The effect of shielding gases on the geometrical features in metal big area additive manufacturing (mBAAM)

Abstract: The purpose of this 2018 Visiting Faculty Program (VFP) award is to understand the effect of shielding gas on the geometric features in metal big area additive manufacturing (mBAAM) using arc welding. The selection of shielding gases in mBAAM comes from experiences in the welding community. However, there is a little to no information on how shielding gas affects different geometrical features in large-scale AM. It is desirable to have different melting characteristics and fluidity for different geometrical features in mBAAM, which cannot be fulfilled by established arc welding practices. During the 10 weeks appointment, a variation of reactive and non-reactive shielding gases (binary and ternary) have been used to deposit three different geometric shapes using two metallic alloys: C-Mn steel and 410 Stainless steel. These distinct as-deposited geometric shapes are 3-d scanned and compared. The fluidity, wetting characteristics, thermal effect is experimentally analyzed. The mechanical properties are investigated and the microstructure is analyzed.

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Introduction

Metal Big Area Additive Manufacturing (mBAAM) is a rapid prototyping technique suitable for manufacturing large, metallic structures. The mBAAM process uses the same heat source required for metal joining (arc welding) and offers significant advantages over currently available metal powder additive manufacturing processes due to lower costs and higher deposition rates. The use of laser and electron beam as power sources in metal powder additive manufacturing has produced high resolution parts. However, the cost of metallic powder is significantly higher than the metallic wire. Metal powder systems are also slow and have small build volumes.

The mBAAM process is similar to automated welding; however, it differs by offering continuous deposition for many hours, complex tool-path planning, and a deposition rate of 3-5 lb/h (Nycz et al, 2017). The use of mBAAM in large-scale additive manufacturing has been well demonstrated under 'Project AME' at ORNL (**Figure 1**).

Figure 1: The world's first 3D printed excavator (left) and vertically printed arm and bucket (right) printed with MBAAM (Nycz, 2017)

Although significant mBAAM process development has occurred, limitations still exist when compared to other metal additive manufacturing processes such as: tie-in near to the edge, multiple starts and stop points, and native robotic framework (Babu, 2016). However, some of these limitations have been eliminated through the development of a native robotic framework (Nycz et al, 2016). Therefore, our hypothesis is that the remaining shortcomings of this process can be overcome by using appropriate combinations of shielding gas in mBAAM. The selection of shielding gas in mBAAM originated from the recommended practice in the welding community. However, in additive manufacturing, due to the complexity of the geometrical size and shape, the information available from the welding community is not sufficient. Considering the geometrical features such as infill layers and overhang (**Figure 2**) structures in mBAAM, infill layers require the fluidity of the weld bead, but the opposite is favorable to achieve an overhang structure. Furthermore, the use of recommended shielding gas in welding has produced defects in AM, which reduced the mechanical properties (Silwal, 2014).

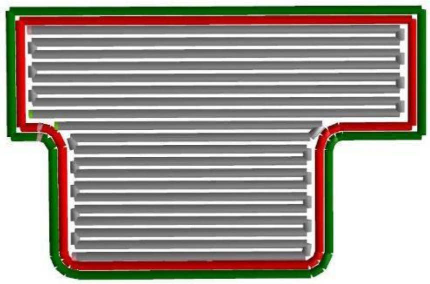
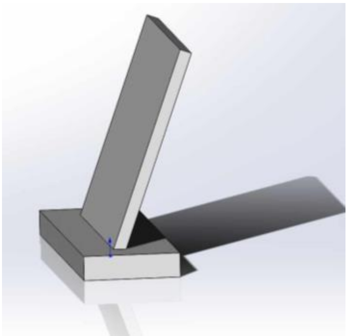

Figure 2: The infill layers (on right) and overhang (on right)

The proposed research project will study the effect of a combination of shielding gases when used to fabricate three specific geometrical patterns: walls, infill, and overhang. The fluidity, wetting characteristics, and mechanical properties will be studied for these geometric configurations. The knowledge gained from this research will allow the proper selection of shielding gas by a control system on-the-fly, improve the overall process, and increase productivity by increasing deposition rate, lowering energy cost, and improving the wetting characteristics. Furthermore, it will help to generate new capabilities in multi-material hybrid mBAAM by defining the appropriate shielding gas mixtures for different metallic alloys. The proposed research aligns with the Department of Energy (DOE) Advanced Manufacturing Office's and ORNL's mission in big area additive manufacturing to assist in applied research and to develop processes that improve manufacturing's energy efficiency.

Hypotheses and research objectives and goals:

The goal of this research is to identify the proper shielding gas in mBAAM for various metallic alloys and use effective (multiple) shielding gases on-the-fly depending upon the geometric configuration.

- The primary objective of this research is to understand the fluidity, wetting, and heat characteristics caused by various shielding gases for different geometrical features.
- The secondary objective is to test the hypothesis that the addition or use of other shielding gas will not degrade and rather improve the mechanical properties of the MBAAM parts.

Progress :

The experiment was performed with Wolf Robotics automated metal inert gas (MIG) welding system. The system is equipped with an ABB IRB 2600 robotic arm with IRC5 controller, a Lincoln Electric R500 Power Wave welder, a water-cooled torch and a dual push-pull wire feeder. The electrode used in this experiment was ER-70S6 (mild steel) and 410 stainless steel. The chemical composition of the ER-70S6 and 410 stainless steel is presented in Table 1. A variable ratio gas blender designed to create a mix of welding shielding gases was used to supply four different percentages of shielding gas combinations; 98 % Ar & 2 % CO_2, 95 % Ar & 5 % CO_2, 90 % Ar & 10 % CO_2 and 75 % Ar & 25 % CO_2 respectively. The flow rate was maintained 40 cu ft/h (18.8 lt/min). Similarly a mass flow controller as well as a manifold was fabricated to make a binary mixture of Argon, Helium, Carbon dioxide, Nitrogen and Oxygen. Four K-type thermocouples were placed on a base plate and an infrared camera was placed at a definite distance from the surface of the base plate for all four experiments. The base plate dimension is 4 × 12 × 0.25 inches (101.6 × 304.8 × 6.35 mm) while the wire diameter is 3/32 inches (Two thermocouples were placed approximately 25 mm from the center of the plate within 100 mm apart while the other two thermocouples were placed approximately 50 mm from the center within 200 mm apart (**Figure 3**). The plate was fastened with 12 clamps to the fixture plate at corners and the mid-location as depicted in **Figure 3**.

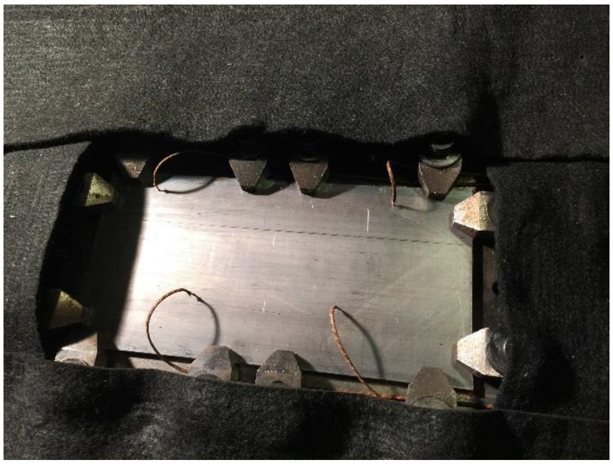

Figure 3: Experimental setup: the blankets are used to protect from spatter

A 150 × 250 × 9 mm wall geometry was sliced with ORNL's slicer with a constant layer thickness of 2.34 mm, while the 1st layer thickness was increased to 3 mm. A lower travel speed was used for the 1st layer in-order to pre-heat the base plate. Each layer consists of two beads. A touch sensing and through arc seam tracking (TAST) were used in the custom built G-code to robotic tool path generator. The wire feed speed (83.3 mm/sec), travel speed (6.7 mm/sec), the current (160 A), voltage (17 V) was set to constant while the Lincoln Electric Surface Tension Transfer® (STT®) mode was used. The Power Wave Manger was used to track the welding parameters. The nozzle of the GMAW gun was changed after every 11 layers while the wire was serviced after each deposited layer. Two different weight percentages of Ar and CO_2 (90-10 % and 98-2 %) were used to deposit infill (#5-6) and overhang (# 7-8) geometry. An industry standard tri-mix (He-Ar-CO_2) as well as Ar-CO_2 mixture was also used to deposits walls (# 10-12). A combination of He-Ar, He-CO2 and Ar-N2 were used to deposits walls of 410 stainless steel (# 13-15).

The printed walls (Experiment # 1-4; Table 1) were wire EDM cut to extract ten sub-size tensile specimens (five horizontal and five vertical) and nine standard Charpy specimens. Table 2 represents the number of experiments performed during the appointment term.

Table 1: Chemical Composition of mild steel electrode and 410 stainless steel electrode

Si	Mn	P	C	S	Fe
0.80-1.15	1.4-1.85	0.025	0.06-0.15	0.035	balance

	#	Shielding Gas						
Metal		**Ar**	**CO2**		**Geometry**	**Dimension**	**Measureme nt**	**Additional Gases**
ER-70S6	1	98	2		2-bead wall		Scan, TC, Infrared	
ER-70S6	2	95	5		2-bead wall		Scan, TC, Infrared	
ER-70S6	3	90	10		2-bead wall		Scan, TC, Infrared	
ER-70S6	4	75	25		2-bead wall		Scan, TC, Infrared	
ER-70S6	5	98	2		in-fill	6 layers, 200 * 200	Scan, TC, Infrared	
ER-70S6	6	90	10		in-fill	6 layers, 200 * 200	Scan, TC, Infrared	
ER-70S6	7	98	2		overhang	20-25 degree	Scan, TC, Infrared	
ER-70S6	8	90	10		overhang	20-25 degree	Scan, TC, Infrared	
ER-70S6	9	95	5		3 different infills		Infrared	
		He	CO2	Ar				Ar+CO2 (95-5)
410 SS	10	**90**	**2.5**	**7.5**	2-bead wall		Scan, Infrared	2nd half layers
ER-70S6	11	**90**	**2.5**	**7.5**	2-bead wall		Scan, Infrared	2nd half layers
410 SS	12	**90**	**2.5**	**7.5**	2-bead wall		Scanned	
410 SS	13	**90**		**10**	2-bead wall		Scan, TC, Infrared	
410 SS	14	**90**	**10**		2-bead wall		Scan, TC, Infrared	
410 SS	15	Ar - 98	Nitrogen 3%		2-bead wall		Scan, TC, Infrared	
ER-70S6	16	Ar-98	Nitrogen 3%		2-bead wall		Scan, TC, Infrared	
ER-70S6	17	Ar-98	Oxygen 3%		2-bead wall		Infrared	

Note: TC – thermocouple

Figure 4 (see Appendix) represents the temperature profiles corresponding to different shielding gas composition at location 1-4 (indicated by a red dot in each Figure). Each peak in the temperature represents heat generation at the base plate (substrate) due to a single bead path totaling of 2 peaks for every layer. One of the thermocouple failed at location 4 corresponding to 2% CO_2, thus no data is presented. Similarly no data is available for shielding gas composition of 25 % CO_2. The measured temperature is higher for 10% CO_2 addition than 5% CO_2 and 2 % CO_2

for every layer at location 1-4. Between 5% CO_2 and 2 % CO_2, the temperature is higher at location 1 corresponding to 5% CO_2(Figure 2), while at location 2 and 3 there has been no significant difference (Figure 4). The depression in the temperature profile encountered approximately 1200 sec represents the service time due to replacement of the nozzle. A similar dip in the temperature profile has been observed at succeeding time intervals.

All the base plate prior to deposition weighs 5 lbs each. After the deposition, the three walls corresponding to CO_2 level 2, 5 and 10 % weigh 11.8 lbs including the base plate. The wall corresponding to CO_2 level 25% weigh 11.6 lbs.

It is evident from the Figure 4 that adding additional CO_2 up to 10% has increased the overall heat input into the molten puddle, thus increasing the temperature of the substrate. This is due to dissociation of CO_2 at the anode while recombination at the cathode (melt pool) thus generating additional energy at the melt pool during the deposition.

The printed walls are presented in Figure 5. The appearance of the surface on the wall reveals formation of silicon oxide. The silicon oxide formation increased as increasing CO_2 in the shielding gas. Silicon acts as a deoxidizer and are added in the ER-70-S6 (0.8 – 1.15 %) electrode in order to avoid the formation of Iron-Oxide. There might be a possibility of forming manganese oxide. The oxide is severe in the top layers compare to the bottom layers. One possibility is the heating of atmospheric oxygen and accumulation of oxygen on the top layers. Another observation is that these oxides are present in a similar location during the build up. This might be due to the preferential locations for these oxides when melt due to differences in the density would like to accumulate in the same location.

The addition of 25% CO_2 has a discontinuous metal transfer in the GMAW STT® as compare to the three different types of CO_2 addition. A stutter (similar to higher offset distance from the contact tip to surface of the base plate in MIG welding) and the depression in welding current was observed. This has led to the reduction in weight as well as excessive spatter. One possible reason could be the increment in contact tip to the substrate distance due to uneven surface, increasing the resistance and thus lowering the current. It may be due to the formation of oxides on the surface or the higher composition of CO_2

Geometric Evaluation: The heat map of the scanned walls are presented in Figure 6. Each scanned wall is compared with the 132 × 250 × 13 mm CAD geometry. The scale bar shows the positive and negative deviation from the CAD dimensions. There is linear trend in the height of the wall, as the composition of the CO_2 increases, the height decreases. This is due to higher penetration due to the addition of CO_2 gas. The difference is significant when the CO_2 composition has been set to 2%, however small marginal difference occurred when the CO_2 composition has been set to 5, 10 and 25 %. Figure 7 represents the scanned walls. The observation of theses scanned wall reveals a smoother surface for lower % of CO_2 compared to higher % of CO2. The mechanical properties and microstructure analysis of the C-Mn steels are currently being undertaken and the results are expected within next week.

For 410 steel, the tri-mix shielding gas (He-Ar-CO_2) and Ar-N_2 (98-2) mixture provides the better appearance as well as the smooth surface compared to the He-CO_2, He-Ar mixture.
The

mechanical properties and microstructure analysis are currently being undertaken and the results are expected within the next week.

Future Work

At the end of the project, it was expected that the following deliverables would be produced.

- The different geometry relationships to the shielding gas
- Effect of shielding gas on the defects and quantification of these defects (porosity level) if present
- The mechanical properties measurement and microstructure characterization of ER70S6 and 316 stainless steel in the context of shielding gas and geometry features
- Publishing the findings into relevant conferences and publishing journal papers

The first two deliverables are presented above. The third deliverable is currently on going and it is expected to be finished within 2-3 weeks. One abstract is submitted to ASME-IMECE and one journal is in preparation. It is expected that after the third deliverable is produced, the PIs will submit the findings to the relevant journal.

Impact on Laboratory or National Missions:

The time required to produce one part in MBAAM can be significantly reduced by increasing travel speed and deposition rate while varying the shielding gases on-the-fly. The results obtained from these experiments will improve the process and increase manufacturing energy efficiency which is the mission of the National Lab.

This collaboration has elucidated the impact of process parameters (percentage level of shielding gas, mixture) on bead topography, fluidity and wetting characteristics, and mechanical properties. These outcomes will provide provide new direction and process innovation in multi-material (hybrid) mBAAM using the appropriate shielding gas on-the-fly.

The MDF facility has now capable of using multiple binary as well as ternary shielding gas mixtures using the in-house developed manifold. This research outcome is within the ORNL MDF technology focus areas; “Improved Performance Characteristics of AM Components”

Conclusions

From the conducted research, the proposed deliverables have been met. The mechanical properties and microstructural analysis work is ongoing and it is expected that the results will be included in the relevant literature. From the current finding, the following specific points can be made from the research findings:

- The 98 Ar- 2 CO_2 has better surface feature than any other Ar-CO_2 weight percentage mixture for Cr-Mn steel.
- The 90 Ar- 10 CO_2 has the higher heat input compared to 75 Ar – 25 CO2 due to STT process.
- Argon and nitrogen as well as helium, argon and CO_2 tri mix has a better surface appearance for 410 stainless steel than helium and argon, helium and CO_2, and argon and CO_2.

Overall, the knowledge gained from this experience will help the PI to incorporate the findings into teaching module at Georgia Southern University. The finding will also help to look for scholarship grants as well as the publications in relevant venues.

Acknowledgement

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References

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Nycz, A., Adediran, A. I., Noakes, M. W., & Love, L. J. (2016). *Large Scale Metal Additive Techniques Review*. Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States). Manufacturing Demonstration Facility (MDF). In Solid FreeForm Symposium, Austin

Appendix:

Participants

Name	Institution	Role	Brief Statement
Bishal Silwal	Georgia Southern University, Statesboro, GA	PI	Design, Planning, Analyzing and Interpreting, literature review
Andrzej Nycz	Oak Ridge National Lab, Oak Ridge, TN	Co-PI	Design, Planning,
Mark W Noakes	Oak Ridge National Lab, Oak Ridge, TN	member	Planning
Christopher Masou	ORNL- Post Bachelor	member	Performing the experiments
Derrek Vaughan	ORNL- Student Intern	member	Gas mixture design and development
David Marsh	ORNL – Student Intern	member	Infrared Camera Labview code development

Scientific Facilities

ORNL-MDF, Material Science and Engineering Lab at ORNL

Notable Outcomes –

Manuscript in preparation: B. Silwal, A. Nycz, M. Noales, D. Marsh, D. Vaughan, C. Masuo; "Ar-CO_2 shielding gases effect on the C-Mn steels for metal big area additive manufacturing"

Technical Presentation: Effect of shielding gas on metal big area additive manufacturing – B. Silwal, A. Nycz, M. Noales, D. Marsh, D. Vaughan, C. Masuo – submitted to ASME IMECE Advance Manufacturing

Research Vibrancy –

The development of the manifold to use multiple shielding gases on the fly has generated multiple research topics to further explore. It is anticipated that the remaining tasks as well as a new gas mixture which was not used this year will be continued next year.

Connection to Programs at Home Academic Institution –

The PI will incorporate the results in one of the undergraduate course (Material Processing - MENG 3333) he is currently teaching. The data available from this research proposal will facilitate the PI to develop a numerical model to understand the shielding gas effects as well as to help the PI in writing grant proposals.

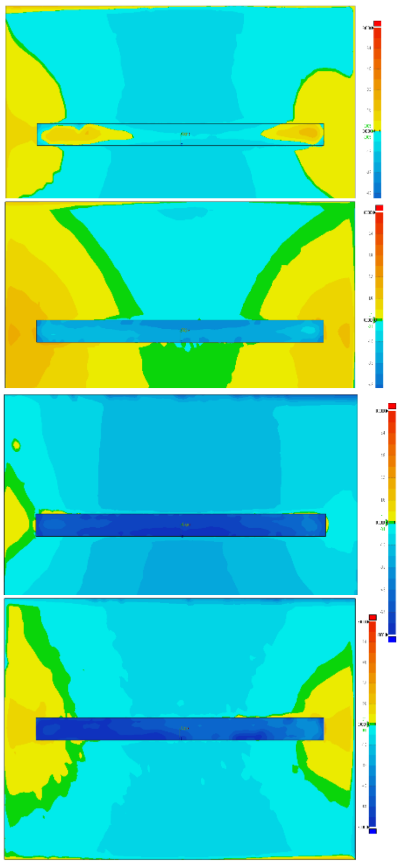

Figure 6: The heat map of the scanned wall (top view) from top to bottom (2 % CO_2, 5 % CO_2, 10 % CO

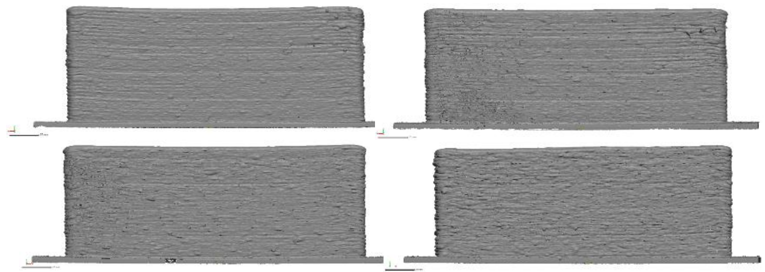

Figure 7: The scanned walls: 2 % CO_2 on the top, 5 % CO_2 on top right, 10 % CO_2 on the bottom and 25 % CO_2 on the bottom right.

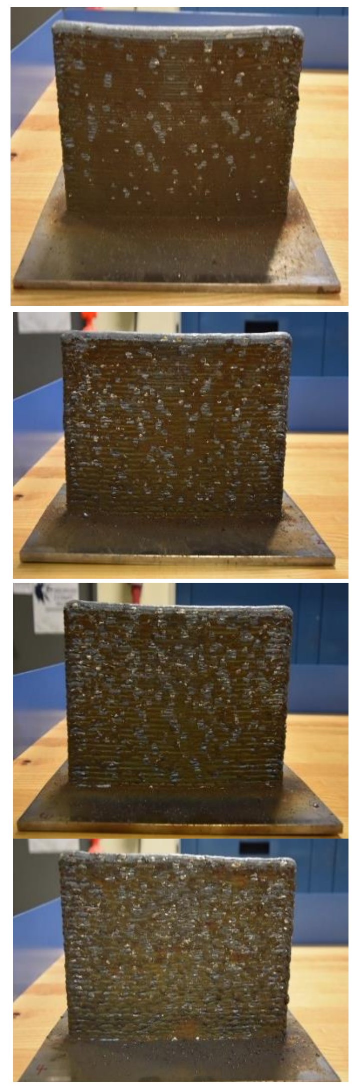

Figure 5: The wall appearance after the deposition; 2% CO2, 5% CO2, 10% CO2 and 25 % CO2 (top

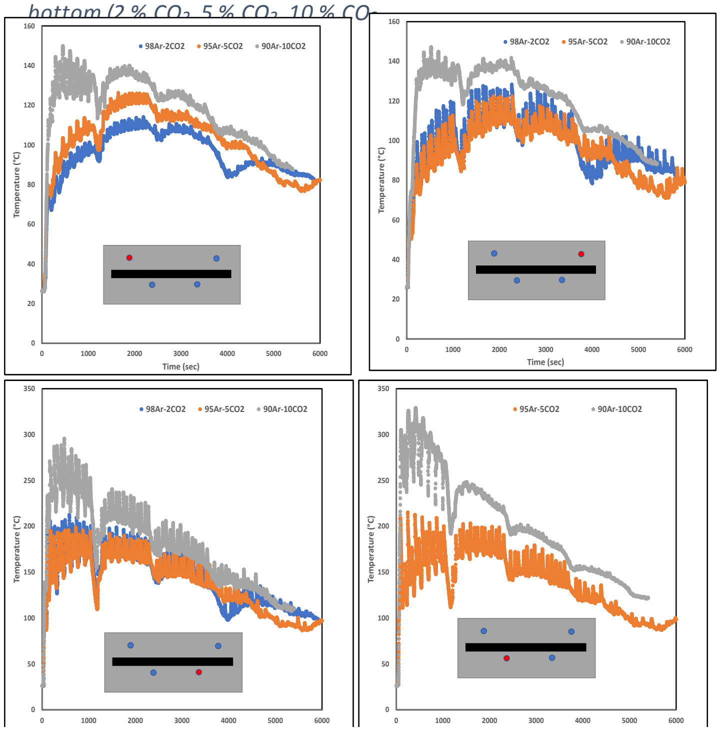

Figure 4: Temperature profile at location 1-4 for different shielding gas composition