s):	800	800			
	Power (W):	195	195			
	Width (mm):	8.0	0			
	Beam offset (mm)	-0.05	Overlap:	0,08		
	Hatching, X:	yes	Alternating:	yes		
	Hatching, Y:	yes	Rotating:	yes		
	Skywriting:	no	Rotated Angle:	—		
	Offset:	yes				
Post Exposure						
Post Exposure Type					4.3.5.4	
First Contour		Standard	OnPart	Downskin	4.3.5.4.1	
	Speed (mm/s):	900	800	1600		
	Power (W):	120	120	120		
	Beam Offset (mm):	0,015	Contour	yes		
	Thickness (mm):	0,040	Post Contour	yes		
	Corridor (mm):	0.040				
Second Contour		Standard	OnPart	Downskin	4.3.5.4.2	
	Speed (mm/s):	—	—	—		
	Power (W):	—	—	—		
	Beam Offset (mm):	—	Contour	no		

	Thickness (mm):	—	Post Contour	no		
	Corridor (mm):	—				
Edges	Edge factor	2.0	Edges	yes	4.3.5.4.3	
	Threshold:	3.0	Post Edge	yes		
	Minimum radius factor:	0				
	Beam offset (mm):	0				
	Speed (mm/s):	900				
	Power (W):	100				

Participant 4 PCD:

Process Control Document

Technical Data

Part Manufacturing Technical Data

Completed by the part manufacturer

	Value	Requirement Section	Approval
Job Number	8-11-2014		
Build File Name:	IN625NISTROUNDROBIN.eosjob	1.2	
Process	DMLS	2.1.1	
Equipment Manufacturer and Model:	EOSINT M270	2.1.2	
Equipment Serial Number:	SI 987		
Laser Manufacturer and Model:		2.1.4	
Laser Serial Number:			
Software Version:	PSW 3.6	2.2	
Date of last preventative maintenance	May 28	2.3	
System Calibration Current	May 28	2.4	
Material Requirements			
Verify Powder Heat/Lot Loaded Matches Feedstock Technical Data	Use SEM with EDS to verify the powder met specification		
Material Condition (Virgin/Recycled)	**Virgin**	3.4	
Process Setup Requirements			
Build Platform Material	1045 steel	4.1.1	
Build Platform Thickness	**~20mm**	4.1.2	
Build Platform Condition	Good	4.1.3	

Build Platform Preheat, °C	80°C				4.1.4	
Recoater Blade Material/Part Number	EOS ceramic blade				4.2	
Process Parameter Settings						
Base Parameter Set	MP1 Performance				4.3.1	
Base Parameter Filename	MP1_Performance_101.eosjob					
Layer Thickness, µm	40				4.3.2	
Sort Parts Method:					4.3.4.2	
Exposure Parameters	Complete Exposure Parameters Table Below				4.3.5	
Pre Contour Type					4.3.5.1	
Skin Exposure Type					4.3.5.2	
Core Exposure Type					4.3.5.3	
Post Contour Type					4.3.5.4	
Skin Thickness (x/y), mm					4.3.5.5	
Skin Thickness (z), mm					4.3.5.6	
Base Radius:					4.3.5.7	
Core open to platform?:					4.3.5.8	
Skin/Core:					4.3.5.9	
Scaling and Offset	.032					
Material Specific Scaling	X, %.19					Y, %.23
Part Specific Undersize/Oversize Beam Offset, mm		4.3.6.3			4.3.6.1	
					4.3.6.2	
Building Screen						
Start Height (mm):					4.3.7.1	
Final Height (mm):					4.3.7.2	
Layer Thickness					4.3.2	
DMLS Settings						
DMLS	Off					Range, (mm)
Pre-exposure	On					Range, (mm)
					4.3.8.1	
					4.3.8.2	
Recoating Screen						
Minimum Charge, %	120					
Maximum Charge, %	150					
Dosing Boost, %	300					

Recoating Speeds (mm/s)	Recoating Speed 1				Recoating Speed 2	4.3.9.4, 4.3.9.5
Dosing Boost, %						
Lower Dispenser Platform		4.3.9.6				
Contact-free outward travel		4.3.9.7				
Build Time Estimation	~11 hours					
Build Chamber Environment	Good				0	
Purge Gas Used	Nitrogen				4.4.1	
Purge Gas Source	Compressed Air				4.4.1	
Flow Rates					4.4.2	
Filtration	1.5setting, not clogged				4.4.3	
Oxygen Set Point	1.3wt%				4.4.4	
Quality Control Checks at Build Start						
System Maintenance and Cleaning Performed					4.5.1	
Pre Build Laser Power Measurement	Setpoint				Display	Measured
Pre Contour						
Stripes					4.5.2	
Up Skin						
Down Skin						
Post Contour						
Edges						
Build Platform Leveling Complete		4.5.3				
Platform Temperature					4.5.6	
Platform Level						
Oxygen Level					4.5.7	
In Process Requirements						
Limits	Max Limit				Min Limit	Max Measured
Build Start Time	12pm	Aug.	11			
Build Interruptions (If Yes, Attach Documentation per 5.2)	No				5.2	
Process Completion						

Platform Temperature at Time of Chamber Opening				6.1.1,6.1.2	
Chamber Oxygen Prior to Opening	The chamber was opened several hours after build was completed			6.1.2	
Recovered Powder Labeling				6.2	
Post Build Laser Power Measurement	Setpoint			Display	Measured
Pre Contour					
Stripes				6.1.5	
Up Skin					
Down Skin					
Post Contour					
Edges					

Exposure Parameters

Completed by the part manufacturer

	Value				**Requirement Section**	**Approval**
Job Number						
Build File Name:						
Pre Exposure						
Pre Exposure Type					4.3.5.1	
First Contour		Standard	OnPart	Downskin	4.3.5.1.1	
	Speed (mm/s):					
	Power (W):					
	Beam Offset (mm):		Contour			
	Thickness (mm):		Post Contour			
	Corridor (mm):					
Second Contour		Standard	OnPart	Downskin	4.3.5.1.2	
	Speed (mm/s):					
	Power (W):					

	Beam Offset (mm):		Contour			
	Thickness (mm):		Post Contour			
	Corridor (mm):					
Edges	Edge factor		Edges		4.3.5.1.3	
	Threshold:		Post Edge			
	Minimum radius factor:					
	Beam offset (mm):					
	Speed (mm/s):					
	Power (W):					
Skin Exposure						
Skin Exposure Type					4.3.5.2	
Stripes	Distance (mm):		Stripe width (mm):		4.3.5.2.1	
	Speed (mm/s):		Stripes overlap (mm):			
	Power (W):		Skywriting:			
	Beam offset (mm)		Offset:			
	Hatching, X		Alternating:			
	Hatching, Y		Rotating:			
UpDown		Upskin	Downskin		4.3.5.2.2	
	Distance (mm):					
	Speed (mm):					
	Power (W):					
	Thickness (mm):					
	X:					
	Y:					
	Alternating:		Overlap with inskin(mm):			

	Skywriting:		Min. length (mm)			
Skip Layer	Skipped Layers				4.3.5.2.3	
	Offset layers:					
	Expose first layer:					
Core Exposure						
Core Exposure Type					4.3.5.3	
Chess		Squares	Gap			
	Distance (mm):					
	Speed (mm/s):					
	Power (W):					
	Width (mm):					
	Beam offset (mm)		Overlap:			
	Hatching, X:		Alternating:			
	Hatching, Y:		Rotating:			
	Skywriting:		Rotated Angle:			
	Offset:					
Post Exposure						
Post Exposure Type					4.3.5.4	
First Contour		Standard	OnPart	Downskin	4.3.5.4.1	
	Speed (mm/s):					
	Power (W):					
	Beam Offset (mm):		Contour			
	Thickness (mm):		Post Contour			
	Corridor (mm):					
Second Contour		Standard	OnPart	Downskin	4.3.5.4.2	
	Speed (mm/s):					
	Power (W):					

	Beam Offset (mm):		Contour			
	Thickness (mm):		Post Contour			
	Corridor (mm):					
Edges	Edge factor		Edges		4.3.5.4.3	
	Threshold:		Post Edge			
	Minimum radius factor:					
	Beam offset (mm):					
	Speed (mm/s):					
	Power (W):					

Participant 5 PCD

Process Control Document

Technical Data

Part Manufacturing Technical Data

Completed by the part manufacturer: *September 16th 2014*

	Value	Requirement Section	Approval
Job Number			
Build File Name:	AM_Round Robin_Inconel 625	1.2	GJ
Process	Laser Powder Bed Fusion	2.1.1	GJ
Equipment Manufacturer and Model:	EOS M270, year of production: 2010	2.1.2	GJ
Equipment Serial Number:	992		GJ
Laser Manufacturer and Model:	IPG, YLR-200-SM-EOS	2.1.4	GJ
Laser Serial Number:	10061428		GJ
Software Version:	PSW, Version 3.5 (Build 71)	2.2	GJ
Date of last preventative maintenance	June 2nd unit June 6th 2014 performed by Mr. Jay Thornburg	2.3	GJ
System Calibration Current	August 22nd 2014	2.4	GJ
Material Requirements			
Verify Powder Heat/Lot Loaded Matches Feedstock Technical Data	EOS_IN625 Lot. No.: 111201_2 Buckets: #4 and #12		GJ
Material Condition (Virgin/Recycled)	**virgin**	3.4	**GJ**
Process Setup Requirements			
Build Platform Material	AlSi 1045 steel, charge no.: 2200 - 4372	4.1.1	GJ
Build Platform Thickness	**22.4 mm**	4.1.2	**GJ**
Build Platform Condition	Virgin, unused	4.1.3	GJ
Build Platform Preheat, °C	80	4.1.4	GJ

Recoater Blade Material/Part Number	HSS 2200_3013				4.2	GJ
Process Parameter Settings						
Base Parameter Set	NIST: MP1_020_100_IN625_020_NIST_V1.eosjob				4.3.1	GJ
Base Parameter Filename	EOS_MP1_020_100_Surface					GJ
Layer Thickness, µm	20				4.3.2	GJ
Sort Parts Method:	Group: alternating between front to back				4.3.4.2	GJ
Exposure Parameters	Complete Exposure Parameters Table Below				4.3.5	
Pre Contour Type	NIST_PreContour_RR_IN625				4.3.5.1	GJ
Skin Exposure Type	NIST_OuterSkin_RR_IN625				4.3.5.2	GJ
Core Exposure Type	NIST_InnterSkin_RR_IN625				4.3.5.3	GJ
Post Contour Type	NIST_PreContour_RR_IN625				4.3.5.4	GJ
Skin Thickness (x/y), mm	3.00				4.3.5.5	GJ
Skin Thickness (z), mm	3.00				4.3.5.6	GJ
Base Radius:	0.00				4.3.5.7	GJ
Core open to platform?:	No				4.3.5.8	GJ
Skin/Core:	Yes				4.3.5.9	GJ
Scaling and Offset						
Material Specific Scaling	X, 0.209%		Y, 0.375%			GJ
Part Specific Undersize/Oversize Beam Offset, mm	0.048	4.3.6.3		0.00	4.3.6.1	GJ
				0.00	4.3.6.2	GJ
Building Screen						
Start Height (mm):	0.02				4.3.7.1	GJ
Final Height (mm):	9.16				4.3.7.2	GJ
Layer Thickness (mm)	0.02				4.3.2	GJ
DMLS Settings						
DMLS	Off				---	Range, (mm)
Pre-exposure	On				0.06	Range, (mm)
					4.3.8.1	GJ
					4.3.8.2	GJ
Recoating Screen						
Minimum Charge, %	150					GJ
Maximum Charge, %	200					GJ
Dosing Boost, %	300					GJ
Recoating Speeds (mm/s)	Recoating Speed 1: 500 Recoating Speed 2: 80					4.3.9.4, 4.3.9.5

Dosing Boost, %			
Lower Dispenser Platform	1.00 mm 4.3.9.6		GJ
Contact-free outward travel	Yes 4.3.9.7		
Build Time Estimation	18:47 (hh:mm)		GJ
Build Chamber Environment		0	
Purge Gas Used	Nitrogen	4.4.1	GJ
Purge Gas Source	Nitrogen generator	4.4.1	GJ
Flow Rates	---	4.4.2	
Filtration	1.5	4.4.3	GJ
Oxygen Set Point	1.3 %	4.4.4	GJ
Quality Control Checks at Build Start			
System Maintenance and Cleaning Performed	Yes	4.5.1	GJ
Pre Build Laser Power Measurement	Not performed before the RR build started. (But after the build was finished and the lens cleaned)	Display	Measured Sep. 18th
Pre Contour	100 20 sec.		101.5 W
Stripes	195 20 sec.	4.5.2	196.8 W
Up Skin	195 20 sec.		197.8 W
Down Skin	195 20 sec.		196.1 W
Post Contour	120 20 sec.		118.7 W
Edges	100 20 sec.		101.9 W
Build Platform Leveling Complete	Yes 4.5.3		GJ
Platform Temperature	81 °C	4.5.6	GJ
Platform Level	---		
Oxygen Level	0.9 %	4.5.7	GJ
In Process Requirements			
Limits	Max Limit	Min Limit	Max Measured
Build Start Time	04:30 PM Sep. 16th 2014		
Build Interruptions (If Yes, Attach Documentation per 5.2)	No interruptions Successfully finished	5.2	GJ
Process Completion			
Platform Temperature at Time of Chamber Opening	80	6.1.1,6.1.2	GJ
Chamber Oxygen Prior to Opening	0.5	6.1.2	GJ

Recovered Powder Labeling	Yes			6.2	GJ
Post Build Laser Power Measurement	Setpoint (After the was finished and the lens untouched)			Display	Measured Sep. 18th
Pre Contour	100	20 sec.			100.8 W
Stripes	195	20 sec.		6.1.5	194.4 W
Up Skin	195	20 sec.			195.8 W
Down Skin	195	20 sec.			196.2 W
Post Contour	120	20 sec.			119.4 W
Edges	100	20 sec.			101.5 W

Exposure Parameters

Completed by the part manufacturer: *September 16th 2014*

	Value				Requirement Section	Approval
Job Number	---					
Build File Name:	AM_Round Robin_Inconel 625.eosjob					
Pre Exposure						
Pre Exposure Type	NIST_PreContour_RR_IN625				4.3.5.1	
First Contour		Standard	OnPart	Downskin	4.3.5.1.1	
	Speed (mm/s):	900.0	800.0	1600.0		
	Power (W):	100.0	100.0	100.0		
	Beam Offset (mm):	0.000	Contour	Yes		
	Thickness (mm):	0.040	Post Contour	No		
	Corridor (mm):	0.040				
Second Contour		Standard	OnPart	Downskin	4.3.5.1.2	
	Speed (mm/s):	50	50	50		
	Power (W):	0	0	0		
	Beam Offset (mm):	0.000	Contour	No		
	Thickness (mm):	0.040	Post Contour	No		

	Corridor (mm):	0.040				
Edges	Edge factor	2.0	Edges	No	4.3.5.1.3	
	Threshold:	3.0	Post Edge	No		
	Minimum radius factor:	0.000				
	Beam offset (mm):	0.000				
	Speed (mm/s):	50				
	Power (W):	0				
Skin Exposure Type	NIST_OuterSkin_RR_IN625				4.3.5.2	
Stripes	Distance (mm):	0.10	Stripe width (mm):	4.00	4.3.5.2.1	
	Speed (mm/s):	800.0	Stripes overlap (mm):	0.10		
	Power (W):	195	Skywriting:	Yes		
	Beam offset (mm)	0.030	Offset:	Yes		
	Hatching, X	Yes	Alternating:	Yes		
	Hatching, Y	Yes	Rotating:	Yes		
			Rot. Angle:	67 °		
UpDown		Upskin	Downskin		4.3.5.2.2	
	Distance (mm):	0.05	0.05			
	Speed (mm):	800.0	3000.0			
	Power (W):	195.0	195.0			
	Thickness (mm):	0.00	0.04			
	X:	Yes	Yes			
	Y:	Yes	Yes			
	Alternating:	No	Overlap with inskin(mm):	0.10		
	Skywriting:	Yes	Min. length (mm)	2.00		
Skip Layer	Skipped Layers	0			4.3.5.2.3	

	Offset layers:	0				
	Expose first layer:	Yes				
Core Exposure Type	NIST_InnterSkin_RR_IN625				4.3.5.3	
Chess		Squares	Gap		4.3.5.3.1	
	Distance (mm):	0.10	0.10			
	Speed (mm/s):	800.0	800.0			
	Power (W):	195.0	195.0			
	Width (mm):	8.00	0.00			
	Beam offset (mm)	-0.050	Overlap:	0.08		
	Hatching, X:	Yes	Alternating:	Yes		
	Hatching, Y:	Yes	Rotating:	Yes		
	Skywriting:	No	Rotated Angle:	67 °		
	Offset:	Yes				
Skip Layer	Skipped Layers	1			4.3.5.3.2	
	Offset layers:	0				
	Expose first layer:	Yes				
Post Exposure Type	NIST_PreContour_RR_IN625				4.3.5.4	
First Contour		Standard	OnPart	Downskin	4.3.5.4.1	
	Speed (mm/s):	900.0	800.0	1600.0		
	Power (W):	120.0	120.0	120.0		
	Beam Offset (mm):	0.015	Contour	Yes		
	Thickness (mm):	0.040	Post Contour	Yes		
	Corridor (mm):	0.040				
Second Contour		Standard	OnPart	Downskin	4.3.5.4.2	

	Speed (mm/s):	50	50	50		
	Power (W):	0	0	0		
	Beam Offset (mm):	0	Contour	No		
	Thickness (mm):	0.06	Post Contour	No		
	Corridor (mm):	0.04				
Edges	Edge factor	2.00	Edges	Yes	4.3.5.4.3	
	Threshold:	3.0	Post Edge	Yes		
	Minimum radius factor:	0.00				
	Beam offset (mm):	0.000				
	Speed (mm/s):	900.0				
	Power (W):	100.0				

Participant 6 PCD:

Process Control Document

Technical Data

Part Manufacturing Technical Data

Completed by the part manufacturer

	Value	Requirement Section	Approval
Job Number			
Build File Name:	NIST_RoundRobbin_IN625	1.2	
Process		2.1.1	
Equipment Manufacturer and Model:	EOS INT M270D	2.1.2	
Equipment Serial Number:	1088		
Laser Manufacturer and Model:	IPG Laser YLR-200-SM	2.1.4	
Laser Serial Number:			
Software Version:	PSW 3.5 (71)	2.2	
Date of last preventative maintenance	September 2014	2.3	
System Calibration Current	yes	2.4	
Material Requirements			
Verify Powder Heat/Lot Loaded Matches Feedstock Technical Data	EOS Nickel Alloy IN 625 LOT M111201-2 Bucket #1 and #10		
Material Condition (Virgin/Recycled)	**Virgin**	3.4	
Process Setup Requirements			
Build Platform Material	NIST provided	4.1.1	
Build Platform Thickness		4.1.2	
Build Platform Condition		4.1.3	

Build Platform Preheat, °C					4.1.4	
Recoater Blade Material/Part Number					4.2	
Process Parameter Settings						
Base Parameter Set					4.3.1	
Base Parameter Filename						
Layer Thickness, µm	20				4.3.2	
Sort Parts Method:					4.3.4.2	
Exposure Parameters	Complete Exposure Parameters Table Below				4.3.5	
Pre Contour Type					4.3.5.1	
Skin Exposure Type					4.3.5.2	
Core Exposure Type					4.3.5.3	
Post Contour Type					4.3.5.4	
Skin Thickness (x/y), mm					4.3.5.5	
Skin Thickness (z), mm					4.3.5.6	
Base Radius:					4.3.5.7	
Core open to platform?:					4.3.5.8	
Skin/Core:					4.3.5.9	
Scaling and Offset	0%					
Material Specific Scaling	X, 0%					Y,0 %
Part Specific Undersize/Oversize Beam Offset, mm	0	4.3.6.3 0	0	0	4.3.6.1	
					4.3.6.2	
Building Screen						
Start Height (mm):	.020mm				4.3.7.1	
Final Height (mm):	9.180mm				4.3.7.2	
Layer Thickness	.020mm				4.3.2	
DMLS Settings						
DMLS	Off					Range, (mm)
Pre-exposure	On					Range, (mm)
					4.3.8.1	
					4.3.8.2	
Recoating Screen						
Minimum Charge, %	150%					
Maximum Charge, %	200%					
Dosing Boost, %	300%					

Recoating Speeds (mm/s)	Recoating Speed 1 500 mm/s					Recoating Speed 2 80 mm/s	4.3.9.4, 4.3.9.5
Dosing Boost, %							
Lower Dispenser Platform Contact-free outward travel				4.3.9.6 4.3.9.7			
Build Time Estimation							
Build Chamber Environment						0	
Purge Gas Used	nitrogen					4.4.1	
Purge Gas Source	Internal generator					4.4.1	
Flow Rates						4.4.2	
Filtration						4.4.3	
Oxygen Set Point						4.4.4	
Quality Control Checks at Build Start							
System Maintenance and Cleaning Performed						4.5.1	
Pre Build Laser Power Measurement	Setpoint					Display	Measured
Pre Contour							
Stripes						4.5.2	
Up Skin							
Down Skin							
Post Contour							
Edges							
Build Platform Leveling Complete		4.5.3					
Platform Temperature						4.5.6	
Platform Level							
Oxygen Level						4.5.7	
In Process Requirements							
Limits	Max Limit					Min Limit	Max Measured
Build Start Time							
Build Interruptions (If Yes, Attach Documentation per 5.2)	Build stopped numerous times. Once for an early blade impact and twice for short feeding. Adjustments were made to correct.					5.2	

Process Completion					
Platform Temperature at Time of Chamber Opening				6.1.1,6.1.2	
Chamber Oxygen Prior to Opening				6.1.2	
Recovered Powder Labeling				6.2	
Post Build Laser Power Measurement	Setpoint			Display	Measured
Pre Contour					
Stripes				6.1.5	
Up Skin					
Down Skin					
Post Contour					
Edges					

Exposure Parameters

Completed by the part manufacturer

	Value				Requirement Section	Approval
Job Number						
Build File Name:						
Pre Exposure						
Pre Exposure Type					4.3.5.1	
First Contour		Standard	OnPart	Downskin	4.3.5.1.1	
	Speed (mm/s):					
	Power (W):					
	Beam Offset (mm):		Contour			
	Thickness (mm):		Post Contour			
	Corridor (mm):					
Second Contour		Standard	OnPart	Downskin	4.3.5.1.2	
	Speed (mm/s):					

	Power (W):					
	Beam Offset (mm):		Contour			
	Thickness (mm):		Post Contour			
	Corridor (mm):					
Edges	Edge factor		Edges		4.3.5.1.3	
	Threshold:		Post Edge			
	Minimum radius factor:					
	Beam offset (mm):					
	Speed (mm/s):					
	Power (W):					
Skin Exposure						
Skin Exposure Type					4.3.5.2	
Stripes	Distance (mm):		Stripe width (mm):		4.3.5.2.1	
	Speed (mm/s):		Stripes overlap (mm):			
	Power (W):		Skywriting:			
	Beam offset (mm)		Offset:			
	Hatching, X		Alternating:			
	Hatching, Y		Rotating:			
UpDown		Upskin	Downskin		4.3.5.2.2	
	Distance (mm):					
	Speed (mm):					
	Power (W):					
	Thickness (mm):					
	X:					
	Y:					

	Alternating:		Overlap with inskin(mm):			
	Skywriting:		Min. length (mm)			
Skip Layer	Skipped Layers				4.3.5.2.3	
	Offset layers:					
	Expose first layer:					
Core Exposure						
Core Exposure Type					4.3.5.3	
Chess		Squares	Gap			
	Distance (mm):					
	Speed (mm/s):					
	Power (W):					
	Width (mm):					
	Beam offset (mm)		Overlap:			
	Hatching, X:		Alternating:			
	Hatching, Y:		Rotating:			
	Skywriting:		Rotated Angle:			
	Offset:					
Post Exposure						
Post Exposure Type					4.3.5.4	
First Contour		Standard	OnPart	Downskin	4.3.5.4.1	
	Speed (mm/s):					
	Power (W):					
	Beam Offset (mm):		Contour			
	Thickness (mm):		Post Contour			
	Corridor (mm):					
Second Contour		Standard	OnPart	Downskin	4.3.5.4.2	

	Speed (mm/s):					
	Power (W):					
	Beam Offset (mm):		Contour			
	Thickness (mm):		Post Contour			
	Corridor (mm):					
Edges	Edge factor		Edges		4.3.5.4.3	
	Threshold:		Post Edge			
	Minimum radius factor:					
	Beam offset (mm):					
	Speed (mm/s):					
	Power (W):					

Participant 7 PCD

Process Control Document

Technical Data

Part Manufacturing Technical Data

Completed by the part manufacturer

	Value	Requirement Section	Approval
Job Number			
Build File Name:		1.2	
Process		2.1.1	
Equipment Manufacturer and Model:		2.1.2	
Equipment Serial Number:			
Laser Manufacturer and Model:		2.1.4	
Laser Serial Number:			
Software Version:		2.2	
Date of last preventative maintenance		2.3	
System Calibration Current		2.4	
Material Requirements			
Verify Powder Heat/Lot Loaded Matches Feedstock Technical Data			
Material Condition (Virgin/Recycled)		3.4	
Process Setup Requirements			
Build Platform Material		4.1.1	
Build Platform Thickness		4.1.2	
Build Platform Condition		4.1.3	

Build Platform Preheat, °C					4.1.4	
Recoater Blade Material/Part Number					4.2	
Process Parameter Settings						
Base Parameter Set					4.3.1	
Base Parameter Filename						
Layer Thickness, µm					4.3.2	
Sort Parts Method:					4.3.4.2	
Exposure Parameters	Complete Exposure Parameters Table Below				4.3.5	
Pre Contour Type					4.3.5.1	
Skin Exposure Type					4.3.5.2	
Core Exposure Type					4.3.5.3	
Post Contour Type					4.3.5.4	
Skin Thickness (x/y), mm					4.3.5.5	
Skin Thickness (z), mm					4.3.5.6	
Base Radius:					4.3.5.7	
Core open to platform?:					4.3.5.8	
Skin/Core:					4.3.5.9	
Scaling and Offset						
Material Specific Scaling	X, %					Y, %
Part Specific Undersize/Oversize Beam Offset, mm		4.3.6.3			4.3.6.1	
					4.3.6.2	
Building Screen						
Start Height (mm):					4.3.7.1	
Final Height (mm):					4.3.7.2	
Layer Thickness					4.3.2	
DMLS Settings						
DMLS	Off					Range, (mm)
Pre-exposure	On					Range, (mm)
					4.3.8.1	
					4.3.8.2	
Recoating Screen						
Minimum Charge, %						
Maximum Charge, %						
Dosing Boost, %						

Recoating Speeds (mm/s)	Recoating Speed 1	Recoating Speed 2	4.3.9.4, 4.3.9.5
Dosing Boost, %			
Lower Dispenser Platform Contact-free outward travel	4.3.9.6 4.3.9.7		
Build Time Estimation			
Build Chamber Environment		0	
Purge Gas Used		4.4.1	
Purge Gas Source		4.4.1	
Flow Rates		4.4.2	
Filtration		4.4.3	
Oxygen Set Point		4.4.4	
Quality Control Checks at Build Start			
System Maintenance and Cleaning Performed		4.5.1	
Pre Build Laser Power Measurement	Setpoint	Display	Measured
Pre Contour			
Stripes		4.5.2	
Up Skin			
Down Skin			
Post Contour			
Edges			
Build Platform Leveling Complete	4.5.3		
Platform Temperature		4.5.6	
Platform Level			
Oxygen Level		4.5.7	
In Process Requirements			
Limits	Max Limit	Min Limit	Max Measured
Build Start Time			
Build Interruptions (If Yes, Attach Documentation per 5.2)		5.2	
Process Completion			

Platform Temperature at Time of Chamber Opening				6.1.1,6.1.2	
Chamber Oxygen Prior to Opening				6.1.2	
Recovered Powder Labeling				6.2	
Post Build Laser Power Measurement	Setpoint			Display	Measured
Pre Contour					
Stripes				6.1.5	
Up Skin					
Down Skin					
Post Contour					
Edges					

Exposure Parameters

Completed by the part manufacturer

	Value				Requirement Section	Approval
Job Number						
Build File Name:	20140916.SLM					
Pre Exposure						
Pre Exposure Type					4.3.5.1	
First Contour (Volume Border)		Standard	OnPart	Downskin	4.3.5.1.1	
	Speed (mm/s):	400				
	Power (W):	125				
	Beam Offset (mm):	3.0	Contour			
	Thickness (mm):	.05	Post Contour			
	Corridor (mm):					
Second Contour		Standard	OnPart	Downskin	4.3.5.1.2	
	Speed (mm/s):					
	Power (W):					

	Beam Offset (mm):		Contour			
	Thickness (mm):		Post Contour			
	Corridor (mm):					
Edges	Edge factor		Edges		4.3.5.1.3	
	Threshold:		Post Edge			
	Minimum radius factor:					
	Beam offset (mm):					
	Speed (mm/s):					
	Power (W):					
Skin Exposure						
Skin Exposure Type					4.3.5.2	
Stripes	Distance (mm):		Stripe width (mm):		4.3.5.2.1	
	Speed (mm/s):		Stripes overlap (mm):			
	Power (W):		Skywriting:			
	Beam offset (mm)		Offset:			
	Hatching, X		Alternating:			
	Hatching, Y		Rotating:			
UpDown		Upskin	Downskin		4.3.5.2.2	
	Distance (mm):					
	Speed (mm):					
	Power (W):					
	Thickness (mm):					
	X:					
	Y:					
	Alternating:		Overlap with inskin(mm):			

	Skywriting:		Min. length (mm)			
Skip Layer	Skipped Layers				4.3.5.2.3	
	Offset layers:					
	Expose first layer:					
Core Exposure						
Core Exposure Type					4.3.5.3	
Chess (Volume Area)		Squares	Gap			
	Distance (mm):					
	Speed (mm/s):	500				
	Power (W):	200				
	Width (mm):					
	Beam offset (mm)	3.0	Overlap:			
	Hatching, X:	0.110	Alternating:			
	Hatching, Y:		Rotating:			
	Skywriting:		Rotated Angle:			
	Offset:					
Post Exposure						
Post Exposure Type					4.3.5.4	
First Contour (Volume Offset)		Standard	OnPart	Downskin	4.3.5.4.1	
	Speed (mm/s):	400				
	Power (W):	100				
	Beam Offset (mm):	4.0	Contour			
	Thickness (mm):		Post Contour			
	Corridor (mm):					
Second Contour		Standard	OnPart	Downskin	4.3.5.4.2	
	Speed (mm/s):					
	Power (W):					

	Beam Offset (mm):		Contour			
	Thickness (mm):		Post Contour			
	Corridor (mm):					
Edges	Edge factor		Edges		4.3.5.4.3	
	Threshold:		Post Edge			
	Minimum radius factor:					
	Beam offset (mm):					
	Speed (mm/s):					
	Power (W):					