Effectiveness of Carbonic Cleaning for Adhesive Bonding Applications

Ahsan Anwar
Principal Process Engineer
Reliabotics LLC.

Paul Botelho
R&D Intern
Reliabotics LLC.

Abstract

Cleaning and surface pretreatment are directly related in many industries today. Traditional pretreatment methods such as alcohol wiping, or air nozzles are used to clean off contaminants and prepare surfaces for adhesion. However, these cleaning techniques are not always effective, especially in bonding applications. They can leave contaminants on the surface which affects the bond strength between two materials. Carbonic Cleaning is a surface pretreatment method that removes contaminants from any material without contact and is ideal in preparing surfaces for adhesive bonding efficiently and consistently. In this study, dry chalk and cutting fluid contaminants were applied to various materials before they were cleaned with an air nozzle, alcohol wipes, or Carbonic Cleaning. After the samples were cleaned, they were joined together with epoxy and pulled apart after curing for twenty-four hours with the force required to break apart the samples recorded. Carbonic Cleaning consistently required the most force to break apart samples regardless of the contaminant or material used. Pairing its cleaning efficiency with its ability to increase breaking force after adhesion, Carbonic Cleaning is an ideal choice as an alternative cleaning method.

Introduction

Carbonic Cleaning utilizes solid CO_2 particles propelled by a temperature-controlled air stream. CO_2 is inert, non-toxic, and non-flammable making it a safe and versatile organic solvent. It is also non-aqueous and sublimes on any material it is cleaning, leaving behind only a clean surface. Carbonic Cleaning uses liquid CO_2 which undergoes a sudden expansion and due to Joule Thomson's theory, it lowers the temperature drastically causing CO_2 to go from liquid to the solid state. These solid CO_2 particles are propelled by a heated, compressed air stream. The air stream has two benefits in Carbonic Cleaning. It adds additional kinetic energy to the CO_2 particles which increases their velocity on impact with a material. It also raises the temperature of the CO_2 particles which changes their shape into sharp and pointed "bullet particles." The fine points of these bullet particles allow CO_2 to easily transfer kinetic energy to the surface of any material during collision. The thermal strains due to temperature of the CO_2 also plays a vital role in cleaning a surface since CO_2 stays solid for temperatures up to -78.5°C. The kinetic energy transferred, thermal strains, and solvent nature of solid CO_2 particles weaken and break the bonds between the surface and contaminants leaving behind only a clean surface.

Adhesives like epoxy are used to join two surfaces together using chemical bonding. They form strong bonds that take thousands of Newtons to break apart, but the strength of the epoxy is directly correlated to the surface area and cleanliness of the material. A larger surface area allows an epoxy to form more bonds between materials which is why sanding is a common pretreatment before adhesion since it increases the bonding surface area by changing the roughness without increasing the actual area of a material. The cleanliness of a surface is very important as well. Contaminants form weak bonds with the surface of the material which reduces the surface area that an epoxy can bond with. With a lower surface area available for bonding due to contaminants, the force required to break apart two materials after an epoxy is applied will decrease dramatically.

Therefore, two clean surfaces that are joined together with epoxy will take more force to break apart than two surfaces that are covered in contaminants.

Surface Preparation

This experiment was conducted in triplicates using 6061 Aluminum, Black ABS, and 304 Stainless Steel. All materials were constructed with the same dimensions, in inches, as shown in **Figure 1**. The contact area of each sample denoted by *Section B* in **Figure 1** was **sanded** using 240 grit aluminum oxide sand paper for all materials except for thirty-six of the ABS samples which had a contact area denoted by *Section C* that was also **sanded**. A calibrator was used to mark 0.5” from the bottom of each material. This allowed all samples to have a consistent 0.5” by 0.25” surface area (*Section B*) to apply epoxy to and bond to one another. For the thirty-six ABS samples that had *Section C* sanded, a calibrator was used to mark 1” from the bottom in addition to the 0.5” mark, so these samples had both *Section B* and *Section C* clearly marked.

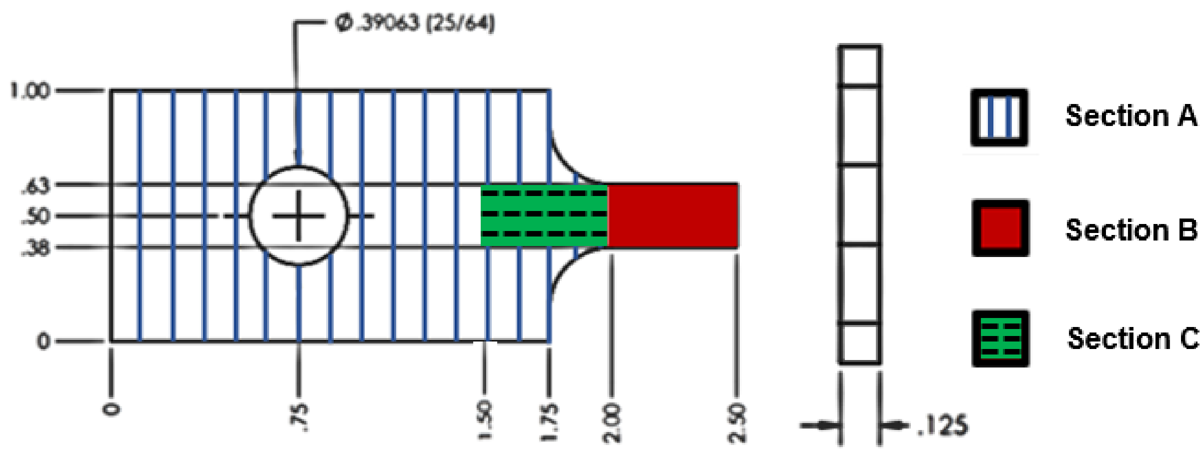

Figure 1. Sample dimensions, in inches, for all materials used. Different Sections are separated to be sanded and treated in all experiments.

The same procedure was used for conducting experiments on Aluminum to Aluminum, Stainless Steel to Stainless Steel, ABS to ABS, and Aluminum to Stainless Steel materials. Eighteen samples of each material were collected. Nine samples had dry chalk dust (DeWalt-level 4) applied as the contaminant to replicate extreme cases of dust particles and dry debris while the other nine had cutting fluid (TAP Magic) applied to replicate common oil contaminants. Before applying dry chalk, masking tape was used to tape above the 0.5” mark made to ensure that only *Section B* was exposed to the dry chalk. Once the dry chalk was evenly applied, the tape was removed, and the samples were ready to be cleaned. Cutting fluid did not need any masking tape before applying; only two drops of oil were evenly spread onto *Section B* and then the samples were ready for cleaning. All cleaning was done in a class 1,000 clean room to ensure that once the samples have been cleaned, no additional contaminants would interfere with the experiment. Three samples for each contaminant underwent one of the three pretreatment methods: air, alcohol wipes, or Carbonic Cleaning. Air and Carbonic Cleaning were both propelled at 16.99 m^3/h**.** Once the samples were cleaned, masking tape was used to tape above the 0.5” mark so only *Section B* was available for all the samples. 3M™ Scotch-Weld™ Epoxy Adhesive (DP420 NS Black) was applied to *Section B* of only one of the samples that was joined together while the other sample did not have any epoxy applied to *Section B*. Both samples overlapped their *Section B*’s and a steel body and jaw 1” max opening spring clamp was used to clamp the samples together for twenty-four hours so the epoxy could cure. Samples were not moved while curing to ensure the epoxy formed the strongest bonds between both surfaces. After each pretreatment, the epoxy was applied immediately after cleaning.

Since the epoxy forms a much stronger bond with metals than plastics, the procedure for Aluminum to ABS and Stainless Steel to ABS experiments was slightly altered. When a metal and a plastic are joined using epoxy overlapping at *Section B*, the epoxy bond is stronger than the forces holding *Section B* to the rest of the plastic. This results in *Section B* breaking off the plastic before the epoxy breaks. To combat this, *Section B* of metallic materials must be bonded to *Section C* of ABS. When preparing these samples, the metals were prepared the same as before, but ABS was treated differently. When applying dry chalk, masking tape was used to tape below the 0.5” mark and above the 1” mark. After the dry chalk was evenly applied to *Section C*, the samples were ready for cleaning. For cutting fluid, two drops of oil were evenly spread on *Section C* and then the samples were ready for cleaning. After the samples were cleaned, ABS samples were taped below the 0.5” mark and above the 1” mark. Epoxy was applied to the metal on *Section B* and then aligned with *Section C* of ABS. The samples were clamped together for twenty-four hours to allow them to cure. Since there is masking tape above and below the surface area that is bonded together, only the force required to break the bonds between the materials was recorded. This is because the bonds between epoxy and masking tape and between the sample and masking tape are much weaker than the bonds between the two materials joined together with epoxy. When the force required to break apart the samples was recorded, it reflected the surface area of 0.5” by 0.25” between the two samples and discounted any epoxy that spilled into the masking tape. Once the samples fully cured, they were placed in an ESM 1500 Mark-10 force-tester. The force-tester measured the force it took to break apart two materials, also known as the breaking force. The top and bottom of the apparatus have clevis pins which lock the samples in place while the force-tester pulls the top sample away in a shear stress test as shown in **Figure 2**.

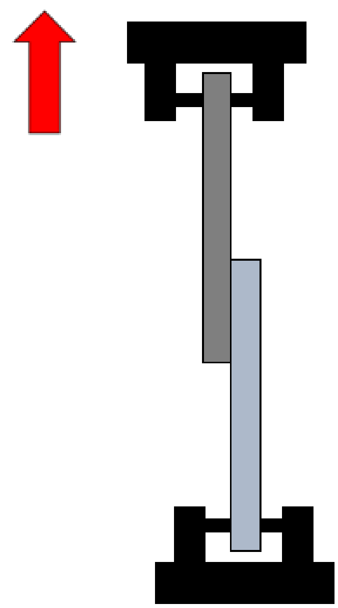

Figure 2. Shear Stress Test set-up for sample materials.

Contaminant Removal Efficiency

After pretreatments of air, alcohol wipes, and Carbonic Cleaning, dry chalk contaminants were visibly reduced for all pretreatments on all surfaces. However, only alcohol wipes and Carbonic Cleaning visibly removed most of the contaminants from the surface while air left behind most of the dry chalk. **Figures 3-5** show dry chalk contaminants on each material before and after all three pretreatments were applied.

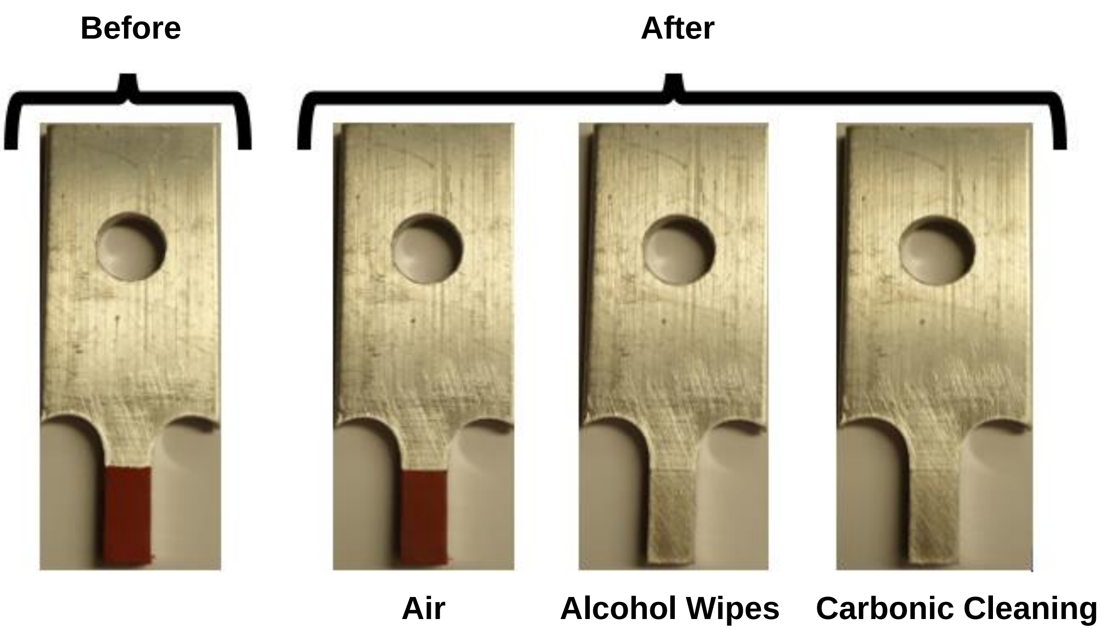

Figure 3. 6061 Aluminum samples with dry chalk applied before cleaning (far left), after air pretreatment (middle left), after alcohol wipe pretreatment (middle right), and after Carbonic Cleaning pretreatment (far right).

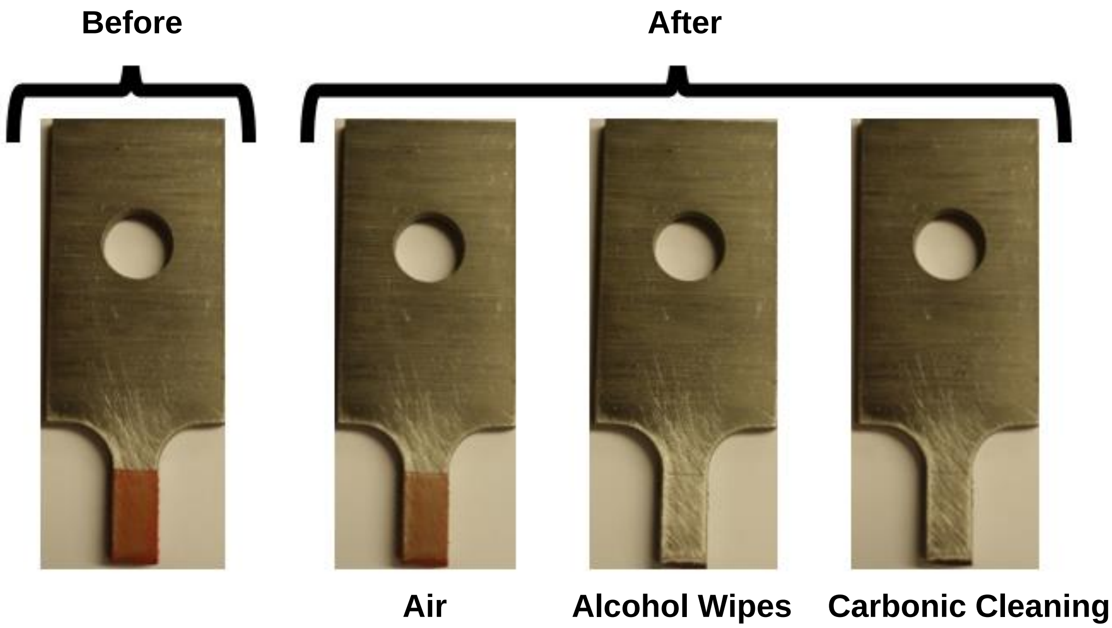

Figure 4. 304 Stainless Steel samples with dry chalk applied before cleaning (far left), after air pretreatment (middle left), after alcohol wipe pretreatment (middle right), and after Carbonic Cleaning pretreatment (far right).

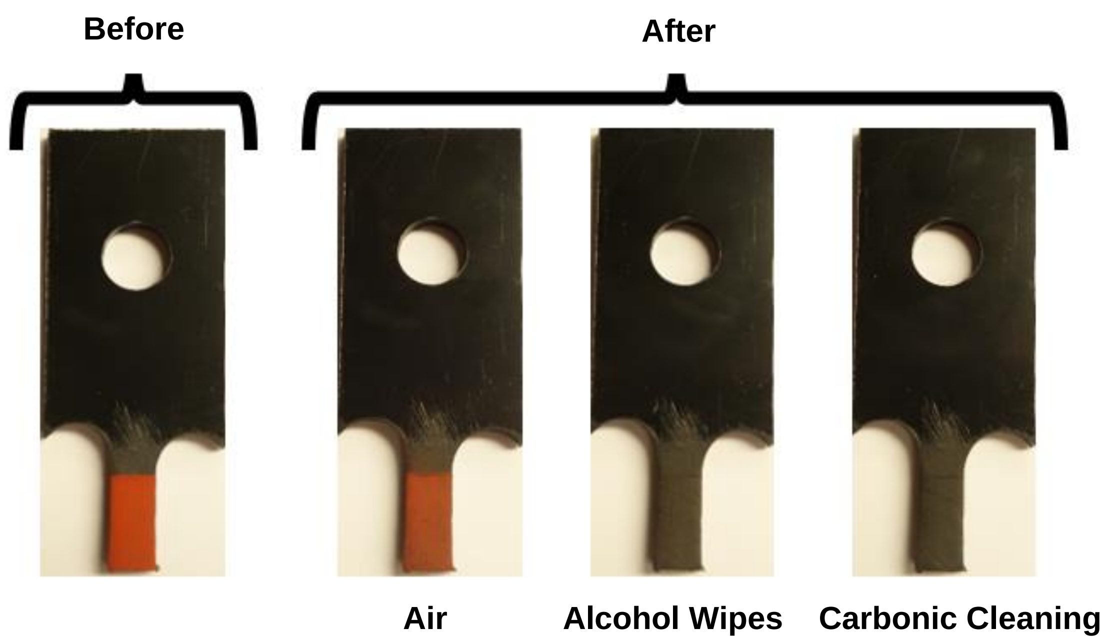

Figure 5. ABS samples with dry chalk applied before cleaning (far left), after air pretreatment (middle left), after alcohol wipe pretreatment (middle right), and after Carbonic Cleaning pretreatment (far right).

Breaking Force and Pretreatment Correlation

The breaking force (N) recorded for dry chalk and cutting fluid contaminants on all combinations of materials and pretreatments used were collected and the data can be seen in **Figures 6-11**. The standard deviation for each data set is displayed on each figure as well. All experiments had P-values under 0.05 signifying that all the data collected is statistically significant. The results indicate that when samples were cleaned using Carbonic Cleaning, it took more force to break apart the two samples than when materials were cleaned with air or alcohol wipes for all materials and contaminants. Alcohol wipes recorded the second most force to break apart the samples for all dry chalk and cutting fluid contaminants. Cutting fluid took less force to break apart than dry chalk for all materials and surface pretreatments except for air on ABS to ABS surfaces.

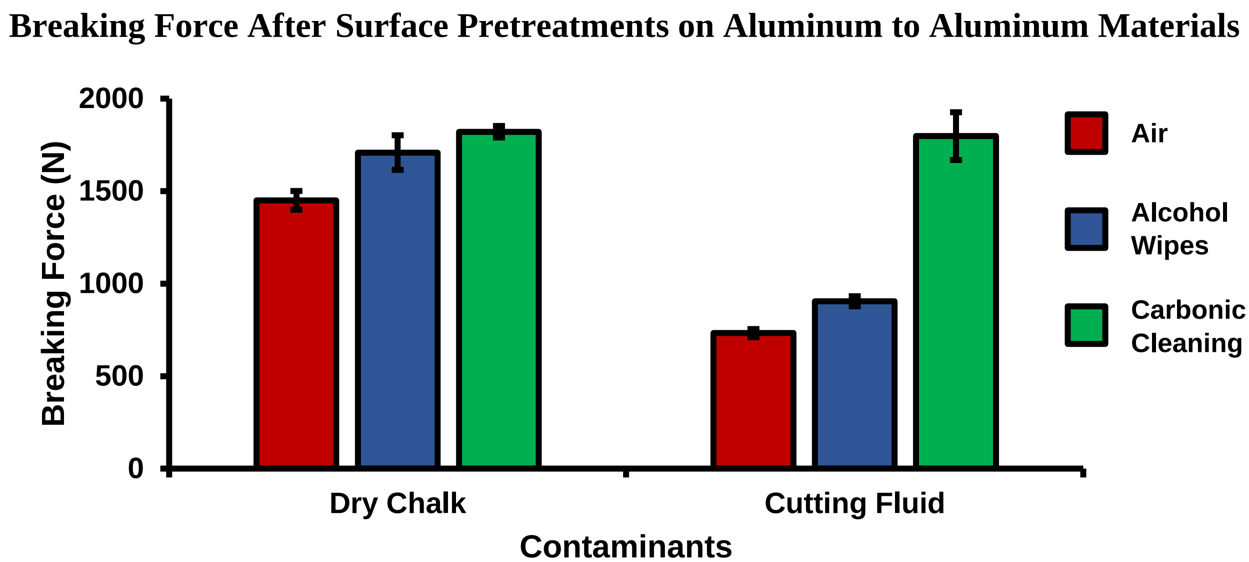

Figure 6. Breaking force (N) measured after force-tester analysis for surface pretreatments of air (red), alcohol wipes (blue), and Carbonic Cleaning (green) on Aluminum to Aluminum surfaces after sanding with dry chalk and cutting fluid contaminants.

Breaking Force After Surface Pretreatments on Stainless Steel to Stainless Steel Materials

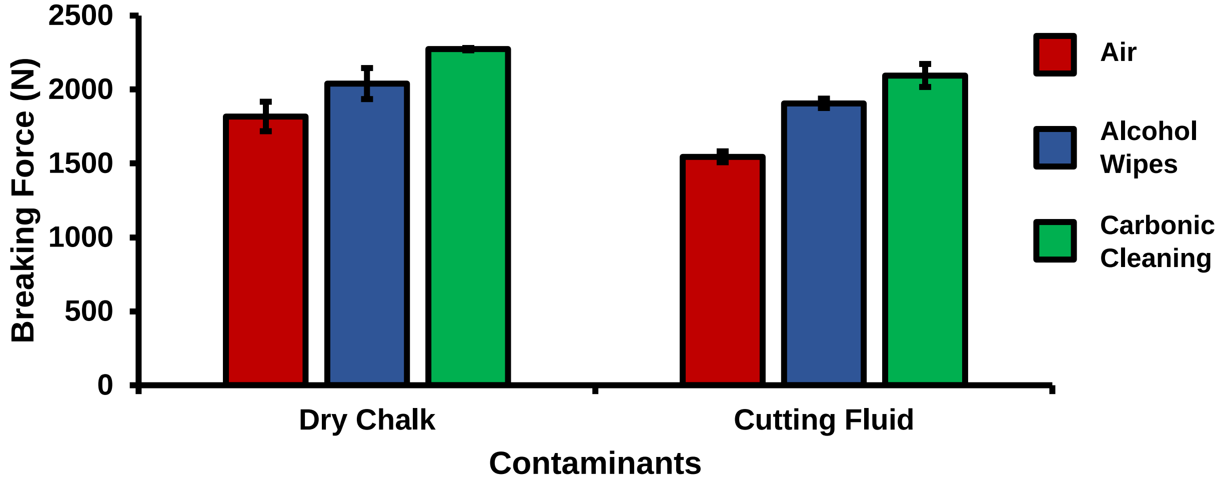

Figure 7. Breaking force (N) measured after force-tester analysis for surface pretreatments of air (red), alcohol wipes (blue), and Carbonic Cleaning (green) on Stainless Steel to Stainless Steel surfaces after sanding with dry chalk and cutting fluid contaminants.

Breaking Force After Surface Pretreatments on ABS to ABS Materials

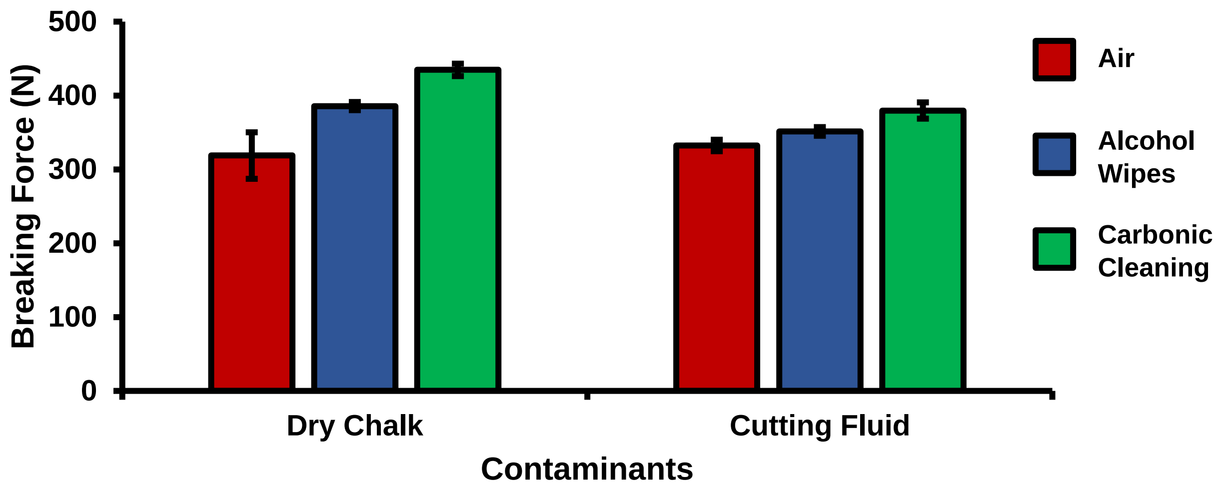

Figure 8. Breaking force (N) measured after force-tester analysis for surface pretreatments of air (red), alcohol wipes (blue), and Carbonic Cleaning (green) on ABS to ABS surfaces after sanding with dry chalk and cutting fluid contaminants.

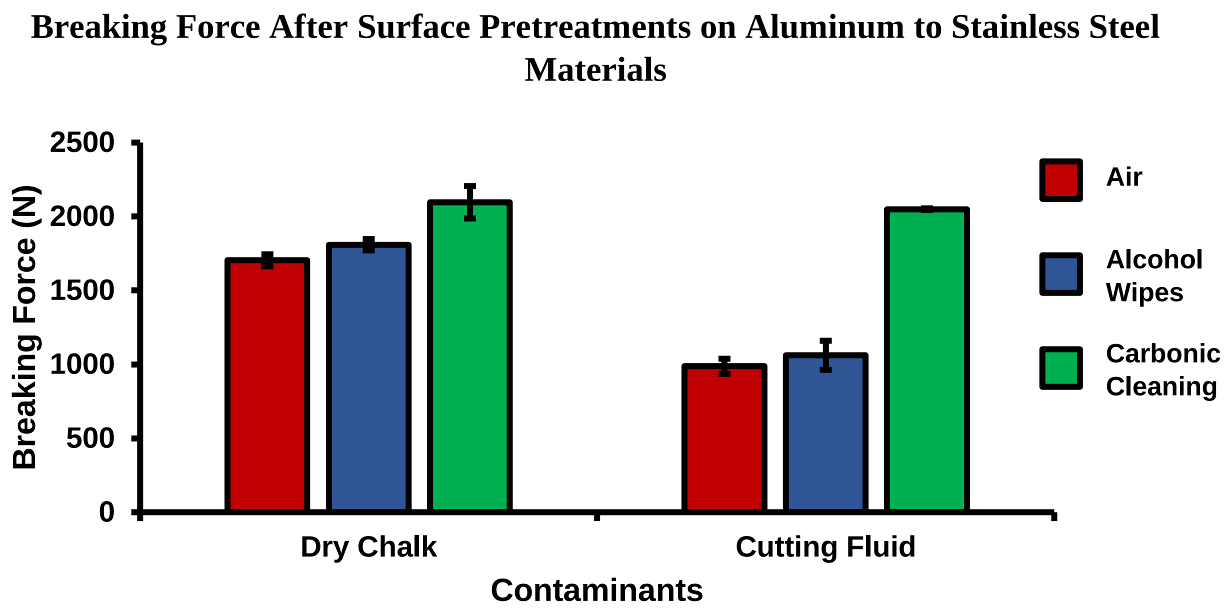

Figure 9. Breaking force (N) measured after force-tester analysis for surface pretreatments of air (red), alcohol wipes (blue), and Carbonic Cleaning (green) on Aluminum to Stainless Steel surfaces after sanding with dry chalk and cutting fluid contaminants.

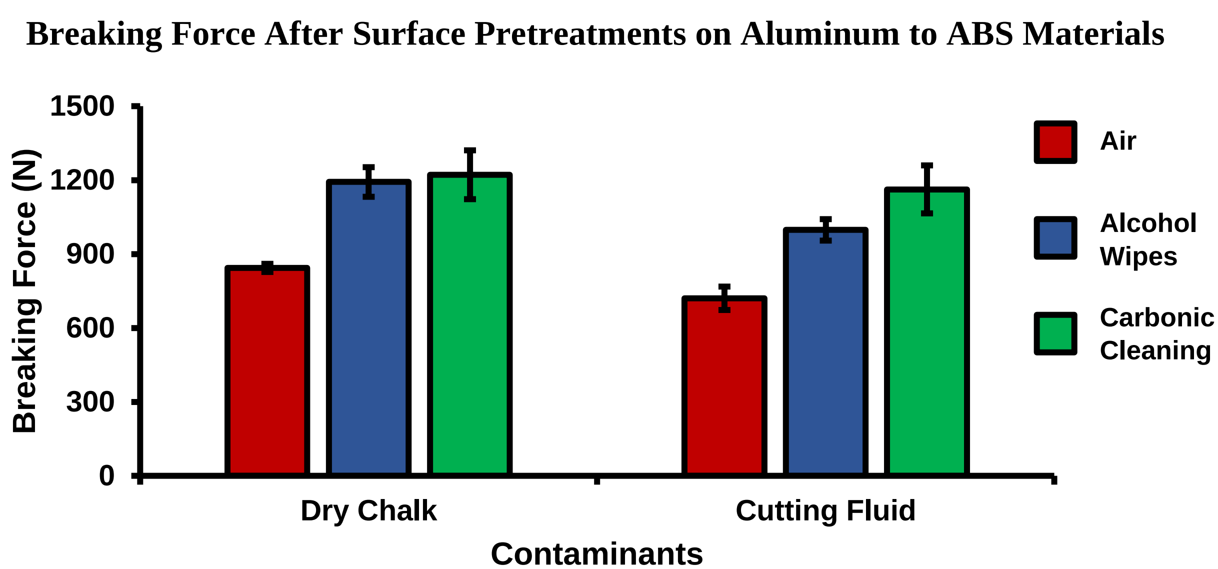

Figure 10. Breaking force (N) measured after force-tester analysis for surface pretreatments of air (red), alcohol wipes (blue), and Carbonic Cleaning (green) on Aluminum to ABS surfaces after sanding with dry chalk and cutting fluid contaminants.

Breaking Force After Surface Pretreatments on Stainless Steel to ABS Materials

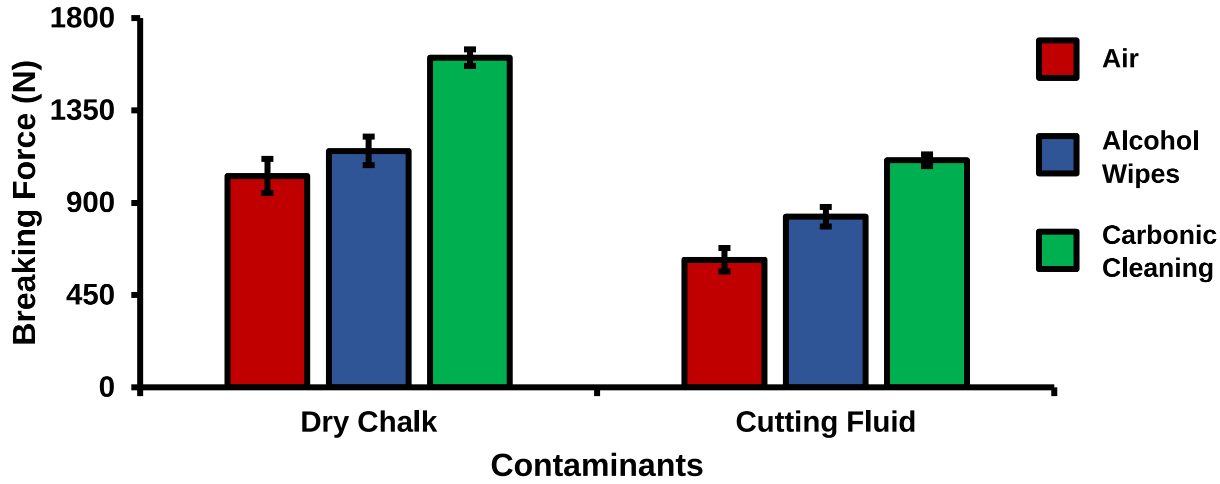

Figure 11. Breaking force (N) measured after force-tester analysis for surface pretreatments of air (red), alcohol wipes (blue), and Carbonic Cleaning (green) on Stainless Steel to ABS surfaces after sanding with dry chalk and cutting fluid contaminants.

Carbonic Cleaning consistently had the highest breaking force regardless of the materials or contaminants used. This indicates that after Carbonic Cleaning, common materials in industry such as 6061 Aluminum, Black ABS, and 304 Stainless Steel form stronger bonds when using an adhesive like epoxy compared to traditional cleaning methods such as air nozzles and alcohol wiping. For a strong adhesive bond to be formed between two surfaces, the surfaces must be clean. This allows the adhesive to make strong bonds between only the two surfaces with no other contaminant particles in-between them. However, when a surface has contaminants on it, the contaminants bond to the surface with forces weaker than an adhesive. If these contaminants are not properly cleaned off of the surface when the adhesive is added, the adhesive will bond to the contaminants and not the surface. Since the contaminants have weak bonds with the surface, these will break first compared to the strong bonds of an adhesive. The more contaminants on a sample, the less surface area for an adhesive to form strong bonds with in-between the surfaces and the weaker the overall strength of the adhesive. Air visibly had the most contaminants left after cleaning and this was reflected in the results. For all experiments, air required **32.0%** less force (N) to break apart two surfaces after cleaning dry chalk and **74.9%** less force to break apart two surfaces after cleaning cutting fluid when compared to Carbonic Cleaning. There is significantly less breaking force required for air than for alcohol wipes for both contaminants. Alcohol wipes required **14.1%** less force to break apart two surfaces after cleaning dry chalk and **41.9%** less force to break apart two surfaces after cleaning cutting fluid when compared to Carbonic Cleaning. Since contaminants remained after an air pretreatment, this resulted in drastically lower breaking forces compared to Carbonic Cleaning which removed most of the contaminants from the surface.

The contaminant chosen directly affected the breaking force required for all materials and pretreatments. Removing cutting fluid resulted in a much lower breaking force than dry chalk for all materials when they were pretreated with air or alcohol wipes but only a small decrease in breaking force when they were pretreated with Carbonic Cleaning. The breaking force (N) decreased **45.1%** for air and **36.9%** for alcohol wipes when the contaminant changed from dry chalk to cutting fluid for all experiments. However, the breaking force for Carbonic Cleaning only decreased by **10.1%** when the contaminant changed from dry chalk to cutting fluid for all experiments. This is an extreme difference between Carbonic Cleaning and traditional pretreatment methods. Regardless if the contaminant is dry or wet, Carbonic Cleaning will clean the surface and increase the breaking force consistently while air and alcohol wipes decrease their cleaning and reduce their pretreatment effectiveness by 35%-45% when switching from a dry to a wet contaminant.

Conclusion

After cleaning dry chalk and cutting fluid contaminants from 6061 Aluminum, Black ABS, and 304 Stainless Steel, Carbonic Cleaning was shown to be very effective at cleaning contaminants off of a surface and increasing the breaking force after adhesion. All surfaces that experienced Carbonic Cleaning required the highest breaking force to pull apart the two samples for both dry chalk and cutting fluid contaminants when compared to air and alcohol wipes. Carbonic Cleaning was effective at cleaning both dry and wet contaminants off of surfaces whereas air and alcohol had drastic differences in breaking force between the two contaminants. Carbonic Cleaning has demonstrated its efficiency and consistency in cleaning a variety of common materials and contaminants in industry and is a proposed alternative method for surface preparation.

Acknowledgements

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Appendix

The following table shows the average breaking force recorded for each material and contaminant tested. The data was recorded in triplicates using the ESM 1500 Mark-10 force tester.

Table 1. Breaking force (N) measured for surface pretreatments of air, alcohol wipes, and Carbonic Cleaning on all surfaces after sanding with dry chalk and cutting fluid contaminants.

	Aluminum-Aluminum		Stainless Steel-Stainless Steel	
Pretreatment	**Dry Chalk Breaking Force (N)**	**Cutting fluid Breaking Force (N)**	**Dry Chalk Breaking Force (N)**	**Cutting fluid Breaking Force (N)**
Air	1450	732.3333	1817.667	1545
Alcohol Wipes	1708.333	904.3333	2040.333	1906.667
Carbonic Cleaning	1821	1797	2273	2095
	ABS-ABS		**Aluminum-Stainless Steel**	
Pretreatment	**Dry Chalk Breaking Force (N)**	**Cutting fluid Breaking Force (N)**	**Dry Chalk Breaking Force (N)**	**Cutting fluid Breaking Force (N)**
Air	318.6667	332.3333	1703.667	987.3333
Alcohol Wipes	385.6667	351.3333	1809	1061.333
Carbonic Cleaning	434.6667	379.6667	2096.333	2049.333
	Aluminum-ABS		**Stainless Steel-ABS**	
Pretreatment	**Dry Chalk Breaking Force (N)**	**Cutting fluid Breaking Force (N)**	**Dry Chalk Breaking Force (N)**	**Cutting fluid Breaking Force (N)**
Air	843.6667	720.3333	1030.667	621.3333
Alcohol Wipes	1192.333	998	1152.333	832
Carbonic Cleaning	1221.667	1162.333	1607	1106.333