Team Second Report

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Context

This image demonstrates the cavitation and spatter patterns that form in a droplet of molten aluminum after contacting the ground, whereupon it instantly cools and retains this shape. This effect was accomplished using a tungsten inert gas (TIG) welder and a ¼" aluminum flux rod that was heated to above its melting point and allowed to drip onto the ground. The way that these droplets seemed to freeze in place after they cooled off was incredibly interesting, and after gathering many droplets, I photographed the droplet with the most interesting shape.

Flow Analysis

This droplet was created through heating aluminum 4043 flux to above its melting point. This molten aluminum then dripped off the flux rod and onto the ground from different heights. Upon impact these droplets quickly reharden in shapes close to their initial impact patterns. This impact forces the liquid aluminum into splatter patterns around the outer edge of the droplet, with a cavity in the center of the droplet. Because the droplets freeze so quickly, both the splatter spines and the cavities are preserved for observation. The reason that these droplets cool so quickly is because of aluminum's high thermal conductivity. In pure aluminum it can get up to around $250\ \frac{W}{m*K}$ [1], while aluminum 4043, the aluminum used to form these droplets, has a thermal conductivity of roughly $163\ \frac{W}{m*K}$ [2]. To compare, water generally has a thermal conductivity around $0.606\ \frac{W}{m*K}$, and air is around $0.026\ \frac{W}{m*K}$. Due to the more permanent nature of this flow, I could photograph the aluminum droplets in a different location from where I created them. All the droplets I managed to create can be seen in Figure 1 below.

Figure 1: All the different drops collected during TIG welding

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[1] (n.d.). Retrieved from https://www.engineeringtoolbox.com/thermal-conductivity-d_429.html

[2] AZoM. (2013, June 11). Aluminum 4043 Alloy (UNS A94043). Retrieved from https://www.azom.com/article.aspx?ArticleID=8685

Upon further deliberation, I decided to take my photographs on top of an old wooden chest because of the interesting texture and warm colors. The image was lit from the front by my camera's built in GN 39/12 flash. I could keep my ISO low and shutter speed reasonable. Because this image is such a close-up I needed a small aperture, which did limit my field of view. Because of the good shutter speed, I didn't need to worry about setting up a tripod. To ensure consistent images the cameral was attached to a small tripod. The camera itself was situated only about 1-2 inches away from the droplets. I tried several different arrangements of the droplets, but eventually decided that only focusing on the most interesting drop produced the best results. The setups for producing and photographing these droplets are outlined in Figures 2 and 3.

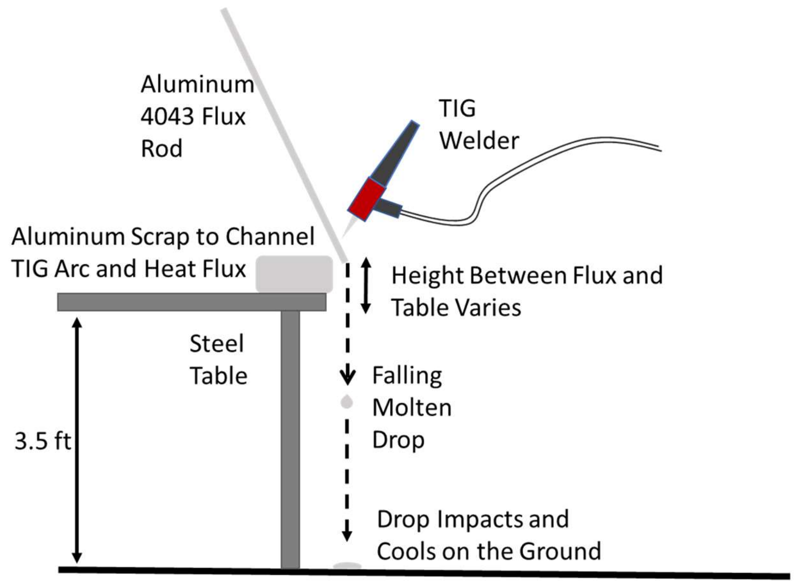

Figure 2: Experimental Droplet Formation Setup

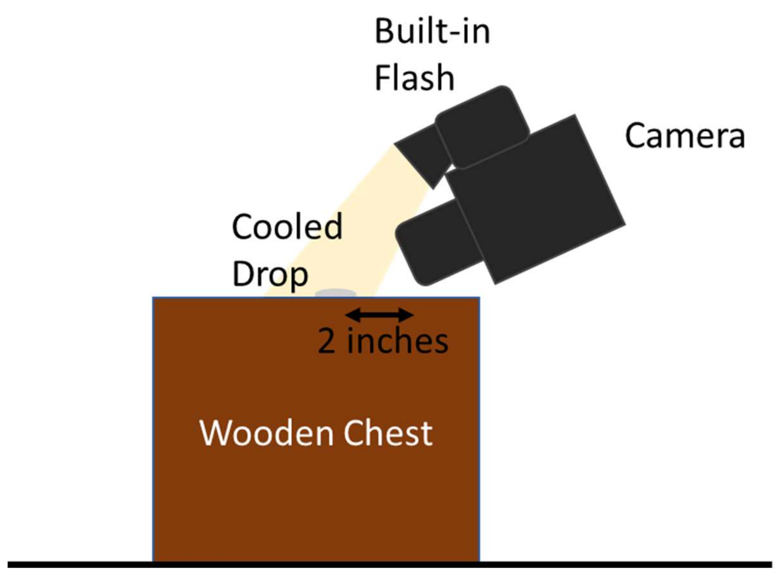

Figure 3: Droplet Photography Setup

The flow pictured is generated from the impact of the liquid metal and the ground. This produces cavitation in the droplet and a splatter originating from the outer edges of the drop. As this splash spreads out, the molten metal's surface tension pulls the material back together into thin filaments, called spines[3], and small droplets, called crowns, at the end of these spines. These formations, observed in my image, are called by Plateau-Rayleigh instabilities[4].

Looking at Figure 1 it becomes obvious that these pieces were formed from of various sized droplets dropped from different heights and at different velocities. A better grasp of what these variables were for my image can be gained through research already done on blood splatter patterns. Through forensic analysis of the splatter pattern in my image, I can assume that this droplet hit the ground at an angle between 80° and 70°[5]. This forensic analysis can also determine the height the drop fell from, but because of the different physical properties of blood and molten aluminum these methods can't be used in this case. Experimentally, this drop fell from roughly 4 feet onto the ground.

To better grasp the physics behind the cavitation and splash found in the drop, the best method is to calculate the Weber Number. This dimensionless value denotes the ratio between the inertial force and the surface tension force between the liquid metal and the ground, and indicates whether the kinetic or surface tension energy is dominant. This value is expressed through the equation

$$W_e = \frac{\rho v^2 l}{\delta}.$$ [6]

In this equation ρ is the liquid density, *v* is the velocity of the drop at impact, *l* is the characteristic length, and δ is the surface tension. Aluminum 4043 differs from pure aluminum in that it is composed of 95% aluminum, 5% silicon, and some trace amounts of other elements. The density of aluminum 4043 is $2690\ \frac{kg}{m^3}$[7]. The droplet velocity is found though the equation $v = \sqrt{2gh}$, where g is $9.81\ \frac{m}{s}$, and h is the distance the droplet fell, roughly 4 feet, or $1.2192\ m$. Inputting these values, $v = \sqrt{2gh} = \sqrt{2 * (9.81\ \frac{m}{s})(1.2192\ m)} = 4.891\ \frac{m}{s}$. The characteristic length is given as the diameter of the drop. The diameter of the flux rod is ¼ inch, or $6.35\ mm$, which is what will be used for characteristic length. Finally, the surface tension at around this aluminum's melting point, 574 °C[8], is found to be around $1.007\ \frac{N}{m}$.[9] Putting all these values together, we get

[3] Almumtin, A. (2013, February 09). Blood spatter analysis. Retrieved from https://www.slideshare.net/amomtan/blood-spatter-analysis-16443482
[4] F. (2013, December 02). Fuckyeahfluiddynamics. Retrieved February 28, 2018, from http://fyfluiddynamics.com/post/68785232957/when-a-water-drop-strikes-a-pool-it-can-form-a
[5] Bloodstain Pattern Analysis. (n.d.). Retrieved from http://www.forensicsciencesimplified.org/blood/principles.html
[6] (n.d.). https://www.engineeringtoolbox.com/weber-number-d_583.html
[7] AZoM. (2013, June 11). Aluminum 4043 Alloy (UNS A94043). Retrieved from https://www.azom.com/article.aspx?ArticleID=8685
[8] AlcoTec Wire Corporation. (n.d.). ALLOY 4043 WELD DATA SHEET. Retrieved from http://www.alcotec.com/us/en/support/upload/a4043tds.pdf
[9] Anson, J. P., Drew, R. A., & Gruzleski, J. E. (1999). The surface tension of molten aluminum and Al-Si-Mg alloy under vacuum and hydrogen atmospheres. *Metallurgical and Materials Transactions B,30*(6), 1027-1032. doi:10.1007/s11663-999-0108-4

$$W_e = \frac{\left(2690\,\frac{kg}{m^3}\right)\left(4.891\,\frac{m}{s}\right)^2(6.25\,mm)}{1.007\,\frac{N}{m}} = 400.$$

Depending on the Weber number, a droplet can exhibit one of three primary phenomena: "The drop 'bounces' then 'floats' on the surface", "the drop 'coalesces'", or "the drop 'splashes'…, creating a 'crown' around a crater".[10] The threshold for this crowning splash is given as any Weber number over roughly 84. Comparing this to this calculated Weber number, the photographed drop clearly exhibits this crowning behavior both experimentally and theoretically.

Another relevant value that can be examined is the Reynolds number of the flow. This value is related to the turbulence of the flow, and is calculated through the equation $Re = \frac{v*l}{\upsilon} = \frac{\rho*v*l}{\mu}$. Both *v* and *l* have already been calculated. and assuming a dynamic viscosity, $\mu = 2.96\ mPa * s$[11], *Re* is calculated as

$$Re = \frac{\rho*v*l}{\mu} = \frac{2690\,\frac{kg}{m^3}*4.891\,\frac{m}{sec}*6.35mm}{2.96\,mPa*s} = 22{,}000.$$

This indicates a turbulent flow. This is corroborated by the droplet patterns in this experiment.

One detail about my droplet that I am still struggling to explain are the two spines stretching out on either side of the droplet. Theoretically, there should be more spines on the droplet more regularly spaced, or no real spine formation. This is the trend that is seen in the rest of my drops in Figure 1. This interesting symmetric pattern is why I chose to photograph this drop, but I don't yet know quite what caused this shape to form in only this drop.

Setup

To create this image, I didn't use any visualization techniques besides my camera's built in flash in normal air. To create the drops the only materials used were a ¼ inch aluminum flux rod, a TIG welder, and a scrap aluminum piece to generate the TIG's arc and heat. The image was taken in a standard room temperature room, at a standard Colorado level of humidity. The image was taken in a room not directly exposed to sunlight, but that was being illuminated by ambient light at the time of the photo.

Photographic Technique

To take this image, I used a fixed FOV 40 mm lens about 1-2 inches away from the droplets. The photos were taken at an aperture of f/3.3, a shutter speed of 1/100 sec, and an ISO of 200. I used a Nikon D7000 to capture this image. This image is totally time resolved because the flow is frozen. If the camera doesn't move as it is taking the photographs, then everything will stay resolved. I believe that the 1/100 shutter speed ensures that this camera movement is minimized. Due to the close-up nature of this image, it is also well resolved spatially.

The initial image pixel size was both 4928x3264, and the final cropped image was 4132x2755.

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[10] When a drop of water falls into water, where do the splashes come from? (n.d.). https://physics.stackexchange.com/questions/156339/when-a-drop-of-water-falls-into-water-where-do-the-splashes-come-from

[11] (n.d.). Retrieved from http://www.kayelaby.npl.co.uk/general_physics/2_2/2_2_3.html

For post-processing, I exported the image to Adobe Lightroom 6. I cropped the image to better frame the droplet and remove distracting elements, and adjusted the image's histogram to better highlight the contrasts in the metal, as well as to draw out the warmer colors in the wooden background and the colder colors in the metal drop. The histogram and color balance settings can be seen in Figure 4.

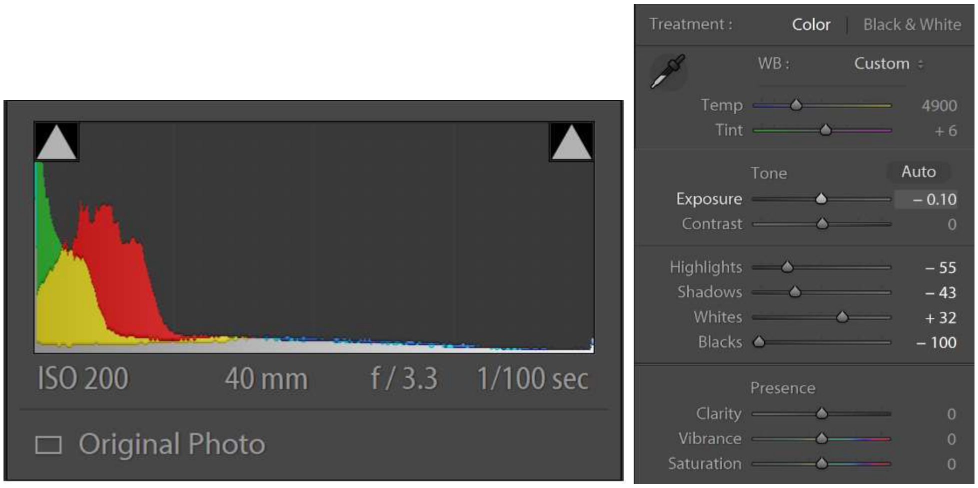

Figure 4: Histogram and Color Settings

Finally, a comparison between the initial and final images can be seen in Figure 5.

Figure 5: Original Raw vs. Final Edited Image

Conclusion

This image demonstrates the impact pattern of a droplet, highlighting the spines and crowning that form due to high velocity low viscosity impacts onto a solid surface. The flow is turbulent, and the crowning effect is the result of a Plateau-Rayleigh instability. I really like the colors in this image, with the warm colored wood nicely contrasting the cold metal drop, and the light contrasts highlighting the details in the drop. I also like how only a thin strip is totally in focus in the image. I think this creates a more visually interesting image, and the unfocused drop in the background looks good. I think I could have increased the depth of field to get more of the droplet in focus. The fact that the two interesting spines are a little out of focus should be fixed. I think this image shows the fluid physics very well. The frozen nature of the drops really helps with understanding the mechanics of what happens to a droplet of liquid after it impacts the ground. If I was to develop this further I would like to attempt to recreate this droplet to really figure out the conditions required for its formation. I would also like to shoot a slow-motion video of this flow to clearly see when exactly the drop freezes.