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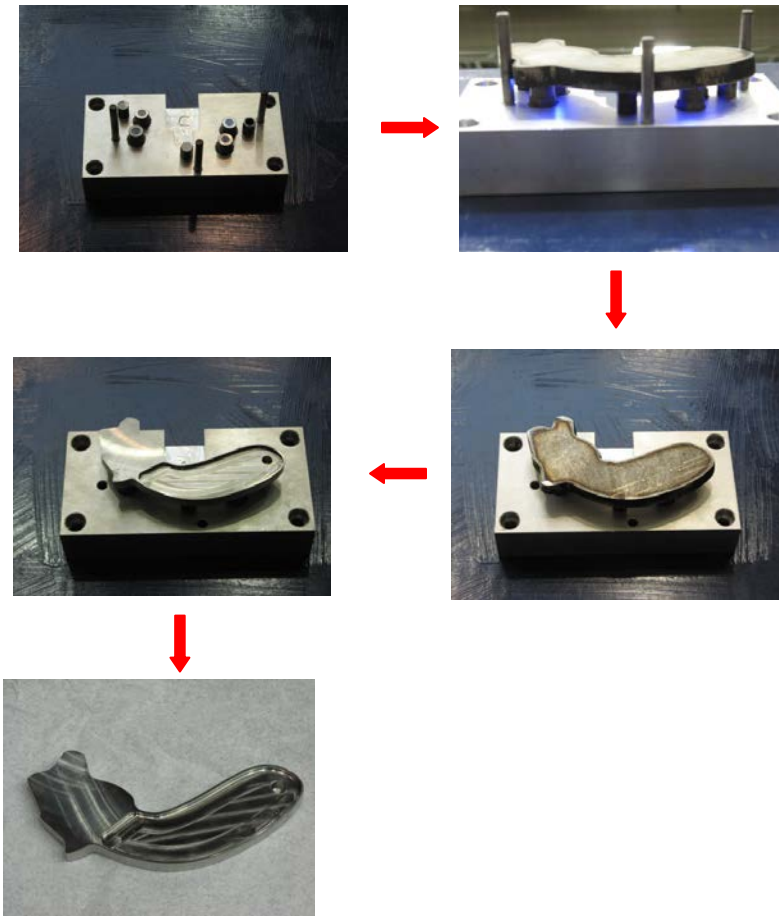
# PHOTO-ACTIVATED ADHESIVE WORKHOLDING (PAAW) TECHNOLOGY (CONCEPT, HISTORY, AND CASE STUDIES)



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## 1. INTRODUCTION

Photo-Activated Adhesive Work-holding (PAAW) is a new technology that was developed at Penn State University to fixture "difficult-to-hold" parts for tight tolerance, manufacturing processes. Its use has grown rapidly in the aerospace industry, and is now spreading into other industries. It is used predominantly for material removal processing of parts made of metallic, ceramic, and composite materials. It is also used to hold parts for in-process inspection and finished part inspection.

Despite its growing popularity, its use is kept proprietary by nearly all end users. Consequently the manner in which is it being used and the benefits that are being derived have not been widely communicated to the general public. The purpose of this document is to provide:

- description of the technology, its technical benefits, and the general characteristics (nonproprietary) of the applications for which it is currently being used
- brief history of its development
- examples of its current use for production applications

The general concept is discussed next.

## 2. GENERAL CONCEPT

The use of PAAW technology allows:

- the on-demand, rapid polymerization of adhesive joints to anchor a workpiece to a fixture with minimum external stress
- the rapid, room temperature, de-bonding of the workpiece from the fixture without damage to either

The critical enablers are grippers, photo-curable adhesive, and photo-curing light. Grippers are the fixturing elements to which the workpiece is adhered to. There are two styles of grippers: Head Out (HO) and Head In (HI) as shown in Figure 2.1. A Head Out gripper screws into the fixture from the workpiece side (Figure 2.2), and cannot be repositioned during the workpiece unload-load cycle. A Head In gripper screws into the fixture from the opposite side (Figure 2.2) and can be repositioned during the workpiece unload-load cycle. This functionality enables a complex workpiece to be loaded into the fixture without interfering with the gripper. It also allows it to be mechanically de-bonded with substantially less stress.

**Figure 2.1 Head Out Gripper (l), Head In Gripper (r)**

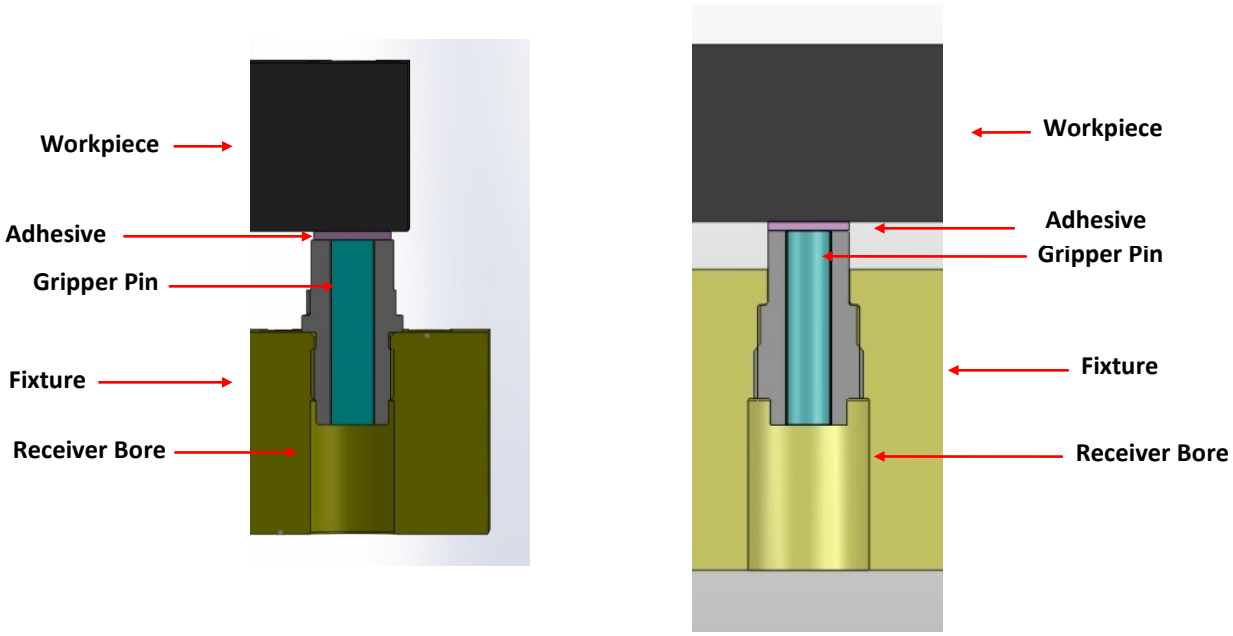



**Figure 2.2 Fixture-Workpiece Assemblies Incorporating Head Out Gripper (l) and Head In Gripper (r)**

A Head Out style gripper is simpler to implement and is suitable for applications in which the workpiece is strong, and the gripper axes are parallel to the principal loading direction of the workpiece into the fixture. A Head In style gripper is more complex to implement, but is suitable for all applications.

Regardless of style, a gripper consists of a metal chassis and a load bearing, optical element called a gripper pin. This is illustrated in Figure 2.3. It also consists of a retention seal that fixes the gripper pin to the chassis.

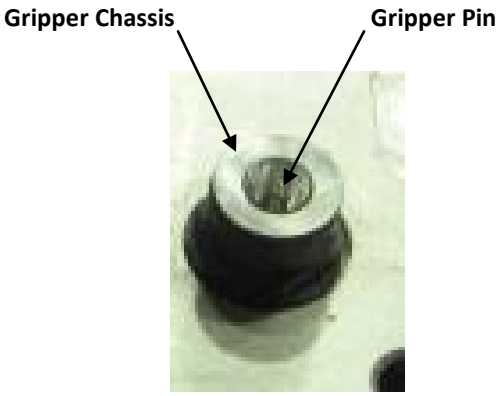



**Figure 2.3 Gripper Components**

An example application is illustrated in Figure 2.4. This is a PAAW shuttle fixture that is used to hold two aluminum workpieces for a machining process. The fixture utilizes four HO grippers.

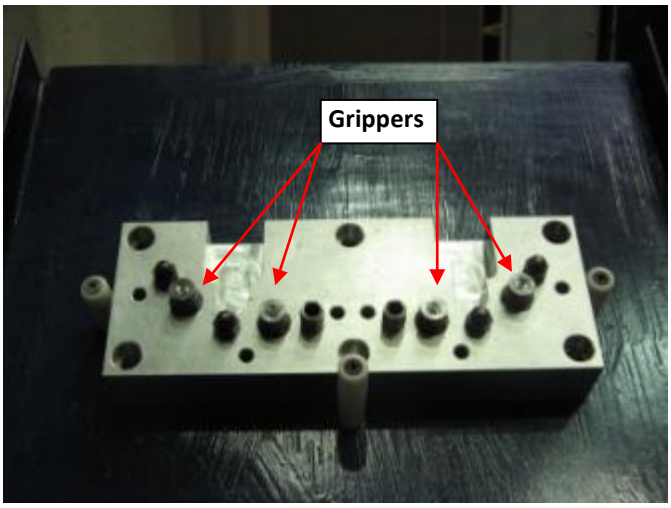



**Figure 2.4 Grippers Illustrated in a PAAW Shuttle Fixture**

A photo-curable, structural adhesive is deposited on top of the gripper prior to workpiece bonding as illustrated in Figure 2.5. The uncured adhesive, which is non-toxic, has the consistency of grease to prevent it from running off the gripper, regardless of orientation.

The workpiece is then registered relative to the fixture. This may be done in a variety of ways. In the example provided, the shuttle fixture utilizes permanently attached locating pads and temporarily attached locating pins as shown in Figure 2.6. The workpieces are registered by placing them into six point contact with the locators (Figure 2.7). This leaves gaps between the workpieces and the grippers which are completely filled in by the adhesive. In no case is the workpiece in direct contact with a gripper.

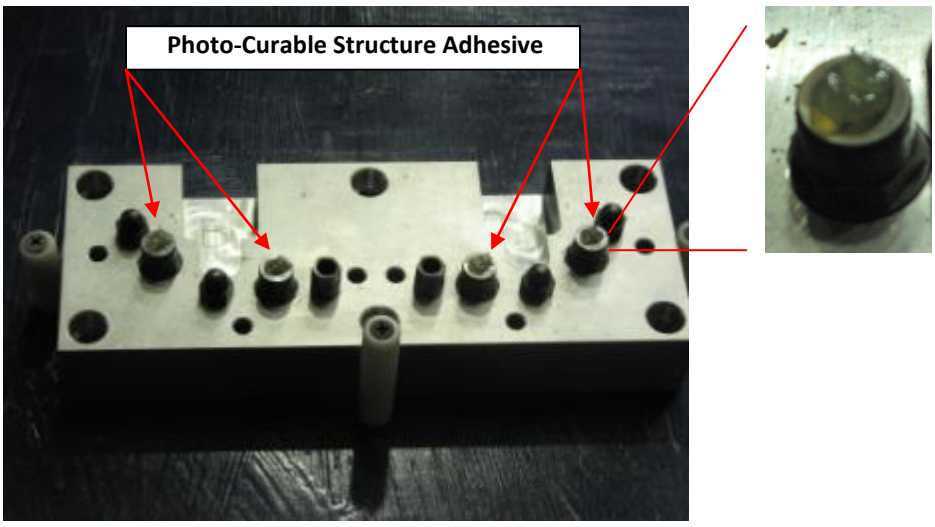



**Figure 2.5 Photo-Curable Structural Adhesive Deposited to the Tops of Grippers**

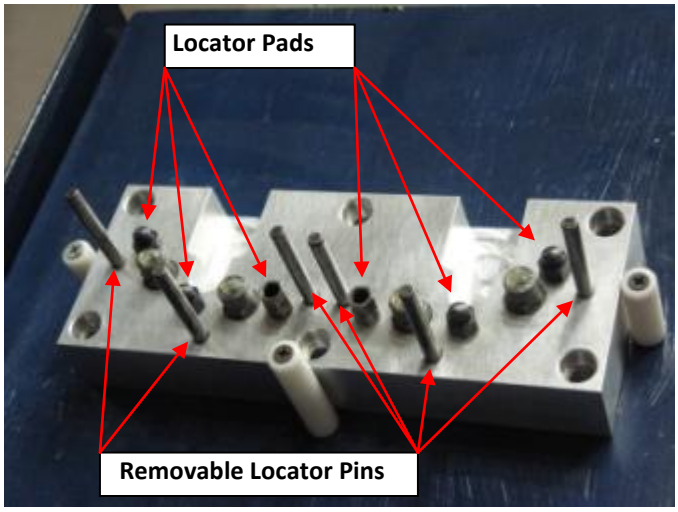



**Figure 2.6 Locators used to Register the Workpieces**

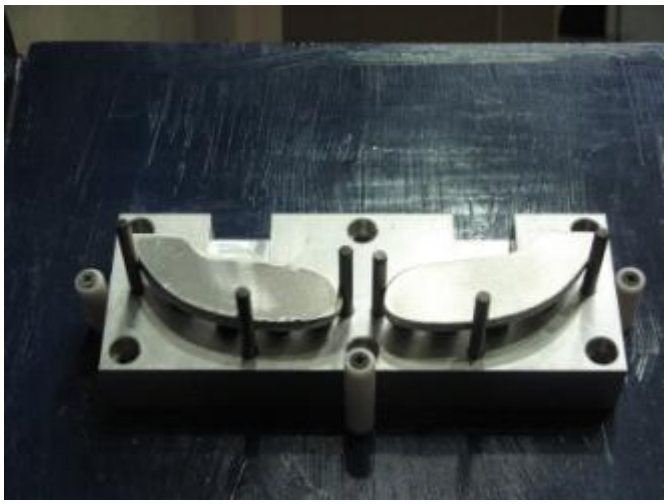


**Figure 2.7 Workpieces Registered Relative to the Locators**

Photo-curing light is sourced via a high intensity spot lamp (Figure 2.8). Light is transferred to the grippers via a light guide with one or more legs. The end of each leg is enclosed within a light guide shroud. Prior to the bonding process, the leg(s) of the light guide are positioned against the backsides of the grippers (Figure 2.9). The shroud mates with a receiving bore on the backside of the fixture to correctly align and restrain it (Figure 2.10). This allows "hands off" photo-curing of the adhesive joints.

Light is then transmitted through each gripper pin (Figure 2.11) into the adhesive for a duration of 20 to 60 seconds, depending on the desired quick strength of the adhesive. For the example application, the duration is 60 seconds. During this process, the adhesive polymerizes, hardens, strengthens, and adheres to both the grippers and workpiece. Shrinkage of the adhesive causes the workpieces to be gently pulled against the locator pads. The resultant adhesive joint is strong, rigid, and visco-elastic. As such it is capable of dissipating vibrational energy. It is also non-toxic.

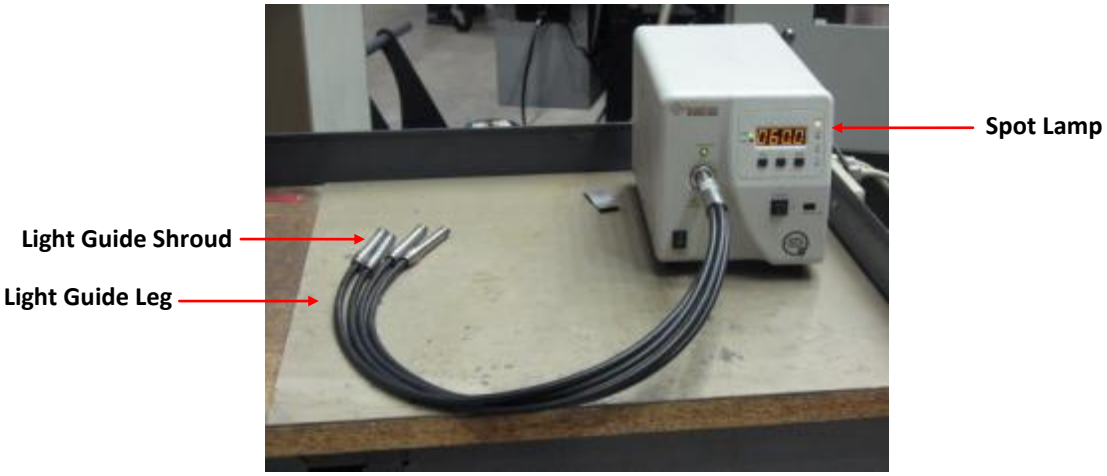



**Figure 2.8 Spot Lamp and 4 X 3mm Light Guide**

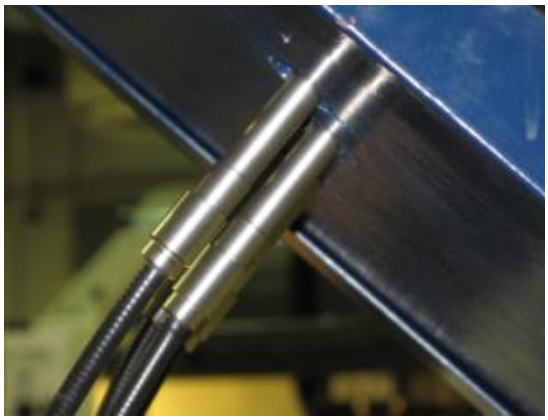


**Figure 2.9 Light Guide Legs Positioned Against the Back Side of the Grippers**

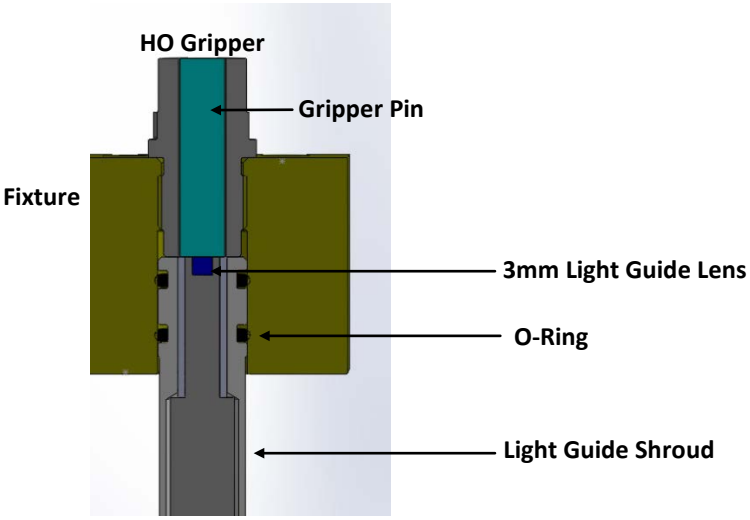



**Figure 2.10 3mm Light Guide Leg and Light Guide Shroud Positioned Against the Back Side of a HO Gripper**

**Figure 2.11 Photo-Cure Light Transmitted Through the Gripper Pins for a Duration of 20 seconds to 60 seconds to Polymerize the Adhesive**

Once all of the adhesive joints have been exposed to light, the light guides are withdrawn and all temporary locators are removed. The workpieces are now ready to undergo one or more manufacturing processes. In the case of the example application, this involves mounting the fixture to the base plate in a three axis, vertical machining center (Figure 2.12). Once done, the two workpieces are machined as illustrated in Figure 2.13.

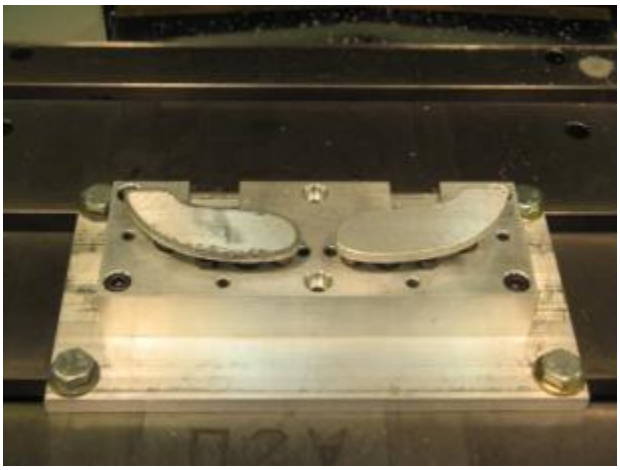


**Figure 2.12 PAAW Shuttle Fixture Mounted in Vertical Machining Center**

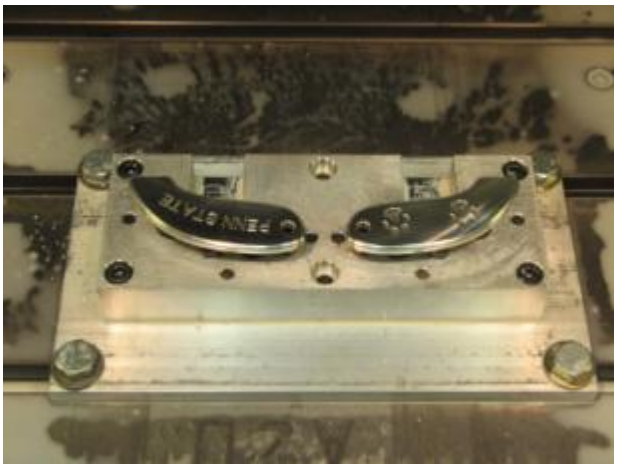


**Figure 2.13 Workpieces after the Completion of the Machining Cycle**

Once the last manufacturing process has been performed, the workpieces are mechanically de-bonded from the grippers. If HO grippers are used, the workpiece must be forced off of the fixture. If HI grippers are used, this option exists, but the adhesive joints may also be broken by counter screwing each gripper in sequence. This is illustrated in Figure 6.5 for an alternative application.

Forcing is the fastest method of de-bonding, but exerts the greatest stress on the workpiece. Counter screwing the grippers exerts minimal stress on the workpiece, but takes longer to do. Which method to use depends on the strength, hardness, and stiffness of the workpiece and the number of adhesive joints holding it. In the example application, the parts are automatically de-bonded by an ejection tool mounted in the spindle of the machining center as shown in Figures 2.14 and 2.15.

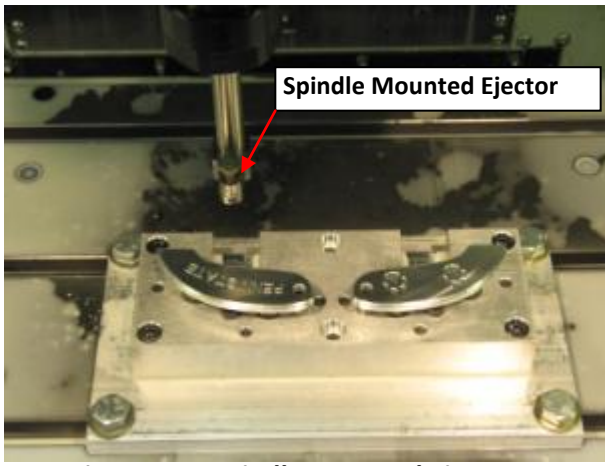



**Figure 2.14 Spindle Mounted Ejector**

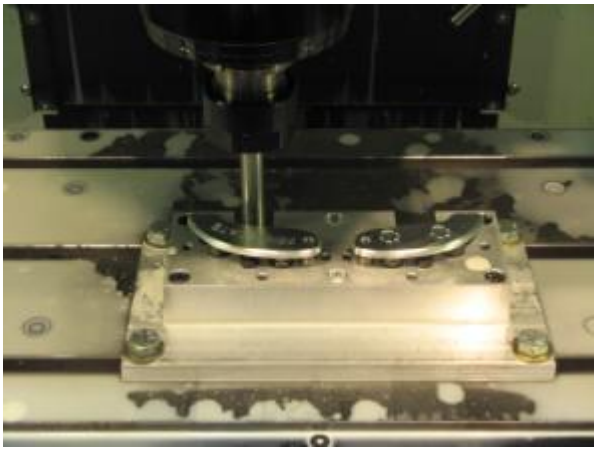


**Figure 2.15 Spindle Mounted Ejector Used to Automatically Force the Machined Workpieces from the Grippers**

Depending on the de-bonding method used, a partial to full layer of hardened adhesive will be left on the grippers as shown in Figure 2.16. Prior to the next bonding cycle, this adhesive must be stripped off of the grippers. This can be done in many ways including the use of a heat gun and scraper or a hot water, power washer. Alternatively, the adhesive can be stripped off the gripper using a spindle mounted, axial adhesive grinder as shown in Figures 2.17 and 2.18.

A peripheral grinding process is also available to strip grippers positioned orthogonally to the spindle axis. This is illustrated in Figures 2.19 -2.21 for an alternative application. These two processes coupled with a sufficient number of machine tool d.o.f. can enable complete grinding automation with no additional capital investment. Alternatively the peripheral grinding process can be carried out manually with a pneumatic grinder.

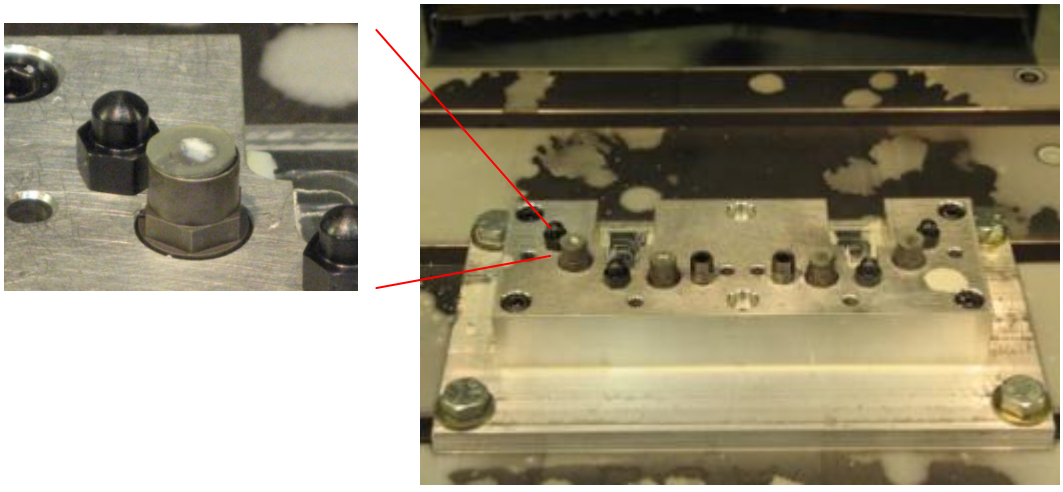


**Figure 2.16 Residual Adhesive Left on Grippers after the Workpieces have been De-Bonded**

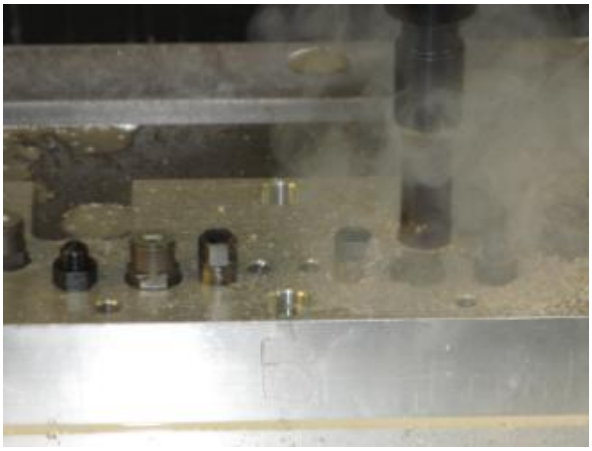


**Figure 2.17 Spindle Mounted , Axial Adhesive Grinder Stripping Residual Adhesive from a Gripper**

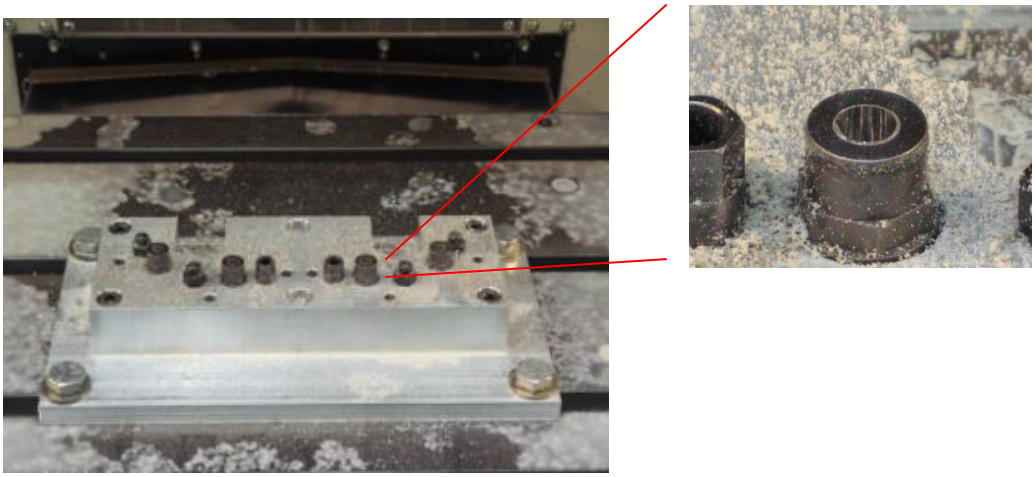


**Figure 2.18 Grippers after Adhesive Grinding Process**

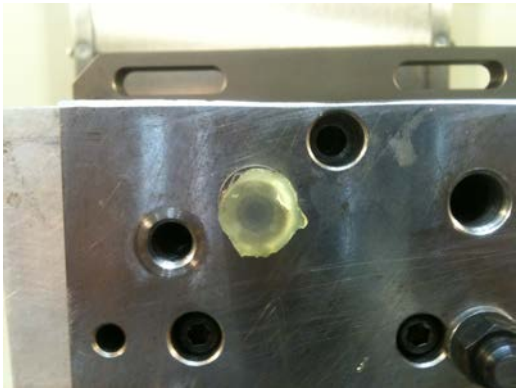


**Figure 2.19 Gripper Oriented Orthogonal to Spindle Axis with Hardened Adhesive Layer**

**Figure 2.20 Spindle Mounted, Peripheral Adhesive Grinder Stripping Hardened Adhesive from a Gripper**

**Figure 2.21 Gripper after Peripheral Grinding Process**

Note that the example provided is a shuttle fixture. Shuttle fixtures are commonly used for PAAW applications in which one or more of the following are true:

- it is necessary to remove the fixture from the base plate in order to provide light guide access to one or more grippers
- it is necessary to remove the fixture from the base plate in order to facilitate the gripper cleaning process after the workpiece has been de-bonded
- cycle time demands make it imperative to decouple the lead time needed for workpiece de-bonding, fixture cleaning, and workpiece bonding from the overall process cycle time

However in many current applications, none of these issues hold, and the PAAW fixture is permanently attached to either the machine tool table, trunion table , or a pallet. Trunion tables are used to swivel the fixture and provide light guide access through its bottom, as well as enable four axis machining or four axis adhesive grinding. Other notable permutations from the example provided are:

- shuttle fixture that utilizes no hard contact locators to locate the workpiece, but instead utilizes a transfer nest to locate the part relative to the grippers
- hybrid fixture that uses permanently mounted locators and mechanical clamps to restrain rigid body motion of the workpiece and uses grippers as supports to restrain deformation of overly compliant sections
- removable truss utilizing grippers that is adhered to compliant sections of the workpiece in order to act as a stiffener

## 3. PAAW TECHNOLOGY ATTRIBUTES

From the standpoint of its ability to hold a workpiece, PAAW technology has many positive attributes. They are as follows:

- Photo-curable adhesives are available to bond nearly all important engineering materials including metals, ceramics, plastics, and composites
- Uncured adhesive is nontoxic, cheap to moderately priced depending on volume purchased, has good shelf life, is soluble in ethanol, and is very easy to clean up
- Uncured adhesive naturally conforms to irregularities in the geometry of the workpiece surface and fills the gap between the workpiece and gripper while exerting negligible external stress on the workpiece
- Adhesive cures on demand
- Thick adhesive joints can easily be cured to fill in large (≈.15" ) gaps between the gripper and workpiece surface, thus facilitating the gripping of irregular and/or non-flat surfaces
- Polymerization of the adhesive exerts negligible external stress on the workpiece in comparison to mechanical clamping while at the same time providing the ability to snug the workpiece against hard contact locators
- Adhesive joints can be formed on the underside of the workpiece, maximizing access to the manufacturing processes to be applied
- Since overhead clamps are not needed, more freedom is available to stiffen a workpiece using adhesive joints in comparison to conventional mechanical supports
- Adhesive joints can be made to be very strong and capable of withstanding large, dynamic forces or substantially weaker by controlling adhesive formulation and the photo-curing process
- Adhesive joints are stiff, visco-elastic, and capable of dissipating vibrational energy in the workpiece
- Adhesive joints can be partially machined away without significantly degrading the holding strength of the fixture
- Adhesive joints can be broken and the workpiece de-bonded without resorting to thermal softening
- Cured adhesive is nontoxic and can be cleaned from the gripper surfaces and workpiece surfaces in a variety of ways without harm to either

In summary, PAAW technology provides an avenue for holding complex workpieces with maximum accessibility, maximum holding stiffness, and minimum set up induced distortion. Furthermore it is capable of holding irregular surfaces that would be difficult if not impossible to hold with vacuum fixturing, and there are no issues with regard to plugging exposed holes. It is also capable of holding nonmagnetic materials and irregular surfaces that that are difficult or impossible to hold with magnetic fixturing.

PAAW technology has two negative attributes in comparison to conventional fixturing, magnetic fixturing, and vacuum fixturing. They are greater set up time for typical parts and residual adhesive.

Figure 3.1 shows the steps necessary to unload and load a workpiece using a conventional fixture and using a PAAW fixture. With regard to a conventional fixture, it takes an operator one to three minutes to carry out all of the prescribed steps for a typical workpiece if manually activated clamps and supports are used. In contrast, it will take an operator longer to execute the necessary steps using PAAW technology. For example, it will take 3.5 minutes to 10 minutes using a shuttle PAAW fixture with four grippers.

Factors affecting the set up time include the level of automation, photo-curing resources, and hand tools employed. Likewise if the number of grippers used in the fixture increases, so will the lead time. If a permanent fixture is used, the lead time will decrease, since no time will be required for shuttle manipulation.

**CONVENTIONAL FIXTURE**

1.Deactivate Clamps
2. Unload Workpiece
3. Load Workpiece
4. Activate Primary Clamps
5. Position Supports
6. Activate Secondary Clamps

**PAAW FIXTURE**

1. Remove Shuttle*
2. Debond Workpiece
3. UnLoad Workpiece
4. Clean Grippers
5. Deposit Adhesive
6. Position Light Guide at each Gripper
7. Photo-cure Adhesive at each Gripper
8. Load Shuttle*

**Figure 3.1 Steps necessary to Unload and Load a Workpiece using Conventional Versus PAAW Fixture (*Shuttle may not be needed)**

Ironically, for the applications in which PAAW technology has been used to replace conventional fixturing, the total set up time necessary to process the part has decreased. This has been due to one of two reasons. The first is that the use of PAAW technology eliminated downstream set ups and their related set up time, resulting in a net set up time reduction. The second is that the parts were difficult to fixture due to some combination of geometric complexity, geometric variability, and excessive compliance. In these specific cases, the operators were forced to use gages to monitor part displacement/distortion during activation of the clamps and supports. The set up times typically ranged from ten minutes to twenty five minutes.

The second negative attribute associated with PAAW is that hardened adhesive may be left on the workpiece surfaces after mechanical de-bonding. This is illustrated in Figure 3.2 for an alternative application. In general this will not be an issue if these surfaces are to be machined in a subsequent set up. However if they are not, then steps must be taken to strip this adhesive off. Fortunately a number of options are available.

One popular method is to strip the adhesive off with a hot water, power spray (Figure 3.3). Another popular method is to soak the workpiece in a hot aqueous solution for a few minutes, and allow the adhesive to hydrolyze and lose its stick. Once removed from the bath, the hardened adhesive is easily peeled off. These methods are described in the E-document “PAAW Technology and Practice.”

**Figure 3.2 Hardened Adhesive left on the Workpiece Surface after Mechanical Debonding**

**Figure 3.3 Workpiece Surface after Hardened Adhesive was Removed by Hot Water Power Spray**

## 4. CHARACTERISTICS OF CURRENT APPLICATIONS

PAAW technology is currently being used for applications, which share one or more of the following characteristics.

- Workpieces being held have high value and are subject to high value added manufacturing processes
- Part print tolerances are extremely tight
- Workpieces are geometrically complex
- Workpieces are geometrically variable
- Workpieces are excessively compliant
- Material removal processes are subject to chatter without adequate workpiece support
- Workpieces are subject to many different manufacturing processes, each of which must be carried out in a different machine tool
- Workpieces are difficult to hold using conventional fixturing, taking ten minutes or more for the operator to activate clamps and supports and use indicators to check for workpiece distortion
- Workpieces must be inspected in the free state condition
- Workpieces must be inspected in the restrained condition

The primary motivation for using PAAW technology in these applications is:

- Five sided access and in some cases six sided access to the workpiece
- Reduction of set up related workpiece distortion and datum establishment variability
- Reduction in total set up time
- Reduction of manufacturing process induced workpiece distortion
- Elimination of machining chatter
- Simplification of fixturing and reduction in fixturing cost
- Elimination of locating/restraining lugs from castings, and the need to subsequently machine them in subsequent set ups

End users have reported substantial cost savings in their applications due to significant reductions in overall process lead time and process scrap rate. They have also realized significant reductions in the fixturing cost due to the elimination of set ups and/or substantial simplification of fixture designs.

## 5. HISTORY OF PAAW TECHNOLOGY DEVELOPMENT

PAAW technology was invented at Penn State University by Prof. Edward C. De Meter in 2002. This led to the award of U.S. Patent No. US 7,172,676 B2, System and Method for Bonding and De-Bonding a Workpiece to a Manufacturing Fixture to The Pennsylvania State University.

The original concept, entitled "Light Activated Adhesive Gripper" (LAAG), differed from current PAAW technology in two significant ways. In the original LAAG concept[1], an Nd:YAG laser beam was transmitted into the adhesive joint to permanently weaken it prior to workpiece de-bonding. This required the impregnation of the adhesive with carbon black to couple with the light. The other difference was that the gripper pin was mounted in a non-movable chassis within the fixture. Consequently the only means to de-bond the workpiece was to force it off.

While technically feasible, the necessity of a high powered laser limited the number of applications that this technology was suitable for. Furthermore the inclusion of carbon black in the adhesive limited the thickness of adhesive joints that could be cured.

In 2005, Prof. De Meter and Mike Powell invented the concept of the head-in style gripper and the twist-off de-bonding concept. This concept eliminated the need to weaken the adhesive joint prior to mechanical de-bonding for most applications. It also eliminated the need for a laser, thus eliminating a tremendous impediment to its applicability. This led to the award of U.S. Patent No. US 7,524,390 B2 Fixture and Method of Holding and De-Bonding a Workpiece with the Fixture.

In 2005, Prof. De Meter and his students also worked with Dr. Wells Cunningham of CTECH LLC to specify, characterize, and validate CTECH 14-90-2 MC, the first adhesive specifically formulated for PAAW applications. Also during this time period, PAAW technology first gained traction in the aerospace industries.

Continued development of gripper technology led to the introduction of the 250 and 330 series of gripper designs (Figure 5.1) in 2010. These were designed to provide the optimum blend of robustness and rigidity. They were also designed to provide the maximum, adhesive joint strength when used in conjunction with CTECH 14-90-2 MC adhesive and commercially available 3mm, 5mm, and 8mm light guides.

**Figure 5.1 Left to Right: 250 X 1100 Head Out Gripper, 330 X 1350 Head Out Gripper, 250 X 1100 Head In Gripper, 330 X 1350 Head In Gripper, 250 X 1500 Head In Gripper, 330 X 1750 Head In Gripper**

During this time frame, Prof. De Meter also created the 250 and 330 series of light guide shrouds illustrated in Figure 5.2. This was done after observing the difficulty of operators trying to position and hold a light guide against the backside of a gripper. The use of a light guide shroud solves this problem and yields two other important benefits. It frees up the hands of the operator so that they can do other productive work during the photo-curing cycle, and it enables a single operator to simultaneously photo-cure multiple adhesive joints.

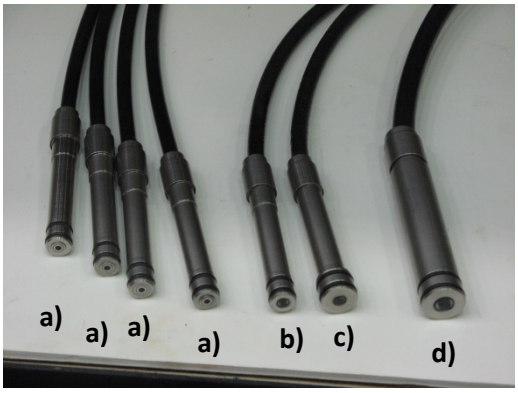



**Figure 5.2 a) 250 HO Shrouds attached to 3 mm Light Guide Legs, b) 250 HO Shroud attached to 5 mm Light Guide Leg, c) 250 HI Shroud attached to 5 mm Light Guide Leg, d) 330 Shroud attached to 8 mm Light Guide Leg**

In 2008, Prof. De Meter invented the axial adhesive grinding process to provide an alternative gripper cleaning method to the use of a heat gun and scraper or an enclosed, hot water, power washer. The limitation of the first method is that it is very slow and tedious to perform. In contrast, the use of the power washer provides a relatively quick means to clean grippers, but is limited to small, shuttle fixtures.

The use of the axial adhesive grinding process enables gripper cleaning to be carried out automatically in the same machine tool as the machining process. Its principal advantages over the other two methods are that it is much faster and cheaper to execute. Furthermore it requires no human intervention other than replacing worn grinding heads.

In 2012, Prof. De Meter and Alejandro Galán invented the peripheral grinding process. This process enables the automated cleaning of grippers whose axes are orthogonal to the spindle axis. It is also capable of being carried out manually through the use of a die grinder. Prof. De Meter and his students continue to research and develop PAAW technology with the aim of expanding its capability, field of use, and scientific understanding.

In the fall of 2012, Prof. De Meter and others founded Blue Photon Technology & Workholding Systems LLC (www.bluephotongrip.com), and signed an agreement with PSU for exclusive patent rights to sell PAAW technology hardware and adhesives to all end users in countries in which the technology is patented. Starting in 2013, Blue Photon will sell advanced versions of the technology developed at PSU. They will also retail adhesives and supporting hardware supplied by strategic partners, and provide design and consulting services.

## 6. PUBLIC DOMAIN APPLICATIONS

A detailed case study on the use, benefits, and costs of using PAAW technology for a machining application can be found in reference[2]. This study was carried out by PSU in collaboration with Precision Grinding and Manufacturing (PGM). It involved a difficult-to-hold aluminum casting that was held for machining processes using conventional clamps and supports. The scrap rates for this application were historically high due to clamping distortion coupled with large casting variation. The set up time was also high due to the steps that the operator took to mitigate the clamping distortion.

PSU created an alternative method to hold the casting using PAAW technology. They also redesigned the machining processes to take advantage of it. The head out style grippers and adhesive grinder were the precursors to the ones described in section 2. Using the PAAW technology, the consumption of critical tolerances was reduced by thirty to sixty percent. Set up time was cut in half. While this application is no longer running, it convinced PGM to apply this technology to other applications.

This section describes three active PAAW applications that are currently in the public domain. All are used to hold a near-net shape workpiece for machining processes. In all cases, residual adhesive left on the workpiece is machined off in a subsequent set up. The first application to be discussed is a hybrid fixture used to hold a magnesium casting at PGM. The second and third are shuttle fixtures used to hold aluminum and stainless steel blanks at PSU. The major characteristics of these applications are summarized in Table 6.1. Each is described in the following subsections.

**Table 6.1 General Characteristics of Public Domain PAAW Applications**

| Characteristic | PGM | PSU #1 | PSU #2 |
|---|---|---|---|
| Workpiece Origination | Magnesium Sand Casting | 6061 Aluminum Form Cut from Plate using a Water Jet | 316 Stainless Steel Form Cut from Plate using a Water Jet |
| Workpiece Envelope Dimensions (in.) | 14 x 14 x 2 | 4.25 x 1.5 x .25 | 5.5 x 2.5 x .4 |
| Fixture Mounting | Permanent Mount to a 4$^{th}$ Axis Table | Shuttle Mount to Machining Center Table | Shuttle Mount to Machining Center Table |
| Gripper | 250 X 1100 HI | 250 X 1100 HO | 250 X 1100 HO |
| Adhesive | CTECH 19-14-2 MC | CTECH 19-14-2 MC | CTECH 19-14-2 MC |
| Adhesive Dispensing | Pneumatic Dispenser | Manual Plunger | Manual Plunger |
| Spot Lamp | 200 W | 200 W | 200 W |
| Light Guide | 8 mm Liquid | 4 x 3 mm High Power Fiber | 5 mm Liquid |
| Light Guide Shroud | Plastic–in house design | 250 HO | 250 HO |
| De-Bonding Method | Manual Twist-Off | Automated Force-Off | Automated Force-Off |
| Gripper Cleaning | Axial Adhesive Grinding with Cutting Fluid | Axial Adhesive Grinding with Cutting Fluid | Axial Adhesive Grinding with Cutting Fluid |
| Closed Door Machining Time (minutes) per Cycle | 8.2 | 6.4 | 25.5 |
| Open Door Time (minutes) per Cycle | 7.5 | 3.1 | 3.2 |
| Total PAAW Activity Time* (minutes) per Cycle | 5.03 | 3.1 | 3.2 |

*includes workpiece de-bonding, gripper cleaning, adhesive deposition, and workpiece bonding

## 6.1 PGM Application

This application involves the machining of a magnesium casting. PGM inherited the application and the conventional fixtures that were used originally to hold it. The casting is very difficult to hold due to its low stiffness and large geometric variability. The original application suffered from a large scrap rate due to the inability of the fixtures to support the workpiece without distorting it or interfering with the machining process. Machining the casting without supports was impossible due to severe chatter.

PGM solved the problem by replacing the conventional fixture used in the first set up with a hybrid PAAW fixture. Since its implementation, chatter and workpiece distortion issues do not exist. They successfully produce this part in production runs of 14 to 28 pieces, with an annual production of approximately 600.

Figure 6.1 illustrates the magnesium casting along with the hybrid fixture that it is mounted in. The fixture is permanently mounted to a $4^{th}$ axis table, which in turn is mounted in a vertical machining center. Figure 6.2 illustrates the features that are machined.

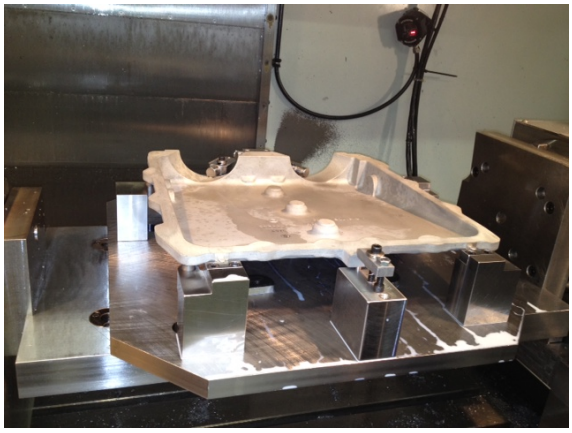
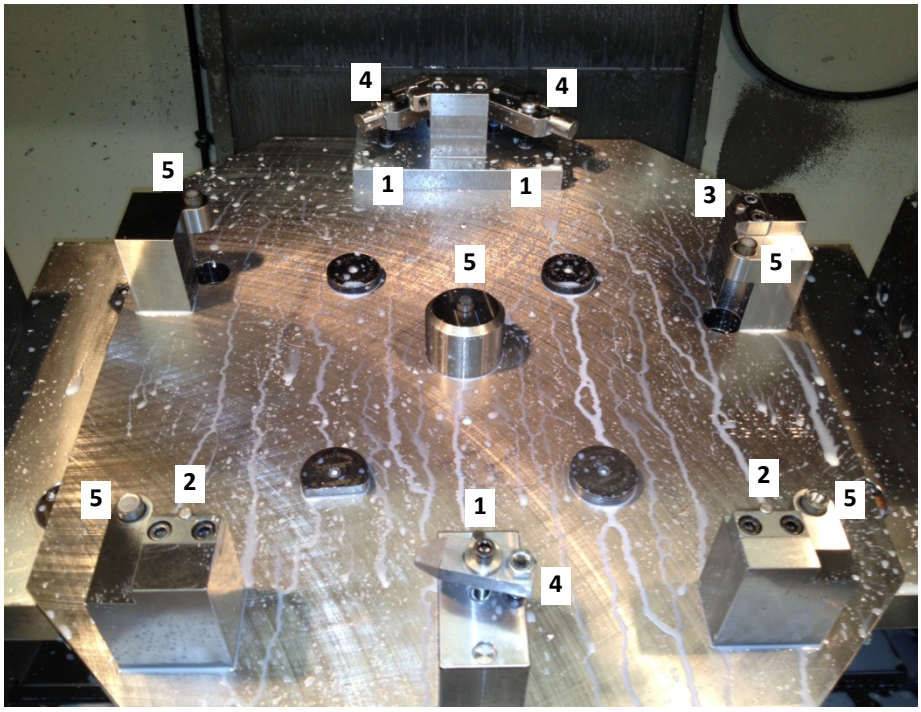


**Figure 6.1 Magnesium Casting Mounted in the Hybrid Fixture**

**Figure 6.2 Machined Casting**

Figure 6.3 illustrates the fixture and its principal components. This design is a hybrid, combining both mechanical clamps and grippers. The ears on the casting are non-functional. They exist to provide features on which to clamp. Out of necessity, the primary datum targets are placed under the ears. Consequently that is where the primary locator pads are positioned within the fixture.




**1: Primary Locator Pad**
**2: Secondary External Locator Pin**
**3: Tertiary External Locator Pin**
**4. Overhead Clamp**
**5. 250 X 1100 HO Gripper**

**Figure 6.3 Hybrid Fixture Utilizing Five 250 X 1100 HI Grippers as Supports**

Without supports, the perimeter is too compliant to machine without generating unacceptable chatter. The same is true for the three machined surfaces in the interior. Conventional, adjustable supports were ruled out for use in this design, because they could not be paired with overhead clamps, which obviously would block access to the surfaces to be machined. The use of five 250 X 1100 HI grippers solved this problem.

At the time this fixture was designed, PGM had little data on the variability of the castings that they were to machine. They were concerned about potential variation in the gripper-to-casting gaps, and the possibility that the workpiece could make contact with the grippers. As a consequence, PGM chose to use head-in grippers rather than head-out grippers, because their greater adjustability. Specifically their nominal position relative to the casting can be backed-off through the placement of spacers at the gripper-manifold interfaces. As it turned out, PGM's concerns were well founded. Once production began, It was determined that the gaps varied by as much as .12 in. due to casting-to-casting variation. As a consequence, the nominal gaps were set to .065 in.

Another reason PGM chose to use head-in grippers was uncertainty whether force-off de-bonding would damage the part. The use of head-in grippers gave them two de-bonding options as opposed to one. As it stands, PGM currently de-bonds the machined casting via manual, twisting of the grippers.

Another important concern in this design was the potential impact of adhesive shrinkage on workpiece distortion. This was mostly due to the very large joint thicknesses that needed to be cured through, coupled with the inherent compliance in the casting. Experiments carried out by PGM revealed that the solidification of the five adhesive joints caused the casting to move no more than .001" at any given location above a gripper. Given the tolerances that were to be held, this error was considered acceptable.

Due to the size of the casting, it was decided that the hybrid PAAW fixture should be permanently mounted to the machining center during a production run. In order to provide easier access to the backsides of the grippers, PGM mounts the fixture to a 4$^{th}$ axis table. After the workpiece is machined, the table is tilted to make it easier for the operator to insert the light guide during the bonding cycle (Figure 6.4), and insert a wrench during the de-bonding cycle (Figure 6.5).

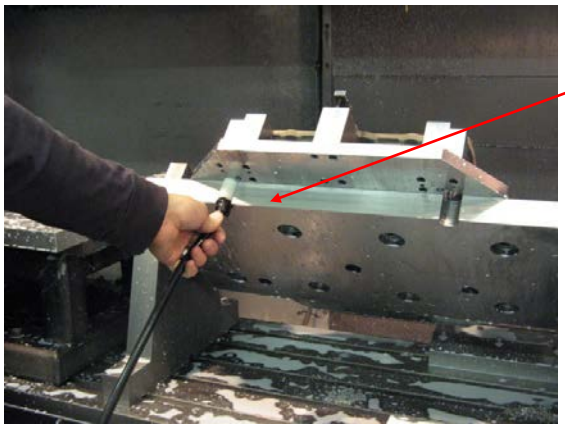



**Figure 6.4 Photo-curing an Adhesive Joint with the Fixture in the Tilted Orientation**

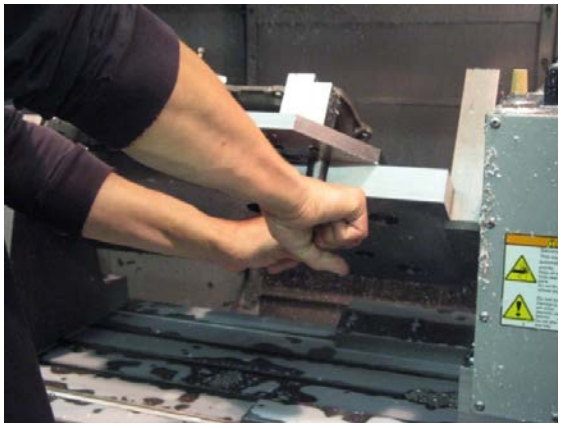


**Figure 6.5 Twist-Off Fracturing of an Adhesive Joint with the Fixture in the Tilted Orientation**

The 4th axis is also needed to orient the top of interior gripper to the axial adhesive grinding process. This gripper would otherwise be at 6.2° to the spindle axis (see Figure 6.8) and would be impossible to grind automatically. With it, all five are successfully cleaned each cycle as shown in Figure 6.6.

PGM uses an automatic pneumatic adhesive dispenser (Figures 6.7 and 6.8) to control the volume of adhesive deposited on the grippers. They prefer this over the use of a manual plunger in order to reduce adhesive waste and to achieve better process control.

PGM uses a 200 W spot lamp (Figure 6.7) in combination with a 8mm light guide to photo-cure the adhesive joints. A 5 mm light guide is a better choice. However during the initial design stage, they ordered the 8 mm, thinking that they were going to use 330 X 1350 HI grippers. Instead of purchasing the additional light guide, they chose to stick with the 8mm.

**Figure 6.6 Gripper after Axial Adhesive Grinding Process**

**Figure 6.7 Pneumatic Adhesive Dispenser (l) and Spot Lamp (r) used for PGM Application**

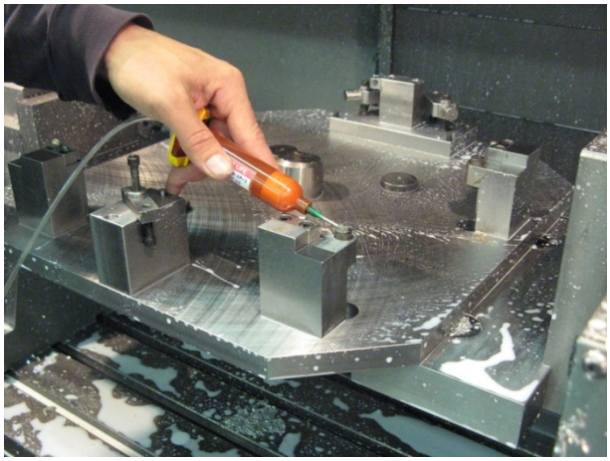


**Figure 6.8 Dispensing the Adhesive on to the Gripper**

PGM is currently using a home-made, plastic light guide (Figure 6.4) shroud In lieu of the 330 PAAW light guide shroud. This decision was made out of necessity, because the coupling hole was errantly designed and fabricated oversized. The plastic shroud works, but requires the operator to hold it in place during photo-curing. In addition, the light guide has the tendency to slide within the shroud due to the inability of the tape to retain it.

## 6.2 PSU Application #1

As part of a manufacturing engineering education initiative, PSU runs a program called the "Nittany Lion" project. Each semester, 20 engineering students are trained to run a variety of manufacturing processes within our manufacturing laboratories. Their intent is to fabricate a "Nittany Lion" figurine (see Figure 6.9) in a production style setting. Approximately 50 units are fabricated each term and distributed to the students.

**Figure 6.9 Nittany Lion Figurine**

The Lion is comprised of a stainless steel core and two, aluminum handle inserts. The handle inserts are first cut from 6061 aluminum plate using an abrasive water jet process. They are subsequently machined (completely) on six sides in two set ups, before going to anodization. A PAAW shuttle fixture

is used to hold two workpieces in the first set up. A vise with soft jaws is used to hold two workpieces in the second set up.

A description of the PAAW application for the handle inserts is provided in section 2. It was desired to hold the parts using a technology that could provide complete five side accessibility and handle the machining forces exerted during face milling. Due to the small footprint of the part, it was felt that a vacuum fixture could not reliably restrain it. Consequently PAAW technology was chosen.

This application was designed with productivity in mind, because the number of student hours to operate the process is small. As a consequence, everything possible to reduce machining time and machine tool down time was employed. This included the use of:

- an automated workpiece ejection process to minimize the time necessary for workpiece de-bonding
- an automated axial adhesive grinding process to minimize the time necessary for gripper cleaning
- a two shuttle fixture system to allow chip making while the next workpiece is loaded and bonded
- a 4 x 3mm light guide with 250 HO shrouds to simultaneously photo-cure the four adhesive joints holding the two workpieces

This is a very successful application. The scrap rate is virtually zero. The only error that occurs is when a student does not correctly position a workpiece against the locators prior to the photo-curing process.

### 6.3 PSU Application #2

The Lion core is made from 316 stainless steel. The initial form is cut from plate with an abrasive water jet process. It is subsequently machined (completely) on six sides in two set ups. It then goes through a wire EDM process to cut out the detailed mouth section. This is followed by bead blasting and a third machining process to engrave the Lion features. A PAAW shuttle fixture is used to hold the workpiece in the first machining set up.

The rationale for using PAAW technology was identical to that used for the aluminum handle inserts. Namely it was desired to use a work holding technology that provides five sided access to the part and is capable of withstanding the large machining forces. The part material is not ferro-magnetic, which ruled out the use of a magnetic fixture. A vacuum fixture is not capable of exerting sufficient frictional forces to restrain the part against the large milling forces. PAAW technology was the logical choice.

Figure 6.10 illustrates the steel workpiece mounted in the PAAW fixture prior to machining. Figure 6.11 illustrates the workpiece after machining and automated de-burring. Figure 6.12 illustrates the PAAW fixture. It incorporates the same grippers and locating scheme as the PAAW fixture used to hold the aluminum handle inserts. The only difference is that four grippers are used to hold the workpiece rather than two.

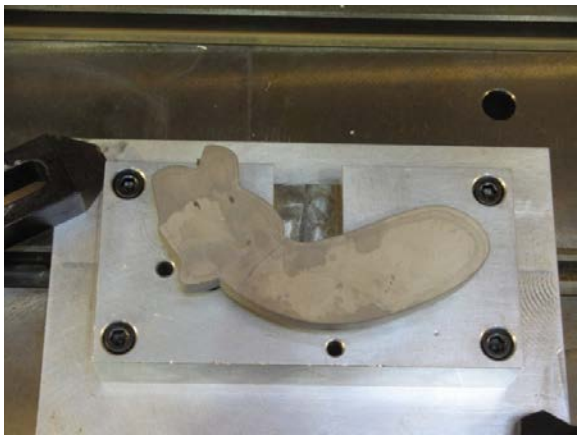


**Figure 6.10 Stainless Steel Workpiece Mounted in the PAAW Fixture Prior to Machining**

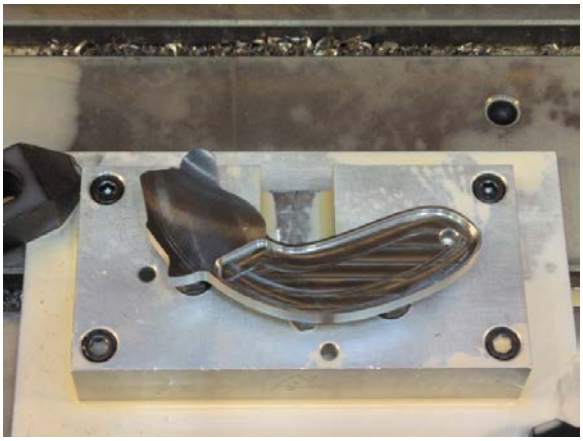


**Figure 6.11 Stainless Steel Workpiece after Machining and De-burring**

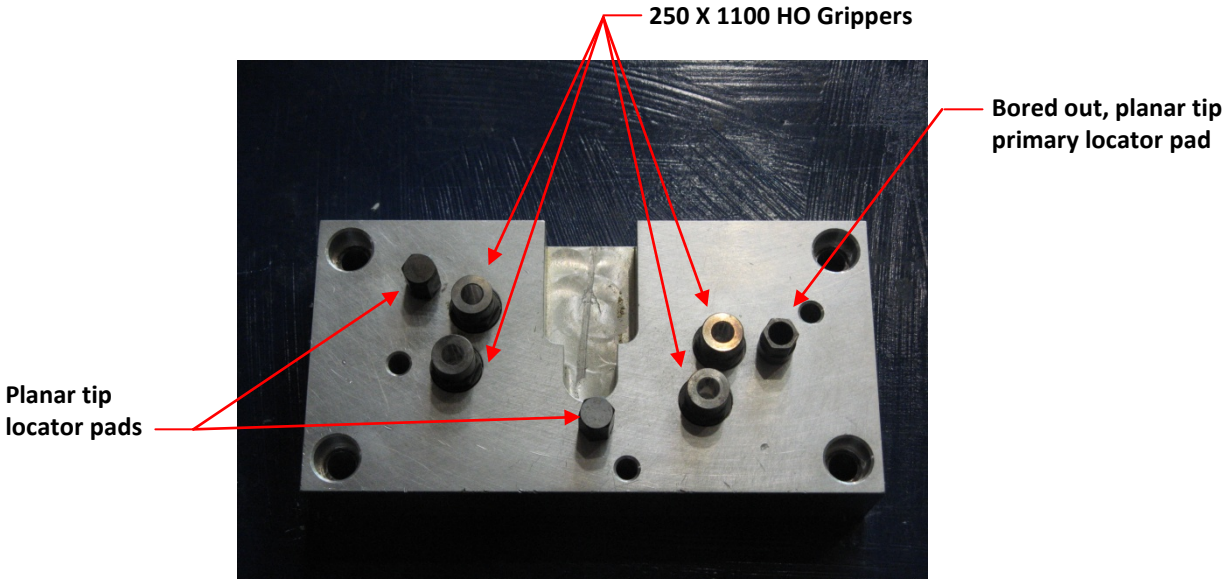



**Figure 6.12 PAAW Fixture Used to Hold the Stainless Steel Workpiece**

The fixture was designed to accommodate five sided machining, including the ¼ inch diameter hole drilled through the workpiece tail. It was also designed to accommodate the automated ejection process. Most of the machining is done using a combination of face milling, peripheral end milling, and pocket end milling processes. The forces exerted on the workpiece during these processes change continuously with regard to region of application, magnitude, and direction. However the directions of these forces are primarily parallel to the primary datum/holding surface of the workpiece. As a consequence, the locating pads do not contribute much to absorbing these loads.

To restrain the workpiece against the milling forces, the four 250 X 1100 HO gripper joints are placed as shown in Figure 6.13. In order to minimize stresses within the adhesive joints, the grippers are placed as close to the periphery of the machined workpiece as possible. In addition, their distance apart is maximized in order to increase the rotational stiffness of the workpiece in the primary datum plane. Since the workpiece itself is stiff, there are no compliant sections needing additional support.

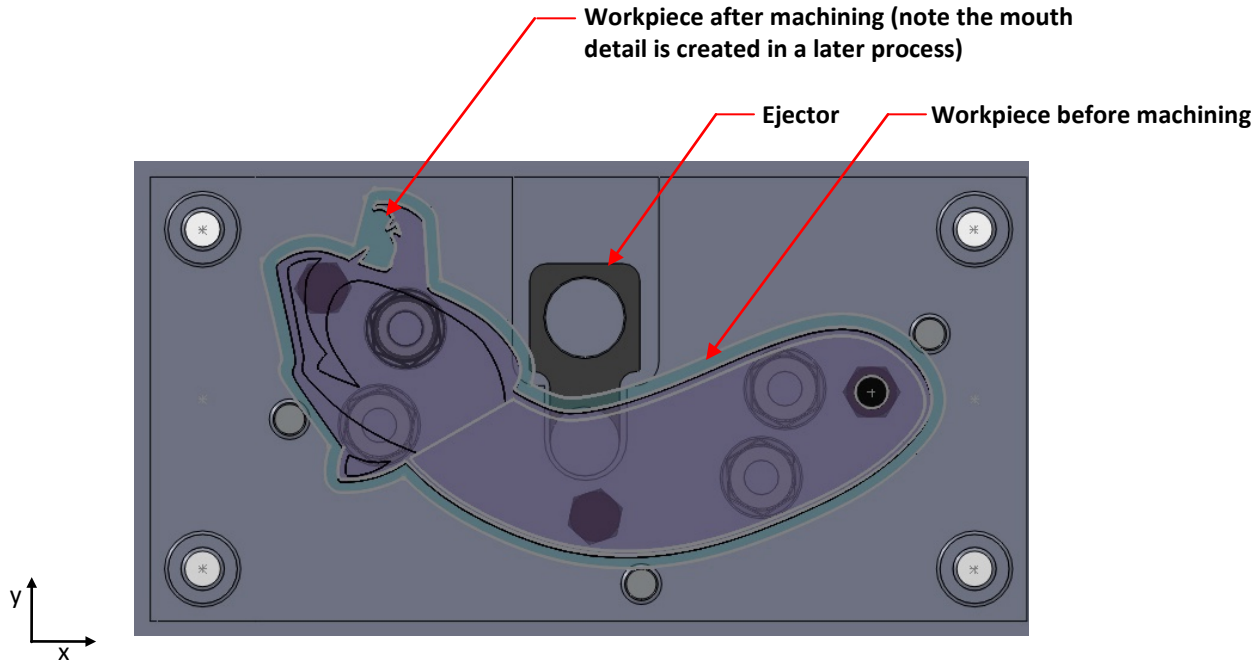



**Figure 6.13 CAD Assembly Illustration of PAAW Fixture, Ejector, Workpiece Prior to Machining, and Workpiece after Machining**

To counteract the large thrust force exerted by the twist drilling process normal to the primary datum plane, a primary locator pad was bored out and placed directly underneath. This not only maximizes the directional stiffness of workpiece in this region, but it also minimizes the stresses within the adhesive joints. The same thought processes and concerns that were applied to this design were also applied to the handle inserts fixture.

The workpiece unload-load cycle for this application is executed in a fashion nearly identical to that used for the aluminum handle inserts. The only exception is that the adhesive joints are photo-cured sequentially with a 5 mm liquid light guide in order to insure greater quick strength. The extra time needed for photo-curing is not an issue because of the exceptionally large machining cycle time (25.5 minutes).

This is a very successful application, with virtually zero scrap rate. Ordinarily one student will run this process on a single machining center with two shuttle fixtures. However when demand is high, a student will run two machining centers with three shuttle fixtures.

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