Selection of I-220H Beryllium for the NIRCam Optical Bench

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ABSTRACT

The Near Infrared Camera (NIRCam) for NASA's James Webb Space Telescope (JWST) is one of the four science instruments to be installed into the Integrated Science Instrument Module (ISIM) on JWST. I-220H beryllium was chosen as the optical bench material for NIRCam based on its high specific stiffness, relatively high thermal conductivity, low CTE at cryogenic temperatures, and overall thermal stability at cryogenic temperatures. Beryllium has cryogenic heritage, but development of a structural bonded joint that could survive cryogenic temperatures was required. This paper will describe the trade studies performed in which bonded, I-220H beryllium was selected.

Keywords: JWST, James Web Space Telescope, NIRCam, beryllium, optical bench, I-220H, cryogenic, adhesive bonding

1. INTRODUCTION

The selection of I-220H beryllium for the Near Infrared Camera (NIRCam) optical bench on the James Webb Space Telescope (JWST) is discussed in this paper. First, an overview of JWST, NIRCam, and the NIRCam optical bench is provided. Various trade studies on the selection of optical bench configuration, materials, and fabrication methods are reviewed. Next, design and manufacturing activities and issues are presented. Last, a status of the NIRCam optical bench is provided.

JWST is a large, infrared-optimized space telescope scheduled for launch in August, 2011. JWST is designed to study the earliest galaxies and some of the first stars formed after the Big Bang. These early objects have a high redshift from our vantage-point, meaning that the best observations of these objects are available in the infrared. JWST's instruments will be designed to work primarily in the infrared range of the electromagnetic spectrum, with some capability in the visible range (Reference 1).

JWST has a 5 year mission (10 year goal), and will reside in an L2 Lissajous orbit, about 1.5 million km (1 million miles) from the Earth. The spacecraft will have a large 6.5 meters (20 feet) primary mirror and a sunshield the size of a tennis court. The sunshade will allow the observatory to be passively cooled by radiating to deep space in order to cool the infrared instruments down to about 35K (-397F) where they can best detect the faintest, infrared images from the beginning of the universe.

NIRCam is the primary scientific instrument on JWST. It is housed within the Integrated Science Instrument Module (ISIM) which sits behind the primary mirror. NIRCam is a science imager in the near infrared wavelength. It also performs wavefront sensing on JWST to align the multiple segments of the primary mirror. The instrument itself is comprised of two identical modules for redundancy and to double the field of view while both modules are operational. Optical components within the instrument include reflective mirrors, refractive lenses and filters, and focal plane arrays.

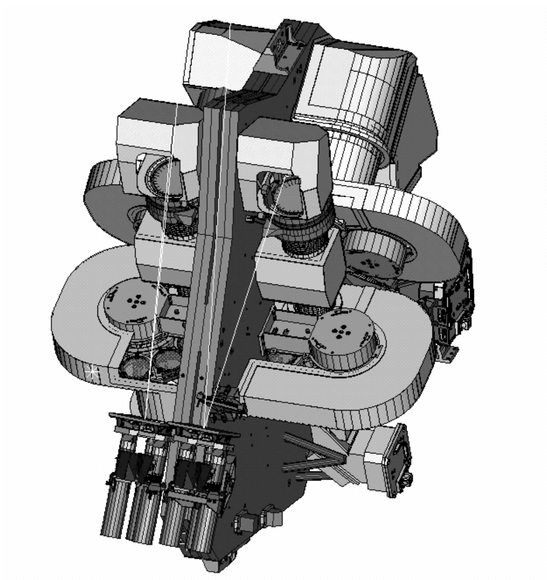

Figure 1. NIRCam

The NIRCam optical bench is the primary structure which supports all the optical equipment and interfaces with ISIM. The driving requirements for the optical bench are:

- Low mass to support NIRCam's tight overall mass budget.
- High stiffness to meet minimum launch frequency requirements and minimize gravity sag distortions during optic integration and alignment.
- Adequate strength to survive launch loads.
- High dimensional stability to maintain optical alignments during cool down from room temperature to 35K and during operation at 35K.
- High thermal conductivity to minimize thermal gradients during operation which cause thermal distortions.

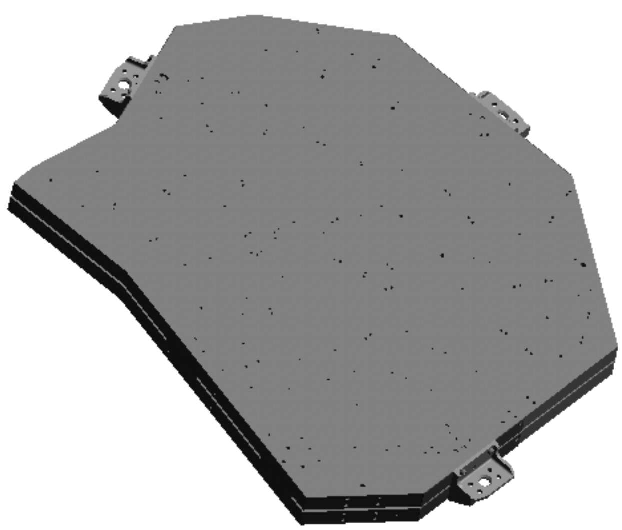

Figure 2. NIRCam Optical Bench

2. TRADE STUDIES

Numerous trade studies were performed to determine the best structural configuration, materials, and fabrication methods for the optical bench.

The first trade involved determining the structural configuration of the instrument. This trade was independent of material selection and is therefore outside the scope of this paper. A discussion of this trade is presented in a companion paper titled "Optical Bench Assembly for the Near-Infrared Camera" (Reference 22).

2.1. Material Trade Study

As mentioned previously, the driving requirements were mass, stiffness, strength, dimensional stability, and thermal conductivity. Candidate materials and their properties are shown below:

Table 1. Candidate Materials (References 2-21)

Material	Stiffness (GPa)	Density (g/cm^3)	Specific Stiffness	Tensile Yield Strength (MPa)	Specific Strength	Fracture Toughness (MPa mm^1/2)	Thermal Conductivity at 30K (W/mK)	CTE at 30K (ppm/K)	CTE at 293K (ppm/K)	dL/L between RT and 30K (ppm)
6061 T651 Aluminum	69	2.7	25	276	102	938	41	1	23.6	-4150
AlBeMet 162H	200	2.1	95	193	92	316	210	0.2 (long) 0.7 (trans)	13.91	-2000
SiC	450	3.2	140	307	96	126	<50	0.1	4.3-4.5	-320
I-220H Beryllium	300	1.86	161	345	185	348	85.6	0.04	11.38	-1298
M55J/954-3 Graphite/Cyanate	107	1.63	65	159	98		0.82	0.04	-0.36	185
6AL-4V Titanium	112	4.43	25	827	187	1700	1.7	6.3	8.8	-2076

Mass is a very high priority for JWST and since the optical bench design is primarily stiffness driven, beryllium and silicon carbide stands out with the highest specific stiffnesses. There are some strength critical areas where beryllium and titanium stands out with the highest specific strengths. However, fracture toughness limits the effective strength of beryllium which will be discussed later.

The optical components on NIRCam are being designed and laid out on the bench to come into alignment at 35K. However, it is desired to minimize the thermal contraction between room temperature at 35K to minimize alignment iterations and maximize optical performance at room temperature (when the optics are out of alignment). The material with the overall lowest CTE over temperature is graphite/cyanate ester followed closely by silicon carbide. Beryllium falls in the middle of the pack.

Dimensional stability at 35K is very important since few adjustments can be made for static or transient distortions once in operation. Beryllium and graphite/cyanate ester by far have the lowest CTE at 35K. However, the thermal conductivity of graphite/cyanate ester is very poor which leads to larger thermal gradients and larger distortions.

Graphite/cyanate ester was the only organic material considered which presents some unique challenges that are not issues for inorganic materials. One issue is moisture absorption and desorption. Although cyanate ester resins are better than epoxy resins in this respect, all organic resins will absorb moisture. Absorption and desorption of moisture will cause the material to expand and contract. The amount of moisture that is absorbed prior to launch and the rate at which it will desorb are difficult to predict and control which makes dimensional stability difficult to predict and control. Second, desorption of moisture on orbit is a contamination risk as water can condense on the instrument optics. NIRCam is very sensitive to contamination and is specified to 300A cleanliness. Last, there are manufacturing issues. NIRCam has a large number of bolted, mechanical interfaces. Graphite/cyanate ester can't simply be tapped like most of the other metals being considered. Some sort of bonded or potted metallic inserts would be required. These add considerable weight (especially if they're Invar) and introduce new issues of bonding dissimilar materials which have to survive cryogenic temperatures.

Silicon carbide presents some similar manufacturing challenges to graphite/cyanate ester. Precision interfaces have to be added after firing due to the dimensional changes which occur after firing. Since silicon carbide is very difficult to machine after firing, numerous precision interfaces are most easily accommodated via secondary bonding of metallic inserts. Then the same issues of weight and bonding dissimilar materials with graphite/cyanate ester come into play.

AlBeMet didn't fare well overall in meeting the driving requirements. Additionally, its isotropy and stability at cryogenic temperatures were not known and seen as a major risk.

Two categories where beryllium doesn't fair as well in are cost and manufacturability. However, most of the candidate materials with the exception of aluminum and titanium are also fairly expensive and challenging to manufacture.

Overall, beryllium performs the best against the driving requirements and is the only material which will allow NIRCam to meet its mass budget. Since mass is so critical, performance takes priority over cost and manufacturability.

2.2. Beryllium Grade Trade Study

Four grades of beryllium were considered. Only hot isostatically pressed (HIP) grades were considered because of their more isotropic properties. Rolled sheet is an efficient material form for to build a mass efficient sandwich structure, but its properties are very anisotropic. The candidate beryllium grades and their critical properties are shown here:

Table 2. Candidate Beryllium Grades (Reference 18)

Grade	Tensile Yield Strength (MPa)	Microyield Strength (MPa)	Fracture Toughness (Mpa mm^1/2)	% Elongation	Isotropy
I-220H Grade 1	345	41	~348	1	Good
I-220H Grade 2	345	69	~348	1	Good
S-200FH	296	-	~348	3	Fair
O-30H	207	21	~348	2	Very Good
I-70H	207	21	~348	2	Good

I-220H was selected for its high yield strength and isotropy. Microyield strength for I-220H is also high, but this is a lower priority for an optical bench versus an optic. Elongation is not quite as good, but strength and isotropy were considered more important. S-200FH was not selected because of its lower strength and greater anisotropy. O-30H was strongly considered because of its very good isotropy, but was eventually ruled out because of its lower strength and higher cost. It was felt that the very good isotropy of 0-30H was not needed for an optical bench versus an optic (Note: the primary mirrors of JWST are being fabricated from O-30H). Last, I-70H was ruled out because of its lower strength.

2.3. Structure Configuration Trade Study

Due to tight mass constraints, it was determined that the optical benches should be closed back sandwich panels (versus open isogrids) for maximum structural and mass efficiency. Three methods of assembling a sandwich panel were considered:

- Thin faceskins bonded or brazed to a honeycomb or ribbed "core".

- A thin faceskin bonded or brazed to the open face of a rib stiffened shell.
- Two back to back rib stiffened shells bonded or brazed along their center line.

Three methods for assembling the bench are bolting, brazing, and bonding.

Details of these configurations and assembly options are discussed in more detail in the companion paper "Optical Bench Assembly for the Near-Infrared Camera" (Reference 22).

A bonded, back to back rib configuration was selected because it would be more dimensionally stable and have fewer issues with cleaning and contamination.

2.4. Adhesive Selection

A number of candidate epoxy adhesives were identified. Adhesives which had known or anecdotal cryogenic heritage include:

- Epibond 1210A/9615-10 (Gravity Probe B and other Lockheed Martin dewars)
- Scotchweld 2216B/A (widely used in bonding optics)
- Eccobond 285/24LV
- Uralane 5772
- Stycast 2850FT
- Masterbond EP21 TCHT-1
- Masterbond EP29 LPSP
- Hysol 9309.3NA (widely used in space structures)
- 3M AF-191 (X-33 Structure)

Desirable characteristics include low modulus and high strength at cryogenic temperatures, low thermal strain, and low outgassing. Initially, Epibond 1210A/9615-10, Scotchweld 2216B/A, and Eccobond 285/24LV were going to be evaluated. However, based on extensive cryogenic heritage at Lockheed Martin, Epibond 1210A/9615-10 was selected.

2.5. Surface Preparation Trade Study

The final trade study involved the selection and evaluation of surface preparation techniques for bonding beryllium.

Beryllium can be acid etched to clean and prepare its surfaces for bonding like other metals. To stabilize and protect the etched surface, an epoxy/phenolic primer such as Cytec BR127 should then be applied. This approach, although unproven at cryo, was assumed to survive cryogenic temperatures and was identified as the lowest risk approach. However, there are other surface treatment requirements for the bench. To minimize optical reflectance, the outside surfaces of the bench have to be black anodized. In order to black anodize the outer surfaces and etch and prime the bond faying surfaces, the bond surfaces would have to be masked which adds cost and time and can cause contamination. It was therefore desirable to determine if bonding to black anodize was feasible. That way the entire bench could just be black anodized without requiring masking and additional etching and priming steps.

The three surface preparation techniques to be tested were:

- Black anodized (only).
- Black anodized and primed.
- Etched and primed.

The substrates for this test were S-200F. Although testing I-220H would have been ideal, S-200F was selected based on availability. It was believed that the grade of beryllium would have no affect on the surface preparation and ultimately the bond strength.

These surface preparation techniques were evaluated by testing double lap shear strength (ASTM D3528) with Epibond 1210A/9615-10 adhesive. Prior to mechanical testing, these bonded coupons were thermal cycled from 77K (LN2) to 313K to simulate the expected thermal extremes the bonded joints would see. Based on prior experience at Lockheed Martin with Epibond 1210-A/9615-10 on other substrate materials, coupons thermal cycled to 4K (LHe, well below the 35K requirement) had similar strength to those only cycled to 77K so only going to 77K would be sufficient. The coupons were tested at room temperature since the optical bench bonded joints only see high loads at room temperature during launch.

The results of the shear tests are shown here:

Table 3. Adhesive Shear Test Results

Anodized			**Anodized and Primed**			**Etched and Primed**	
Coupon	**Strength (MPa)**		**Coupon**	**Strength (MPa)**		**Coupon**	**Strength (MPa)**
A1	27		AP1	34		EP1	34
A2	24		AP2	32		EP2	33
A3	31		AP3	33		EP3	32
A4	25		AP4	33		EP4	35
A5	24		AP5	35		EP5	31
A6	31		AP6	35		EP6	32
A7	27		AP7	34		EP7	35
Average:	27		Average:	34		Average:	33
Std. Dev:	3		Std. Dev:	1		Std. Dev:	1
B-Basis Allowable:	**18**		B-Basis Allowable:	**30**		B-Basis Allowable:	**29**

The anodized-only coupons performed surprisingly well. There was much concern that the bare anodized surface would seal before the coupons could be bonded or would absorb moisture which would degrade the bond strength.

The anodized and primed coupons actually performed slightly better than the etched and primed coupons. Therefore, the bond faying surfaces would not have to be masked during the anodization process. Although the anodized-only coupons have adequate strength, it was decided to go with the anodized and primed configuration. Adding primer is a relatively easy operation to perform, greatly increases the shear strength, and provides a little more “insurance” that the otherwise porous anodized surface doesn’t get contaminated and can be easily cleaned before bonding.

One coupon from each configuration was saved and not tested to failure. After the testing was completed, it was decided to take these coupons all the way down to 4K (LHe) to make sure nothing unusual would happen between the thermal cycling temperature of 77K and the required operating temperature of 35K. These coupons all survived thermal cycling (i.e. didn’t fall apart) and inspection of photomicrographs showed no visible cracks in the bondline. At the time of this publication, these coupons have not yet been tested to failure in shear.

Photomicrographs of the bonded coupons after thermal cycling to 4K are shown here:

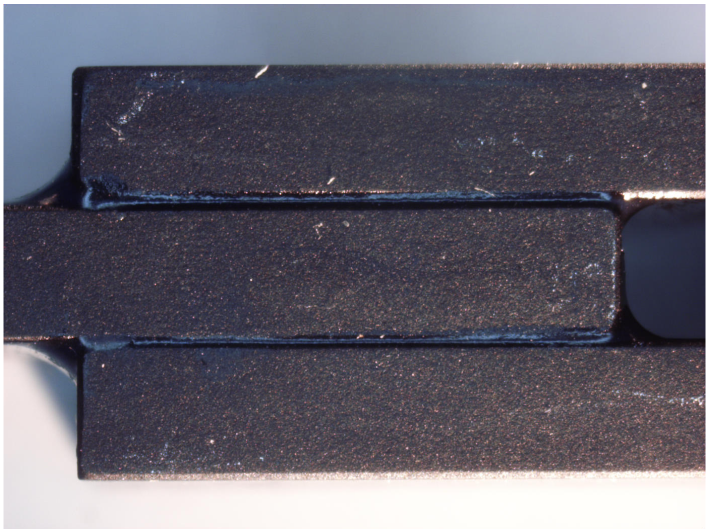
Figure 3. Anodized Bond Coupon

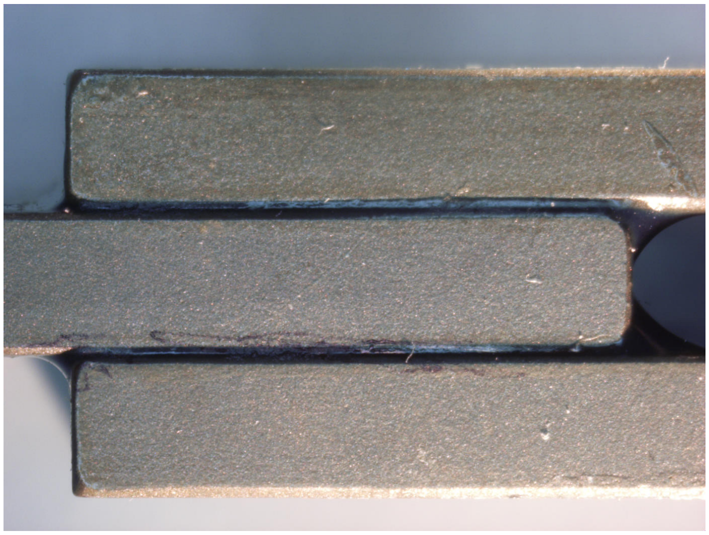
Figure 4. Etched and Primed Bond Coupon

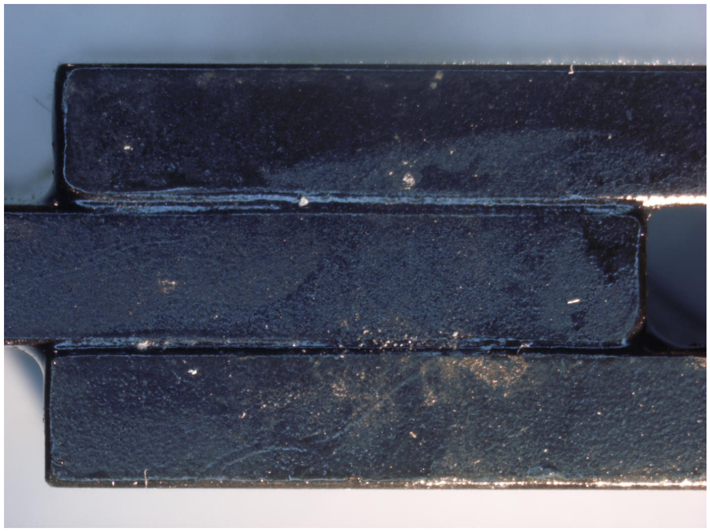

Figure 5. Anodized and Primed Bond Coupon

3. DESIGN ISSUES

A few issues came up during the design phase which are applicable to the material selection.

Reworkability is a logistical issue for beryllium. Since Lockheed Martin does not have the capability to machine beryllium in house, any rework requires sending the optical bench back to AXSYS, the machine shop supplier. This is a challenge for NIRCam since there are a large number of threaded inserts on the bench for interfacing to optical components, thermal straps, alignment references, harness straps, vent holes, and light baffles. Having to define and freeze all these interfaces up front to avoid later rework and resulting schedule impact was a challenge. The optical bench will also have to be returned to AXSYS if any of the threaded inserts or other features are damaged and have to be repaired.

Another design issue is the low fracture toughness of beryllium. The bench is mostly designed for stiffness, but there are a few places where stresses are high and showing positive structural margins of safety was difficult. A small crack or flaw in one of these areas will grow over time as the area is loaded and unloaded and may grow large enough to fail the part. Brittle materials such as beryllium require that a “safe life” analysis is performed if the part affects flight safety or is mission critical. This analysis requires that a minimum detectable flaw does not grow large enough to fail over all the load cycles that the part will see in its lifetime. To add a margin of safety, this analysis is usually extended to 4 lifetimes since determining the exact number and magnitude of load cycles is difficult. Although I-220H has a specified minimum yield strength of 345 MPa, the equivalent allowable in some circumstances to meet safe life is only 95 MPa. This makes beryllium more difficult to design with and can significantly add to the mass of the part if it’s strength critical.

4. HEAT TREATING AND MICROYIELD ISSUE

Overall, I-220H for NIRCam was successfully HIPed (hot isostatically pressed). However, it failed to meet the Grade 2 microyield strength (also known as precision elastic limit or PEL) specification of 69 MPa. The root causes are believed to be consolidation temperature and low iron/aluminum ratio.

The HIP consolidation temperature for NIRCam was increased to 1000C for NIRCam. This change was made from an 830C HIP temperature after the Gran Canary Telescope experienced a mirror failure. The higher temperature improves elongation which is needed during machining to reduce the risk of fracture. However, the higher temperature adversely affects microyield.

Another possible root cause of the low microyield is a low iron/aluminum ratio. This is a property of the raw beryllium powder which is difficult to control. The ratio for NIRCam was apparently within specifications, but at the low end. The iron content can have a large affect on microyield.

After discovery of low microyield, a number of steps were taken to try to increase microyield and to make sure no other properties were degraded. Microyield after the first heat treat was 61 MPa. Brush Wellman performed an additional heat treatment on the material with a slower (<20C/hour) cooling rate to attempt to improve microyield. The results after this treatment were:

Table 3. Microyield Strength After Slower Heat Treatment

X1 = 63 MPa	Z1 = 57 MPa
X2 = 64 MPa	Z2 = 63 MPa
X3 = 59 MPa	Z3 = 63 MPa

These results show no statistically significant change indicating that the heat treatment neither improved nor degraded microyield.

There was additional concern that further heat treatments at AXSYS might affect structural properties. Samples were taken and heat treated to simulate AXSYS heat treatments. A comparison of properties before and after the heat treat are presented here:

Table 4. Structural Properties Before and After Heat Treatments

Property	**Original Results**	**Result after Heat Treatment**
Yield Strength, MPa (X/Z)	576/582	579/567
Ultimate Strength, MPa (X/Z)	493/495	487/483
Elongation (X/Z)	3.8%/4.0%	4.2%/3.5%
Microyield, MPa (X/Z)	57/64	586

Again, there was no indication that additional heat treatments would adversely affect structural properties.

Ultimately, microyield is not a critical property for the NIRCam optical bench and the disposition was to “use as is”. The material was procured to the Brush Wellman specification which included a microyield specification since I-220H can also be used an optical material (where microyield is a critical property). The justification to “use as is” was based on the following:

- Global stresses which would cause the whole bench to deform are only around 28 MPa (well below microyield strength).
- Localized areas with high stress will strain harden during structural testing which occurs prior to integration of optical components where dimensional stability is required.
- Expected plastic deformations are on the order of nanometers and are well within the range of adjustability of the optical components which is on the order of micrometers.
- Loads seen after optics integration will be less than loads during structural test so no additional yielding is expected.

Figure 6. NIRCam I-220H after HIP

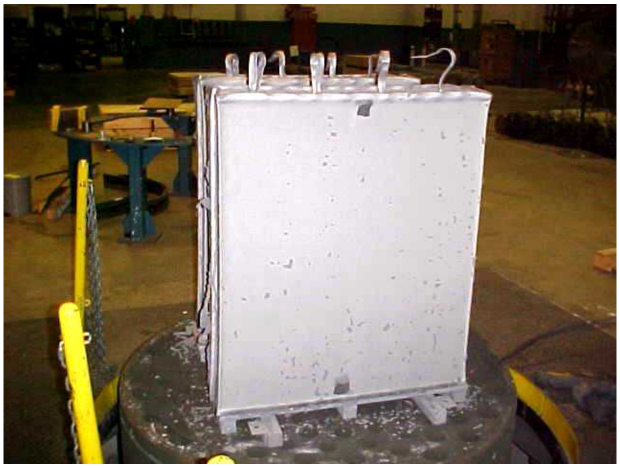

Figure 7. NIRCam I-220H after HIP

5. STATUS

At the time of this publication, the I-220H beryllium has been successfully HIPed, decanned, heat treated, and is starting to be machined. After the numerous machining and etching steps, the parts will be anodized and primed. They will then be delivered to Lockheed Martin where they will be adhesively bonded. After bonding, the benches will undergo a structural qualification test. Upon successful completion of the structural test, the optical components will be integrated to the benches and tested. Full instrument testing includes cryogenic optical testing and structural, vibration testing. NIRCam will then be delivered to NASA for integration into Integrated Science Instrument Module (ISIM) and ultimately integration into JWST.

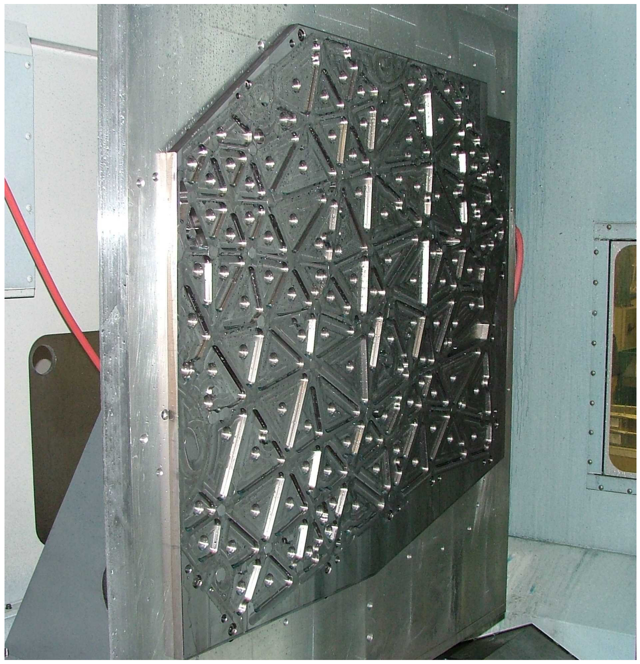

Figure 8. NIRCam I-220H During Machining

6. CONCLUSION

I-220H beryllium was chosen for the optical bench on NIRCam instrument on JWST. Numerous trade studies were performed to pick the best materials and construction methods. An adhesively bonded, rib sandwich structure was selected. A combination of adhesive and surface preparation was qualified to survive launch loads and cryogenic operational temperatures. Minor design issues of reworkability and fracture toughness were encountered and overcome. Also, a minor manufacturing issue of heat treating and micro-yield strength was dealt with.

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