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VIBRATION REDUCTION USING MATERIAL JETTED PARTS FOR SANDER GRIPS

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Abstract

Workers in many industries are exposed to harmful vibrations that negatively impact their comfort and long-term health through tools such as hand-held sanders. Here we show that using material jetting we can produce durable and effective vibration protection equipment that reduces vibrations felt by the user by an average of 23% to 45%. We developed 3D printed vibration absorbing grips made from a blend of TangoBlack+ and uncured liquid. The grips were deployed at a Boeing factory and survived 1 month of usage. The grips were best at absorbing higher-frequency vibrations, able to reduce frequencies above 1kHz by over 20dB. Our results demonstrate promising capabilities of material jetting viscoelastic materials for direct part production of ergonomic components. Moreover, these grips could be improved and used to dampen vibrations on other tools such as bucking bars and used in various other industries.

Introduction

Hand-arm vibration syndrome is a condition that effects millions of workers in the United States each year [1,2]. We have taken materials that can only be 3D printed using material jetting [3] and applied them to help reduce vibration exposure for workers using sanding tools. We believe this represents one of the first viable production applications of material jetting [8,9] for end use devices rather than for prototyping or tooling [8].

The vibrations generated from power tools can induce Raynaud's phenomenon and lead to nerve damage [1,2]. That tingling sensation you feel every time you use a sander isn't just a minor inconvenience, it's a sign that you are being exposed to harmful vibrations. Symptoms include numbness, pain and blanching of skin. Since 1983 NIOSH has recommended, work be engineered to reduce exposure to vibrations [2], and the European Union adopted a directive in 2002 to improve worker safety around vibration [4]. Currently there is no standard for solving vibration besides the uses of rubberized grips and careful tool design. In the manufacturing of aircraft, almost every surface of the interior needs to be sanded. Despite efforts at automating the sanding process, the current standard for manufacturing requires manual sanding operations [5]. This requires workers to spend a large percentage of their shift at a Boeing Interiors Responsibility Center (IRC) to be spend sanding and being exposed to vibrations.

In previous work, Lipton and MacCurdy developed a 3D printable viscoelastic energy absorbing material that combines TangoBlack+, an acrylate polymer, on a PolyJet with a non-curing liquid, specifically the Polyethylene Glycol used as a model cleaning fluid [3]. This same technique can be used to produce hydraulic parts [6] or microfluidic devices [7]. By varying the liquid concentrations between 0 and 25% a close cell structure could be produced that contained the liquid but was able to achieve tan deltas between 0.3 and 1 at 1 Hz and had a power law relationship with frequency, increasing damping as frequency increased. This made it an ideal material for absorbing impacts or vibrations.

The process of forming this liquid containing material required the use of material jetting. Material jetting has the advantage of being able to combine large numbers of materials together. By adding a non-curing liquid to the set of printable materials its possible to make a closed cell material where the cells are liquid filled. While phase separation materials can entrap liquids in materials, material jetting allows for precise spatial control over the size and distribution of liquid inclusions [11]. The only limitation is that this material is not durable enough to survive a shop environment without a protective coating. The surface easily picks up debris, tears, and swells in the presence of water and other liquids.

In this work we present a design for an adaptor for a Sioux 5” sander made from this printed material that can survive the operating requirements for vibration protection at a Boeing IRC. For a design to be acceptable it must be able to: 1) survive the working conditions without mechanical degradation, 2) provide sufficient protection from vibration, 3) easily integrate with existing tooling, and 4) be acceptable to the workers using the tool. This required us to select a coating for the 3D printed material to ensure compatibility with the working environment and long term survivability. We filtered a series of candidate coatings down into a final coating material of Loctite Shoe Glue. We also conducted a series of shop trials where we iterated our design based on user feedback. After generating the final design, we conducted vibration testing to determine how effective the final design was at protecting workers. In this paper we:

- Determine that Loctite Shoe Glue is a viable protective coating material for PolyJet elastomers.
- Validate a design for a sander grip using four shop trials
- Determined that our design can provide 32% vibration reduction into the finger and 45% reduction into the palm

Background

Damping is a critical tool in vibration control. While the standard form of a damper is a dashpot filled with liquid, viscoelastic materials are widely used for vibration and impact protection. Viscoelastic materials rely on hysteretic effect to generate a loss modulus that converts cyclic loading into heat. Viscoelasticity is critical to the extrusion process in Direct Ink Write (DIW) [14], however in Material Jetting (MJ) processes the materials are jetted as viscous liquids and cure into solid materials.

A unique property of MJ is its ability to blend materials together at the voxel level. This allows for the creation of “digital materials” with controllable properties. Typically this involved the blending of a rigid material such as VeroWhite with a rubbery material such as TangoBlack+ (TBP). Previous investigation of MJ material blends found that the elastic properties can be modeled using a Mooney–Rivlin model [13]. The viscoelastic properties of blends of TBP and VeroWhite+ at low frequencies closely model the isostrain boundary [15]. All material jetted materials from Stratasys exhibit a strong frequency dependent response in their storage and loss modulus [16]. Recent work has shown that when a non-curing liquid is included, the materials can take on a wider range of material properties. This allows method allows for direct control of the storage and loss modulus using a random percentage of the non-curing liquid[3]. This has been used to make components for robots as well as making tissue simulators where the complex viscoelastic response is critical to performance[12]. We therefor think that MJ processes and material are ideally suited for making a viscoelastic vibration absorber.

Despite the utility of MJ for making high resolution parts and parts with digital materials, there are many challenges with the jetting materials. Often coatings are used to overcome a material deficiency [19]. Previous researchers have used PDMS coatings to promote cell compatibility in MJ devices[17]. To overcome the water absorption in many MJ materials researchers have used diamond-like carbon coatings[18]. While these past efforts have identified methods for coating for their specific applications, none were appropriate for the environment we expected the sander to operate in. Therefore, we needed to search for a suitable coating that would provide both chemical and mechanical protection to the MJ parts.

Coating Material Selection

The goal of coating material selection was to find a material that protects the grip from wear and debris experienced in a shop environment. This includes mechanical stresses and abrasions, as well as exposure to chemicals and dust. Our process consisted of generating a set of candidate materials and then filtering them based on performance on a series of tests. We first filtered for bonding to the substrate materials. Next we filtered for chemical resistance, Finally we filtered for expected environmental conditions.

We generated our candidate material list from materials that were commercially available across different industries, including automotive, housing, sports, and adhesives. We selected across application methods including spraying, dipping, and painting. We selected them to be either specifically formulated for protecting surfaces, or had acrylate chemistry which would be compatible with the acrylate based resins similar to those used in the PolyJet process[10].All the materials tested can be found in Table 1.

Table 1: Materials tested as protective coatings.

Sealing Materials	Adhesives
Flex Seal	Scigrip Acrylic Adhesive
Gorilla Patch & Seal	Scotch-weld Instant Adhesive
Bondo Undercoating	Loctite Shoe Glue
Rejuvenate Seal	Loctite Extreme Glue
Rustoleum Leak Seal	Loctite Vinyl Fabric & Plastic
Spray Electrical Tape	Loctite 4902
Liquid Electrical Tape	Loctite 480
Smooth on Urecoat	Loctite 431
Alex Flex Crown Molding	Loctite 408
	Gorilla Super Glue

To produce samples for testing we 3D printed small 10 mm x 5 mm test rectangles of Agilus30 material using a Stratasys J750 printer. We used Agilus because at the time we had just received the J750 and did not have the Tango Black+ (TBP) that is the basis of our mixed materials. We believed that Agilus was a reasonable stand in since they are both acrylate chemistries. After printing the samples, we cleaned them in the Stratasys pressure washer and then allowed them time to dry (24 hours) we then either directly applied coating materials to the surface, or we sanded the surface and then applied the material. For each of our materials we followed the manufacturer's directions for application of materials. Each sample was left to dry for an additional 24 hours.

Mechanical Resistance Testing

Our first filter was a series of tests to determine if the coating material could remain bonded to the 3D printing material. Specifically we conducted: peel tests, compression/torsion tests, light and heavy abrasion tests. For each test scale we used is as follows: No Issues, Minor defects, Fails. For no issues, the sample looked and felt the exact same before and after the test. For Minor defects, there are some minor defects and delamination before and after the test, but the majority of the coating is intact and functional. For a failure, the coating completely delaminates or is warped beyond use. Because all the samples eventually peeled with enough effort, we chose to rank the difficulty needed to peel the material on a scale of 1 to 5, with 5 being impossible to peel, 4 being peels with significant and intentional effort, and 1 being peeling very easily. The numerical value for the peel test was classified with 5 being No issue, 4 and 3 being Minor defect and 1 or 2 being a failure.

For peel tests the goal was to see how easy or difficult it was to peel off the coating, especially if someone were to intentionally try and peel it off. We performed this test by attempting to peel off the coating from one of the corners of the cube by hand using our fingernails. For the compression and torsion tests, the goal of this test was to simulate conditions of sander vibrations and user handling of the grip. We performed this test by vigorously twisting each sample to about 45 degrees and then compressing each sample several times to see if there were any delamination's of the coating. The light abrasion test had the goal of stimulating the grip being scratched by a fingernail, tool, or other object. We performed this test by scratching the sample several times with our own nails, observing for any delamination that may have occurred on the coating. Finally the heavy abrasive testing was to check for the limits of how much abrasion the coating can tolerate and to determine if it left any debris on surfaces that would be difficult to clean. We performed this test by rubbing the coated side of the sample on a sandpaper 10 times to observe if there were any remnants on the sandpaper or coating delamination. The results are summarized in Table 2. A red highlight indicates fail, yellow indicates minor defects, and green indicates no issues.

From these tests, we found that coating a sanded test rectangle versus directly applying the coating did not make any difference in the outcome of the mechanical tests. We conclude from this that most of the issues of bonding were chemical in nature rather than mechanical. We found that some materials were excellent at providing protection but were prone to pealing and others were excellent at peal resistance but had pore protection. We then tried to create lamina where the peal resistant materials were applied as a first layer and then protective materials were overlayed. Universally this led to the failure of the entire structure on peal testing and the notion of multilayer coatings was abandoned. We concluded that four materials were viable coatings, namely Smooth-On Urecoat, Loctite Shoe Glue, Loctite Extreme Glue and liquid electrical tape. All the materials except liquid electrical tape had the best peal resistance and at least two categories with no issues.

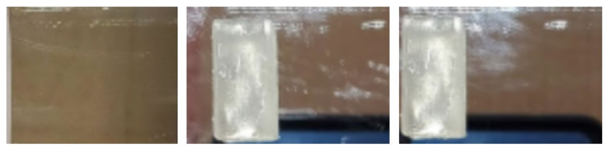
Table 2: The results from initial mechanical testing of the materials. Red indicates a failed test. Yellow indicates minor defects. Green represents a passing result.

	Peel	Compression/Torsion	Fingernail	Sandpaper
Flex Seal	Yellow	Yellow	Green	Red
Gorilla Patch and Seal	Red	Red	Red	Red
Bondo Undercoating	Red	Red	Red	Red
Rejuvenate Seal	Yellow	Yellow	Red	Red
Rustoleum Leak Seal	Red	Green	Red	Red
Spray electrical Tape	Red	Yellow	Red	Red
Liquid Electrical Tape	Red	Green	Green	Yellow
Scigrip Acrylic Adhesive	Red	Red	Red	Red
Loctite 480	Yellow	Yellow	Green	Red
Urecoat	Yellow	Green	Green	Yellow
Scotch-weld Instant Adhesive	Yellow	Red	Yellow	Red
Loctite Shoe Glue	Yellow	Green	Green	Yellow
Loctite Extreme Glue	Yellow	Green	Green	Yellow
Loctite Vinyl Fabric and Plastic	Red	Yellow	Yellow	Red
Loctite 4902	Red	Red	Red	Red
Gorilla Super Glue	Yellow	Red	Yellow	Yellow
Loctite 431	Yellow	Red	Green	Yellow
Alex Flex Crown Molding	Red	Green	Green	Green
Loctite 408	Red	Red	Red	Red

Chemical Resistance and Environmental Testing

The second filter focuses on the chemical resistance of the coating materials. To survive in a production environment, a tool must be able to survive encounters with Isopropyl Alcohol (IPA) Methyl Ethyl Ketone (MEK) and Acetone. To test compatibility, we put a layer of these materials onto 5 different coated samples. We then checked for any delamination or degradation after one hour and after 24 hours. We chose these times since it represented the expected times that a material might be in contact with the chemicals in a production environment. From these tests, we found that none of the four down selected materials degraded when exposed to the three chemicals (IPA, MEK, or Acetone).

The final filter focused on environmental considerations, namely, transfer to smooth surfaces and dust attraction. The goal of the smooth transfer test was to see if the material left any debris on a surface that could not be cleaned with IPA. We rubbed the coated rectangles against a glass surface 10 times to look for scuff marks or smudges on the glass. We then checked if any marks could be cleaned off with IPA. We also found that after performing the smooth transfer test, there were some minor remnants that were left on the glass surface, but the scuff marks were easily removed with an IPA wash. This can be seen in Figure 1. To test dust attraction, we sprinkled sawdust onto the coated rectangle. We attempted to brush it off using a brush. We then blew off the sawdust with an air gun, and finally, we performed an IPA wash. This test checks how much dust remains on the grip surface, since it will be exposed to dust in the shop. After performing the dust attraction test, we found that much of the sawdust could be removed by brushing it off. The sawdust was completely cleared after blowing it off with compressed air.



Before Test Scuffs Left Post IPA Wash

Figure 1: Scuff tests were conducted to determine if the coatings were leave a mark when dragged on smooth surfaces and if any remnant could be easily removed with IPA. We found that scuffs were left but were easily cleaned.

After completing the tests on the Agilus samples, we were able to conclude that the two best candidates to go forward with were Urecoat and Loctite Shoe Glue because they performed better on the Sandpaper test and the Peel Test. A visual summary of the results is viewable in Table 3, with the same color-coded key as before. During the initial testing phase we bonded the Urecoat and Loctite Shoe Glue to the TBP and 25% liquid filled TBP blend and found that the Urecoat could not bond to the materials with added Polyethylene-Glycol. Therefor we selected Loctite Shoe Glue as the coating material.

Table 3: Results from the combined test on the coating materials. We determined Urecoat and Loctite Shoe Glue were the best coating materials.

	Peel	Compression/Tor	Fingernail	Sandpaper	MEK	IPA	Acetone	Smooth transfer	Dust attraction
Urecoat	4								
Loctite Shoe Glue	4								
Loctite Extreme Glue	4								
Liquid electrical tape	1								

Initial Design and Improvements

The second component of our efforts was to improve the geometry of the gripper. We conducted a series of shop trials and engaged in an iterative design approach based on user feedback. Our gripper needed to interface with the 5” Sioux Sander that is the standard at the Boeing Interiors Responsibility Centers in Everett, Washington and Ladson, South Carolina. We conducted a total of four shop trials, during which we asked users to sand flat and curved panels using different versions of the grip. We then asked users for feedback on vibration reduction, comfort, and updates they would like to see. We started with an initial design and generated new versions. The first iteration focused on defining the attachment mechanism and shape of the tool. The second and third iteration focused on durability and survivability. The final iteration focused on performance.

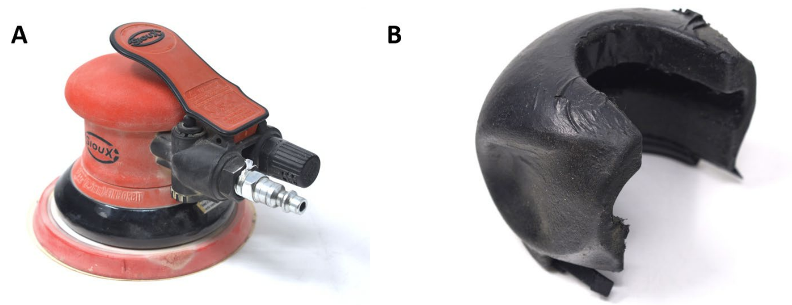


Figure 2: The Sioux Sander 5" pneumatic power tool (A) is the base tool for our protective grip. Our initial design (B) used claps that were deemed to hard to replace and was too large to be comfortable

Our preliminary grip design was made out of TangoBlack+ material, with a 25% liquid infill. The shape was designed to fit over the rubber grip that comes with the sander and had a clasping mechanism at the base. It was designed to fit over the tool in order to ensure that no modifications to the tool were required to use the grip. We also maximized the amount of material around the tool in order to provide maximal vibration protection. From initial feedback from users, we learned that the design was too hard to apply to the tool.

First Iteration and Shop Trial

Our first design improvement focus was on improving the mechanism by which the grip is secured to the sander. We determined that removing the red rubber grip was a reversable process and provided enough mechanical features for grasping and alignment. We evaluated three methods for attaching to the tool at this point. The first clasping mechanism was a two-piece clasp that maintains the same shape as the standard rubber grip. However, it is made of VeroPureWhite, which is a hard plastic that can be printed on the J750. The two pieces clip together. There were several issues with this design, including difficulty installing and removing the grip, as well as problems with the clips snapping off. The part is shown in the figure 3. The second clasping mechanism we tested was a copy of the stock rubber piece out of the grip material, TangoBlack+(TBP). It was still difficult to install and remove and was also prone to tearing. The part is shown in figure 4.The final mechanism was a sliding mechanism. It was designed to tightly fit the geometry of the top front half of the tool and extended as a uniform cross section for the back half. This enabled it to slide onto the sander. The part is shown in the figure 5. We found this design to be easy to use and stable. In addition to the clasping mechanism, we also wanted to incorporate padding that goes on the lever used to turn the sander on and off. The initial lever pad design has a hard VeroPureWhite portion that clasps onto the lever, and a thick layer of TangoBlack+ padding. This can be seen in Figure 6.

For this first shop trial and all subsquet trials we went to the Boeing Interiors Responsibility Center (IRC) in Everett Washington. All users were workers at the IRC who regularly sanded as part of their job. We asked them to take a part that was in their queue and to sand it with the base tool, and with one of our improved tools. We then asked them questions about their experience and solicited feedback. This questions can be seen in Appendix A. We also recorded any unsolicited comments about the device and its performance.

Figure 3: Hard Shell clasp mechanism

Figure 4: TBP copy of the red cover. This was prone to tearing.

Figure 5: The sliding design for attaching to the sander.

Figure 6: The claps for attaching to the lever pad of the gripper.

For the first round of shop trial testing we had the users compare the base tool, to one made with just TBP and one with a 25% liquid concentration. We found that users generally noticed a significant reduction in vibration with both the TBP and 25% liquid designs. However, they found the shape of the grip itself to be large and difficult to control. Users also wanted more space near the top to press down on and to be able to hold the sander in multiple positions. Some users preferred the TBP, others preferred the 25% liquid inclusion, but both groups had similar comments about the general shape of the grip.

Second Iteration and Shop Trial

Based on the user feedback from the first shop trial, we focused on making the grip easier to control and hold from different positions. We determined that creating a "mushroom"-style grip, can be held from all sides. Within the second round of design updates, there were several iterations that we went through prior to the shop trial. In figure 7 we see the initial conceptual design in A and the final version of the design in B. The design has the curved side cutouts, and the space for the lever pad was an indented cutout, with a layer of plastic on top of the base tool. There is also a chamfer at the back for users to press forward. Users can hold the grip with their fingers over the rounded edge, or over either of the straight side edges

Figure 7: The grip was redesigned form concept (A) to initial design (B) to be more of a mushroom style grip.

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Using the same procedures as the initial shop trial we investigated the design performance. We found that users generally found much less vibration than the base tool and significantly preferred the updated grip shape because it resulted in less strain and could be held in any direction. Users were excited about the grip, and several were ready to use them. However, there were some issues with breakage of the clasp portion (see figure 7B) and some users found the grips too flimsy towards the tail.

Third Iteration and Shop Trial

Based on the results of the second round, we determined that improving the hard clasp portion to mitigate breakage issues was critical. We approached this by identifying regions of stress concentrations and reinforcing or adding relief cuts in those areas. The first identified stress concentration was the top of the clap, which cracked from being put on and removed from the sander. Since the top portion did not contribute much to securing the grip on the sander, we decided to remove the top portion and have just a ring that slides on to the sander. The next stress concentration we identified was the ring cracking, since it needs to be stretched to be put on the sander and is also squeezed during use. We experimented with multiple ways to add relief cuts to prevent this. We tried adding two relief cuts on either side of the center line and one cut directly at the centerline. We also tested relief cuts through both the top and ring portions or just through the top. This can be seen in figure 8. We ultimately decided to go with the third option because it does not make the grip too flimsy, while making it flexible enough to withstand enough tension and compression.

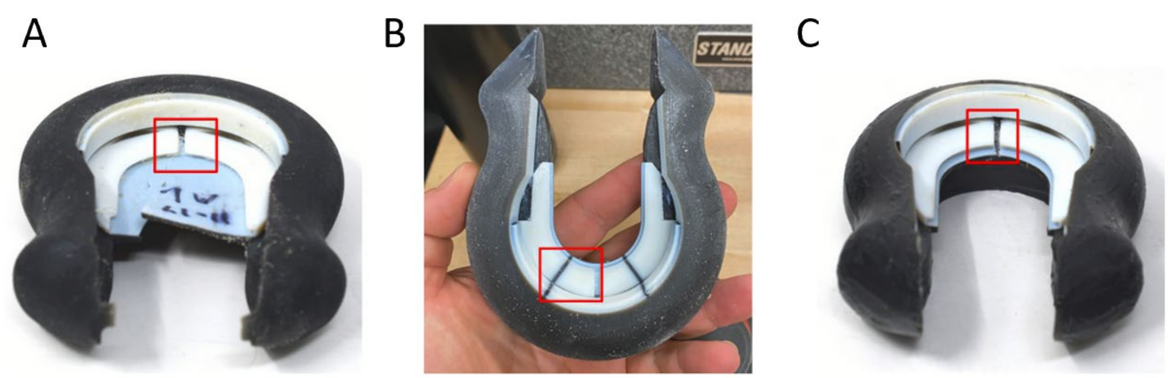

Figure 8: Stress concentrations and relief cuts. The base design (A) had stress concentrations in the ring and the top causing cracks. We tried cuts through the clasp at two locations (B) and 1 location (C) and found that the single design worked best.

We tested the designs using the same procedures as the previous shop trials. User feedback was similar as the previous round. Users found that vibration decreased and liked the shape of the grip, as well as the control they had over the sander. This was not unexpected as we did not make any significant changes to the shape of the grip from trial two. The design updates did help in preventing cracks, however, there were still some issues with difficulty installing and removing the grip. Additionally, users still found the tails of the grip to be flimsy. Another important point is that when the lever is pressed down, the grip presses inwards into the lever pad, keeping it engaged even when the user releases the lever. There were also some issues with breakage of the lever pad clips.

Fourth Iteration and Shop Trial

Based on the results of the previous results we determined that it was important to reinforce the tail for safety reasons in addition to user preference. We also determined that we needed to change the base materials that we were using for rigid sections of the tool to improve performance under bending. Therefor the fourths design iteration focused on reinforcing the tails and finding a better material for the hard portions that would be more flexible and less prone to breakage.

To find the flexural material we tested different mixtures of TBP with VeroPureWhite and VeroFlexWhite, which is a flexible material from Stratasys. We printed lever pad samples with different mixtures preset by the J750 Digital material library. We performed cyclic attaching and detatching of the lever pad onto the tool to determine the best material. We decided on RGDFLX8530, a blend of TBP and VeroFlexWhite, because it was the only material strong enough to hold the cover on the lever pad while being flexible enough to be removed and resecured through 15 cycles.

To reinforce the tails we extended the side ring further back to add additional support. We made versions of this piece with different thicknesses of the extended tails to identify the best thickness. This was done by rapidly putting the piece on and taking it off the sander, with varying degrees of roughness to simulate use in a shop environment. We considered how many removal cycles it took for the part to break, and the selected version sustained over 100 cycles. After identifying the thickness of the tails we extended them further down the shaft of the sander. This increased the contact area with the sander and provided increased reinforcement. We had to curve

Figure 9: The addition of curved supports allowed the tails of the grip to anchor on the rear of the sander and provide support against bending

the extended portion outwards to prevent interference with the sander. We also increased clearance between the grip and lever pad by enlarging the cutout to prevent issues with the grip keeping the lever pushed down. The changes are boxed and shown in Figure 9.

We conducted the shop trial with the same procedure as the previous rounds. The fourth shop trial found that users were excited about the grips and ready to use them. They noticed a significant reduction in vibrations, and found the grip comfortable and durable. The improvements with changing the material for the hard portions and extending the tails made a noticeable difference in minimizing breakage and making the grip sturdier.

Accelerometer Data

With the design finalized we quantified the improvement the sander grip made on the workers exposure to vibrations. We measured the vibration at three relevant points, the fingertips, the palms, and the wrist. We needed to measure the effect when sanding on curved surfaces and on flat surfaces because we had observed in previous trials that it changed the amount of vibration the users experience and the shape of their hands when gripping the tool. Finally, we need to compare the liquid filled material with the solid TBP and the base tool.

For this study we worked with 5 workers at Boeing Evert IRC to trial the device and record vibration data. To measure vibrations, we attached a PCB TLD356A26 triaxial accelerometer to the workers using a 3d printed holder that would attach Velcro to the sensor. Our procedure consisted of having the worker first select either a curved or flat piece for them to sand. The workers were then asked to sand as they normally would on a tool with the original red base grip attached. While they sanded, we recorded the acceleration for 15 seconds. We then asked them to use the sander with the hard grip attached to sand as they normally would for 15 seconds while we recorded the acceleration data. Finally, we asked the workers to use the sander with the soft base attached to sand for 15 seconds as they normally would, while we recorded their acceleration. Once this was completed, we re-attached the accelerometer with the 3D printed holder onto the subject's palm and repeated the data collection. Finally, we attached the sensor to the wrist and repeated the data collection. Several users were able to complete the process for both curved and flat pieces of material.

To analyze the data collected we compared the magnitude of the accelerations the workers experienced as well as the power spectral density of the vibrations. We examined the mean accelerations the workers experienced as a condition of the power tools as seen in Table 4. An example of the resulting user data can be seen in Figure 10 with a refined analysis in Figure 11.

Using the mean acceleration data from Table 4 we compared the effect of the hard and soft pads with the base tool as seen in Table 5. We saw that there were no appreciable vibrations transmitted to the workers in their wrists and the relative effect of the padding was approaching noise. For this reason, we did not compare the effect the hard (TBP) and soft (25% Liquid) pad had on wrist vibrations. From Table 5 we can see that for every worker there was a 7% to 60% reduction in the vibrations transmitted to the palm of the worker. The average reduction for the hard tool was 40% and 41% for the soft pad. However, for an individual worker the soft pad could make a 16% improvement over the hard pad or up to 23% improvement for the hard pad over the soft pad. This demonstrates that the workers grip makes a significant difference on whether the hard or soft pad is better. If we allow the worker to choose their most effective pad, the mean vibration reduction for a worker is 45% into their palm.

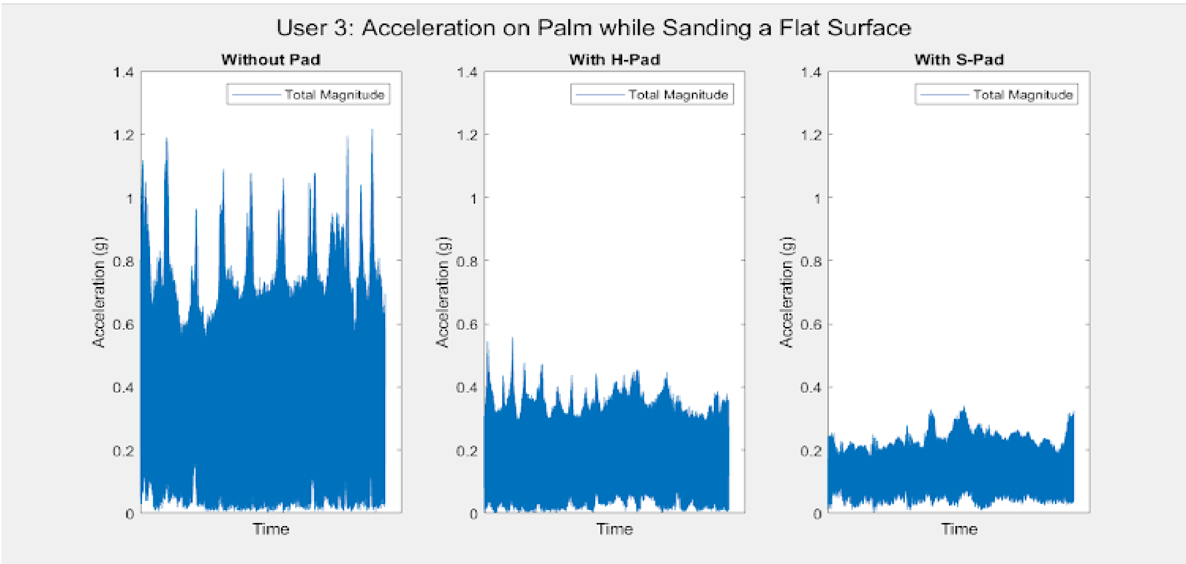

Figure 10: Am example of the accelerations experienced by a user's palm during sanding a flat surface with the base tool, a hard pad, and a soft pad. Both pads visible reduced vibration transmission

Table 4: The average accelerations experienced by a worker when sanding a flat or curved surface

		Average Acceleration (g)								
		Finger			Palm			Wrist		
User	Panel	Base	Hard	Soft	Base	Hard	Soft	Base	Hard	Soft
1	Flat	0.68740	0.33022	0.57624	0.46780	0.21084	0.18610	0.02019	0.02101	0.02453
1	Curved	0.35554	0.34447	0.24237	0.17408	0.13060	0.14048	0.03259	0.02864	0.02784
2	Flat	0.97761	0.13356	0.09330	0.26524	0.17061	0.14583	0.01777	0.01615	0.02151
3	Flat	0.23006	0.23182	0.29228	0.42776	0.21181	0.14466	0.01438	0.00804	0.01071
4	Curved	0.28599	0.18878	0.12696	0.31596	0.20671	0.18221	0.04135	0.03737	0.04042
5	Flat	0.48910	0.32491	0.31229	0.43460	0.21450	0.20240	0.04718	0.03852	0.03046
5	Curved	0.15825	0.20847	0.18035	0.16683	0.11616	0.15562	0.03360	0.03502	0.03844

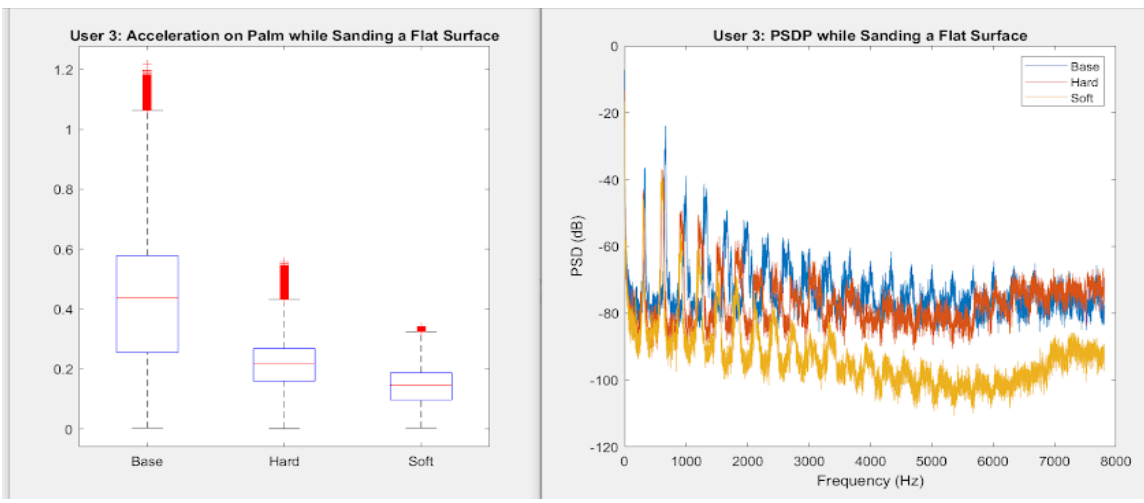

Figure 11: A Box plot and power spectral density of the vibration a user experienced in their palm while sanding on a flat surface. We can see a dramatic reduction in the amount of acceleration into the users palm when using the soft pad. The effect is more dramatic at frequencies over 1kHz where the soft pad has over 20dB less energy transmitted.

Table 5: The reduction in average vibration relative to the base tool for workers on various surfaces, locations, and padding types.

		Finger		Palm	
User	Panel	Hard	Soft	Hard	Soft
1	Flat	-52%	-16%	-55%	-60%
1	Curved	-3%	-32%	-25%	-19%
2	Flat	-86%	-90%	-36%	-45%
3	Flat	1%	27%	-50%	-66%
4	Curved	-34%	-56%	-35%	-42%
5	Flat	-34%	-36%	-51%	-53%
5	Curved	32%	14%	-30%	-7%

The worker-to-worker variability is more extreme in the case of vibration protection into the finger. For one worker, using the tool reduced vibrations by 90%, while for another it increased vibrations by 27%. For the finger the hard pad has an average reduction in mean vibration of 23.6% while the soft pad had a reduction of 22.1%. However, if a worker chose the most appropriate grip, the mean vibration reduction into fingers would be 32.5%. We believe this wide variation is a result of how much the worker was gripping the pad. Some workers used the soft structure of the grip as a signal to increase their pressure and therefor the amount of vibration transmitted.

Across all but two trials, we noticed that the softer pad was able to reduce the power spectral density by often 20dB for frequencies above 1kHz when compared with the base tool and hard tool. Combined with the mean acceleration data from above we note that the softer tool is more protective against high frequencies.

Conclusion

In this study we developed a novel piece of personal protective equipment that must be fabricated by material jetting. We determined that Loctite shoe glue was the best coating material that would protect the closed liquid filled material from environmental hazards. We conducted a series of shop trials and iteratively improved the design of the grip to have a mushroom feature that workers found exciting and could provide substantial fabrication protection. Vibration data showed that the sander grips would provide on average 32% vibration reduction into the finger and 45% reduction into the palm. This device shows how novel materials produced through material jetting may enable direct part production for commercial applications requiring the enhanced mechanical properties that multi-material printing enables.

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Appendix A: User Feedback Questionnaire

Participant Number
Sander
Did you feel more or less Vibration than the base tool
What percentage change (+ increase - decrease)
How would you describe the grip?
How Good was your grip on the new design (1 poor 10 great)
How durable did the new design feel (1 not durable, 10 super durable)
How secure does the design feel on the tool (1 not secure 10 Very secure)
On a scale from 1-10 1 being much worse and 10 being much better how would you rate the gripper relative to the base tool
What would you change about the design of the grip?
Any other comments