Final Report

Metals AM Design for Manufacturing

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Statement of Disclaimer

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Introduction

We are looking to improve upon the current post processing techniques for metal additive manufacturing (AM). This project, sponsored by Lawrence Livermore National Laboratory (LLNL), will investigate ways to improve the design of stainless steel 316 parts made by AM, and how these designs will help with post processing techniques. We hope that the findings regarding stainless steel will apply to to improve the AM and post processing handshake in general. In particular, the project will focus on including different features in different basic part design shapes to aid in fixturing and post-processing of the part made by AM. This will largely focus on including features for kinematic mounting that can be used to fixture the part in a machine for post processing or for inspection. Kinematic mounts will be added to parts that are to be milled and extension will be added to parts processed by the mill. This type of mounting can improve the accuracy of the part orientation in the machines as well as making positioning of the part more easily repeatable. Various ways of incorporating these mounts into the part design will be tested with post-processing to determine the most beneficial configuration. The information gathered will be used to create a design guide for LLNL to use with their AM processes when determining which type of mounting system would be the most useful in each situation.

Background

There are many steps that must be undertaken to bring a design from conceptualization to a manufactured physical part using additive manufacturing. A design begins as a 3D Computer Aided Design (CAD) model created via SolidWorks or another CAD program. Once its form and dimensions are finalized, the CAD file can be saved as an STL file, which saves the 3D model without additional construction data, much like how a PDF can be created from a word processing document as if it were printed. The generated STL file can then be processed by an AM system's software, which an operator uses to determine parameters such as build orientation, scale, or number of parts made in one machine cycle. Once the AM machine is set up, the machine cycle can be started to create the design. A slicer program assigns 2D layers which are stacked to create the part. After the parts are finished being built, parts are removed from the build plate using tools such as a band saw or EDM.

How AM Works

While there are a multitude of powder bed fusion (PBF) processes the basic steps are all relatively similar and tend to follow the Selective Laser Melting (SLM) approach. Thin layers of powder (approximately .03-.05 mm thick) are spread across the build surface usually with a roller. This powder is often maintained at an elevated temperature using infrared heaters or resistive heaters within the build platform. This reduces the power requirements for the laser to melt the material as the temperature rise needed has been diminished. Also this cuts down on the amountof warping of the part due to thermal expansion or contraction.

Fusion Methods

The most commonly used fusion mechanism for metal alloys is full melting. In this process the entire region of material is melted and then re-solidified with a new bonded layer. It should be kept in mind that full melting does result in part growth which needs to be accounted for either in a shrinking of the actual design or in post processing.

The machine at LLNL that will be used in this study makes use of a Selective Laser Melting (SLM) process similar to those just discussed. It is a process in which thin layers of metal powder are spread over the build surface and fused through melting via laser. With SLM, this takes place inside a chamber filled with an inert gas, see Figure 1. The lasers used in SLM are powerful enough to result in full melting as discussed above.

When designing for AM, part orientation within the machine can drastically affect the part's physical properties. While the inclusion of supports can keep a part from moving or warping during a build cycle, it is best to minimize their use in a design to eliminate additional post processing. Oftentimes, parts can be too big for an AM machine to build, so splitting a part in two to be built then assembling afterwards is recommended.

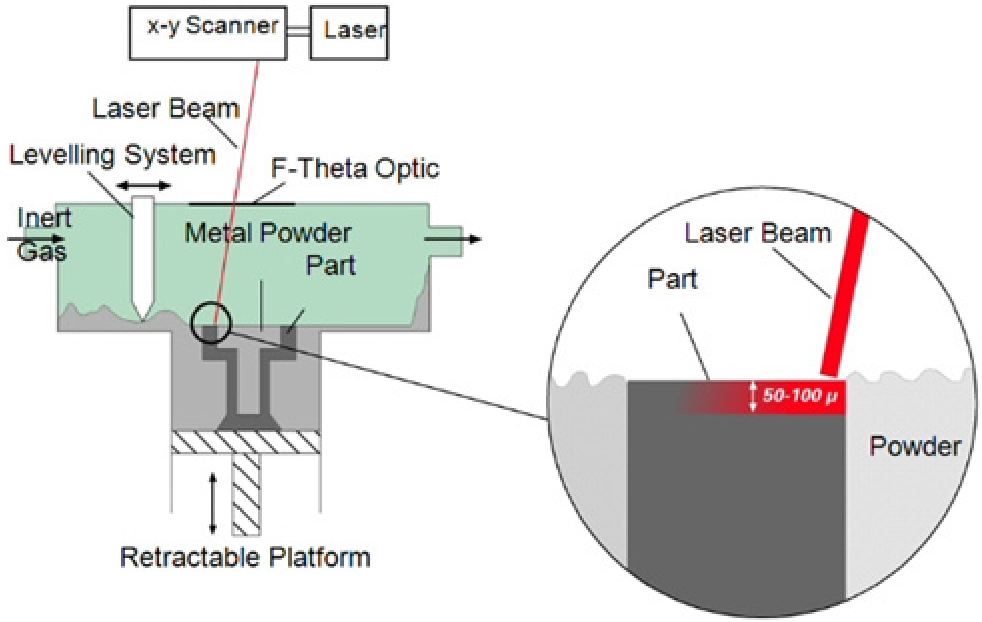

Figure 1. Diagram of SLM machine

Supports

Supports are a common part of the AM build process. Supports are used in the AM process as a byproduct of the build process. These supports help resist distortion while the part is being made. In addition to having supports, the orientation and location of the part in the machine is critical to production time and surface finish of the parts being built. Parts built in the wrong orientation can increase production time dramatically, as many more layers of powder will need to be used to complete the part. AFter the build process, the supports can easily be removed from the part.

Surface Finish

There are a variety of different surface finishes that can be accomplished with additive manufacturing through various post processing techniques. Matte finishes are made through bead blasting. Wet or dry sanding can give a smooth, polished finish. Tumbling is commonly used for external surface finish while abrasive flow machining is used to smooth the inside of parts.

While these methods do improve the surface finish, they can also have a negative impact on the form of the part by rounding corners in ways that were not originally intended. To create finer Dyes and chromes can be added on the part after the previously mentioned processes to create even finer surface finishes.

Accuracy

Accuracy of build parts is very important to consider when applying post processing methods on parts made through AM. The typical AM machine can make parts within a few thousandths of an inch. If parts are made quickly then parts will be less accurate. Computer programs are built into AM machines which can scale the part so they are built more accurately. For example, AM machines can scale parts in order to account for shrinkage by altering the STL file and making it bigger or adding skin.

Kinematic Mounts

Kinematic mounts can be used to simplify the process of positioning a part in multiple machines by creating repeatability of the same orientation every time. The kinematic mount is a way to constrain the part in all six degrees of freedom without being over constrained. Because the mount requires the part to be constrained in a specific orientation the set-up process is much quicker. Once the datums have been specified the first time they do not need to be re-specified every time the part is in the machine, thus reducing the required time for the process to be carried out.

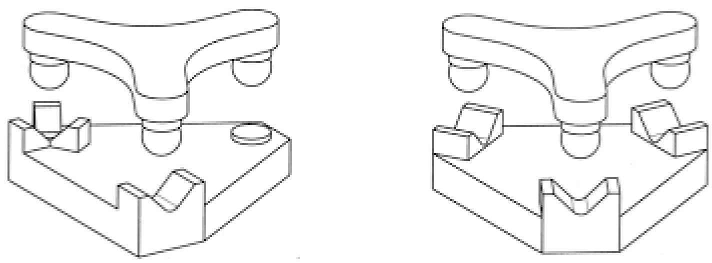

Figure 2. Two types of kinematic mounts. On the left is the V, cone, and flat method, while on the right is the three V method. The bottom piece would be fixed in the machine while the top piece would be connected to the part.

These features perfectly constrain the orientation of the part in the machine, but it still will need to be clamped down so that it does not move while being machined (seen in the post processing section). The most effective way to clamp parts in these types of mounts is to align the clamps with the mating features. In other words the clamp would come down directly above the ball and V contact points.

Design Requirements and Specifications

Our objective is to improve post processing techniques and design for post processing for metal additive manufacturing.

After the parts are manufactured many different post processing techniques can be applied to the parts although it is efficient to maintain the same orientation while these processes are applied. A mounting feature needs to be added to the parts or the build plate in order to aid with post processing orientation. A kinematic mount is the easiest feature to add to a part to create precision and repeatability of post processing techniques. Different types of kinematic mounting are needed for the varying geometries and different post processing methods. Where kinematic mounts are unnecessary or are incompatible with the parts, kinematic mounting works with gravity, and where gravity cannot be used a different mounting technique is needed, different mounting features can be developed to allow different post processing methods.

The metrics we are to evaluate directly relate to the cost of producing different AM parts. Parts made with AM should be able to meet a certain tolerance which is specified by the maker of the machine. Parts that do not meet the necessary tolerances are a waste of money, and cost the manufacturer to lose much time. Time in building AM parts is very important as it directly relates to the cost of a part. The longer it takes to build a part, the more it costs. By building parts with AM and creating new designs, the time it takes to make a part should decrease. The surface finish of AM parts is not always what the customer wants, so it is necessary to consider surface finish when trying to find total cost.

The total cost of producing the parts will determine if building these AM parts is economical. The previously stated metrics will be taken into account when determining the total cost. In addition the volume of material used and cost of extra fixturing equipment will be taken into account when determining the total cost. The total time for building the part, set up, machining the part, and inspection will be used to determine the total time for this process. The cost of the kinematic mounting features must be lower than traditional fixturing methods in order for kinematic mounting to be implemented onto future parts.

By developing mounting features the post processing of metal AM parts should become easily repeatable, have improved precision or feature accuracy, take less time post process, and less expertise to post process. Stated below are some economic goals we hope to achieve in this research:

- Post processing machining time should be reduced by 10%,
- Final inspection time should be reduced by 20%
- Total time spent creating the part should be reduced by 10%
- Total cost of producing part from start to finish to be reduced by 15%

A control test will need to be developed in order to compare the new mounting and process techniques. By comparing the times to produce the parts, it is easily shown whether or not these processes are economically feasible.

Design Development

To fulfill our objective we have developed four different styles of part designs with multiple types of mounting each for placement in post processing and inspection equipment. Each part shape will be built with a kinematic mount on the build plate (if applicable), the part itself (if applicable), or not at all. These varying mounting techniques will all be post processed in the same way and the results of doing so will be compared. The tolerances of the parts, inspection time, and machining time are going to be compared. Using this gathered information we will be able to help LLNL develop a design guide to assist with their additive manufacturing processes in the future.

The part shapes that will be investigated must be commonly used and relatively simple to machine as the main focus of the study is to investigate the benefits of using a kinematic mount. These shapes will include a bowl, a cube, a rod, and an octahedron. The octahedron is not necessarily a simple part, but it will be useful to evaluate the benefits of placing the kinematic mount on the surface of a more complex part. The parts must be machined in the same way for each type of mount being used and the same features must be inspected. The bowl is a commonly used shape in AM at LLNL so investigating the best way to fixture this type of part will be highly beneficial. The cube shape may be simple, but it will give us many reference surfaces to inspect and allow us to accurately compare the three mounting techniques. The rod will provide the opportunity to test using the lathe and mill as well as inspecting with and without kinematic mounting features. Lastly, the octahedron will allow us to test the benefits of including kinematic mounting features on the surface of a part with a more complex geometry.

The kinematic mount must fix the orientation of the part in the desired machine for post processing or inspection. The same mounting configuration must be compatible with each machine being used throughout the entire manufacturing and inspection process. The kinematic mount must also provide fast set-up and a repeatable position of the part.

Kinematic Mount Design

There are two main configurations used for kinematic mounting which were discussed in the background information section. These are the 3 V's method where three spheres mate with three V grooves, and the V, cone, flat method where these three features mate with spheres on the second part. Fixturing with three grooves is the favored method, but the option also exists to use two half cylinders which function like the sides of the V groove. However, since AM machines' resolution for building round features is limited, it seems prudent to limit the number of rounded surfaces in the design to only those that are necessary, making the V groove the most likely candidate for use in our kinematic mounts.

One challenge in designing the kinematic mounts was how to incorporate these features onto the build plate used in the AM machines. There are two main possibilities for including these features on the build plate. The first is to machine grooves into the bottom of the plate before parts are built on the opposite side in the AM machine. The build plate would then be clamped down onto the other plate over the surface where the V's and spheres mate. The second possibility would have become necessary if the build plates could not be machined. In that instance the 3 V's would have been built onto the top of the build plate around the perimeter by using AM at the same time as the main part is being built. Since these mating features would be on the same side of the build plate as the part is on it would not be as simple to fix in the machines. This would require a type of collar to fit over the part and mate with the V's. This collar would then have to be fixed in the machine in a known configuration in order to still reduce the required set-up time. Because of these disadvantages to using the collar system as well as the added possibility of positioning inaccuracies, this project will make use of build plates with three V-grooves machined into the build plate on the opposite side that the part is built. This type of kinematic mounting will be used for one version of each of the part shapes to be milled. In every use of kinematic mounting features the part or build plates must be clamped together over the mating surface between the spheres and the grooves. The kinematic mounting features to be used with the build plates are shown in Figure 3 below.

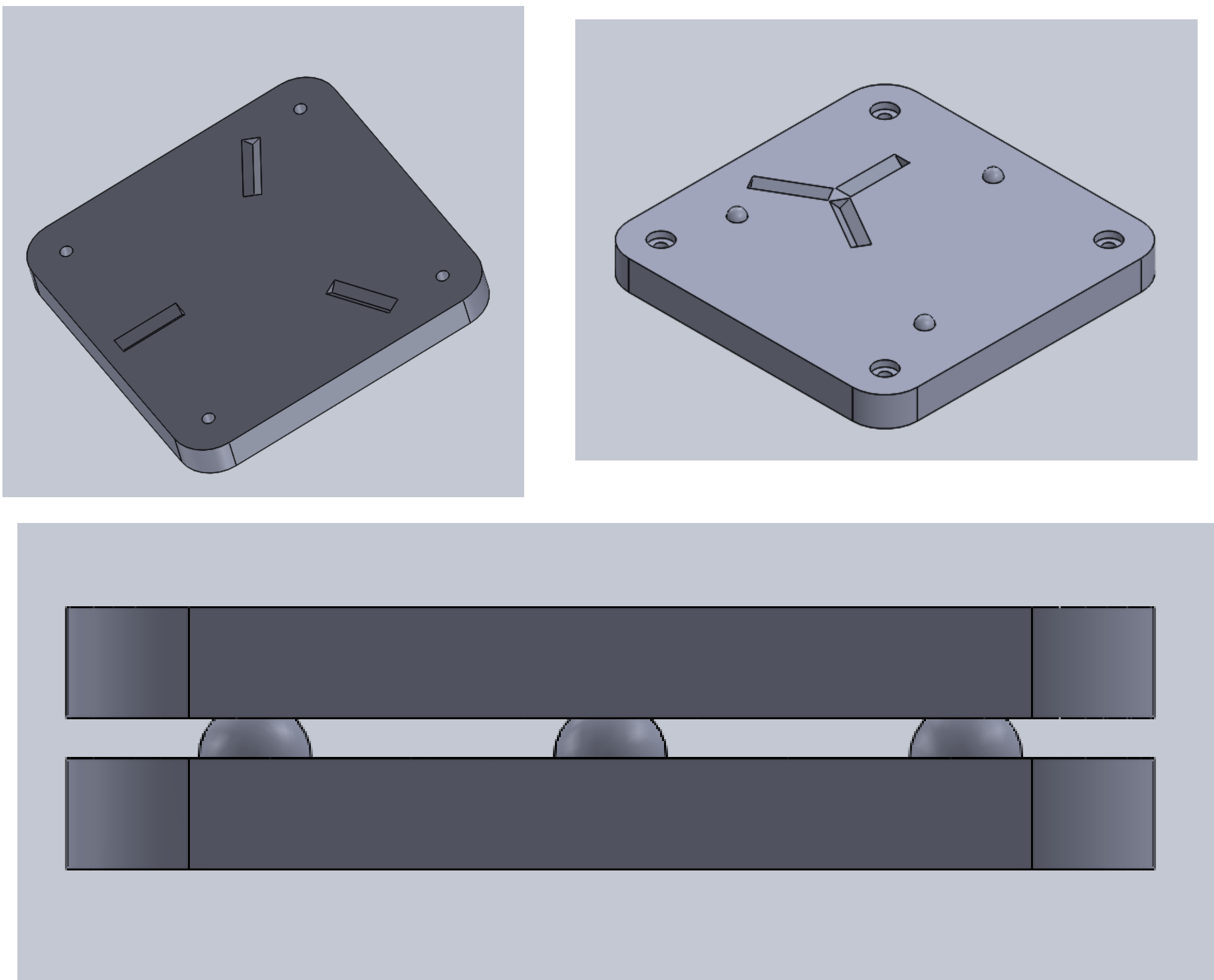

Figure 3. Model of build plates with V-grooves and hemispheres for kinematic mounting. The top left image shows the V-grooves machined on the bottom of the build plate on which the parts will be built. The top right image shows the bottom build plate that will be fixed in the mill or the CMM during machining and inspection. The outer ring of hemispheres will mate to the grooves on the top plate and the smaller ring of grooves will mate with the hemispheres on the individual parts. The bottom image shows these two plates mated via the kinematic mounting features discussed above.

Part Design

Bowl

Figure 4 below shows a concept sketch of the basic layout of the design for the salad bowl shaped part. This part shape will be designed with a variation on the kinematic mounting design discussed previously since that is not the ideal configuration to fix a part in a lathe. The lathe chucks act to fix a part radially and the only dimension left to specify is the z-direction.

One version of the part will simply have a rod extension from the base of the bowl that will be fixed in the lathe traditionally. A second bowl, shown below, will be built with a stepped rod coming off of the base of the bowl. This rod will have a larger diameter step at the end and a narrower section between this and the bowl itself. This will allow the rod to be located in the lathe in the z-direction without needing to include build supports for the inclusion of kinematic mounting features. Drawings of each of these parts are included in Appendix B.

The effects of machining both the inside and outside surfaces of this part with the various mounting configurations will then be tested. The bowl will be built upwards from the “centerline of the sphere”. When necessary the part will be removed from the build plate using wire EDM. After the machining and inspection is completed the bowl can be fixed in a lathe with chucks expanding from the inside in order to remove the remaining kinematic mounting features and build supports. An extension from the bowl will be used to cut off the rod from the bottom. This extension can then easily be removed using wire EDM or a bandsaw.

These two variations of the basic bowl shaped part will be used to compare the accuracy of inspected features, the material cost, and the time required for the entire manufacturing and inspection process.

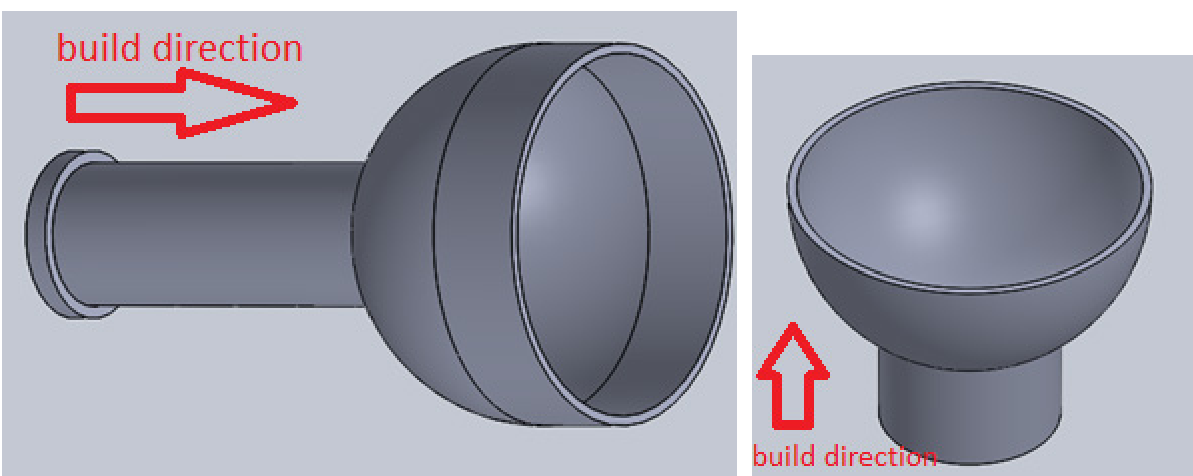

Figure 4. Concept sketch of salad bowl shaped part with kinematic mounting step on the left and without on the right

Cube

The concept sketch for the cube based design is shown in Figure 5 on the following page. This part has a very basic shape, but will allow us to robustly test the capabilities of the kinematic mount and some of the capabilities of the AM machine itself. We can leave two opposing sides of the cube unfinished in order to quantify the properties of parts straight out of the AM machine and to use as a baseline for subsequent inspections. Two other opposing sides will be machined in order to test for flatness and parallelism and holes will be drilled in a fifth side to test the precision of the part position in the machine. The final side of the cube will either be blank, attached to the build plate, or have kinematic mounting features built into it. In order to reduce the build time and material cost this cube will be hollow but with thick walls so as to prevent the part geometry to be affected during machining. This will result in approximately ⅛" thick walls.

Four variations of the cube shape will be produced and tested. The first will be a standard cube that is fixed in the mill using traditional hard jaws or soft jaws. The second variation will be to leave the cube fixed to the build plate throughout the entire machining and inspection process. The build plate will have kinematic mounting features on the face opposite the cube which will mount with the opposing kinematic mounting features on a second build plate that will be left in the machine. Once the final inspection is completed, the cube will be removed from the build plate using either wire EDM or a bandsaw. The third part variation is the one shown in Figure 5 on the next page with hemispheres on one side that will mate with grooves on the build plate in the mill or CMM to form the kinematic mount. The final variation will have grooves in place of the spheres pictured below. For this part a ball bearing of 0.5 inch diameter will be placed between the grooves on the part and the build plate. This will help us to determine the ideal method of kinematic mounting.

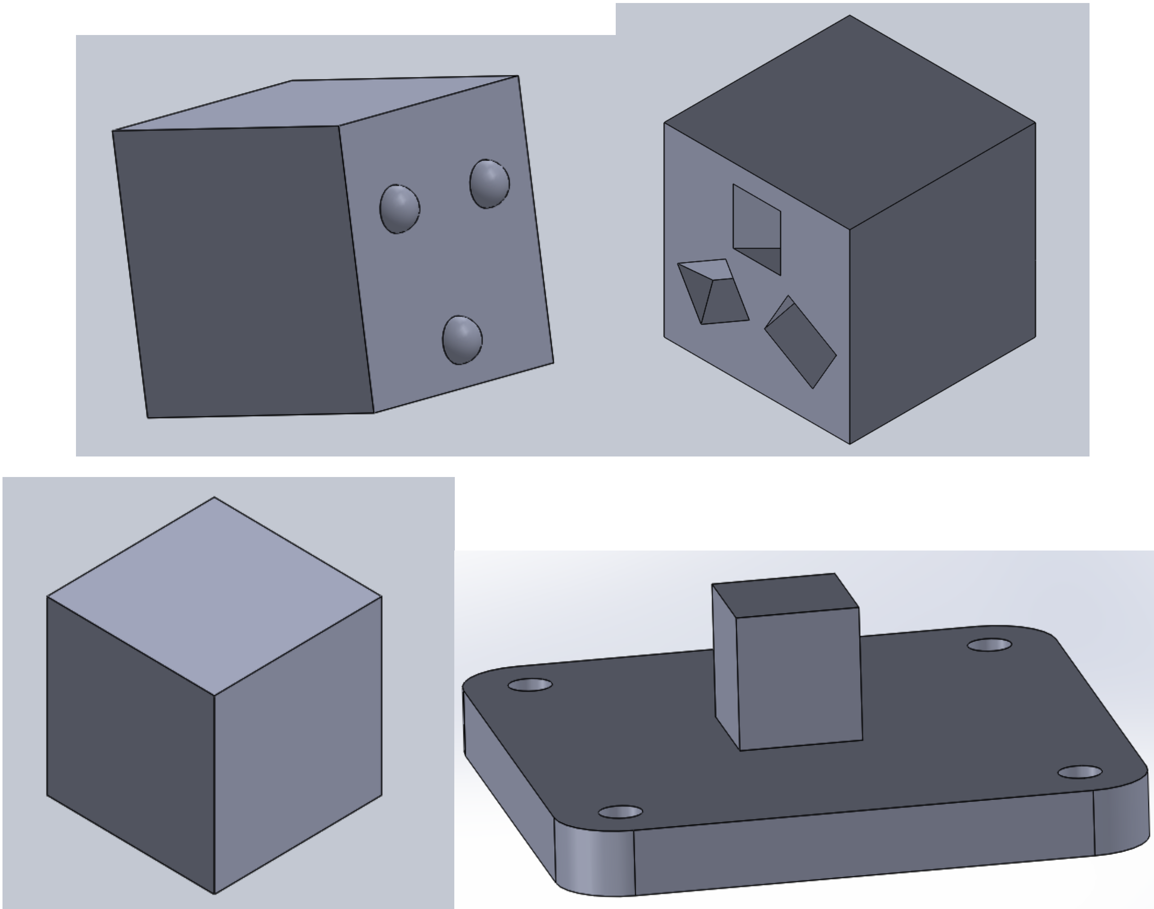

Figure 5: Concept design of cube part variations. The top left image shows the cube with kinematic mounting hemispheres on the part itself, while the top right shows the cube with kinematic mounting grooves on the part itself. Ball bearings go between these grooves and those on the plate to mount this cube. The bottom left image shows the standard cube being used as the control, and the bottom right shows the cube that remained attached to the build plate throughout post-processing.

Cylinder

The cylindrical rod shaped part is the most difficult to usefully incorporate the kinematic mount into the design. Since it is already very simple to fix this type of part in a lathe in order to constrain the radial motion, we will be employing the same type of step that was discussed with the bowl shaped part in order to constrain the part position in the z-direction. The cylindrical part that is shown in Figure 6 will therefore be very simple to build in the AM machine with it simply being a solid cylinder at this point. Once the rod is fixed in the lathe two steps will be machined into it; one with a radius leading to the upper step and one without. One end of the rod will also be machined to include either a cone or a round. This part is different from the other two in that it only needs to be fixed in the machine in one way and fixed one way during inspection.

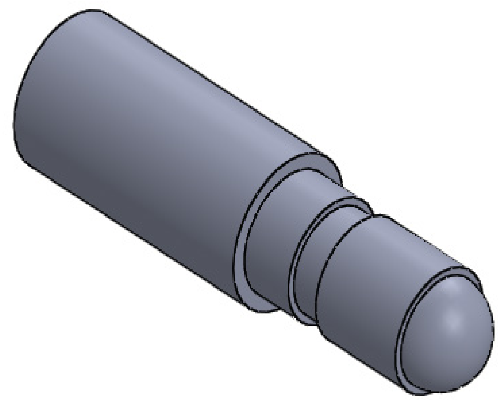

Figure 6: Concept design of cylinder after machining on the lathe.

Octahedron

An octahedron was designed in order to develop a part with difficult to determine datums and fixturing. The octahedron as shown in Figure 7 below will have features that must be machined on the sides opposite the kinematic mounts. One side will have a hole machined into as pictured below. The other sides will be faced in order to test the mounting features. Kinematic mounts were included on 4 faces to use as datums. Using these datums we will evaluate machining times, and precision. These times will be compared to an octahedron which will be fixtured and machined without the kinematic features included in Figure 7 on the next page. The octahedron will have the same four variations discussed for the cube.

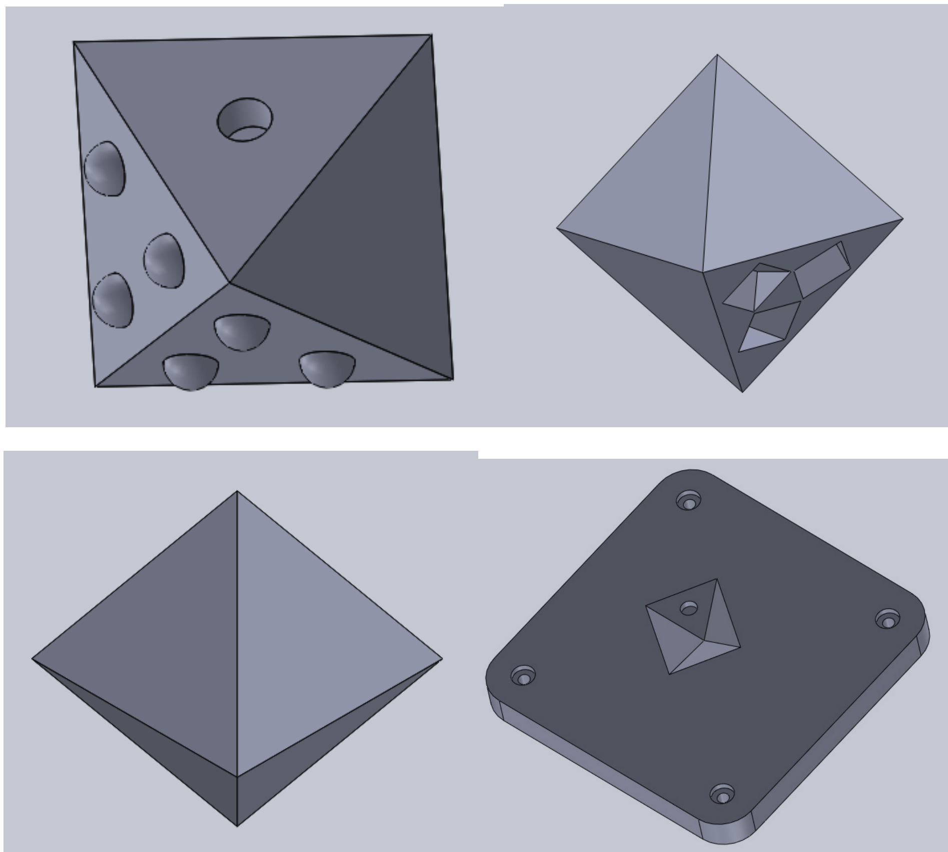

Figure 7: Concept designs of octahedron part variations. The top left image shows the octahedron with kinematic mounting hemispheres on multiple faces after hole is drilled. The top right shows the octahedron with kinematic mounting grooves that match up to ball bearings between the part and the grooves on the kinematic mounting plate. The bottom right shows the normal octahedron that is used as a control, and the bottom right shows the octahedron which remains attached to the build plate throughout post-processing.

Post Processing

The build plates with the kinematic mounting features described in the Design Development section were be machined at LLNL from the currently used AM build plates. The parts discussed previously were then built at LLNL using AM. Those that were to remain attached to the plate with kinematic mounting features throughout post-processing were heat treated and left on the plates after building. The rest were removed with wire EDM after undergoing the typical heat treatment for 316 stainless steel AM parts. These parts were then be sent to Cal Poly for machining on either the Haas CNC mill or lathe and inspection on the CMM as discussed in more detail in the following sections. First, we outline the additional parts needed to complete the post-processing.

Parts Purchased

The build plates discussed in the previous section with the kinematic mounting features built in as well as all AM parts will be provided by LLNL, and most of the fixturing equipment needed is readily available in the Cal Poly manufacturing labs. However, since soft jaws can only be used a limited number of times these parts may need to be ordered. It may be possible to reuse a set of soft jaws for the mill that have been used for a demonstration in a manufacturing class, but still have enough material left to machine for our applications. of no longer being easily machinable to the desired shape. If this is not a possibility, 1”x2” aluminum bar stock can be ordered from McMaster-Carr ($32.03 for 2’) to create soft jaws using jigs available in the manufacturing labs. The machining operations on the lathe will also require one set of soft jaw chucks for the bowl and cylinder parts that use a step for location in the z-direction. This can be ordered from MSC for $62.84.

To machine our parts made from 316 Stainless Steel, carbide tooling is necessary, as all end mills in the labs that are free for student use are made of high speed steel. These were purchased from both McMaster-Carr and MSC, in the quantities and prices listed below in Table 1:

Table 1. Specification of parts and tooling ordered

Part	Supplier	Part #	Material	Dimensions	Cost	Quantity
Bar stock	Mcmaster -Carr	8975K237	6061-T6 Aluminum	1”x2”x2’	$32.03	1
Lathe soft jaws set	MSC	66153107	6061-T6 Aluminum	N/A	$62.84	1
Flat End Mill	MSC	87829826	AlTiN-coated Carbide	Ø¾”, 4-flute	$165.95	2
Ball end mill	MSC	09308776	AlTiN-coated Carbide	Ø½”, 4-flute	$74.92	1

Size C Jobber Drill	MSC	61696142	TiAlN-coated Carbide	Ø.2420”, 2-flute	$33.73	1
CNMG lathe tool insert	McMaster-Carr	3244A611	Carbide		$13.79	2
CNMG lathe tool insert holder	McMaster-Carr	3288A741	N/A		$60.52	1
CCMT lathe tool insert	McMaster-Carr	3244A631	Carbide		$10.94	2
CCMT lathe tool insert holder	McMaster-Carr	3288A811	N/A		$51.47	1

Machining
All machining operations were performed on either a Haas VF2 mill or TL-1 lathe. Machining using CNC machines was determined to better reflect the end application of the findings of this report, as AM parts are often built to complex geometries and forms that manual machining operations cannot post-process. For each part variation, a routing sheet was written, summarizing all operations performed on the part beginning from the AM process to final inspection. Job plans specifically documented the machining operations performed in the manufacturing labs as well as the necessary tooling. For future reference, setup sheets for each mounting variation were written so that future projects can replicate the fixturing methods used for this study. See appendix for all documents.

Part models were first created using Solidworks, and HSMworks (the CAM extension for Solidworks) was used to generate CNC toolpaths.

Parts machined in the Haas VF2 mill included the cube and octahedron parts. The cube without kinematic features was secured using a vise and machinist parallels, while the octahedron without KM features required the machining of soft jaws to be held in a vise inside the mill. All the other parts were clamped onto the bottom build plate using various configurations of step blocks and toe clamps, while the bottom build plate itself was clamped in a vise with the jaws reversed. The parts on build plates with kinematic features required three step block and toe clamp setups, one above each kinematic coupling, and the parts with kinematic features were secured using a single clamping setup.

Machining operations on the cube parts was done using a ¾” AlTiN-coated, 4-flute, carbide flat end mill (FEM). As opposed to the HSS end mills originally proposed. This added additional costs to required tooling, but was determined to be necessary to machine heat-treated stainless steel, a material known to be difficult to machine compared to aluminum. A 2-flute, AlTiN-coated, carbide size C drill was also initially planned to be used drill a .5” deep hole on all cube parts, but broke through a spindle speed miscalculation. As a result, that data point was not able to be collected as originally planned.

While machining the cube on the build plate and the cube without kinematic features were completed without incident, the machining operations on the cube parts with kinematic features had to be altered. Since the toe clamps available for use in the manufacturing lab at Cal Poly are about an inch thick, the sides of the cube could only be machined half-way down to avoid the spindle crashing into the top of the clamp. Since the cubes with KM features were clamped from the top, it was also not possible to face the top of the part without crashing into the clamping setup, damaging both the clamp and end mill. Instead, the top-facing operation was carried out by clamping the cubes into the vise, without using kinematic mounting. This added an additional step in the operation, as well as time.

Machining operations on the octahedron on the build plate were completed, but additional inspection on the parts was necessary to find the location and orientation of the octahedron relative to out specified work coordinate system (WCS). This was done using a test indicator and coordinate system in the VF2. Additionally, manual adjustments to the Y offset needed after probing to account for part growth from AM process, compared to the CAD model. The octahedron’s faces were machined using an initial pass with the ¾” FEM, and finished using a ½”, AlTiN-coated, 4-flute, carbide ball end mill (BEM). For the octahedron without KM features, soft jaws were necessary to hold the part securely for machining, as the its geometry is very eccentric compared to a cube. Similar to the octahedron on the build plate, the X offset needed to be manually adjusted after probing to account for part dimensional deviation from the CAD model. Machining the octahedron with kinematic spheres on all four lower faces on was completed without incident, except only half of each face was machined to avoid any possibility of damaging the clamp or tooling by crashing. Since the octahedron with kinematic grooves only had grooves on two opposite faces, it was impossible to rotate it 90° to machine the adjacent face using the kinematic plate. This operation was instead completed using the soft jaws for the blank octahedron, and the additional time added as a result was noted.

The lathe parts without kinematic steps were fixtured in the lathe chuck like any other lathe part, but the rod and bowl with kinematic steps were fixtured in a set of soft jaws with a slot turned on the inside. This slot was both wider and deeper than the kinematic step, such that the slot could only be used to locate the part along the Z axis by mating the top of the step to the outermost lip of the slot. To make the slot, a specialized lathe tool had to be ground in order to turn the interior, and was noted as an additional operation in machining both lathe parts with kinematic steps.

The rod without a kinematic step was machined without incident using a CNMG insert (and holder), a general-purpose, (½”, 45°) carbide tool for lathe parts, However, turning the profile of the rod with kinematic step using the slotted soft jaws produced significantly more chatter than the rod held using typical chucks. This was due to the stickout of the part in order to utilize the kinematic coupling of the slot and step, as well as the smaller contact surface and softer (aluminum compared to steel) material of the soft jaws. The first issue can be mitigated by machining the slot deeper into the soft jaws, it would require the purchase of a boring bar or another specialized tool, which was not feasible given time constraints. Using steel soft jaws instead may also provide significant improvement.

Turning the outer profile of the bowl parts was initially intended to be carried out using a CCMT (¼", 45°) carbide insert (and holder), but its angle was too shallow to machine the outside radius of the bowl. Instead, a VNMG (⅜", 15°) carbide insert was used. Similar to the stepped rod, when machining the bowl with a kinematic step, the stickout and aluminum soft jaws produced chatter, but this was remedied by using the lathe tailstock to compress an ordinary tennis ball inside the bowl to dampen vibrations. In both bowl parts, machining the inner radius of the part produced extensive vibrations, and a solution was not found due to time constraints.

Inspection

Parts were inspected before machining to account for any part growth or shrinkage during the AM process and to adjust the toolpaths accordingly. They were inspected again after machining, this time using the Zeiss CMM in the Cal Poly manufacturing lab, in order to obtain comparison metrics for the different mounting styles being tested. Figure 8 on the following page shows an example of the First Article Inspection Report (FAIR) sheet and the corresponding drawing indicating the features of interest for inspection. We measured the same dimensions and characteristics for all variations of the basic part shapes in order to make an accurate comparison of each. The example shown is for the version of the cube that remained attached to the build plate throughout the machining and inspection process.

Using a coordinate measuring machine (CMM), we were be able to test the geometric dimensions and tolerances (GD&T) and see how they vary from the original geometries. The time to set-up the part in the CMM, create the inspection plan using Calypso software, and inspect the part were recorded for each variation of the part and added to the total post processing time. After the inspection plan is run Calypso creates a record of everything measured with the nominal values, the tolerances, and the deviations. These documents are included in Appendix G for the parts we measured. The deviation from the nominal value for each feature or dimension measured was recorded in order to determine if there is any difference in the tolerance that different part variations were able to meet.

CAL POLY SAN LUIS OBISPO			First Article Inspection Sheet				
			Name:	Maren Cosens			
			Part:	Cube on build plate			
			Date:	May 6, 2016			
			Drawing:	FAIR_cube1			
Dimension ID	Description	Nominal Size	Limits	Actual	Device	Comments	Pass/Fail
A	Width	1.97	0.01	1.9703	CMM		Pass
B	Height 1	1.99	0.01	1.9953	CMM		Pass
C	Flatness	--	0.01	0.0001	CMM		Pass
D	Perpendicularity	--	0.01	0.0000	CMM	May be due to small # of points measured	Pass
E	Parallelism	--	0.01	0.0007	CMM		Pass
NOTES:				INSPECTOR: Maren Cosens			

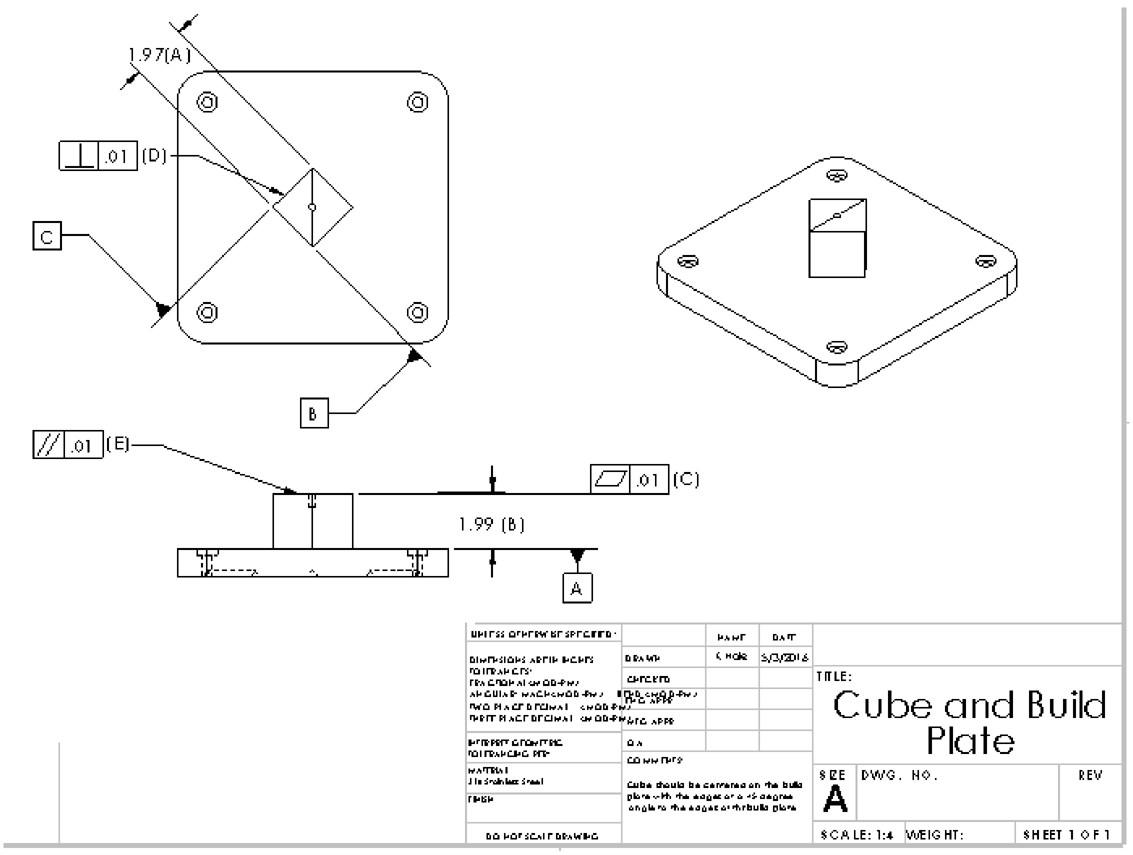

Figure 8. FAIR drawing and inspection sheet for the cube that remained attached to the build plate throughout machining and inspection

For the set-up and timing of the inspection process it was assumed that the bottom build plate with the kinematic mounting hemispheres and grooves would remain on the CMM and be aligned properly. The milled parts attached to the build plate or with their own kinematic mounting features would then simply be aligned on this plate as shown in the images in Figure 9 below. The traditional part with no kinematic mounting features would have to be aligned individually. For the octahedron it was much easier to set the datums of the CMM with the build plate than it was for the octahedron on its own.

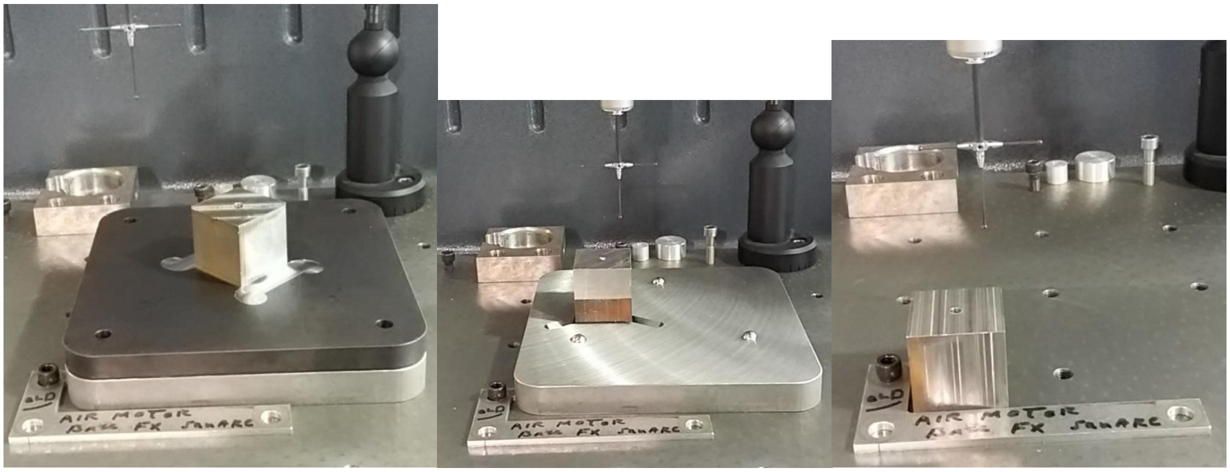

Figure 9. The left image shows the cube on the build plate aligned in the CMM via the bottom build plate. The middle image shows the parts with either kinematic mounting grooves or spheres being placed in the grooves of the bottom build plate for inspection, and the right-most image shows the normal cube with no kinematic features aligned in the CMM for inspection. The octahedron parts would be aligned in the same way.

For inspection of the lathe parts we could not move the chucks so both parts had to be fixed in the same way, upright with silly putty holding the parts in place so they would not fall over when contacted by the CMM probe. This is shown for the example of the cylinders in Figure 10 below. Even though the process was the same, it was easier to apply the silly putty to the parts with the kinematic mounting step so that it would hold the part in place on the table. This didn't result in a significant difference in time though.

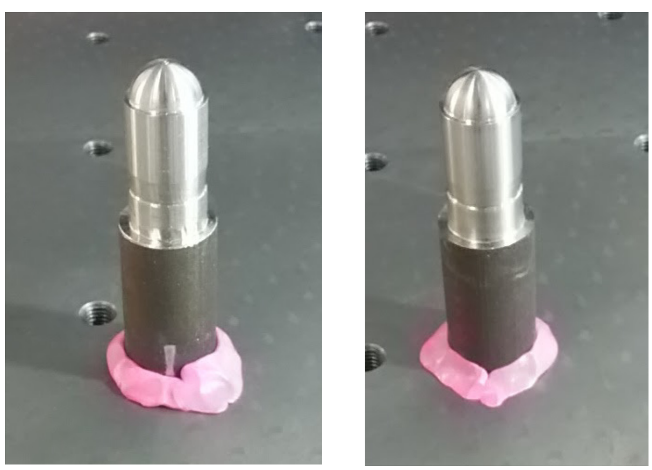

Figure 10. Fixing of the cylinders in the CMM using silly putty. The part with the kinematic mounting step is on the left, though both are fixed in the exact same way. The same method was employed for the bowl parts.

Analysis

Each part was evaluated based upon two main criteria: the manufacturing and inspection time required and the ability to meet tight tolerances of the design and the geometry (how close the measured value is to the nominal value).

The ability to meet the specified tolerances was evaluated using the Zeiss CMM in the Cal Poly manufacturing lab. The deviations of each measured feature from the nominal value was recorded and an average deviation determined for each part variation. These were then compared across each part type to determine the most effective mounting method for meeting tight tolerances for each type of part.

The total time was determined by timing the set-up or the machine and fixturing of the part, the actual machining cycle, and the time required for inspection including setting up the part and creating the inspection plan on the software Calypso. The set-up time in the machines includes the time to machine soft-jaws if they were required for a specific part variation (octahedron without kinematic mounting features). These tests were conducted in the same manner and by the same person on each variation of the part designs: one group with no kinematic mounting features (as a control), and the others with the kinematic mounting best suited to that style of part. The total time required for post processing was determined for each part variation and compared across the part type in order to determine the most cost effective mounting methods for each style of part.

The results for each style of part are discussed below. It is important to remember that for the parts that have kinematic mounting features the set-up time for the bottom mounting plate is not included in the analysis shown in the tables. This is because the kinematic mounting plate is assumed to remain in the machine between operations so it would already be there when machining is needed. If however, this plate needed to be removed and set-up every time, this would add $32 to the cost of the kinematic mounted parts. This plate also took 17 hours to machine (3 for the grooves and 14 for the hemispheres), but this is not included in the analysis because it, like the lathe chuck soft jaws ($159 total; ~$63 for the soft jaws and ~$98 to machine), is reusable and a one-time cost.

Cubes

The table below shows the total post-processing time required for each variation of the cube part. This time has been converted to an estimated cost for the machining and inspection required using an average hourly rate that the lab pays for machining. The last column of the table also shows the results of the tolerance analysis with the average deviation from a given dimension or features nominal value for each part. More detailed values for the time study with the time and cost of each step are shown in Appendix E, while the detailed tolerance analysis is shown in Appendix F.

Table 2. Total time required for post-processing of cube part variations along with the corresponding cost and the average deviation of the dimensions and features from the specified value.

Part Variation	Total Time (min:sec)	Total Time (min)	Cost/hour ($)	Total Cost ($)	Average Deviation (in)
Cube on plate	47:40.4	47.67283	230	182.75	0.00095
Cube no KM	23:39.6	23.65883	230	90.69	0.00155
Cube KM spheres	45:09.1	45.15167	230	173.08	0.00273
Cube KM grooves	45:29.4	45.49017	230	174.38	0.00273

As you can see from Table 2 there is a clear discrepancy in the cost of the traditional cube (at ~$91) and the cubes with kinematic mounting features on the part itself or the build plate. The cube on the build plate was able to meet slightly better tolerances in our study, but since it is a small difference this could just be for these specific iterations and may not hold for a larger sample. Therefore, for a simple part that can be easily fixed in a vice it is not advantageous to use kinematic mounting features in the part design.

Cylinders

Table 3. Total time required for post-processing of cylinder part variations along with the corresponding cost and the average deviation of the dimensions and features from the specified value.

Part Variation	Total Time (min:sec)	Total Time (min)	Cost/hour ($)	Total Cost ($)	Average Deviation (in)
Cylinder w/ Step	28:02.0	28.0330	230	107.46	0.0037
Cylinder	22:56.1	22.9345	230	87.92	0.0003

As you can see from Table 3, the cylinder with the kinematic mounting step is more expensive than the normal cylinder due to the need to replace the chuck jaws with custom soft jaws. This does not, however, result in a huge difference in the total time required. The main difference apparent in this table is the difference in the average deviation from the feature nominal value seen in the cylinder with the kinematic mounting step. Contrary to what we would have expected, the inclusion of the step greatly increased the deviation. This is not due to the step itself, but due to the fact that in order for us to machine soft jaw chucks with a groove in them for our lathe we had to use aluminum chucks instead of the normal steel chucks. This combined with a smaller contact surface between the chucks and the parts resulted in a significant increase in chatter during machining. If steel soft jaw chucks could be machined it would be possible that an improvement in the tolerances may be achieved. However, the deviation for the normal cylinder is so small that this may not be worth the investment of time and money.

Octahedrons

Table 4. Total time required for post-processing of octahedron part variations along with the corresponding cost and the average deviation of the dimensions and features from the specified value.

Part Variation	Total Time (min:sec)	Total Time (min)	Cost/hour ($)	Total Cost ($)	Average Deviation (in)
Octahedron on plate	58:05.5	58.091	230	222.68	0.0012
Octahedron no KM	97:56.0	97.949	230	375.47	0.0040
Octahedron KM spheres	54:55.8	54.930	230	210.56	0.0027
Octahedron KM grooves	58:29.4	58.490	230	224.21	0.0031

As you can see in Table 4, for the case of the more complicated octahedron, the traditional part with no kinematic mounting features is significantly more time consuming and therefore expensive. This is due to the necessity of machining soft jaws for the normal octahedron, which is not necessary for the other versions of the part. Buying stock to machine soft jaws from would also add about $8 to this cost. Looking at the deviations you can also see that the normal octahedron is also furthest from the nominal dimensions. While this value is close enough to the deviations seen for the octahedrons on the parts themselves that the difference may not hold for a larger sample, it is clear that the octahedron which remains on the build plate can meet much tighter tolerances. Since the cost of this style of mounting is also significantly lower than traditional fixturing it is recommended that parts like the octahedron with complex geometries be machined attached to a build plate with kinematic mounting features built in.

Bowls

Table 5. Total time required for post-processing of bowl part variations along with the corresponding cost and the average deviation of the dimensions and features from the specified value.

Part Variation	Total Time (min:sec)	Total Time (min)	Cost/hour ($)	Total Cost ($)	Average Deviation (in)
Bowl w/ Step	20:47.0	20.783	230	79.67	0.0723
Bowl	16:23.9	16.398	230	62.86	0.0014

Like to the cylinder parts, the bowl with the kinematic mounting step took longer to post-process due to the time required to replace the lathe chucks with the soft jaw chucks with a groove. Also, like the cylinder parts, the increase in chatter using the aluminum chucks resulted in significantly lower tolerances for the kinematic mounted bowls. However, the cylindrical extension at the top of this bowl variation made inspection of the top face of the part significantly easier. If this was not required in the final design it would have to be removed and then the benefit would be lost. If tolerances tighter than those seen for the regular bowl are needed than it may be worthwhile to investigate the use of steel soft jaws with a groove in order to make use of the kinematic mounting step.

Conclusions

For a simple part that will be machined on a mill like the cube shape we tested there is no clear benefit to using kinematic mounting over traditional fixturing. It is in fact faster to use the traditional fixturing of a machine vice rather than using toe clamps over kinematic mounting surfaces. There is a slight difference in the tolerances we measured, but this is so small it may not hold for a larger sample. Therefore, for a part that can easily be fixtured in a vice we recommend not using kinematic mounting.

For parts that are machined on the lathe further research would need to be done using steel soft jaws in order to test the effectiveness of the kinematic mounting step and groove. With the aluminum soft jaws we had to use there was a significant amount of chatter which caused the parts to have significantly larger deviations from the nominal dimensions as well as a very poor surface finish. However, the deviations and time required for the traditional versions of both the cylinder and the bowl indicate that this is probably not required in most situations. If there is an instance where a part needs to meet much tighter tolerances than those shown for the cylinder and bowl in Tables 3 and 5 then the kinematic step with steel soft jaws should be investigated.

However, for a part with a complex geometry, like our octahedron, that would normally require soft jaws to machine on the mill, there were benefits seen to using kinematic mounting features. The time required to machine soft jaws makes the cost of machining the traditional part with no kinematic mounting features much higher. The normal octahedron also saw the greatest deviation from the nominal dimensions of all of the part variations, with the octahedron on the build plate having by far the smallest deviations. Therefore, for complex geometries we recommend using a kinematic mounting plate and keeping the part on the build plate throughout post-processing, Once all machining is complete the part would then be removed from the build plate using wire EDM as it would normally have been before the machining began,

Recommendations for Future Work

While working with the parts we noticed that further testing could be used to validate and build upon some of the conclusions we have made. There are different factors which could have affected the post processing of the parts that we did not consider, but could affect the results.

We believe that the surface finish on the kinematic mounting features on the parts could have affected the results. The parts made by additive manufacturing had a very rough surface finish, and probably did not sit as flush as possible within the grooves. A simple process such as sand blasting could help improve the surface finish of the parts, which may correlate to greater accuracy and repeatability in the position of the parts.

Because mainly simple geometries were used as testing parts, we believe it would be beneficial to test more complex geometries, and different ways kinematic mounting features could be added to the parts. The complex geometry part we tested, the octahedron, benefitted from having kinematic mounting features, so to further validate this claim we believe it would be beneficial for other complex geometries to be tested which are frequently used at LLNL.

Another future area of study relates to the machining capabilities we had. Cal Poly had limited machining capabilities and times available to machine the parts. More complex machining capabilities such as a machine with a fifth axis, would help to machine more complex geometries. Also testing steel soft jaws to machine the parts on the lathe would be beneficial, as it would more than likely reduce chatter caused by the machine.

Hopefully the above recommendations can be tested by LLNL or future Cal Poly students, as it would greatly benefit the research being done by the lab.

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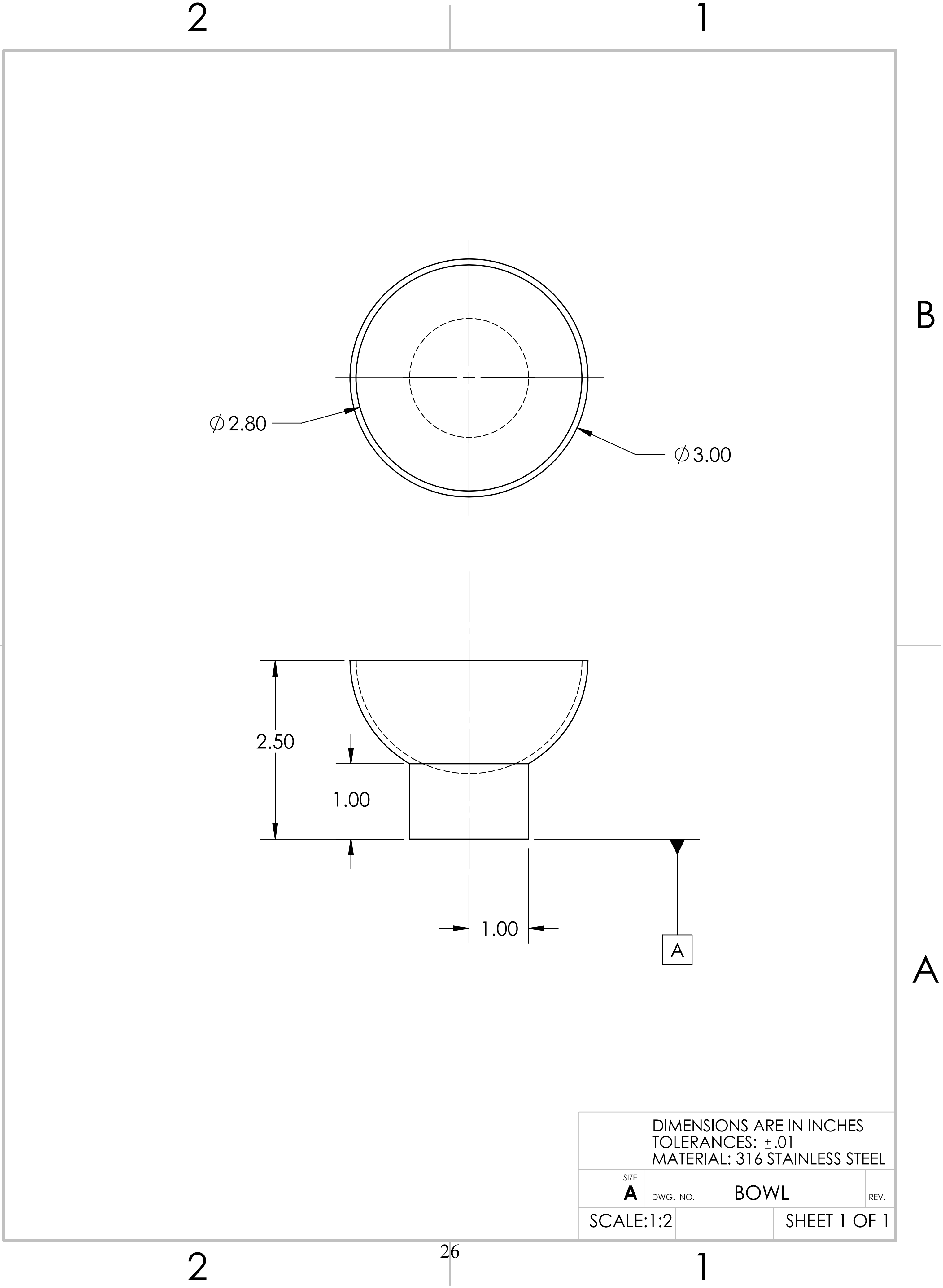
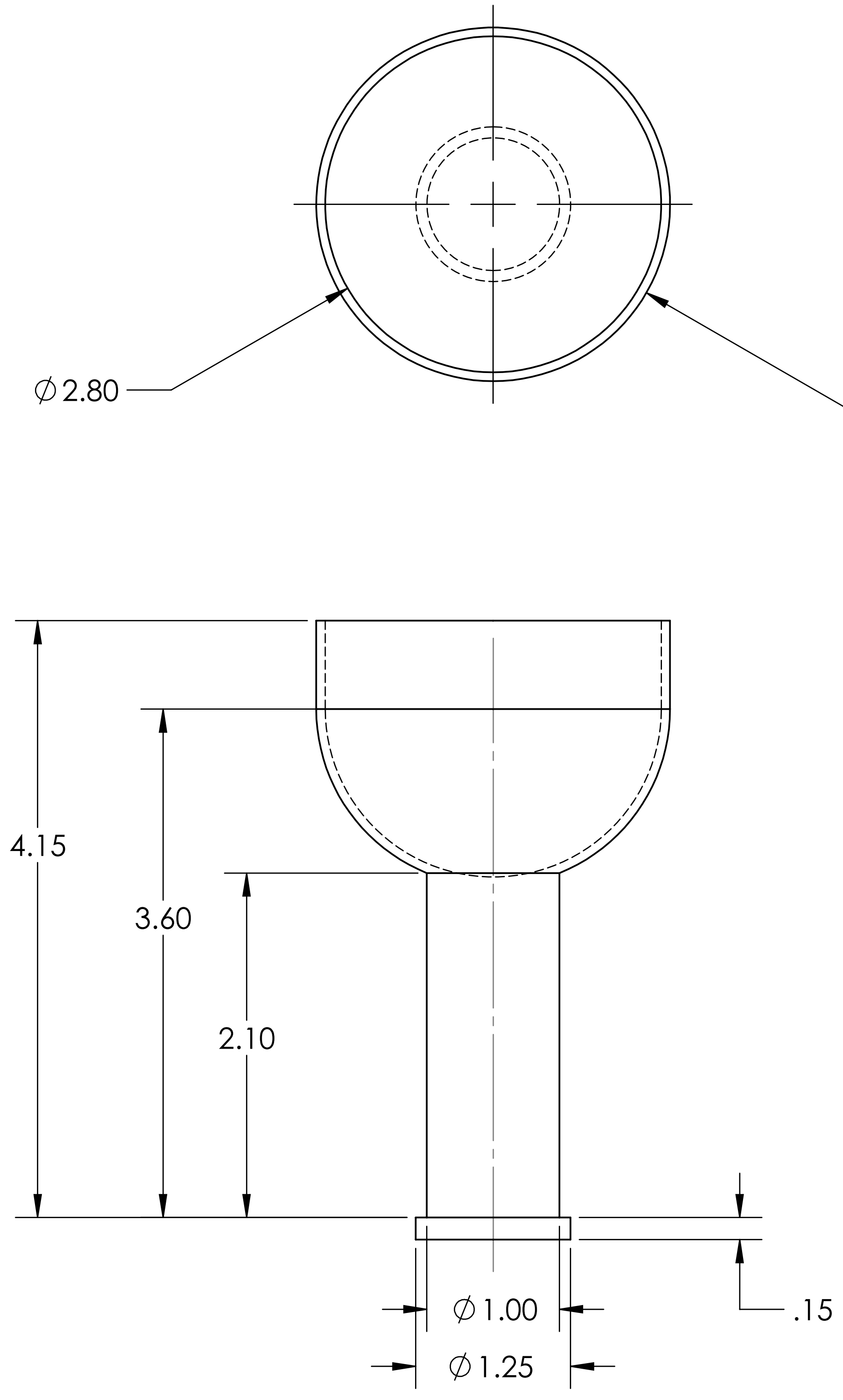
Fellowes, David. “Kinematic and Quasi-Kinematic Constraints: What They Are & How They Work.” 11 Dec. 2006. Web. 12 Nov. 2015.

Gibson, I., D. W. Rosen, and B. Stucker. Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing. New York: Springer, 2010. Print.

Appendix A: Part Drawings

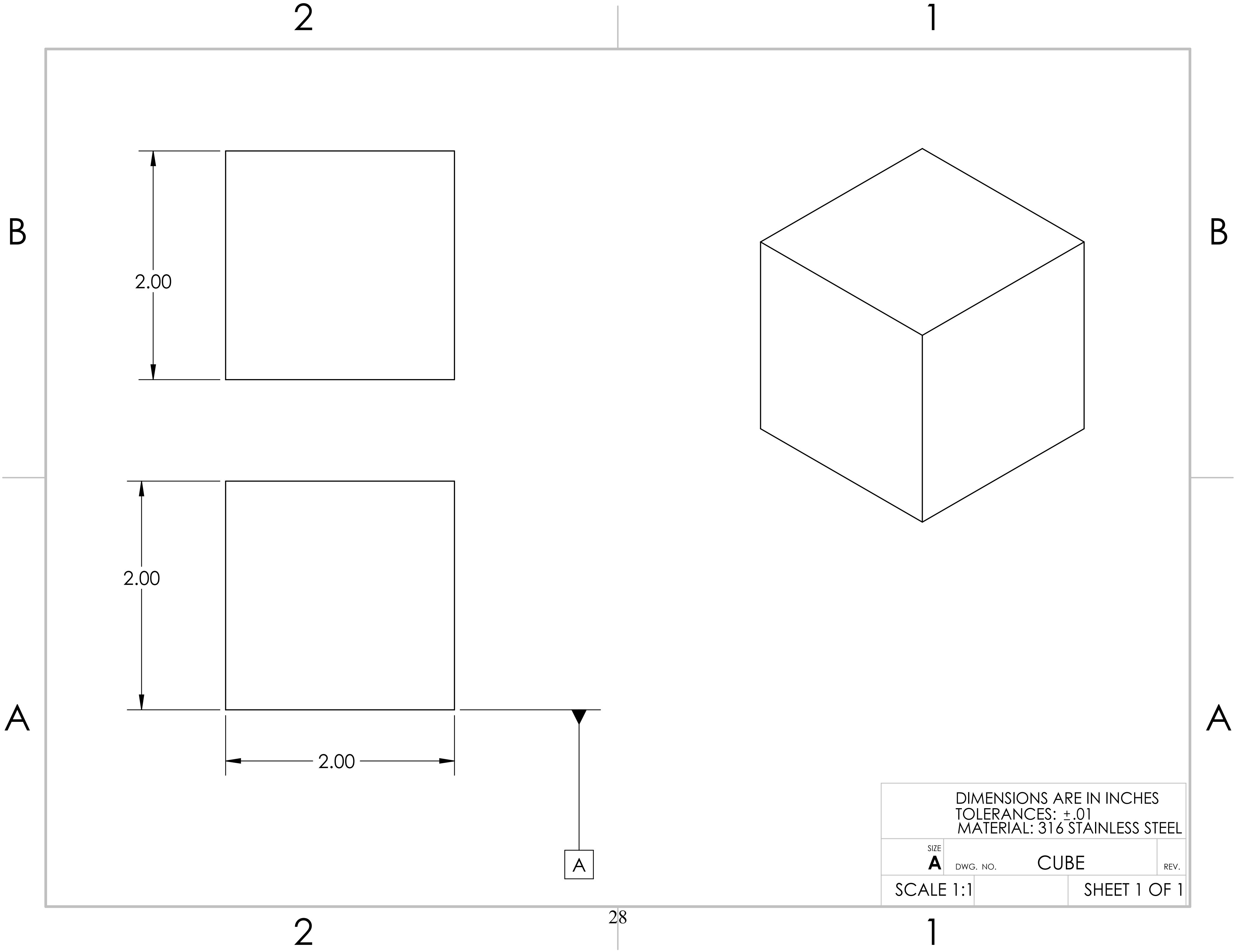


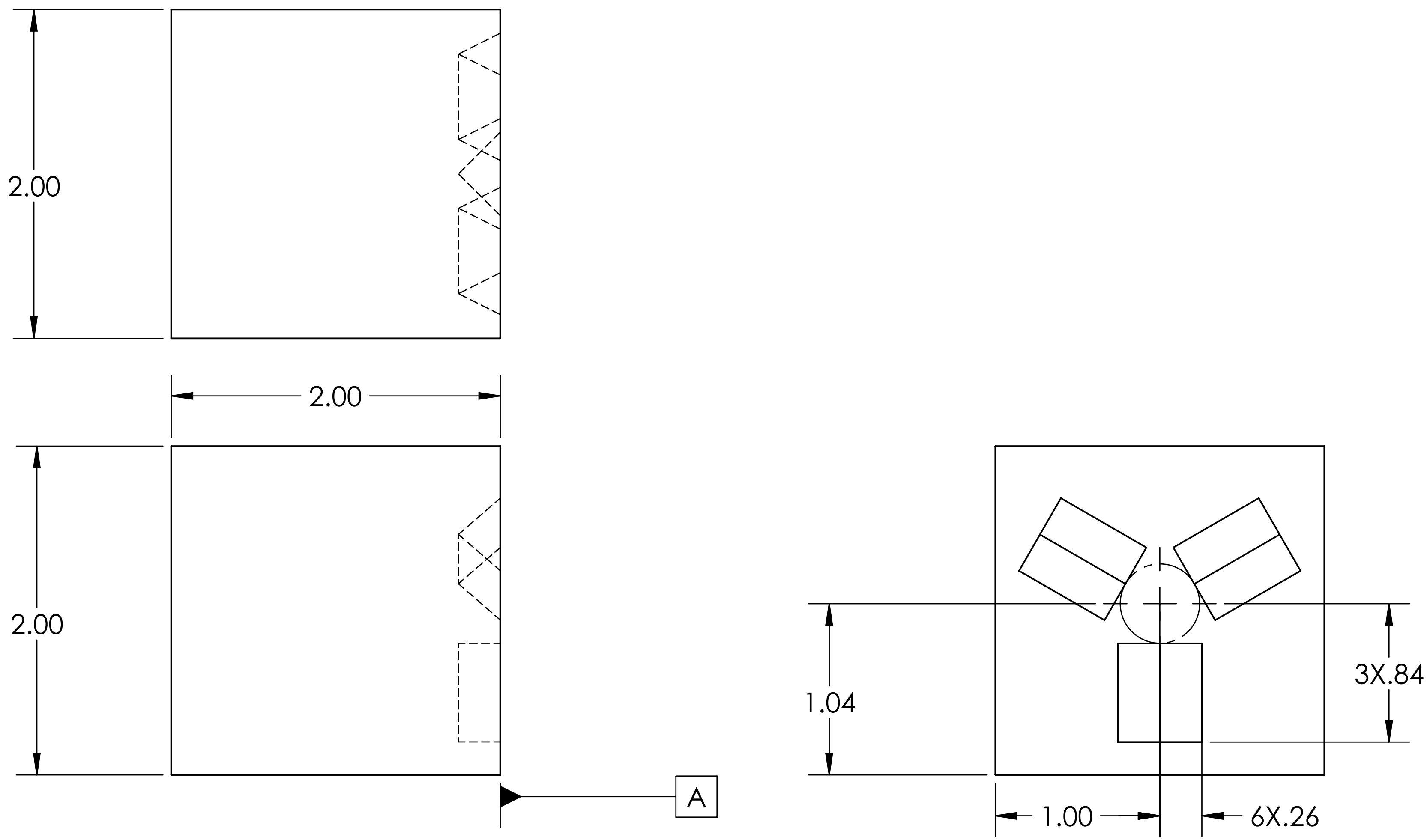
2
1
B
A
∅2.80
∅3.00
2.50
1.00
1.00
A
DIMENSIONS ARE IN INCHES
TOLERANCES: ±.01
MATERIAL: 316 STAINLESS STEEL
SIZE
A
DWG. NO.
BOWL
REV.
SCALE:1:2
SHEET 1 OF 1



DIMENSIONS ARE IN INCHES
TOLERANCES: ±.01
MATERIAL: 316 STAINLESS STEEL

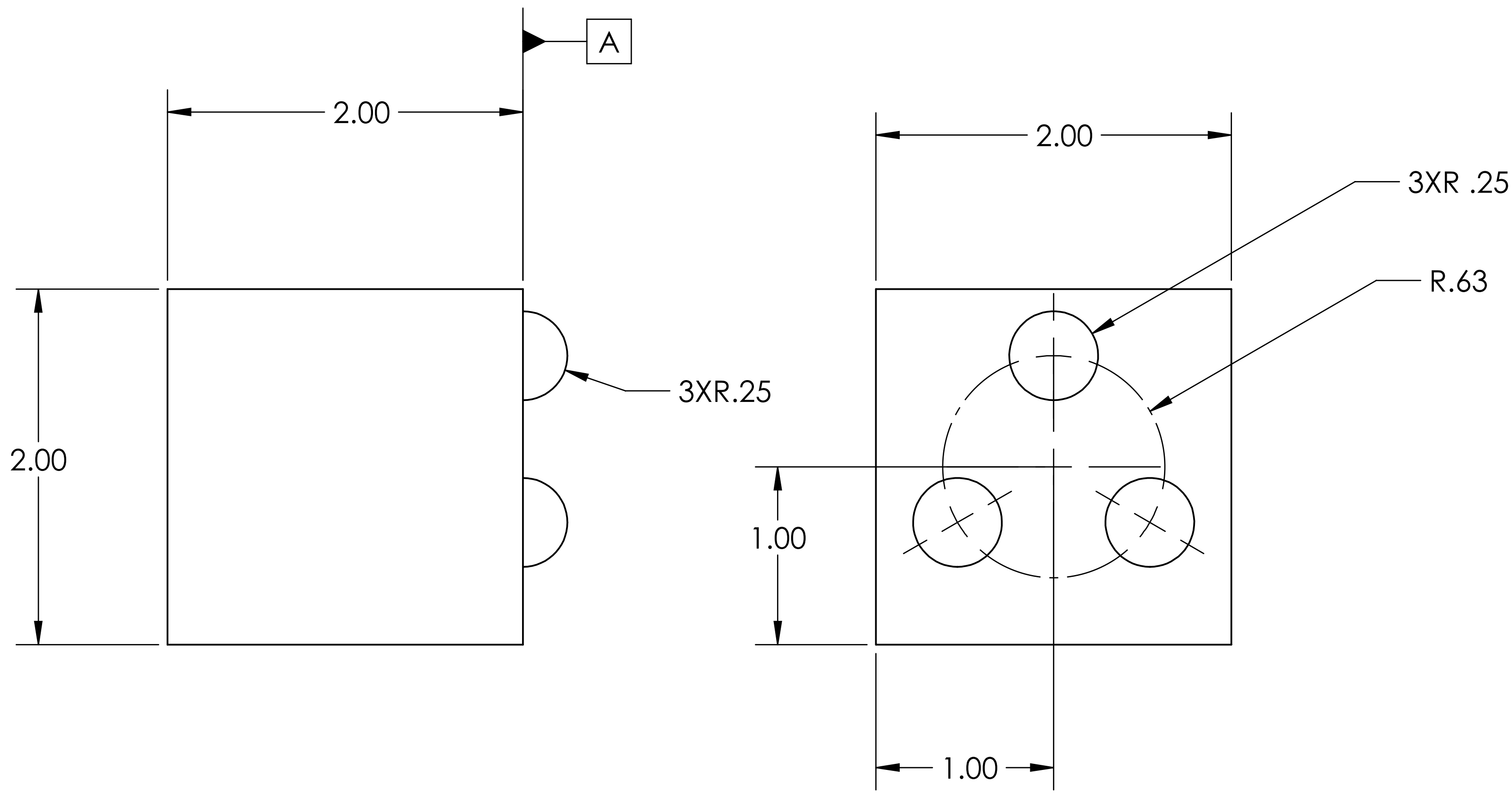
SIZE A	DWG. NO. STEPPED BOWL	REV.
SCALE:1:2		SHEET 1 OF 1


2
1
B
A
2.00
2.00
2.00
A
DIMENSIONS ARE IN INCHES
TOLERANCES: ±.01
MATERIAL: 316 STAINLESS STEEL
SIZE
A
DWG. NO.
CUBE
REV.
SCALE 1:1
SHEET 1 OF 1



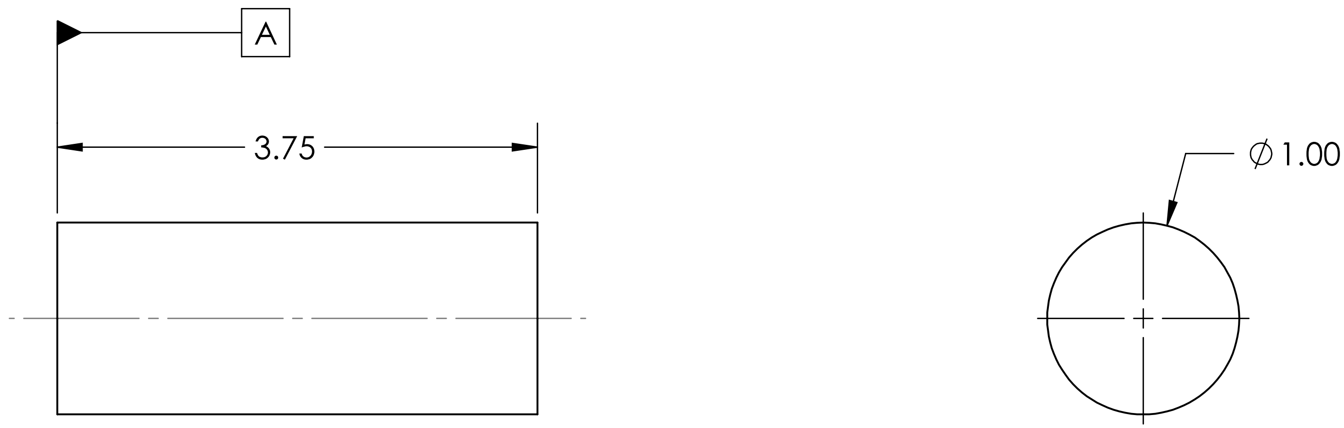
DIMENSIONS ARE IN INCHES
TOLERANCES: ±.01
GROOVES FORM 90°
MATERIAL: 316 STAINLESS STEEL

SIZE A	DWG. NO. CUBE WITH GROOVES		REV.
SCALE:1:1		SHEET 1 OF 1	

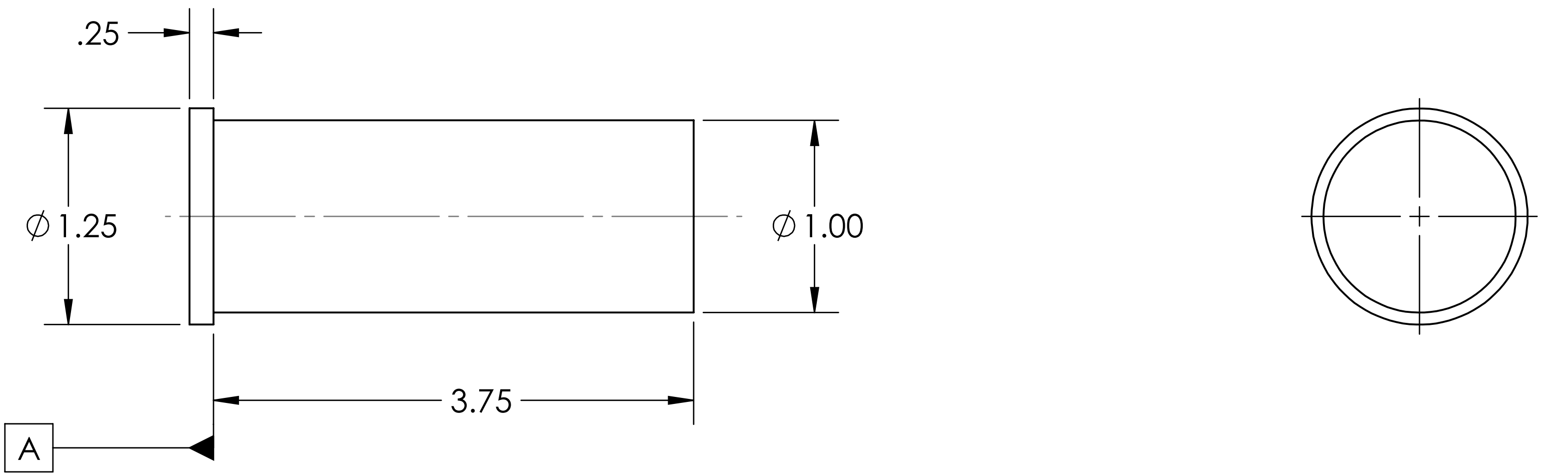


DIMENSIONS ARE IN INCHES
TOLERANCES: ±.01
MATERIAL: 316 STAINLESS STEEL

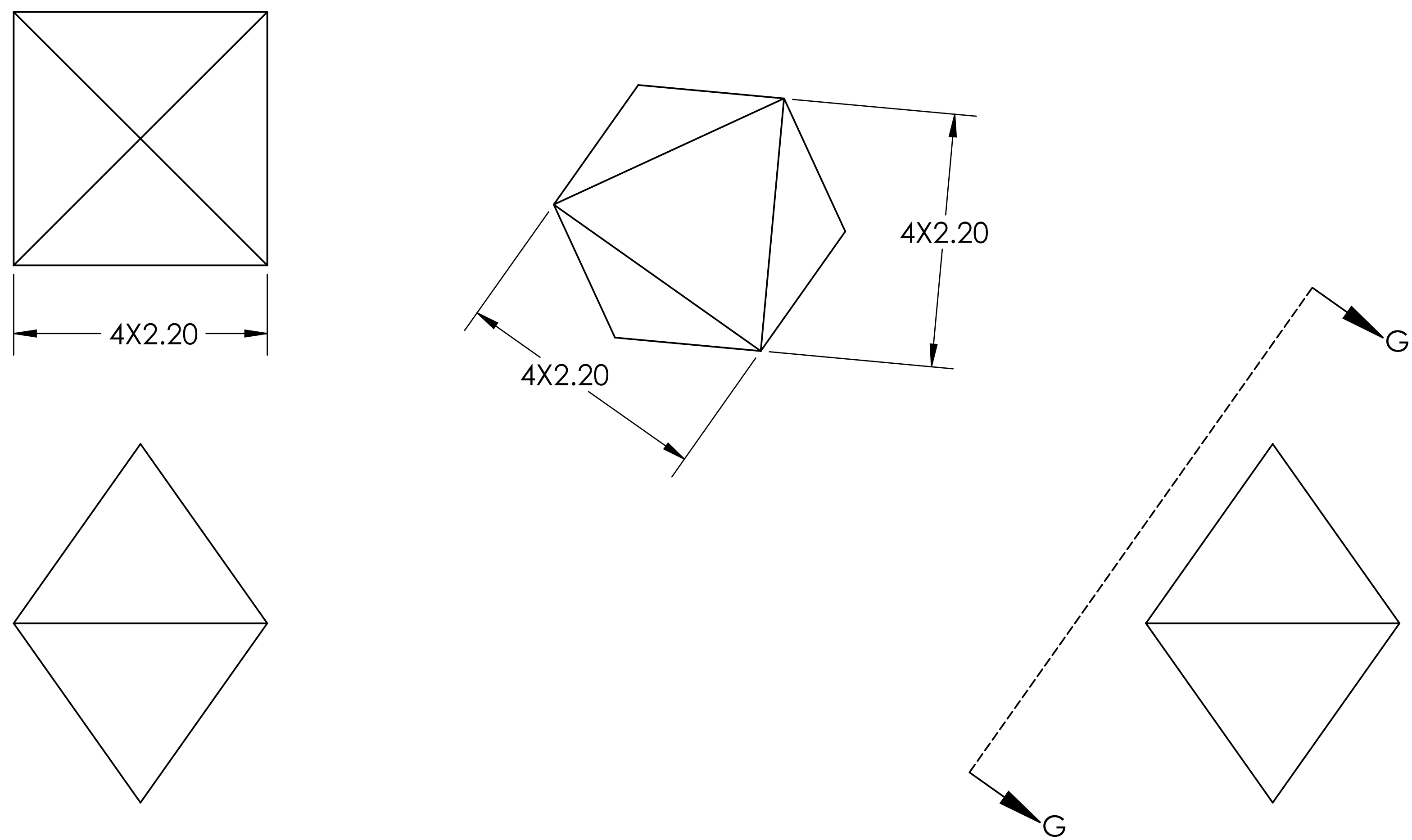
SIZE A	DWG. NO.	CUBE WITH KM	REV.
SCALE:1:1		SHEET 1 OF 1	



DIMENSIONS ARE IN INCHES TOLERANCES: ±.01 MATERIAL: 316 STAINLESS STEEL			
SIZE A	DWG. NO.	CYLINDER	REV.
SCALE 1:2		SHEET 1 OF 1	



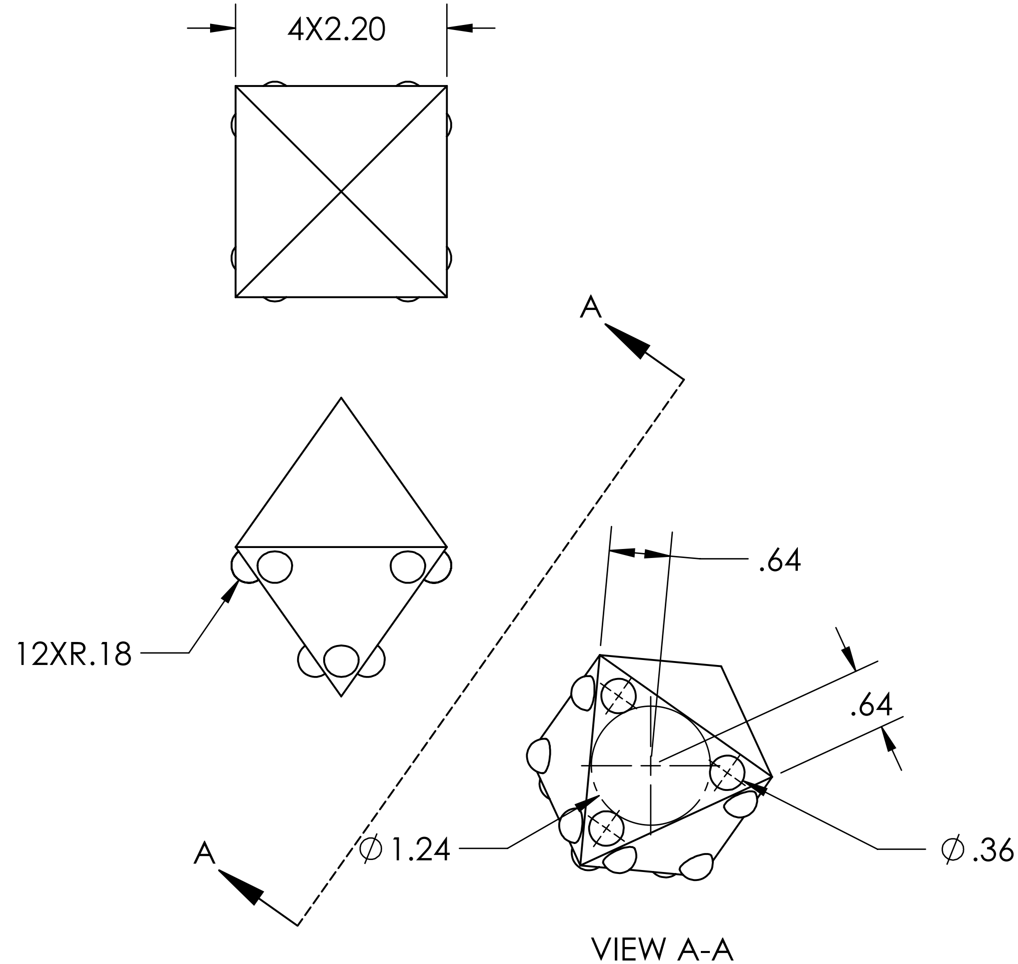
DIMENSIONS ARE IN INCHES TOLERANCES: ±.01 MATERIAL: 316 STAINLESS STEEL		
SIZE **A**	DWG. NO. STEPPED CYLINDER	REV.
SCALE 1:2		SHEET 1 OF 1



DIMENSIONS ARE IN INCHES
TOLERANCES: ±.01
MATERIAL: 316 STAINLESS STEEL
EACH FACE IS AN EQUILATERAL TRIANGLE
ANGLE BETWEEN FACES IS 109.42°

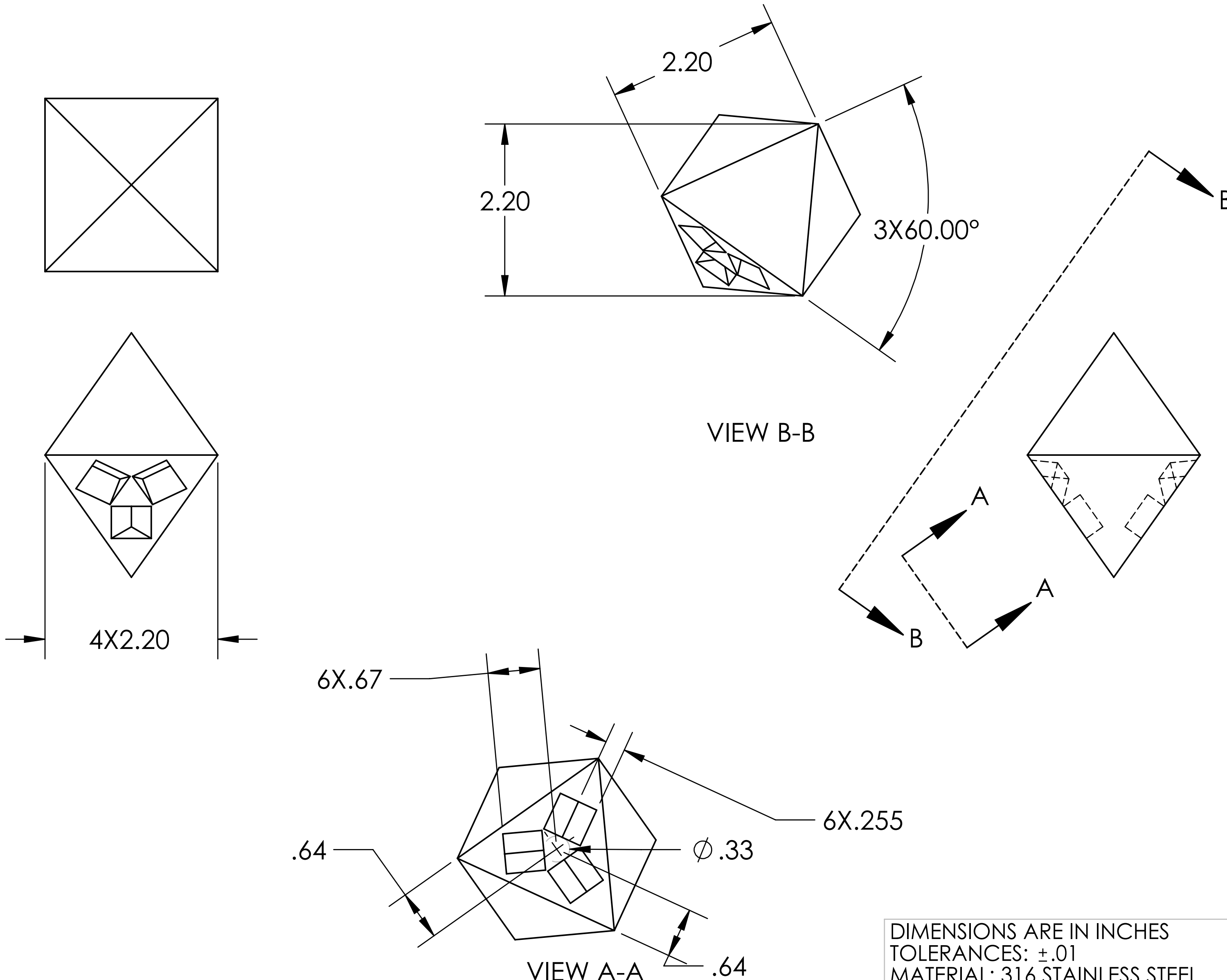
SIZE	DWG. NO.	REV.
A	OCTAHEDRON	

SCALE 1:2		SHEET 1 OF 1



DIMENSIONS ARE IN INCHES
TOLERANCES: ±.01
MATERIAL: 316 STAINLESS STEEL
EACH FACE IS AN EQUILATERAL TRIANGLE
ANGLE BETWEEN FACES IS 109.42°
MAIN DATUM FROM FACE WITH KM FEATURE
FOUR SIDES HAVE KM FEATURES

SIZE A	DWG. NO. KM OCTAHEDRON	REV.
SCALE 1:2		SHEET 1 OF 1



DIMENSIONS ARE IN INCHES
TOLERANCES: ±.01
MATERIAL: 316 STAINLESS STEEL
EACH FACE IS AN EQUILATERAL TRIANGLE
ANGLE BETWEEN FACES IS 109.42°
MAIN DATUM FROM FACE WITH GROOVE
TWO OPPOSITE SIDES HAVE GROOVES

SIZE	DWG. NO.	REV.
A	GROOVED OCTAHEDRON	
SCALE 1:2		SHEET 1 OF 1

Appendix B: Part Routings

CAL POLY SAN LUIS OBISPO	Part Routing	
	NAME	Ben Wong
	PART	Bowl with kinematic step

Sequence	**Operation**	**Complete**
10	Build bowl through additive manufacturing in AM machine	□
20	Separate bowl from build plate with wire EDM	□
30	Heat treatment	□
40	Machining operation on bowl inside Haas TL1	□
50	Remove bowl from Haas TL1, clean off chips	□
60	Fixture bowl in coordinate measuring machine (CMM)	□
70	Measure bowl with CMM; collect results	□

CAL POLY SAN LUIS OBISPO	**Part Routing**	
	NAME	Ben Wong
	PART	Bowl without kinematic features

Sequence	Operation	Complete
10	Build bowl through additive manufacturing in AM machine	□
20	Separate bowl from build plate with wire EDM	□
30	Heat treatment	□
40	Machining operation on Bowl inside Haas TL1	□
50	Remove bowl from Haas TL1, clean off chips	□
60	Fixture Bowl in coordinate measuring machine (CMM)	□
70	Measure Bowl with CMM; collect results	□

CAL POLY SAN LUIS OBISPO	**Part Routing**	
	NAME	Ben Wong
	PART	Cube attached to build plate

Sequence	Operation	Complete
10	Machine kinematic mounting features onto blank build plate	□
20	Build cube through additive manufacturing in AM machine	□
30	Heat treatment	□
40	Machining operation on cube inside Haas VF2	□
50	Remove cube/build plate from Haas VF2, clean off chips/coolant	□
60	Fixture cube/build plate to mating kinematic mount in coordinate measuring machine (CMM)	□
70	Measure cube/build plate with CMM; collect results	□

CAL POLY SAN LUIS OBISPO	Part Routing	
	NAME	Ben Wong
	PART	Cube with kinematic features

Sequence	Operation	Complete
10	Build cube through additive manufacturing in AM machine	☐
20	Separate cube from build plate with wire EDM	☐
30	Heat treatment	☐
40	Machining operation on cube inside Haas VF2	☐
50	Remove cube from Haas VF2, clean off chips/coolant	☐
60	Fixture cube with mating kinematic mount in coordinate measuring machine (CMM)	☐
70	Measure cube with CMM; collect results	☐

CAL POLY SAN LUIS OBISPO	Part Routing	
	NAME	Ben Wong
	PART	Cube **without** kinematic features

Sequence	Operation	Complete
10	Build cube through additive manufacturing in AM machine	□
20	Separate cube from build plate with wire EDM	□
30	Heat treatment	□
40	Machining operation on cube inside Haas VF2	□
50	Remove cube from Haas VF2, clean off chips/coolant	□
60	Fixture cube in coordinate measuring machine (CMM)	□
70	Measure cube with CMM; collect results	□

CAL POLY SAN LUIS OBISPO	Part Routing	
	NAME	Ben Wong
	PART	Cylinder with kinematic step

Sequence	**Operation**	**Complete**
10	Build cylinder through additive manufacturing in AM machine	☐
20	Separate cylinder from build plate with wire EDM	☐
30	Heat treatment	☐
40	Machining operation on cylinder inside Haas TL1	☐
50	Remove cylinder from Haas TL1, clean off chips	☐
60	Fixture cylinder in coordinate measuring machine (CMM)	☐
70	Measure cylinder with CMM; collect results	☐

CAL POLY SAN LUIS OBISPO	Part Routing	
	NAME	Ben Wong
	PART	Cylinder without kinematic features

Sequence	Operation	Complete
10	Build cylinder through additive manufacturing in AM machine	□
20	Separate cylinder from build plate with wire EDM	□
30	Heat treatment	□
40	Machining operation on cylinder inside Haas TL1	□
50	Remove cylinder from Haas TL1, clean off chips	□
60	Fixture cylinder in coordinate measuring machine (CMM)	□
70	Measure cylinder with CMM; collect results	□

CAL POLY SAN LUIS OBISPO	**Part Routing**	
	NAME	Ben Wong
	PART	Octahedron attached to build plate

Sequence	**Operation**	**Complete**
10	Machine kinematic mounting features onto blank build plate	□
20	Build octahedron through additive manufacturing in AM machine	□
30	Heat treatment	□
40	Machining operation on Octahedron inside Haas VF2	□
50	Remove Octahedron/build plate from Haas VF2, clean off chips/coolant	□
60	Fixture Octahedron/build plate to mating kinematic mount in coordinate measuring machine (CMM)	□
70	Measure Octahedron/build plate with CMM; collect results	□

CAL POLY SAN LUIS OBISPO	Part Routing	
	NAME	Ben Wong
	PART	Octahedron with kinematic features

Sequence	Operation	Complete
10	Machine kinematic mounting features onto blank build plate	□
20	Build octahedron through additive manufacturing in AM machine	□
30	Heat treatment	□
40	Machining operation on octahedron inside Haas VF2	□
50	Remove octahedron from Haas VF2, clean off chips/coolant	□
60	Fixture octahedron to mating kinematic mount in coordinate measuring machine (CMM)	□
70	Measure Octahedron/build plate with CMM; collect results	□

CAL POLY SAN LUIS OBISPO	Part Routing	
	NAME	Ben Wong
	PART	Octahedron with kinematic features

Sequence	Operation	Complete
10	Build octahedron through additive manufacturing in AM machine	□
20	Separate octahedron from build plate with wire EDM	□
30	Heat treatment	□
40	Machining operation on octahedron inside Haas VF2	□
50	Remove octahedron from Haas VF2, clean off chips/coolant	□
60	Fixture octahedron in coordinate measuring machine (CMM)	□
70	Measure octahedron with CMM; collect results	□

Appendix C: Job Plan

	JOB PLANNER	
CAL POLY SAN LUIS OBISPO	*NAME:*	Ben Wong
	PART	Bowl without kinematic features
	DRAWING REV:	A
	MATERIAL:	316 stainless steel

Notes: This details the machining operations performed in a Haas TL1 Lathe. The additive manufacturing and heat treatment processes will be completed off campus at Lawrence Livermore National Laboratories

OP #	Operation Description	Machine Tool	Tooling and fixtures required	Op Time	Approval
41	Set tool offsets off of bowl edge and outer diameter	CNMG431 VNMG432B CCMT-21.51	Haas TL1 Lathe Chuck wrench	4:06	
42	Face .010" off bowl edge	CNMG431		4:09	
43	Remove .010" from OD of part	VNMG432B			
44	Remove .010" from ID of part	CCMT-21.51			

CAL POLY
SAN LUIS OBISPO

JOB PLANNER	
NAME:	Ben Wong
PART	Bowl with kinematic features
DRAWING REV:	A
MATERIAL:	316 SST

Notes: This details the machining operations performed in a Haas TL1 Lathe. The additive manufacturing process will be completed off campus at Lawrence Livermore National Laboratories

OP #	Operation Description	Machine Tool	Tooling and fixtures required	Op Time	Approval
41	Grind specialized grooving tool to shape, cut kinematic groove into chuck soft jaws	Internal grooving tool, HSS		~20:00-30:00	
42	Fixture part in chuck soft jaws			5:44	
43	Locate part zero off bowl OD and KM feature	CNMG431 VNMG432B CCMT-21.51	Haas TL1 Lathe Chuck key Allen wrenches	2:33	
44	Face .010" from of part	CNMG431		6:18	
45	Remove .010" from OD of part	VNMG432B			
46	Remove .010" from ID of part	CCMT-21.51			

CAL POLY SAN LUIS OBISPO	JOB PLANNER	
	NAME:	Ben Wong
	PART	Cube attached to build plate
	DRAWING REV:	A
	MATERIAL:	316 SST

Notes: This details the machining operations performed in a Haas VF2 vertical mill. The additive manufacturing and heat treatment processes will be completed off campus at Lawrence Livermore National Laboratories

OP #	Operation Description	Machine Tool	Tooling and fixtures required	Op Time	Approval
41	Locate part origin off corner of build plate	Renishaw probe	Haas VF2 Vertical Mill Kurt vise 1 ⅛” - 2 ½” Step blocks Stepped toe clamps		
42	Face .010” from top (+Z) face	¾” 4-flute carbide end mill			
43	Face .010” from back (+Y) face				
44	Face .010” from front (-Y) face				
45	Drill .5” deep C hole on top (+Z) face	.242” (C) Drill)			

CAL POLY SAN LUIS OBISPO		JOB PLANNER
	NAME:	Ben Wong
	PART	Cube with Kinematic Features
	DRAWING REV:	A
	MATERIAL:	316 SST

Notes: This details the machining operations performed in a Haas VF2 vertical mill. The additive manufacturing and heat treatment processes will be completed off campus at Lawrence Livermore National Laboratories

OP #	Operation Description	Machine Tool	Tooling and fixtures required	Op Time	Approval
41	Fixture cube itself into Kurt vise using machinist parallels		Haas VF2 Vertical Mill Kurt Vise 1 ¾” Machinist parallels		
42	Locate part origin off part edges	Renishaw probe			
43	Face .010” from top (+Z) face	¾” 4-flute carbide end mill			
44	Fixture cube onto KM grooves on build plate, clamp down		Haas VF2 Vertical Mill Kurt Vise 1 ⅛” - 2 ½” Step blocks Stepped toe clamps		
45	Locate part origin off corner of build plate and cube top	Renishaw probe			
46	Face .010” from back (+Y) face	¾” 4-flute carbide end mill			
47	Face .010” from front (-Y) face				
48	Drill .5” deep C hole on top (+Z) face	.242” (C) Drill)			

CAL POLY SAN LUIS OBISPO	JOB PLANNER	
	NAME:	Ben Wong
	PART	Cube **without** Kinematic Features
	DRAWING REV:	A
	MATERIAL:	316 SST

Notes: This details the machining operations performed in a Haas VF2 vertical mill. The additive manufacturing and heat treatment processes will be completed off campus at Lawrence Livermore National Laboratories

OP #	Operation Description	Machine Tool	Tooling and fixtures required	Op Time	Approval
41	Locate part origin part edges	Renishaw probe	Haas VF2 Vertical Mill Kurt Vise		
42	Face .010" from top (+Z) face	¾" 4-flute carbide end mill			
43	Drill .5" deep C hole on top (+Z) face	.242" (C) Drill)			
44	Flip cube 90° in vise, re-probe X and Z offsets	Renishaw probe			
45	Face .010" from left (+X) face	¾" 4-flute carbide end mill			
46	Flip cube 180° in vise, re-probe X and Z offsets	Renishaw probe			
47	Face .010" from right (-X) face	¾" 4-flute carbide end mill			

CAL POLY SAN LUIS OBISPO	JOB PLANNER	
	NAME:	Ben Wong
	PART	Cylinder
	DRAWING REV:	A
	MATERIAL:	316 SST

Notes: This details the machining operations performed in a Haas TL1 Lathe. The additive manufacturing and heat treatment processes will be completed off campus at Lawrence Livermore National Laboratories

OP #	Operation Description	Machine Tool	Tooling and fixtures required	Op Time	Approval
41	Fixture part into chuck jaws	CNMG432B	Haas TL1 Lathe Chuck key		
42	Locate tool offsets off of part OD and face			4:02	
43	Turn outer profile of part, rough passes			11:47	
44	Turn outer profile of part, finish pass				

	JOB PLANNER
NAME:	Ben Wong
PART	Cylinder with kinematic features
DRAWING REV:	A
MATERIAL:	316 SST

Notes: This details the machining operations performed in a Haas TL1 Lathe. The additive manufacturing and heat treatment processes will be completed off campus at Lawrence Livermore National Laboratories

<table>
<tr><th>OP #</th><th>Operation Description</th><th>Machine Tool</th><th>Tooling and fixtures required</th><th>Op Time</th><th>Approval</th></tr>
<tr><td>41</td><td>Fix soft jaws into chuck</td><td></td><td rowspan="6">Haas TL1 Lathe

Chuck key</td><td>5:44</td><td></td></tr>
<tr><td>42</td><td>Cut kinematic features on chuck soft jaws</td><td>Internal grooving tool</td><td>5:00-10:00</td><td></td></tr>
<tr><td>43</td><td>Fixture part in chuck soft jaws using kinematic slot</td><td></td><td></td><td></td></tr>
<tr><td>44</td><td>Locate tool offsets off of part OD and kinematic feature</td><td rowspan="3">CNMG432B</td><td>4:02</td><td></td></tr>
<tr><td>45</td><td>Turn outer profile of part, rough passes</td><td rowspan="2">10:16</td><td></td></tr>
<tr><td>46</td><td>Turn outer profile of part, finish pass</td><td></td></tr>
</table>

CAL POLY
SAN LUIS OBISPO

JOB PLANNER	
NAME:	Ben Wong
PART	Octahedron attached to build plate
DRAWING REV:	A
MATERIAL:	316 SST

Notes: This details the machining operations performed in a Haas VF2 vertical mill. The additive manufacturing and heat treatment processes will be completed off campus at Lawrence Livermore National Laboratories

<table>
<tr><th>OP #</th><th>Operation Description</th><th>Machine Tool</th><th>Tooling and fixtures required</th><th>Op Time</th><th>Approval</th></tr>
<tr><td>41</td><td>Fix build plate onto bottom plate</td><td></td><td rowspan="4">Haas VF2 Vertical Mill

Kurt Vise

1 ⅛” - 2 ½” Step blocks

Stepped Toe clamps</td><td></td><td></td></tr>
<tr><td>42</td><td>Locate part origin off corner of build plate</td><td>Renishaw probe</td><td>6:47</td><td></td></tr>
<tr><td>43</td><td>Face .010” from top (+Z) face</td><td>¾” 4-flute carbide end mill</td><td rowspan="2">30:33</td><td></td></tr>
<tr><td>44</td><td>Face .010” from back (-Y) face</td><td>½” 4-flute carbide ball end mill</td><td></td></tr>
</table>

CAL POLY
SAN LUIS OBISPO

JOB PLANNER	
NAME:	Ben Wong
PART	Octahedron with kinematic features
DRAWING REV:	A
MATERIAL:	316 SST

Notes: This details the machining operations performed in a Haas VF2 vertical mill. The additive manufacturing and heat treatment processes will be completed off campus at Lawrence Livermore National Laboratories

<table>
<tr><th>OP #</th><th>Operation Description</th><th>Machine Tool</th><th>Tooling and fixtures required</th><th>Op Time</th><th>Approval</th></tr>
<tr><td>41</td><td>Fix bottom plate into vise</td><td></td><td rowspan="5">Haas VF2 Vertical Mill
Kurt Vise
1 ⅛” - 2 ½” Step blocks
Stepped Toe clamps</td><td></td><td></td></tr>
<tr><td>42</td><td>Fixture octahedron onto KM grooves on build plate, clamp down</td><td></td><td>12:13</td><td></td></tr>
<tr><td>43</td><td>Locate part origin off corner of build plate and top face of part</td><td rowspan="5">Renishaw probe
¾” 4-flute carbide end mill
½” 4-flute carbide ball end mill</td><td>6:01</td><td></td></tr>
<tr><td>44</td><td>Face .010” from back (-Y) face</td><td rowspan="4">29:03</td><td></td></tr>
<tr><td>45</td><td>Unclamp part, rotate 90°, clamp down</td><td></td></tr>
<tr><td>46</td><td>Re-probe Z offset off of top face of part</td><td></td><td></td></tr>
<tr><td>47</td><td>Face .010” from back (-Z) face</td><td></td><td></td></tr>
</table>

CAL POLY SAN LUIS OBISPO	JOB PLANNER	
	NAME:	Ben Wong
	PART	Octahedron **without** kinematic features
	DRAWING REV:	A
	MATERIAL:	316 SST

Notes: This details the machining operations performed in a Haas VF2 vertical mill. The additive manufacturing and heat treatment processes will be completed off campus at Lawrence Livermore National Laboratories

OP #	Operation Description	Machine Tool	Tooling and fixtures required	Op Time	Approval
41	Cut soft jaws	¼” FEM ¼” BEM 1/16” BEM	Haas VF2 Vertical Mill 1 ⅛” - 2 ½” Step blocks Stepped Toe clamps Soft Jaws Kurt Vise	22:14	
42	Attach soft jaws to Kurt vise				
43	Fixture part in soft jaws; tighten jaws				
44	Locate part origin off corner of soft jaws and parts right (-X) edge	Renishaw probe ¾” 4-flute carbide flat end mill ½” 4-flute carbide ball end mill		7:13	
45	Face .010” from right (-X) face			41:45	
46	Open jaws; rotate part 90°; tighten vise				
47	Locate part X offset off right (-X) edge				
48	Face .010” from back (-Y) face				

Appendix D: Setup Sheets

CAL POLY

SAN LUIS OBISPO

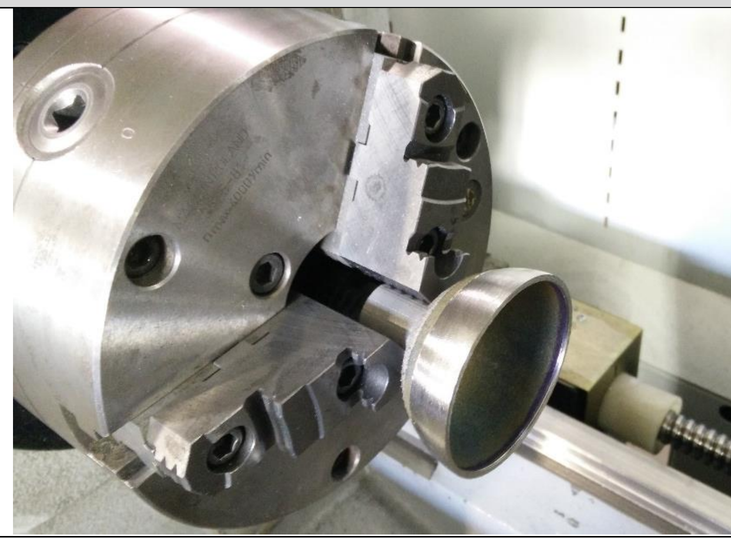
Manual Operation Setup Sheet			
NAME:	Ben Wong	*MACHINE TOOL:*	Haas TL-1
PART:	Bowl	*PRINT:*	
DRAWING REV:		*QTY MACHINED:*	1
MATERIAL:	316 SST	*MGR APPROVAL:*	

Note: A CCMT tool was originally purchased to turn the outer profile, but a VNMG tool was used instead as a better alternative. The VNMG was provided by the manufacturing labs, open for student use. Tennis ball was used to dampen vibrations caused during machining.

OP #	Machining Operation Description
40	Secure part in chuck jaws. Load tool inserts into tool holders, and load holders into tool posts. Find X and Z offsets for each tool by using hand jog to bring the tool in contact with part. Set offset a distance where rotating the spindle by hand peels a single chip from the part. After the facing operation with the CNMG and before the turning operation with the VNMG, stop the spindle and place a tennis ball into bowl; secure using the tailstock. Resume the operation as normal.

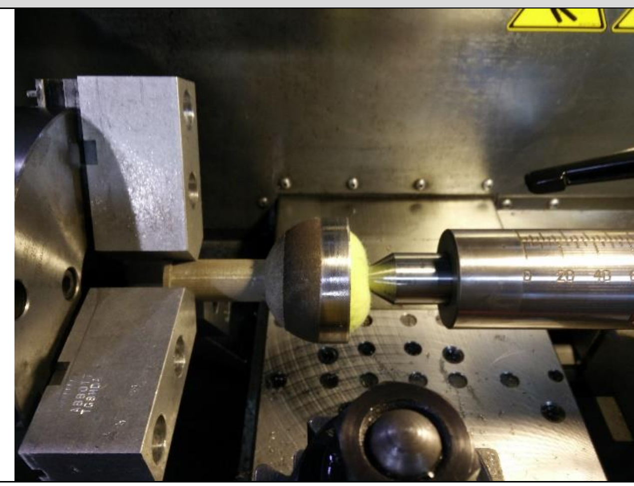
T#	Tooling Description	Surface Speed (fpm)	RPM	Chip Load (IPR)	Linear Feed Rate (IPM)
T1	CNMG	392	1500	.003	6
T2	VNMG	392	1500	.003	4.5

Setup Figure



CAL POLY SAN LUIS OBISPO	Manual Operation Setup Sheet			
	NAME:	Ben Wong	*MACHINE TOOL:*	Haas TL-1
	PART:	Bowl with KM	*PRINT:*	
	DRAWING REV:		*QTY MACHINED:*	1
	MATERIAL:	316 SST	*MGR APPROVAL:*	
Note: A CCMT tool was originally purchased to turn the outer profile, but a VNMG tool was used instead as a better alternative. The VNMG was provided by the manufacturing labs, open for student use. Tennis ball was used to dampen vibrations caused during machining.				

OP #	Machining Operation Description
40	Replace chuck jaws with soft jaws with cut slot. Secure part in chuck jaws; mate top of step to outermost lip of slot. Load tool inserts into tool holders, and load holders into tool posts. Find X and Z offsets for each tool by using hand jog to bring the tool in contact with part. Set offset a distance where rotating the spindle by hand peels a single chip from the part. After the facing operation with the CNMG and before the turning operation with the VNMG, stop the spindle and place a tennis ball into bowl; secure using the tailstock. Resume the operation as normal.

T#	Tooling Description	Surface Speed (fpm)	RPM	Chip Load (IPR)	Linear Feed Rate (IPM)	Setup Figure
T1	CNMG	392	1500	.003	6	
T2	VNMG	392	1500	.003	4.5	

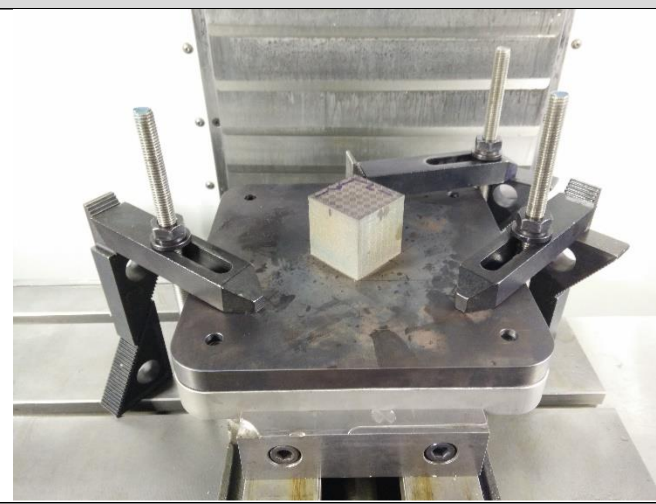
CAL POLY
SAN LUIS OBISPO

Manual Operation Setup Sheet			
NAME:	Ben Wong	*MACHINE TOOL:*	Haas VF2
PART:	Cube on build plate	*PRINT:*	
DRAWING REV:		*QTY MACHINED:*	1
MATERIAL:	316 SST	*MGR APPROVAL:*	

OP #	Machining Operation Description
40	Reverse the vise jaws to accommodate bottom kinematic plate. Tighten vise and tap down plate with plastic mallet. Use step blocks and a toe clamp to secure part to kinematic coupling. To secure clamp over rear kinematic coupling, reverse toe clamp and use small step block, as picture. Locate G54 off of plate's top right corner using the Renishaw probe and appropriate probe macros (navigate to menu with MDI->PGRM/CONVRS->VQC). Handle jog the probe to within 10mm of the surface to be measured. Load tools into tool holders and then into the tool changer using the manual tool release button (MDI->"T#"->ATC FWD). Find the height and diameter offset of each tool using a probe macro. Load .nc file generated beforehand with a flash drive. Verify that no tools were left inside machine before closing the doors and pressing 'Cycle start'. Keep rapid movements at 5% and a hand on 'feed hold'. Carefully watch the entire machining operation.

T#	Tooling Description	Surface Speed (fpm)	RPM	Chip Load (IPT)	Linear Feed Rate (IPM)
T4	¾" Flat end mill	300	1530	.003	18.33
T25	Renishaw probe	N/A	N/A	N/A	N/A

Setup Figure



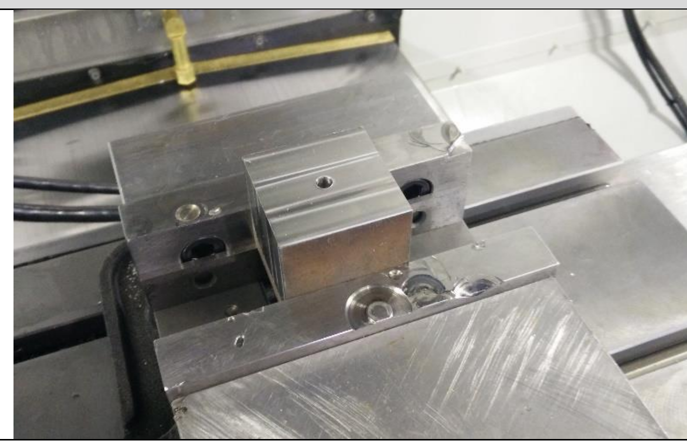
CAL POLY
SAN LUIS OBISPO

Manual Operation Setup Sheet			
NAME:	Ben Wong	*MACHINE TOOL:*	Haas VF2
PART:	Cube no KM	*PRINT:*	
DRAWING REV:		*QTY MACHINED:*	1
MATERIAL:	316 SST	*MGR APPROVAL:*	

OP #	Machining Operation Description
40	Use a vise and a set of 1 ⅝” machinist parallels to secure the cube. Tighten vise and tap down part with plastic mallet. Locate G54 part’s top right corner using the Renishaw probe and appropriate probe macros (navigate to menu with MDI->PGRM/CONVRS->VQC). Handle jog the probe to within 10mm of the surface to be measured. Load tools into tool holders and then into the tool changer using the manual tool release button (MDI->”T#”->ATC FWD). Find the height and diameter offset of each tool using a probe macro. Load .nc file generated beforehand with a flash drive. Verify that no tools were left inside machine before closing the doors and pressing ‘Cycle start’. Keep rapid movements at 5% and a hand on ‘feed hold’. Carefully watch the entire machining operation. Flip cube and re-secure in vise for next operation. Probe Z offset again. Repeat for third operation.

T#	Tooling Description	Surface Speed (fpm)	RPM	Chip Load (IPT)	Linear Feed Rate (IPM)
T4	¾” Flat end mill	300	1530	.003	18.33
T25	Renishaw probe	N/A	N/A	N/A	N/A

Setup Figure



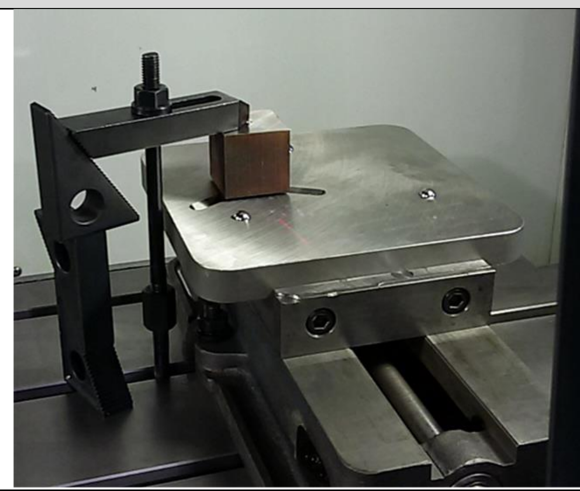
CAL POLY
SAN LUIS OBISPO

Manual Operation Setup Sheet			
NAME:	Ben Wong	*MACHINE TOOL:*	Haas VF2
PART:	Cube with KM features	*PRINT:*	
DRAWING REV:		*QTY MACHINED:*	1
MATERIAL:	316 SST	*MGR APPROVAL:*	

OP #	Machining Operation Description
40	Reverse the vise jaws to accommodate bottom kinematic plate. Tighten vise and tap down plate with plastic mallet. Use step blocks and a toe clamp to secure part to kinematic coupling. For cube with kinematic grooves, place SST ball bearing underneath before clamping Locate G54 plate’s top right corner and top of cube using the Renishaw probe and appropriate probe macros (navigate to menu with MDI->PGRM/CONVRS->VQC). Handle jog the probe to within 10mm of the surface to be measured. Load tools into tool holders and then into the tool changer using the manual tool release button (MDI->”T#”->ATC FWD). Find the height and diameter offset of each tool using a probe macro. Load .nc file generated beforehand with a flash drive. Verify that no tools were left inside machine before closing the doors and pressing ‘Cycle start’. Keep rapid movements at 5% and a hand on ‘feed hold’. Carefully watch the entire machining operation.

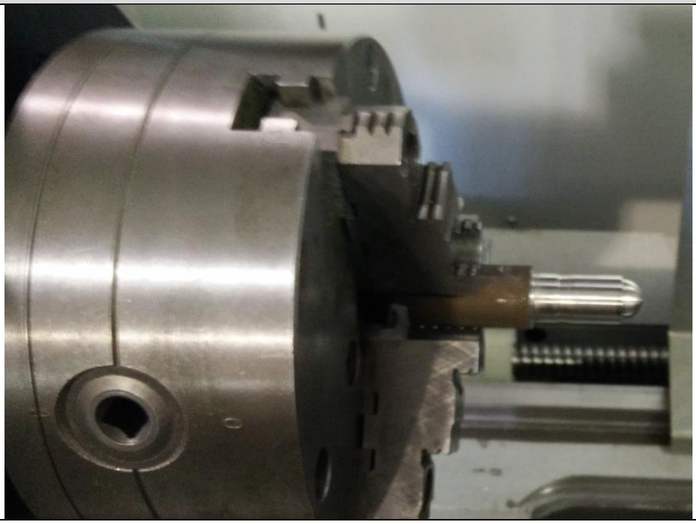
T#	Tooling Description	Surface Speed (fpm)	RPM	Chip Load (IPT)	Linear Feed Rate (IPM)
T4	¾” Flat end mill	300	1530	.003	18.33
T5	½” Ball end mill	300	2290	.003	27.5
T25	Renishaw probe	N/A	N/A	N/A	N/A

Setup Figure



CAL POLY SAN LUIS OBISPO	Manual Operation Setup Sheet			
	NAME:	Ben Wong	*MACHINE TOOL:*	Haas TL-1
	PART:	Cylinder no KM	*PRINT:*	
	DRAWING REV:		*QTY MACHINED:*	1
	MATERIAL:	316 SST	*MGR APPROVAL:*	

OP #	Machining Operation Description
40	Secure part in chuck jaws. Load tool inserts into tool holders, and load holders into tool posts. Find X and Z offsets for each tool by using hand jog to bring the tool in contact with part. Set offset a distance where rotating the spindle by hand peels a single chip from the part. Lubricate part using spray bottle of WD-40.

T#	Tooling Description	Surface Speed (fpm)	RPM	Chip Load (IPR)	Linear Feed Rate (IPM)	Setup Figure
T1	CNMG	392	1500	.003	6	

CAL POLY
SAN LUIS OBISPO

Manual Operation Setup Sheet

NAME:	Ben Wong	*MACHINE TOOL:*	Haas TL-1
PART:	Cylinder with KM	*PRINT:*	
DRAWING REV:		*QTY MACHINED:*	1
MATERIAL:	316 SST	*MGR APPROVAL:*	

OP #	Machining Operation Description
40	Replace chuck jaws with soft jaws with cut slot. Secure part in chuck jaws; mate top of step to outermost lip of slot. Load tool inserts into tool holders, and load holders into tool posts. Find X and Z offsets for each tool by using hand jog to bring the tool in contact with part. Set offset a distance where rotating the spindle by hand peels a single chip from the part. Lubricate part using spray bottle of WD-40.

T#	Tooling Description	Surface Speed (fpm)	RPM	Chip Load (IPR)	Linear Feed Rate (IPM)
T1	CNMG	392	1500	.003	6

Setup Figure

	Manual Operation Setup Sheet			
CAL POLY SAN LUIS OBISPO	*NAME:*	Ben Wong	*MACHINE TOOL:*	Haas VF2
	PART:	Octahedron on build plate	*PRINT:*	
	DRAWING REV:		*QTY MACHINED:*	1
	MATERIAL:	316 SST	*MGR APPROVAL:*	

OP #	Machining Operation Description
40	Reverse the vise jaws to accommodate bottom kinematic plate. Tighten vise and tap down plate with plastic mallet. Use step blocks and a toe clamp to secure part to kinematic coupling. To secure clamp over rear kinematic coupling, reverse toe clamp and use small step block, as picture. Locate G54 off of plate's top right corner using the Renishaw probe and appropriate probe macros (navigate to menu with MDI->PGRM/CONVRS->VQC). Handle jog the probe to within 10mm of the surface to be measured. Load tools into tool holders and then into the tool changer using the manual tool release button (MDI->"T#"->ATC FWD). Find the height and diameter offset of each tool using a probe macro. Handle jog each tool around part to ensure the neither the tool nor the spindle will crash into the clamps Load .nc file generated beforehand with a flash drive. Verify that no tools were left inside machine before closing the doors and pressing 'Cycle start'. Keep rapid movements at 5% and a hand on 'feed hold'.

T#	Tooling Description	Surface Speed (fpm)	RPM	Chip Load (IPT)	Linear Feed Rate (IPM)
T4	¾" Flat end mill	300	1530	.003	18.33
T5	½" Ball end mill	300	2290	.003	27.5
T25	Renishaw probe	N/A	N/A	N/A	N/A

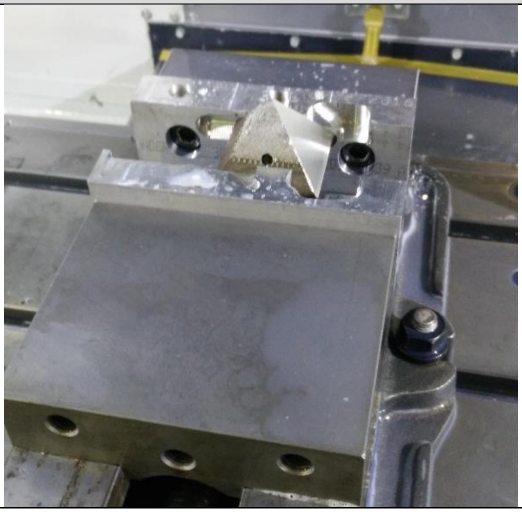
Setup Figure

CAL POLY SAN LUIS OBISPO	Manual Operation Setup Sheet			
	NAME:	Ben Wong	*MACHINE TOOL:*	Haas VF2
	PART:	Octahedron no KM	*PRINT:*	
	DRAWING REV:		*QTY MACHINED:*	1
	MATERIAL:	316 SST	*MGR APPROVAL:*	

OP #	Machining Operation Description
40	Replace jaws in vise with soft jaws for the octahedron. Insert octahedron into vise and clamp. Locate G54 off Y and Z face of soft jaw, but the right edge of the octahedron for X, using the Renishaw probe and appropriate probe macros (navigate to menu with MDI->PGRM/CONVRS->VQC). Handle jog the probe to within 10mm of the surface to be measured. Load tools into tool holders and then into the tool changer using the manual tool release button (MDI->"T#"->ATC FWD). Find the height and diameter offset of each tool using a probe macro. Load .nc file generated beforehand with a flash drive. Verify that no tools were left inside machine before closing the doors and pressing 'Cycle start'. Keep rapid movements at 5% and a hand on 'feed hold'. Carefully watch the entire machining operation. Rotate part and re-secure in vise for next operation. Probe X offset again.

T#	Tooling Description	Surface Speed (fpm)	RPM	Chip Load (IPT)	Linear Feed Rate (IPM)
T4	¾" Flat end mill	300	1530	.003	18.33
T5	½" Ball end mill	300	2290	.003	27.5
T25	Renishaw probe	N/A	N/A	N/A	N/A

Setup Figure



CAL POLY
SAN LUIS OBISPO

Manual Operation Setup Sheet			
NAME:	Ben Wong	*MACHINE TOOL:*	Haas VF2
PART:	Octahedron with KM features	*PRINT:*	
DRAWING REV:		*QTY MACHINED:*	1
MATERIAL:	316 SST	*MGR APPROVAL:*	

OP #	Machining Operation Description
40	Reverse the vise jaws to accommodate bottom kinematic plate. Tighten vise and tap down plate with plastic mallet. Use step blocks and a toe clamp to secure part to kinematic coupling. For octahedron with KM grooves, place SST ball bearings inside grooves. Locate G54 plate's top right corner and top of octahedron using the Renishaw probe and appropriate probe macros (navigate to menu with MDI->PGRM/CONVRS->VQC). Handle jog the probe to within 10mm of the surface to be measured. Load tools into tool holders and then into the tool changer using the manual tool release button (MDI->"T#"->ATC FWD). Find the height and diameter offset of each tool using a probe macro. Load .nc file generated beforehand with a flash drive. Verify that no tools were left inside machine before closing the doors and pressing 'Cycle start'. Keep rapid movements at 5% and a hand on 'Feed hold'. Carefully watch the entire machining operation. Release toe clamp and rotate octahedron 90° for next operation. Probe Z offset again (top of part).

T#	Tooling Description	Surface Speed (fpm)	RPM	Chip Load (IPT)	Linear Feed Rate (IPM)
T4	¾" Flat end mill	300	1530	.003	18.33
T5	½" Ball end mill	300	2290	.003	27.5
T25	Renishaw probe	N/A	N/A	N/A	N/A

Setup Figure

Appendix E: Time Study Data

Table E.1. Total time and cost for all parts

Part		Total Time (min:sec)	Total Time (min)	Cost/hour ($)	Total Cost ($)
	Bottom KM Plate	08:22.1	8.368333	230	32.08
Cubes	Cube on plate	47:40.4	47.67283	230	182.75
	Cube no KM	23:39.6	23.65883	230	90.69
	Cube KM spheres	45:09.1	45.15167	230	173.08
	Cube KM grooves	45:29.4	45.49017	230	174.38
Cylinders	Cylinder step	28:02.0	28.033	230	107.46
	Cylinder	22:56.1	22.9345	230	87.92
Octahedrons	Octahedron on plate	58:05.5	58.091	230	222.68
	Octahedron no KM	97:56.0	97.94917	230	375.47
	Octahedron KM spheres	54:55.8	54.9295	230	210.56
	Octahedron KM grooves	58:29.4	58.4895	230	224.21
Bowls	Bowl step	20:47.0	20.78367	230	79.67
	Bowl	16:23.9	16.39783	230	62.86

*All calculations of cost from the time for each operation assumes a cost to the lab of $230 per hour for machining.

Cubes

Table E.2. Time for each operation performed on the cube attached to the build plate

Cube on Build Plate			
Operation	Time (min:sec)	Time (minutes)	Total Cost ($)
Set-up	13:57.2	13.95333	53.49
Machining	21:15.5	21.25833	81.49
Remove from Machine	02:57.8	2.963333	11.36
Inspection	09:29.9	9.497833	36.41
Total	47:40.4	47.67283	182.75

Table E.3. Time for each operation performed on the standard cube

Cube with no KM features				
Operation	Notes	Time (min:sec)	Time (minutes)	Total Cost ($)
Set-up 1	face 1	03:36.3	3.605	13.82
Machining 1		01:03.3	1.055	4.04
Set-up 2	face 2	04:39.3	4.655	17.84
Machining 2		00:50.8	0.846667	3.25
Set-up 3	face 3	04:18.0	4.3	16.48
Machining 3		00:54.9	0.915	3.51
Inspection		08:16.9	8.282167	31.75
Total		23:39.6	23.65883	90.69

Table E.4. Time for each operation performed on the cube with kinematic mounting hemispheres built directly onto the part

Cube with KM spheres				
Operation	Notes	Time (min:sec)	Time (minutes)	Total Cost ($)
Set-up 1	in vice	03:10.0	3.166667	12.14
Machining 1	top face	01:15.1	1.251667	4.80
Set-up 2	on build plate	06:39.0	6.65	25.49
Machining 2	machine sides	25:54.0	25.90067	99.29
Inspection		08:11.0	8.182667	31.37
Total		45:09.1	45.15167	173.08

Table E.5. Time for each operation performed on the cube with kinematic mounting grooves built into the part. Ball bearings were placed between these grooves and the build plate grooves to complete the kinematic mounting.

Cube with KM grooves				
Operation	Notes	Time (min:sec)	Time (minutes)	Total Cost ($)
Set-up 1	in vice	03:10.0	3.166667	12.14
Machining 1	top face	01:13.2	1.219167	4.67
Set-up 2	on build plate	06:51.3	6.854333	26.27
Machining 2	machine sides	25:54.0	25.90067	99.29
Inspection		08:21.0	8.349333	32.01
Total		45:29.4	45.49017	174.38

Cylinders

Table E.6. Time for each operation performed on the cylinder with the step built in for kinematic mounting

Cylinder with Step			
Operation	Time (min:sec)	Time (minutes)	Total Cost ($)
Set-up	09:46.3	9.771667	37.46
Machining	10:16.0	10.26667	39.36
Inspection	07:59.7	7.994667	30.64622
Total	28:02.0	28.033	107.46

Table E.7. Time for each operation performed on the normal cylinder

Normal Cylilnder			
Operation	Time (min:sec)	Time (minutes)	Total Cost ($)
Set-up	03:51.0	3.85	14.76
Machining	11:47.0	11.78333	45.17
Inspection	07:18.1	7.301167	27.99
Total	22:56.1	22.9345	87.92

Octahedrons

Table E.8. Time for each operation performed on the octahedron attached to the build plate

Octahedron on Build Plate			
Operation	Time (min:sec)	Time (minutes)	Total Cost ($)
Set-up	17:11.1	17.1855	65.88
Machining	30:33.0	30.55	117.11
Remove from Machine	02:57.8	2.963667	11.36
Inspection	07:23.5	7.391833	28.34
Total	58:05.5	58.091	222.68

Table E.9. Time for each operation performed on the octahedron without any kinematic features

Octahedron with no KM features			
Operation	Time (min:sec)	Time (minutes)	Total Cost ($)
Soft jaws	39:09.9	39.1645	150.1306
Set-up	10:49.3	10.822	41.48433
Machining	41:45.0	41.75	160.0417
Inspection	06:12.8	6.212667	23.81522
Total	97:56.0	97.94917	375.4718

Table E.10. Time for each operation performed on the octahedron with hemispheres built directly on the part for kinematic mounting

Octahedron with KM spheres			
Operation	Time (min:sec)	Time (minutes)	Total Cost ($)
Set-up	18:14.0	18.23333	69.89444
Machining	29:03.0	29.05	111.3583
Inspection	07:38.8	7.646167	29.31031
Total	54:55.8	54.9295	210.5631

Table E.11. Time for each operation performed on the octahedron with kinematic mounting grooves built into the part. Ball bearings were placed between these grooves and the build plate grooves to complete the kinematic mounting.

Octahedron with KM grooves			
Operation	Time (min:sec)	Time (minutes)	Total Cost ($)
Set-up	18:19.0	18.31667	70.21389
Machining	32:25.0	32.41667	124.2639
Inspection	07:45.4	7.756167	29.73197
Total	58:29.4	58.4895	224.2098

Bowls

Table E.12. Time for each operation performed on the bowl with a step for kinematic mounting

Bowl with Step			
Operation	Time (min:sec)	Time (minutes)	Total Cost ($)
Set-up	07:57.0	7.95	30.48
Machining	06:18.0	6.3	24.15
Inspection	06:32.0	6.533667	25.04572
Total	20:47.0	20.78367	79.67

Table E.13. Time for each operation performed on the bowl without any kinematic mounting features

Bowl without Step			
Operation	Time (min:sec)	Time (minutes)	Total Cost ($)
Set-up	04:06.0	4.1	15.72
Machining	04:09.0	4.15	15.91
Inspection	08:08.9	8.147833	31.23336
Total	16:23.9	16.39783	62.86

Appendix F: Tolerance Deviation Data

Cubes

Table F.1. Deviations from the nominal value found during inspection of the cube attached to the build plate using the Zeiss CMM

Cube on Plate		
Feature	Tolerance (in)	Actual Deviation (in)
Flatness (top)	0.01	0.0001
Parallelism (sides)	0.01	0.0007
Perpendicularity	0.01	0
Width	0.01	0.0030
Average	0.01	0.0010

Table F.2. Deviations from the nominal value found during inspection of the standard cube using the Zeiss CMM

Cube no KM		
Feature	Tolerance (in)	Actual Deviation (in)
Flatness (top)	0.01	0.0001
Parallelism (sides)	0.01	0.0023
Perpendicularity	0.01	0.0005
Width	0.01	0.0033
Average	0.01	0.0016

Table F.3. Deviations from the nominal value found during inspection of the cube with kinematic mounting hemispheres built onto the part using the Zeiss CMM

Cube KM spheres		
Feature	Tolerance (in)	Actual Deviation (in)
Flatness (top)	0.01	0.0009
Parallelism (sides)	0.01	0.0001
Perpendicularity	0.01	0.0001
Width	0.01	0.0098
Average	0.01	0.0027

Table F.4. Deviations from the nominal value found during inspection of the cube with kinematic mounting grooves built into the part using the Zeiss CMM

Cube KM grooves Inspection		
Feature	Tolerance (in)	Actual Deviation (in)
Flatness (top)	0.01	0
Parallelism (sides)	0.01	0.0003
Perpendicularity	0.01	0.0006
Width	0.01	0.0100
Average	0.01	0.0027

Cylinders

Table F.5. Deviations from the nominal value found during inspection of the cylinder with the kinematic mounting step using the Zeiss CMM

Cylinder with Step		
Feature	Tolerance (in)	Actual Deviation (in)
Cylindricity (lower section	0.01	0
Cylindricity (upper section)	0.01	0.0022
Length (bottom step to top step)	0.01	0.0089
Average	0.01	0.0037

Table F.6. Deviations from the nominal value found during inspection of the cylinder without a kinematic mounting step using the Zeiss CMM

Cylinder no Step		
Feature	Tolerance (in)	Actual Deviation (in)
Cylindricity (lower section	0.01	0
Cylindricity (upper section)	0.01	0.0005
Length (bottom step to top step)	0.01	0.0004
Average	0.01	0.0003

Octahedrons

Table F.7. Deviations from the nominal value found during inspection of the octahedron attached to the build plate using the Zeiss CMM

Octahedron on Plate		
Feature	Tolerance (in)	Actual Deviation (in)
Flatness (side)	0.01	0.0009
Angularity	1	0.0014
Average	0.505	0.00115

Table F.8. Deviations from the nominal value found during inspection of the standard octahedron using the Zeiss CMM

Octahedron no KM		
Feature	Tolerance (in)	Actual Deviation (in)
Flatness (side)	0.01	0.0011
Angularity	1	0.0069
Average	0.505	0.0040

Table F.9. Deviations from the nominal value found during inspection of the octahedron with kinematic mounting hemispheres built onto the part using the Zeiss CMM

Octahedron KM spheres		
Feature	Tolerance (in)	Actual Deviation (in)
Flatness (side)	0.01	0.0012
Angularity	1	0.0042
Average	0.505	0.0027

Table F.10. Deviations from the nominal value found during inspection of the octahedron with kinematic mounting grooves built into the part using the Zeiss CMM

Octahedron KM grooves Inspection		
Feature	Tolerance (in)	Actual Deviation (in)
Flatness (side)	0.01	0.0011
Angularity	1	0.0051
Average	0.505	0.0031

Bowls

Table F.11. Deviations from the nominal value found during inspection of the bowl with kinematic mounting step using the Zeiss CMM

Bowl with Step		
Feature	Tolerance (in)	Actual Deviation (in)
Cylindricity	0.01	0.0018
Flatness (top face)	0.01	0.0049
Perpendicularity (top to cylinder)	0.01	0.2103
Average	0.01	0.072333

Table F.12. Deviations from the nominal value found during inspection of the bowl with no kinematic mounting step using the Zeiss CMM. Since this bowl did not have a cylindrical extension at the top, the roundness of the bowl had to be measured instead of the cylindricity of that extension.

Bowl no Step		
Feature	Tolerance (in)	Actual Deviation (in)
Roundness 1	0.01	0
Roundness 2	0.01	0.0001
Flatness (top face)	0.01	0.0041
Average	0.01	0.0014

Appendix G: Inspection Output files

```
================================================================================
       Z E I S S  /  C A L Y P S O  5.8.08  Default Printout
--------------------------------------------------------------------------------
Measurement Plan              Operator          Date                     Part No
cube_buildplate              Maren Cosens       May 6, 2016                    2
DURAMAX
--------------------------------------------------------------------------------
Names                    Description            Statistic / References      -1-
Symbol / References           Actual     Nominal    Tolerance     Dev.  Histogr.
================================================================================
Plane4("Flatness1")      Minimum Zone Plane       #P     (4)
--------------------------------------------------------------------------------
 Z                            1.9965      2.0000    S           0.0001
 X                           -5.5643     -6.0956  Min     (1)   0.0000
 Y                           -4.4815     -6.0956  Max     (4)   0.0000
 A1 X/Z                      -0.0337      0.0000 Form           0.0001
 A2 Y/Z                       0.2386      0.0000

Flatness1                Flatness
--------------------------------------------------------------------------------
Plane4                                                 0.0100   0.0001     |-


Plane6("Parallelism1")   Outer Tangential Plane    #P     (4)
--------------------------------------------------------------------------------
 X                           -5.8961     -6.2370    S           0.0000
 Y                           -4.4678     -4.8228  Min     (2)   0.0000
 Z                            1.4297      0.0000  Max     (3)   0.0000
 A1 Z/-X                     -0.2486      0.0000 Form           0.0000
 A2 Y/-X                     45.0038     45.0000

Plane5("Parallelism1")   Least Squares Plane       #P     (4)
--------------------------------------------------------------------------------
 Y                           -5.9939     -6.2370    S           0.0005
 Z                            1.4375      0.0000  Min     (1)  -0.0005
 X                           -4.6358     -4.8228  Max     (2)   0.0002
 A1 X/-Y                     44.9962     45.0000 Form           0.0007
 A2 Z/-Y                      0.2486      0.0000

Parallelism1             Parallelism
--------------------------------------------------------------------------------
Plane5                                                 0.0100   0.0007     |-
Plane6

Plane4("Perpendicularity1")
                        Outer Tangential Plane    #P     (4)
--------------------------------------------------------------------------------
 Z                            1.9965      2.0000    S           0.0002
 X                           -5.5643     -6.0956  Min     (1)  -0.0002
 Y                           -4.4815     -6.0956  Max     (3)   0.0000
 A1 X/Z                      -0.0268      0.0000 Form           0.0002
 A2 Y/Z                       0.2223      0.0000

Plane6("Perpendicularity1")
                        Least Squares Plane       #P     (4)
--------------------------------------------------------------------------------
 X                           -5.8961     -6.2370    S           0.0000
 Y                           -4.4678     -4.8228  Min     (2)   0.0000
 Z                            1.4297      0.0000  Max     (1)   0.0000
 A1 Z/-X                     -0.2491      0.0000 Form           0.0000
 A2 Y/-X                     45.0040     45.0000

Perpendicularity1        Perpendicularity
--------------------------------------------------------------------------------
Plane6                                                 0.0100   0.0000     |
Plane4

Plane6("Cartesian Distance1")
```

```
==============================================================================
       Z E I S S  /  C A L Y P S O  5.8.08  Default Printout
------------------------------------------------------------------------------
Measurement Plan             Operator          Date                    Part No
cube_buildplate             Maren Cosens       May 6, 2016                   2
DURAMAX
------------------------------------------------------------------------------
Names                    Description           Statistic / References      -2-
Symbol / References          Actual     Nominal    Tolerance     Dev.  Histogr.
==============================================================================
                        Least Squares Plane       #P     (4)
------------------------------------------------------------------------------
 X                          -5.8961     -6.2370    S            0.0000
 Y                          -4.4678     -4.8228  Min      (2)   0.0000
 Z                           1.4297      0.0000  Max      (1)   0.0000
 A1 Z/-X                    -0.2492      0.0000 Form            0.0000
 A2 Y/-X                    45.0040     45.0000

Plane5("Cartesian Distance1")
                        Least Squares Plane       #P     (4)
------------------------------------------------------------------------------
 Y                          -5.9939     -6.2370    S            0.0003
 Z                           1.4374      0.0000  Min      (4)  -0.0002
 X                          -4.6358     -4.8228  Max      (3)   0.0001
 A1 X/-Y                    44.9842     45.0000 Form            0.0003
 A2 Z/-Y                     0.3603      0.0000

Cartesian Distance1      Cartesian Distance
------------------------------------------------------------------------------
Plane5                                                 0.0100
Plane6                       1.9703      2.0000       -0.0100  -0.0297   -0.0197



Plane1("Cartesian Distance2")
                        Least Squares Plane       #P     (4)
------------------------------------------------------------------------------
 Z                          -0.0001      0.0000    S            0.0060
 X                          -8.8006     -9.6457  Min      (2)  -0.0030
 Y                          -0.6493      0.0000  Max      (1)   0.0031
 A1 X/Z                      0.0001      0.0000 Form            0.0061
 A2 Y/Z                      0.0010      0.0000

Plane4("Cartesian Distance2")
                        Least Squares Plane       #P     (4)
------------------------------------------------------------------------------
 Z                           1.9965      2.0000    S            0.0001
 X                          -5.5643     -6.0956  Min      (1)   0.0000
 Y                          -4.4815     -6.0956  Max      (4)   0.0000
 A1 X/Z                     -0.0329      0.0000 Form            0.0001
 A2 Y/Z                      0.2379      0.0000

Cartesian Distance2      Cartesian Distance
------------------------------------------------------------------------------
Plane4                                                 0.0100
Plane1                       1.9953      1.9900       -0.0100   0.0053     |---
```

```
================================================================================
       Z E I S S  /  C A L Y P S O  5.8.08  Default Printout
--------------------------------------------------------------------------------
Measurement Plan              Operator          Date                     Part No
Cube_noKM                     Maren Cosens      May 6, 2016                    2
DURAMAX
--------------------------------------------------------------------------------
Names                    Description            Statistic / References      -1-
Symbol / References           Actual     Nominal    Tolerance     Dev.  Histogr.
================================================================================
Plane1("Flatness1")      Minimum Zone Plane        #P     (4)
--------------------------------------------------------------------------------
 Z                            0.0000      0.0000    S            0.0001
 X                            0.2802      0.0000  Min     (1)   0.0000
 Y                            0.2253      0.0000  Max     (3)   0.0000
 A1 X/Z                       0.0006      0.0000 Form           0.0001
 A2 Y/Z                       0.0001      0.0000

Flatness1                Flatness
--------------------------------------------------------------------------------
Plane1                                                0.0100   0.0001     |-


Plane1("Perpendicularity1")
                        Outer Tangential Plane    #P     (4)
--------------------------------------------------------------------------------
 Z                            0.0002      0.0000    S            0.0002
 X                            0.2802      0.0000  Min     (1)  -0.0002
 Y                            0.2253      0.0000  Max     (4)   0.0000
 A1 X/Z                       0.0046      0.0000 Form           0.0002
 A2 Y/Z                       0.0042      0.0000

Plane2("Perpendicularity1")
                        Least Squares Plane       #P     (4)
--------------------------------------------------------------------------------
 Y                            0.0003      0.0000    S            0.0003
 Z                           -0.4907     -2.0000  Min     (2)  -0.0002
 X                            0.1758      0.0000  Max     (1)   0.0002
 A1 X/-Y                     -0.0005      0.0000 Form           0.0005
 A2 Z/-Y                      0.0042      0.0000

Perpendicularity1        Perpendicularity
--------------------------------------------------------------------------------
Plane2                                                0.0100   0.0005     |-
Plane1

Plane2("Parallelism1")   Outer Tangential Plane    #P     (4)
--------------------------------------------------------------------------------
 Y                            0.0005      0.0000    S            0.0004
 Z                           -0.4906     -2.0000  Min     (3)  -0.0004
 X                            0.1758      0.0000  Max     (1)   0.0000
 A1 X/-Y                     -0.0096      0.0000 Form           0.0004
 A2 Z/-Y                     -0.0805      0.0000

Plane4("Parallelism1")   Least Squares Plane       #P     (4)
--------------------------------------------------------------------------------
 Y                            1.9874      1.9900    S            0.0019
 Z                           -0.6370     -2.0000  Min     (4)  -0.0011
 X                            0.1680      0.0000  Max     (1)   0.0012
 A1 Z/Y                       0.0805      0.0000 Form           0.0023
 A2 X/Y                       0.0096      0.0000

Parallelism1             Parallelism
--------------------------------------------------------------------------------
Plane4                                                0.0100   0.0023     |-
Plane2

Plane4("Cartesian Distance1")
```

```
================================================================================
       Z E I S S  /  C A L Y P S O  5.8.08  Default Printout
--------------------------------------------------------------------------------
Measurement Plan              Operator          Date                     Part No
Cube_noKM                    Maren Cosens       May 6, 2016                    2
DURAMAX
--------------------------------------------------------------------------------
Names                    Description             Statistic / References      -2-
Symbol / References           Actual     Nominal    Tolerance     Dev.  Histogr.
================================================================================
                        Least Squares Plane       #P     (4)
--------------------------------------------------------------------------------
 Y                            1.9881      1.9900    S            0.0001
 Z                           -0.6369     -2.0000  Min     (4)    0.0000
 X                            0.1680      0.0000  Max     (3)    0.0000
 A1 Z/Y                      -0.0146      0.0000 Form            0.0001
 A2 X/Y                       0.0951      0.0000

Plane2("Cartesian Distance1")
                        Least Squares Plane       #P     (4)
--------------------------------------------------------------------------------
 Y                            0.0004      0.0000    S            0.0002
 Z                           -0.4906     -2.0000  Min     (3)   -0.0001
 X                            0.1758      0.0000  Max     (4)    0.0001
 A1 X/-Y                     -0.0004      0.0000 Form            0.0003
 A2 Z/-Y                     -0.0441      0.0000

Cartesian Distance1      Cartesian Distance
--------------------------------------------------------------------------------
Plane2                                                 0.0100
Plane4                        1.9867      1.9900      -0.0100  -0.0033   --|
```

```
================================================================================
       Z E I S S  /  C A L Y P S O  5.8.08  Default Printout
--------------------------------------------------------------------------------
Measurement Plan              Operator          Date                     Part No
cube_KMspheres               Maren Cosens       May 6, 2016                    2
DURAMAX
--------------------------------------------------------------------------------
Names                    Description            Statistic / References      -1-
Symbol / References           Actual     Nominal    Tolerance     Dev.  Histogr.
================================================================================
Plane1("Flatness1")      Minimum Zone Plane        #P     (4)
--------------------------------------------------------------------------------
 Z                           -0.0001      0.0000    S           0.0009
 X                            0.1588      0.0000  Min     (2)  -0.0004
 Y                            0.4535      0.0000  Max     (1)   0.0004
 A1 X/Z                      -0.0021      0.0000 Form           0.0009
 A2 Y/Z                      -0.0024      0.0000

Flatness1                Flatness
--------------------------------------------------------------------------------
Plane1                                                 0.0100   0.0009     |-


Plane1("Perpendicularity1")
                        Outer Tangential Plane    #P     (4)
--------------------------------------------------------------------------------
 Z                            0.0003      0.0000    S           0.0017
 X                            0.1588      0.0000  Min     (4)  -0.0017
 Y                            0.4534      0.0000  Max     (2)   0.0000
 A1 X/Z                      -0.0360      0.0000 Form           0.0017
 A2 Y/Z                       0.0317      0.0000

Plane2("Perpendicularity1")
                        Least Squares Plane       #P     (4)
--------------------------------------------------------------------------------
 Y                           -0.0004      0.0000    S           0.0001
 Z                           -0.5224     -2.0000  Min     (1)  -0.0001
 X                            0.1795      0.0000  Max     (2)   0.0000
 A1 X/-Y                     -0.0006      0.0000 Form           0.0001
 A2 Z/-Y                      0.0317      0.0000

Perpendicularity1        Perpendicularity
--------------------------------------------------------------------------------
Plane2                                                 0.0100   0.0001     |-
Plane1

Plane2("Parallelism1")   Outer Tangential Plane    #P     (4)
--------------------------------------------------------------------------------
 Y                           -0.0005      0.0000    S           0.0000
 Z                           -0.5225     -2.0000  Min     (4)   0.0000
 X                            0.1795      0.0000  Max     (1)   0.0000
 A1 X/-Y                      0.0000      0.0000 Form           0.0000
 A2 Z/-Y                      0.0508      0.0000

Plane4("Parallelism1")   Least Squares Plane       #P     (4)
--------------------------------------------------------------------------------
 Y                            1.9795      1.9900    S           0.0001
 Z                           -0.7425     -2.0000  Min     (1)  -0.0001
 X                            0.2721      0.0000  Max     (2)   0.0000
 A1 Z/Y                      -0.0508      0.0000 Form           0.0001
 A2 X/Y                       0.0000      0.0000

Parallelism1             Parallelism
--------------------------------------------------------------------------------
Plane4                                                 0.0100   0.0001     |-
Plane2

Plane4("Cartesian Distance1")
```

```
================================================================================
       Z E I S S  /  C A L Y P S O  5.8.08  Default Printout
--------------------------------------------------------------------------------
Measurement Plan              Operator          Date                    Part No
cube_KMspheres               Maren Cosens      May 6, 2016                   2
DURAMAX
--------------------------------------------------------------------------------
Names                    Description           Statistic / References      -2-
Symbol / References           Actual     Nominal    Tolerance     Dev.  Histogr.
================================================================================
                        Least Squares Plane       #P     (4)
--------------------------------------------------------------------------------
 Y                            1.9796      1.9900    S            0.0000
 Z                           -0.7425     -2.0000  Min     (4)   0.0000
 X                            0.2721      0.0000  Max     (3)   0.0000
 A1 Z/Y                      -0.0384      0.0000 Form            0.0000
 A2 X/Y                       0.0025      0.0000

Plane2("Cartesian Distance1")
                        Least Squares Plane       #P     (4)
--------------------------------------------------------------------------------
 Y                           -0.0004      0.0000    S            0.0000
 Z                           -0.5225     -2.0000  Min     (4)   0.0000
 X                            0.1795      0.0000  Max     (3)   0.0000
 A1 X/-Y                      0.0001      0.0000 Form            0.0000
 A2 Z/-Y                      0.0504      0.0000

Cartesian Distance1      Cartesian Distance
--------------------------------------------------------------------------------
Plane2                                                 0.0100
Plane4                        1.9802      1.9900      -0.0100  -0.0098 ----|
```

```
================================================================================
       Z E I S S  /  C A L Y P S O  5.8.08  Default Printout
--------------------------------------------------------------------------------
Measurement Plan              Operator          Date                    Part No
cube_KMgrooves                Maren Cosens      May 6, 2016                   2
DURAMAX
--------------------------------------------------------------------------------
Names                    Description            Statistic / References      -1-
Symbol / References           Actual     Nominal    Tolerance     Dev.  Histogr.
================================================================================
Plane1("Flatness1")      Minimum Zone Plane        #P     (4)
--------------------------------------------------------------------------------
 Z                            0.0000      0.0000    S           0.0000
 X                            0.2237      0.0000  Min     (2)   0.0000
 Y                            0.2617      0.0000  Max     (1)   0.0000
 A1 X/Z                       0.0000      0.0000 Form           0.0000
 A2 Y/Z                       0.0011      0.0000

Flatness1                Flatness
--------------------------------------------------------------------------------
Plane1                                                 0.0100   0.0000     |-


Plane1("Perpendicularity1")
                        Outer Tangential Plane    #P     (4)
--------------------------------------------------------------------------------
 Z                            0.0000      0.0000    S           0.0000
 X                            0.2237      0.0000  Min     (2)   0.0000
 Y                            0.2617      0.0000  Max     (1)   0.0000
 A1 X/Z                       0.0007      0.0000 Form           0.0000
 A2 Y/Z                       0.0004      0.0000

Plane2("Perpendicularity1")
                        Least Squares Plane       #P     (4)
--------------------------------------------------------------------------------
 Y                            0.0008      0.0000    S           0.0005
 Z                           -0.4236     -2.0000  Min     (2)  -0.0003
 X                            0.2619      0.0000  Max     (1)   0.0003
 A1 X/-Y                      0.0036      0.0000 Form           0.0006
 A2 Z/-Y                      0.0004      0.0000

Perpendicularity1        Perpendicularity
--------------------------------------------------------------------------------
Plane2                                                 0.0100   0.0006     |-
Plane1

Plane2("Parallelism1")   Outer Tangential Plane    #P     (4)
--------------------------------------------------------------------------------
 Y                            0.0012      0.0000    S           0.0001
 Z                           -0.4235     -2.0000  Min     (3)  -0.0001
 X                            0.2619      0.0000  Max     (2)   0.0000
 A1 X/-Y                     -0.0032      0.0000 Form           0.0001
 A2 Z/-Y                     -0.1682      0.0000

Plane4("Parallelism1")   Least Squares Plane       #P     (4)
--------------------------------------------------------------------------------
 Y                            1.9820      1.9900    S           0.0002
 Z                           -0.6848     -2.0000  Min     (2)  -0.0001
 X                            0.1659      0.0000  Max     (3)   0.0002
 A1 Z/Y                       0.1682      0.0000 Form           0.0003
 A2 X/Y                       0.0032      0.0000

Parallelism1             Parallelism
--------------------------------------------------------------------------------
Plane4                                                 0.0100   0.0003     |-
Plane2

Plane2("Cartesian Distance1")
```

```
================================================================================
       Z E I S S  /  C A L Y P S O  5.8.08  Default Printout
--------------------------------------------------------------------------------
Measurement Plan              Operator          Date                     Part No
cube_KMgrooves               Maren Cosens       May 6, 2016                    2
DURAMAX
--------------------------------------------------------------------------------
Names                    Description            Statistic / References      -2-
Symbol / References           Actual     Nominal    Tolerance     Dev.  Histogr.
================================================================================
                        Least Squares Plane       #P     (4)
--------------------------------------------------------------------------------
 Y                            0.0012      0.0000    S           0.0000
 Z                           -0.4235     -2.0000  Min     (3)   0.0000
 X                            0.2619      0.0000  Max     (4)   0.0000
 A1 X/-Y                     -0.0009      0.0000 Form           0.0000
 A2 Z/-Y                     -0.1558      0.0000

Plane4("Cartesian Distance1")
                        Least Squares Plane       #P     (4)
--------------------------------------------------------------------------------
 Y                            1.9819      1.9900    S           0.0001
 Z                           -0.6848     -2.0000  Min     (4)   0.0000
 X                            0.1659      0.0000  Max     (3)   0.0000
 A1 Z/Y                       0.1445      0.0000 Form           0.0001
 A2 X/Y                       0.0010      0.0000

Cartesian Distance1      Cartesian Distance
--------------------------------------------------------------------------------
Plane4                                                0.0100
Plane2                        1.9800      1.9900     -0.0100  -0.0100 ----|
```

```
================================================================================
       Z E I S S  /  C A L Y P S O  5.8.08  Default Printout
--------------------------------------------------------------------------------
Measurement Plan              Operator          Date                     Part No
cylinder_step                Maren Cosens       May 12, 2016                   2
DURAMAX
--------------------------------------------------------------------------------
Names                    Description            Statistic / References      -1-
Symbol / References           Actual     Nominal    Tolerance     Dev.  Histogr.
================================================================================
Cylinder1("Cylindricity1")
                        Least Squares Cylinder    #P     (5)  External
Least Squares Fit instead of Minimum Zone Fit !
Probing strategy / Check No. of Points !
--------------------------------------------------------------------------------
 X                       72917.4957      0.0000    S           0.0000
 Y                      -88706.9192      0.0000  Min     (4)   0.0000
 Z                           0.0000      0.0000  Max     (1)   0.0000
 D                         406.1396      0.8000 Form           0.0000
 A1 X/Z                     89.8406      0.0000
 A2 Y/Z                    -89.8690      0.0000

Cylindricity1            Cylindricity
--------------------------------------------------------------------------------
Cylinder1                                             0.0100   0.0000     |


Cylinder2("Cylindricity2")
                        Minimum Zone Cylinder     #P    (16)  External
--------------------------------------------------------------------------------
 X                           0.0308      0.0000    S           0.0010
 Y                          -0.0013      0.0000  Min    (14)  -0.0011
 Z                           0.6500      0.6500  Max     (7)   0.0011
 D                           0.7821      0.8000 Form           0.0022
 A1 X/Z                      0.2598      0.0000
 A2 Y/Z                      0.0228      0.0000

Cylindricity2            Cylindricity
--------------------------------------------------------------------------------
Cylinder2                                             0.0100   0.0022     |-


Plane2("Cartesian Distance1")
                        Least Squares Plane       #P     (4)
--------------------------------------------------------------------------------
 Z                           1.3741      1.3750    S           0.0277
 X                           0.1361      0.1222  Min     (4)  -0.0168
 Y                          -0.4031     -0.5239  Max     (1)   0.0142
 A1 X/Z                     -4.1517      0.0000 Form           0.0311
 A2 Y/Z                     -2.3600      0.0000

Plane1("Cartesian Distance1")
                        Least Squares Plane       #P     (3)
--------------------------------------------------------------------------------
 Z                           0.0000      0.0000    S           0.0000
 X                           0.1755      0.1527  Min     (1)   0.0000
 Y                          -0.6191     -0.6549  Max     (1)   0.0000
 A1 X/Z                      0.0000      0.0000 Form           0.0000
 A2 Y/Z                      0.0000      0.0000

Cartesian Distance1      Cartesian Distance
--------------------------------------------------------------------------------
Plane1                                                0.0100
Plane2                       1.3839      1.3750      -0.0100   0.0089     |----
```

```
================================================================================
       Z E I S S  /  C A L Y P S O  5.8.08  Default Printout
--------------------------------------------------------------------------------
Measurement Plan              Operator          Date                    Part No
cylinder                      Maren Cosens      May 12, 2016                  2
DURAMAX
--------------------------------------------------------------------------------
Names                    Description           Statistic / References      -1-
Symbol / References           Actual     Nominal    Tolerance     Dev.  Histogr.
================================================================================
Cylinder1("Cylindricity1")
                        Minimum Zone Cylinder     #P     (5)  External
--------------------------------------------------------------------------------
 X                            0.0000      0.0000    S           0.0000
 Y                            0.0000      0.0000  Min     (2)   0.0000
 Z                            0.0000      0.0000  Max     (1)   0.0000
 D                            0.7722      0.8000 Form           0.0000
 A1 X/Z                       1.6276      0.0000
 A2 Y/Z                       0.0000      0.0000

Cylindricity1            Cylindricity
--------------------------------------------------------------------------------
Cylinder1                                              0.0100   0.0000     |


Cylinder2("Cylindricity2")
                        Minimum Zone Cylinder     #P    (16)  External
--------------------------------------------------------------------------------
 X                            0.0089      0.0000    S           0.0002
 Y                            0.0016      0.0000  Min     (8)  -0.0003
 Z                            0.6500      0.6500  Max    (11)   0.0003
 D                            0.7728      0.8000 Form           0.0005
 A1 X/Z                       0.0114      0.0000
 A2 Y/Z                       0.2154      0.0000

Cylindricity2            Cylindricity
--------------------------------------------------------------------------------
Cylinder2                                              0.0100   0.0005     |-


Plane2("Cartesian Distance1")
                        Least Squares Plane       #P     (4)
--------------------------------------------------------------------------------
 Z                            1.3765      1.3750    S           0.0001
 X                            0.1628      0.1615  Min     (1)  -0.0001
 Y                           -0.5175     -0.5132  Max     (2)   0.0001
 A1 X/Z                      -0.3153      0.0000 Form           0.0002
 A2 Y/Z                       0.0988      0.0000

Plane1("Cartesian Distance1")
                        Least Squares Plane       #P     (3)
--------------------------------------------------------------------------------
 Z                            0.0000      0.0000    S           0.0000
 X                            0.1977      0.2019  Min     (1)   0.0000
 Y                           -0.6285     -0.6415  Max     (2)   0.0000
 A1 X/Z                       0.0000      0.0000 Form           0.0000
 A2 Y/Z                       0.0000      0.0000

Cartesian Distance1      Cartesian Distance
--------------------------------------------------------------------------------
Plane1                                                 0.0100
Plane2                        1.3746      1.3750      -0.0100  -0.0004    -|
```

```
================================================================================
       Z E I S S  /  C A L Y P S O  5.8.08  Default Printout
--------------------------------------------------------------------------------
Measurement Plan             Operator          Date                      Part No
octahedron_buildplate        Maren Cosens      May 18, 2016                    2
DURAMAX
--------------------------------------------------------------------------------
Names                        Description             Statistic / References      -1-
Symbol / References              Actual     Nominal    Tolerance     Dev.  Histogr.
================================================================================
Plane4("Flatness1")          Minimum Zone Plane        #P    (38)
--------------------------------------------------------------------------------
 Z                               3.5474      3.4161    S             0.0003
 X                              -5.3491     -5.5334  Min    (10)  -0.0005
 Y                               0.4075      0.2568  Max    (14)   0.0005
 A1 Y/-Z                        20.0826     20.1039 Form             0.0009
 A2 X/-Z                        14.9508     15.0000

Flatness1                    Flatness
--------------------------------------------------------------------------------
Plane4                                                  0.0100   0.0009     |-


Plane5("Angularity1")        Outer Tangential Plane    #P     (4)
--------------------------------------------------------------------------------
 Y                               1.7874      1.7963    S             0.0000
 Z                               4.8068      3.9796  Min     (3)   0.0000
 X                              -5.2521     -5.6890  Max     (1)   0.0000
 A1 Z/Y                         -0.0422      0.0000 Form             0.0000
 A2 X/Y                          0.0109      0.0000

Plane4("Angularity1")        Least Squares Plane       #P    (38)
--------------------------------------------------------------------------------
 Z                               3.5479      3.4161    S             0.0003
 X                              -5.3491     -5.5334  Min     (2)  -0.0006
 Y                               0.4072      0.2568  Max    (14)   0.0008
 A1 Y/-Z                        20.0545     20.1039 Form             0.0014
 A2 X/-Z                        14.9467     15.0000

Angularity1                  Angularity
--------------------------------------------------------------------------------
Plane4                                                  1.0000   0.0014     |-
Plane5
```

```
================================================================================
       Z E I S S  /  C A L Y P S O  5.8.08  Default Printout
--------------------------------------------------------------------------------
Measurement Plan              Operator          Date                     Part No
octahedron                   Maren Cosens      May 18, 2016                   1
DURAMAX
--------------------------------------------------------------------------------
Names                    Description            Statistic / References      -1-
Symbol / References           Actual     Nominal    Tolerance     Dev.  Histogr.
================================================================================
Plane4("Flatness1")      Minimum Zone Plane        #P    (19)
--------------------------------------------------------------------------------
 X                           -2.3782     -2.5648    S            0.0004
 Y                            0.5444      0.3938  Min    (13)  -0.0006
 Z                           -1.2799     -1.4505  Max     (2)   0.0006
 A1 Z/-X                     22.2268     22.2077 Form            0.0011
 A2 Y/-X                     31.3848     30.0000

Flatness1                Flatness
--------------------------------------------------------------------------------
Plane4                                                 0.0100   0.0011     |-


Plane1("Angularity1")    Outer Tangential Plane    #P     (3)
--------------------------------------------------------------------------------
 Z                            0.0000      0.0000    S            0.0000
 X                           -1.6262     -2.1881  Min     (1)   0.0000
 Y                            0.3407      0.0000  Max     (3)   0.0000
 A1 X/Z                       0.0000      0.0000 Form            0.0000
 A2 Y/Z                       0.0000      0.0000

Plane4("Angularity1")    Least Squares Plane       #P    (19)
--------------------------------------------------------------------------------
 X                           -2.3814     -2.5648    S            0.0020
 Y                            0.5435      0.3938  Min     (1)  -0.0040
 Z                           -1.2768     -1.4505  Max    (18)   0.0029
 A1 Z/-X                     22.5013     22.2077 Form            0.0069
 A2 Y/-X                     31.4057     30.0000

Angularity1              Angularity
--------------------------------------------------------------------------------
Plane4                                                 1.0000   0.0069     |-
Plane1
```

```
===============================================================================
       Z E I S S  /  C A L Y P S O  5.8.08  Default Printout
-------------------------------------------------------------------------------
Measurement Plan             Operator          Date                     Part No
Octahedron_KMspheres        Maren Cosens       May 18, 2016                   2
DURAMAX
-------------------------------------------------------------------------------
Names                   Description             Statistic / References      -1-
Symbol / References          Actual     Nominal    Tolerance     Dev.  Histogr.
===============================================================================
Plane4("Flatness1")     Minimum Zone Plane        #P  (1658)
-------------------------------------------------------------------------------
 X                           2.2450      2.6221    S            0.0003
 Y                           0.1650      0.3813  Min    (52)  -0.0006
 Z                          -0.4005     -1.6182  Max   (972)   0.0006
 A1 Y/X                     29.4937     30.0000 Form            0.0012
 A2 Z/X                     22.7198     22.2077

Flatness1               Flatness
-------------------------------------------------------------------------------
Plane4                                                0.0100   0.0012     |-


Plane1("Angularity1")   Outer Tangential Plane    #P     (3)
-------------------------------------------------------------------------------
 Z                           0.0000      0.0000    S            0.0000
 X                           0.6089     -0.2182  Min     (1)   0.0000
 Y                           0.9833      0.7557  Max     (1)   0.0000
 A1 X/Z                      0.0000      0.0000 Form            0.0000
 A2 Y/Z                      0.0000      0.0000

Plane4("Angularity1")   Least Squares Plane       #P  (1658)
-------------------------------------------------------------------------------
 X                           2.2432      2.6221    S            0.0012
 Y                           0.1640      0.3813  Min    (52)  -0.0017
 Z                          -0.4006     -1.6182  Max  (1372)   0.0025
 A1 Y/X                     29.4942     30.0000 Form            0.0042
 A2 Z/X                     22.1067     22.2077

Angularity1             Angularity
-------------------------------------------------------------------------------
Plane4                                                1.0000   0.0042     |-
Plane1
```

Z E I S S / C A L Y P S O 5.8.08 Default Printout

Measurement Plan	Operator	Date	Part No
octahedron_KMgrooves	Maren Cosens	May 18, 2016	2
DURAMAX			

Names	Description		Statistic / References			-1-
Symbol / References	Actual	Nominal	Tolerance		Dev.	Histogr.
Plane4("Flatness1")	Minimum Zone Plane		#P	(1223)		
X	-2.2393	-2.5648	S		0.0003	
Y	0.3969	0.3938	Min	(439)	-0.0005	
Z	-0.5638	-1.4505	Max	(681)	0.0005	
A1 Z/-X	22.2378	22.2077	Form		0.0011	
A2 Y/-X	32.7973	30.0000				
Flatness1	Flatness					
Plane4				0.0100	0.0011	|-
Plane1("Angularity1")	Outer Tangential Plane		#P	(3)		
Z	0.0000	0.0000	S		0.0000	
X	-1.4321	-2.1881	Min	(1)	0.0000	
Y	0.4142	0.0000	Max	(1)	0.0000	
A1 X/Z	0.0000	0.0000	Form		0.0000	
A2 Y/Z	0.0000	0.0000				
Plane4("Angularity1")	Least Squares Plane		#P	(1223)		
X	-2.2416	-2.5648	S		0.0015	
Y	0.3965	0.3938	Min	(1203)	-0.0030	
Z	-0.5623	-1.4505	Max	(13)	0.0021	
A1 Z/-X	22.8118	22.2077	Form		0.0051	
A2 Y/-X	32.7980	30.0000				
Angularity1	Angularity					
Plane4				1.0000	0.0051	|-
Plane1						

```
================================================================================
       Z E I S S  /  C A L Y P S O  5.8.08  Default Printout
--------------------------------------------------------------------------------
Measurement Plan              Operator          Date                    Part No
bowl_step                    Maren Cosens       May 19, 2016                  1
DURAMAX
--------------------------------------------------------------------------------
Names                    Description            Statistic / References     -1-
Symbol / References           Actual     Nominal    Tolerance     Dev.  Histogr.
================================================================================
Plane1("Flatness1")      Minimum Zone Plane        #P    (14)
--------------------------------------------------------------------------------
 Z                           -0.0026      0.0000    S            0.0021
 X                           -0.6908     -0.7211  Min     (8)  -0.0025
 Y                           -1.8832     -1.8554  Max     (2)   0.0025
 A1 X/Z                      -0.0253      0.0000 Form            0.0049
 A2 Y/Z                      -0.0720      0.0000

Flatness1                Flatness
--------------------------------------------------------------------------------
Plane1                                                 0.0100   0.0049     |--


Cylinder1("Cylindricity1")
                        Minimum Zone Cylinder     #P     (8)  External
--------------------------------------------------------------------------------
 X                            0.0032      0.0000    S            0.0013
 Y                           -0.0498      0.0000  Min     (1)  -0.0009
 Z                           -0.6364     -0.6364  Max     (2)   0.0009
 D                            2.9586      2.9600 Form            0.0018
 A1 X/Z                      -0.3690      0.0000
 A2 Y/Z                       4.6109      0.0000

Cylindricity1            Cylindricity
--------------------------------------------------------------------------------
Cylinder1                                              0.0100   0.0018     |-


Cylinder1("Perpendicularity1")
                        Least Squares Cylinder    #P     (8)  External
Least Squares Fit instead of Tangential Fit !
Probing strategy / Check No. of Points !
--------------------------------------------------------------------------------
 X                            0.0000      0.0000    S            0.0010
 Y                           -0.0458      0.0000  Min     (3)  -0.0010
 Z                           -0.6364     -0.6364  Max     (2)   0.0012
 D                            2.9595      2.9600 Form            0.0022
 A1 X/Z                       0.0000      0.0000
 A2 Y/Z                       4.1201      0.0000

Plane1("Perpendicularity1")
                        Least Squares Plane       #P    (14)
--------------------------------------------------------------------------------
 Z                            0.1357      0.0000    S            0.0774
 X                           -0.6912     -0.7211  Min     (1)  -0.1084
 Y                           -1.8794     -1.8554  Max     (9)   0.1019
 A1 X/Z                       0.0000      0.0000 Form            0.2103
 A2 Y/Z                       4.1201      0.0000

Perpendicularity1        Perpendicularity
--------------------------------------------------------------------------------
Plane1                                                 0.0100   0.2103    0.2003
Cylinder1
```

```
==============================================================================
       Z E I S S  /  C A L Y P S O  5.8.08  Default Printout
------------------------------------------------------------------------------
Measurement Plan              Operator          Date                   Part No
bowl                         Maren Cosens       May 19, 2016                 1
DURAMAX
------------------------------------------------------------------------------
Names                    Description            Statistic / References     -1-
Symbol / References           Actual     Nominal    Tolerance     Dev.  Histogr.
==============================================================================
Plane1("Flatness1")      Minimum Zone Plane        #P    (10)
------------------------------------------------------------------------------
 Z                            0.0010      0.0000    S            0.0018
 X                           -1.3819     -1.4195  Min     (9)  -0.0021
 Y                            1.4292      1.4195  Max     (2)   0.0021
 A1 X/Z                       0.0119      0.0000 Form            0.0041
 A2 Y/Z                      -0.0311      0.0000

Flatness1                Flatness
------------------------------------------------------------------------------
Plane1                                                  0.0100   0.0041     |--


Sphere1("Roundness1")    Minimum Zone Sphere       #P     (4)  External
------------------------------------------------------------------------------
 X                            0.0000      0.0000    S            0.0000
 Y                            0.1119      0.0000  Min     (1)   0.0000
 Z                           14.0328      0.0000  Max     (1)   0.0000
 D                           28.2495      2.9850 Form            0.0000

Roundness1               Roundness
------------------------------------------------------------------------------
Sphere1                                                 0.0100   0.0000     |


Sphere2("Roundness2")    Minimum Zone Sphere       #P     (5)  External
------------------------------------------------------------------------------
 X                            0.0002      0.0000    S            0.0001
 Y                           -0.0016      0.0000  Min     (1)  -0.0001
 Z                           -4.2207      0.0000  Max     (2)   0.0001
 D                            8.7392      2.9850 Form            0.0001

Roundness2               Roundness
------------------------------------------------------------------------------
Sphere2                                                 0.0100   0.0001     |-
```