# Maritime Applications of Wire Arc Additive Manufacturing

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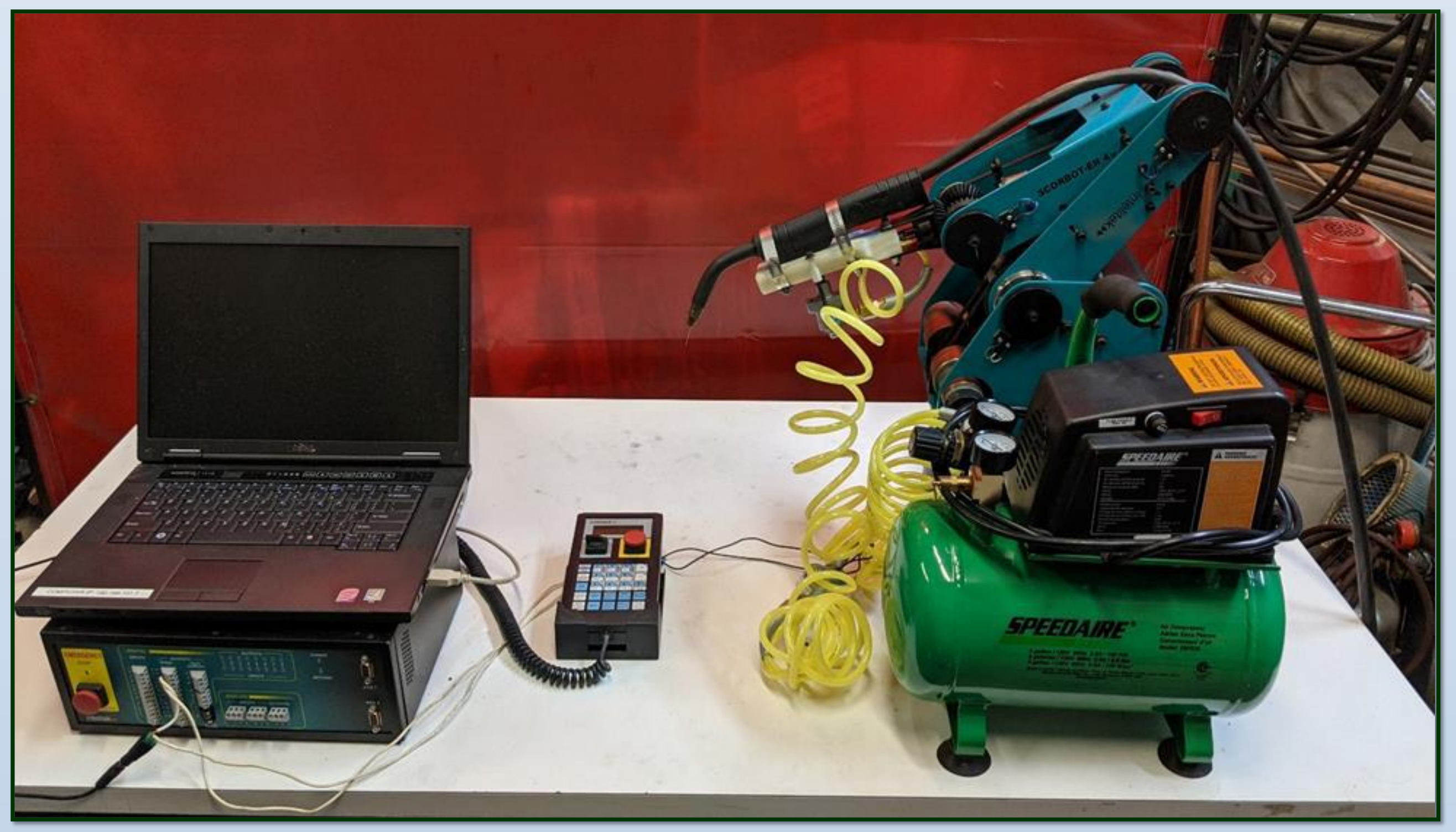
## ABSTRACT

Additive Manufacturing (AM) is a process where components are created by continually adding material one layer at a time. Several benefits of "additive" manufacturing versus traditional "subtractive" machining processes include a reduction of material waste, ease of producing complex parts by reducing the amount of production steps, and the reduction of manufacturing lead-time. The Wire Arc Additive Manufacturing (WAAM) process, which uses Metal Inert Gas (MIG) welding, is demonstrated to analyze its potential application for maritime utilization. This report shows how the flexural yield strength of welded plates changes with different amounts of metal additive reinforcement. A standard three-point bending test was conducted to determine the difference in flexural yield strength and to observe material behavior. Finally, it is discussed that AM processes, such as WAAM, are still being developed but their potential in the maritime industry, especially for the benefit of bringing supplies to our warfighters overseas, is clear.

## INTRODUCTION

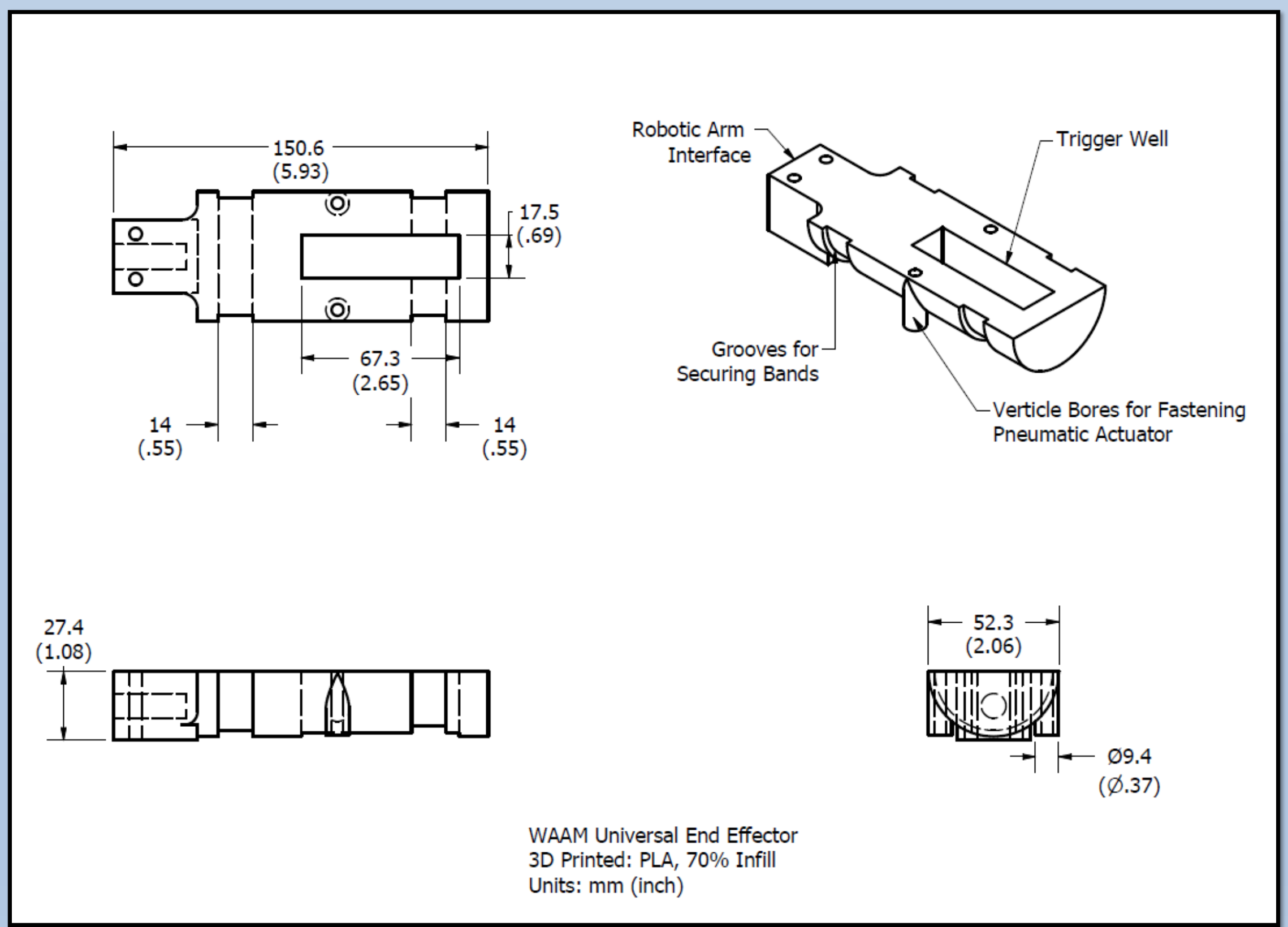
Wire Arc Additive Manufacturing (WAAM) is a Directed Energy Deposition (DED) processed defined in ISO/ASTM52900 as the "process in which focused energy is used to fuse materials by melting as they are being deposited". WAAM is the term used for all arc welding wire-based additive manufacturing processes. WAAM and its use in the maritime industry can have practical applications onboard vessels such as printing replacement parts for mission critical engineering systems, as well as in shipyards for designing, prototyping, as well as fabricating actual end use parts such as propellers.

This report analyzes the use of WAAM to reinforce metal plates using an industrial robot, MIG welder, and student-designed and 3D printed parts. A homemade robotic welding 3D printer was designed and used to place additive layers on 1018 steel plates. Six metal plates had one weld bead and another six metal plates had two weld beads placed on them (one on top of the other) by the robotic welding 3D printer. In addition, six metal plates with no weld beads were used as a control for analysis. The 3-point bending flexure test was performed with an Instron machine to analyze the flexural properties of each of the metal plates. Finally, hardness testing was conducted and stress-strain curves were created to determine the flexural yield strength of each of the metal plates.



**Design of End Effector and WAAM System**

A universal end effector was designed to fit most standard MIG welding guns and attach to an existing industrial robot arm. Over two design iterations, a final design was chosen that uses pipe clamps as securing bands and a pneumatic actuator which is controlled by the robot's control system to press the MIG gun trigger. Fused deposition modeling (FDM) style 3D printing was chosen as the method of manufacturing the end effector because of its ease of use and availability. A pneumatic actuator was chosen to allow the MIG gun trigger to be actuated without disassembling and re-wiring.

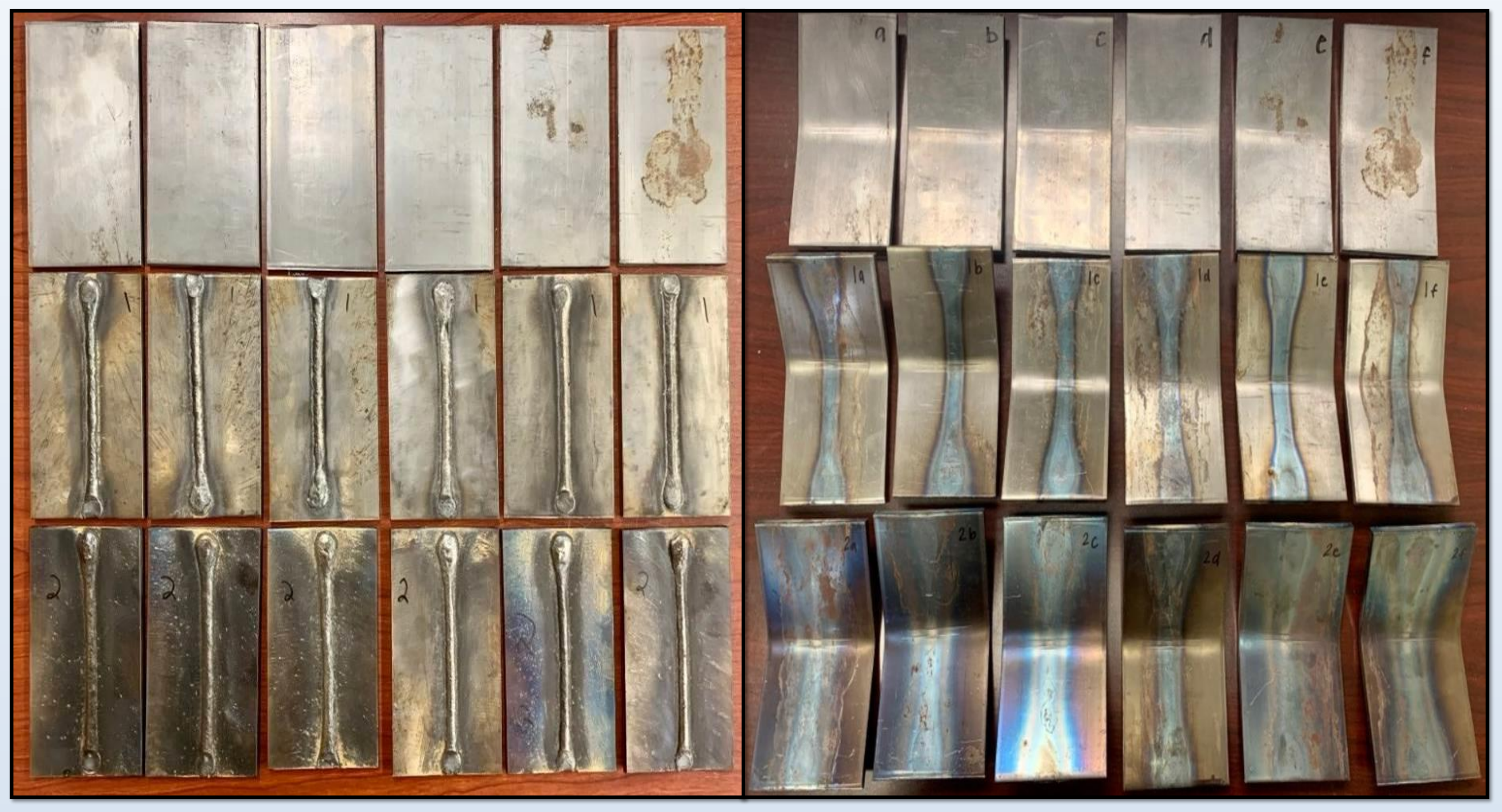


WAAM Universal End Effector
3D Printed: PLA, 70% Infill
Units: mm (inch)

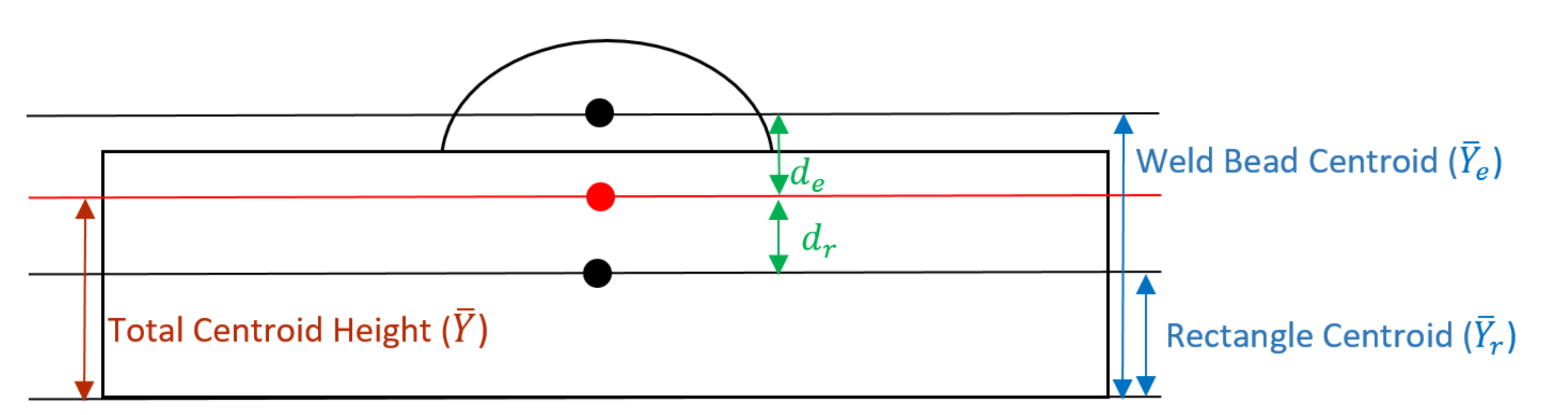
The WAAM system consists of an industrial robotic arm, programmable control system, 3D printed end effector, welder actuation system, and MIG welder. This system is equipped with ScoreBase operating software, a five axis robotic arm, controller unit, a teach pendent, and communication wiring. A computer and monitor connect to the PLC device via USB wiring and the PLC device connects to the robot by serial communication. The end effector connects the robotic arm to the welding gun and allows the robot to move with five degrees of freedom. The welder is a Metal Inert Gas (MIG) welder manufactured by Lincoln Electric.

## EXPERIMENTAL DESIGN AND THEORY

In the experiment, the WAAM 3D printer was used to put additive weld beads on metal plates. The different types of metal plates are one weld bead, two weld beads (one on top of the other), and a control plate with no weld beads. There are six metal plates for each of the three types of metal plates. The flexural strength and ductile behavior of the metal plates with various weld beads can be determined from the analysis of data from a standard 3-point bending test. The procedure used for the test was followed in accordance with ASTM D790 standard for performance of flexural tests.



The cross section of the weld plates were modelled as rectangles with the weld beads being modelled as half-ellipses on the surface. Using the parallel axis theorem, the centroids of each shape was calculated and the shapes used to get the total centroid height of the cross section for use in bending stress equation for development of stress-strain curves.



*Normal Bending Stress ($\sigma_x$):*

$$\sigma_x = \frac{M_{Max}\bar{Y}}{I_x}$$

Where,
$M_{Max}$ = Maximum Bending Moment
$\bar{Y}$ = Centroid Height
$I_x$ = Moment of Inertia with respect to the x-axis

*Centroid Height ($\bar{Y}$):*

$$\bar{Y} = \frac{\sum A_i\bar{Y}_i}{\sum A_i} = \frac{(A_r\bar{Y}_r + A_e\bar{Y}_e)}{(A_r + A_e)}$$

Where,
$A_r$ = Area of Rectangle
$\bar{Y}_r$ = Centroid of Rectangle
$A_e$ = Area of Semi-Ellipse
$\bar{Y}_e$ = Centroid of Semi-Ellipse

*Parallel Axis Theorem for Calculating $I_x$:*

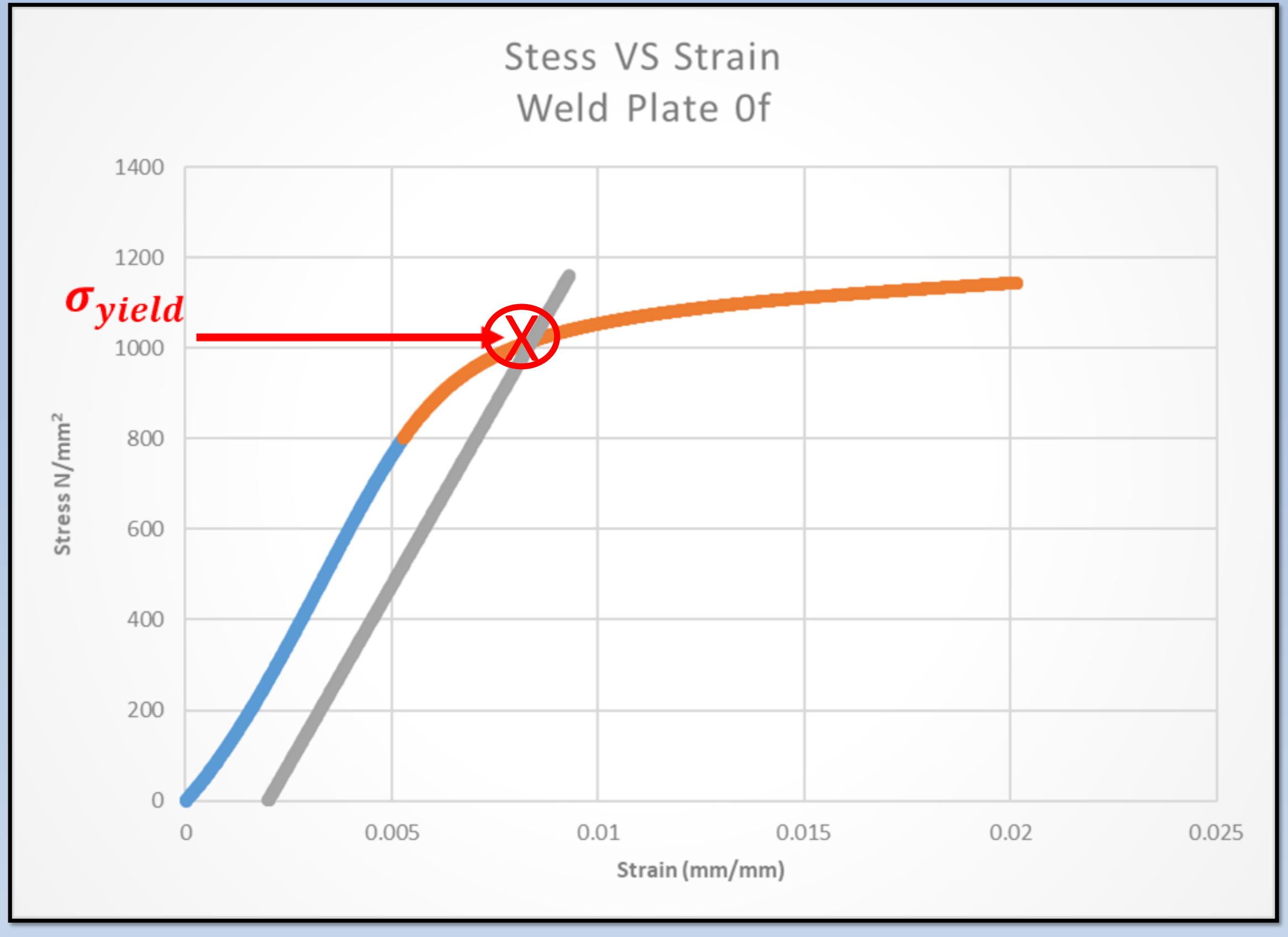
$$I_x = \sum(I_n + A{d_n}^2) = (I_r + A_r{d_r}^2) + (I_e + A_e{d_e}^2)$$

Where,
$I_x$ = Moment of Inertia of an Area with respect to the x − axis
$I_n$ = Moment of Inertia of the Area with respect to the centroidal axis parallel to the x-axis
$A$ = Area of object
$d_n$ = distance between two axes

and,
$I_r$ = Moment of Inertia, Rectangle (metal plate)
$A_r$ = Area of Rectangle
$d_r$ = distance between the centroid of the metal plate with weld and the centroid of the rectangle
$I_e$ = Moment of Inertia, Semi-Ellipse (weld bead)
$A_e$ = Area of Semi-Ellipse
$d_e$ = distance between the centroid of the metal plate with weld and the centroid of the semi-ellipse

## EXPERIMENTAL RESULTS

After the stress and strain for each metal plate was calculated, the data was plotted to make a stress-strain curve for each of the metal plates. The figure below shows one example of the stress-strain graph for weld plate #0-f. After the stress and respective strain was calculated for each data point, the 0.2% offset method was used to help extrapolate the flexural yield strength for each of the metal plates. The blue portion of the graph is the elastic (linear) region of the deformation curve. The slope of the linear portion was determined and used to create the 0.2% offset line. The offset line is horizontally offset by 0.2% (Strain of 0.002) from the origin and parallel to the elastic region of the graph. The orange portion of the graph is the plastic deformation of the metal plate. After the linear portion of the graph was determined and the 0.2% offset line drawn, the flexural yield strength was extrapolated using the intersection of the 0.2% offset line and the stress-strain curve.



## EXPERIMENTAL RESULTS (Cont.)

The flexural yield strength for each of the metal plates is shown below. The average flexural yield strength for the metal plate with no welds, one weld, and two welds is 1000 MPa, 930 MPa, and 823 MPa, respectively. The flexural strength of the metal plates decreased as the welds were added to the plate. The reason for this could be the welding material and the temperature of the weld.

FLEXURAL YIELD STRENGTH

| Weld Plate No Welds | Yield Strength (MPa) | Weld Plate 1 Weld | Yield Strength (MPa) | Weld Plate 2 Welds | Yield Strength (MPa) |
|---|---|---|---|---|---|
| 0a | 1000 | 1a | 990 | 2a | 845 |
| 0b | 1000 | 1b | 950 | 2b | 845 |
| 0c | 1000 | 1c | 900 | 2c | 820 |
| 0d | 1000 | 1d | 910 | 2d | 830 |
| 0e | 1000 | 1e | 930 | 2e | 800 |
| 0f | 1000 | 1f | 900 | 2f | 800 |
| **Average :** | **1000** | **Average :** | **930** | **Average :** | **823** |

Rockwell Hardness – B tests was performed on the metal plates after welding, in accordance with ASTM E18 hardness standard procedure. This test determines the hardness of the plates, as seen below.

HARDNESS ROCKWELL B

| Weld Plate No Welds | Hardness | Weld Plate 1 Weld | Hardness | Weld Plate 2 Welds | Hardness |
|---|---|---|---|---|---|
| | 96 | Next to Weld | 95 | Next to Weld | 94 |
| | 97 | Next to Weld | 96 | Next to Weld | 98 |
| | 96 | Next to Weld | 102 | Next to Weld | 100 |
| | | Next to Weld | 99 | Next to Weld | 99 |
| | | On Weld | 91 | On Weld | 87 |
| | | On Weld | 99 | On Weld | 80 |
| | | On Weld | 92 | On Weld | 86 |
| | | On Weld | 101 | On Weld | 80 |

The temperature of the weld can affect the hardness and the flexural strength of the metal. A heat treatment can be performed after welding, called Post Weld Heat Treatment (PWHT) to maintain or improve material strength and material properties. The drastic temperature change of the weld onto the weld plate can be seen in the discoloration of the weld plates after welding. The figure in the center column shows the weld plate discoloration on the underside of the weld plates. The decreased hardness on the welds can be explained by the additional temperature changes with the one weld and the two welds.

## EXPERIMENTAL CONCLUSIONS

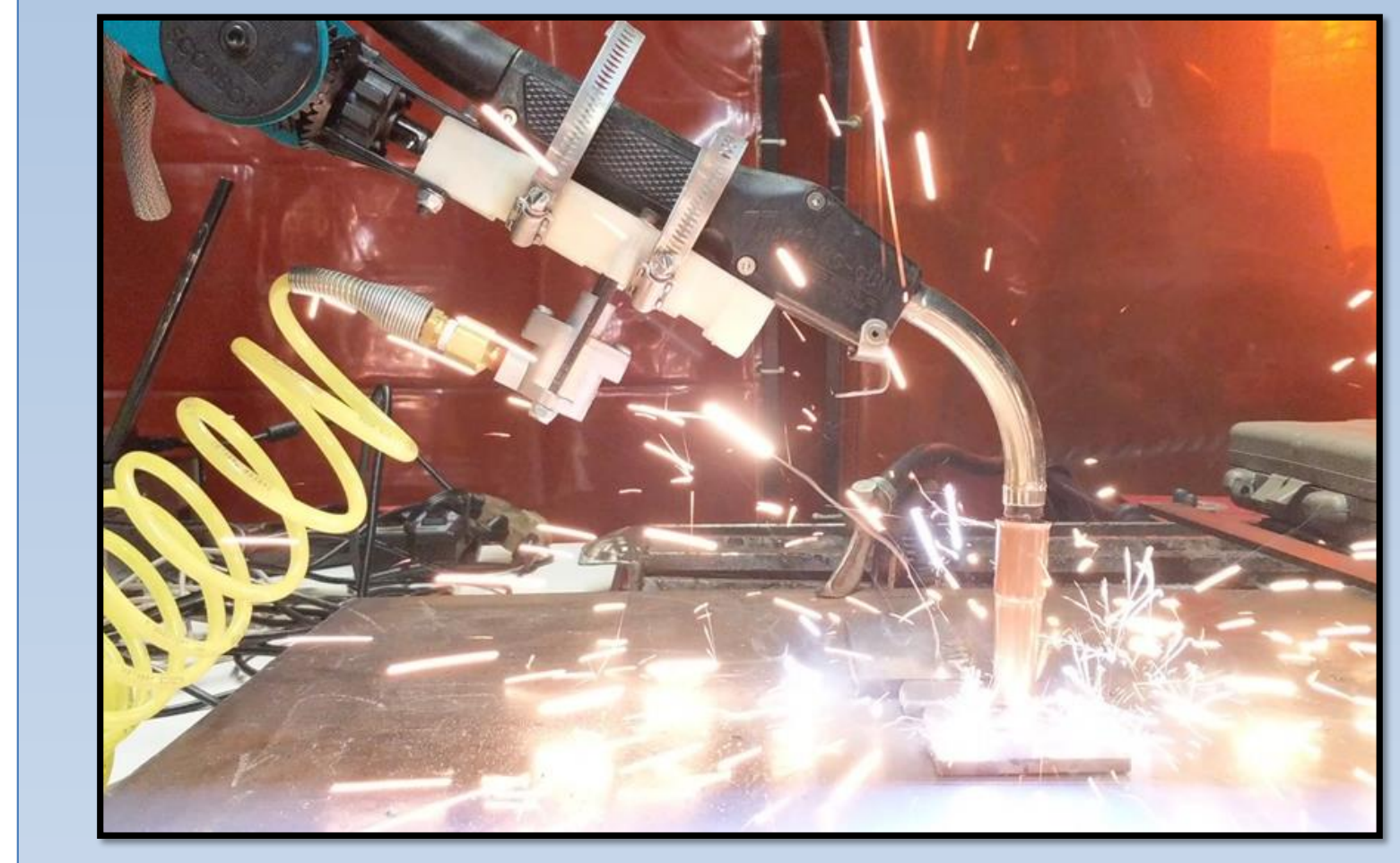
In this experiment, the effects of changing properties of 1018 steel were seen and analyzed after the steel was welded. The steel changed in its material properties including hardness and flexural yield strength. These material properties changed because of the high temperatures of the welding process and un-controlled cooling. No post-weld heat treatments were performed in an attempt to maintain the material properties of the metal plates. The temperature of welding can change by changing the voltage of the welder. With less voltage, the temperature of welding will decrease, and this could mean the material properties of the metal could be maintained. When using metal additive manufacturing to add reinforcement or create tools/objects, the material properties need to be understood in order to predict the quality and life of the material. For practical applications of WAAM in the maritime industry, it is important to note the material properties of metal after welding additive metal layers.

## MARITIME APPLICATION CONCLUSIONS

Through extensive literature research and experimental work, it is shown that Additive Manufacturing, and WAAM in particular, has a clear future in the maritime industry. There are a great many types of AM processes that can be used for many applications within the industry. Prototyping for design work could be done with many types of printers but are most easily and inexpensively utilized by Fused Deposition Modelers. Fabrication of mission critical replacement parts while on ship are also being investigated using the same FDM modelers but there is potential to use other newer technologies and different materials. Finally, fabrication of actual end-use parts are being realized with the help of metal AM technologies such as WAAM. As with any type of technology, the trick is knowing the limits of each individual machine and consumable materials that are at your disposal. WAAM has a particularly good fit in the maritime industry because it is a relatively inexpensive technology for printing metals (steel) and can print in relatively large part dimensions compared to desktop sized modelers currently on the market.

## REFERENCES

1. Additive manufacturing — General principles — Terminology. 2015. 52900. https://www.iso.org/obp/ui/#iso:std:iso-astm:52900:ed-1:v1:en..
2. 7 Families of Additive Manufacturing. Additive Manufacturing. [Online] [Cited: February 25, 2022.] https://www.additivemanufacturing.media/cdn/cms/7_families_print_version.pdf.
3. Stereolithography: The First 3D Printing Technology. s.l. : The American Society of , 2016. https://www.asme.org/wwwasmeorg/media/resourcefiles/aboutasme/who%20we%20are/engineering%20history/landmarks/261-stereolithography.pdf.
4. ISO/ATSM 52900. International Standard of Organization. [Online] ISO, 2018. International Standard of Organization.
5. Baker, Ralph. Mathod of Making Decorative Articles. US1533300A United States, April 14, 1925.
6. Strickland, J. Applications of Additive Manufacturing in the Marine Industry. s.l. : Proceedings of Practical Design of Ships and Other Floating Structures, PRADS2016, September 2016.
7. DeVisser, K. Qualification and certification of 3D printed parts for naval ships. s.l. : Naval Postgraduate School, Masters Thesis, December 2017.
8. E. Nicholls, W. Han, J. Davis. Additive manufacturing laboratories at sea and their added-value to the navy's seagoing warfighter. s.l. : Naval Postgraduate School, MBA Professional Project Thesis, December 2019.
9. Krassenstein, B. Denmark Shipping Company, Maersk. s.l. : www.3dprint.com, July 2014.
10. Damen. World's first class approved 3D printed ship's propeller unveiled. [Online] Daman Shipyards Group, November 2017. https://archive.damen.com/en/news/2017/11/worlds_first_class_approved_3d_printed_ships_propeller_unveiled.
11. A. Josten, M. Hofemann,. Arc-welding based additive manufacturing for body reinforcement in automotive engineering. s.l. : Weld World, 2020.
12. Richard G Budynas, J. Keith Nisbett. Shigley's Mechanical Engineering Design. New York : McGraw Hill Education, 2020.
13. Why Post-Weld Heat Treatments Are So Important. STI Group . [Online] February 8, 2016. https://setxind.com/fabrication/post-weld-heat-treatments-are-important/.
14. Jonnie Liew Zhong Li, Mohd Riza Alkahari, Nor Ana Binit Rosli, Rafidah Hasan, Mohd Nizam Sudin, Faiz Redza Ramli. Review of Wire Arc Additive Manufacturing. Melaka, Malaysia : Center of Advanced Research on Energy, 2018.
15. Kirlin, Kolbe. Design and Testing of WAAM End Effector. Kings Point, NY : Kings Point Scholar, 2021.
16. Stress-Strain Curve: Strength of Materials. SMLease Design. [Online] [Cited: February 28, 2022.] https://www.smlease.com/entries/mechanical-design-basics/stress-strain-curve-diagram/.
17. Li, Johnnieew Zhong. Review of Wire Arc Additive Manufacturing for 3D Metal Printing. s.l. : Research Gate, 2019.



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