Topical. Permanent Low-Earth Orbit Testbed for Welding and Joining: A Path Forward for the Commercialization of Space

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Abstract. NASA, defense, academia, and commercial space companies seek to develop orbital manufacturing to enhance mission capabilities. In-space welding and joining are needed for space-based manufacturing. We propose a permanent low-earth orbital welding and joining testbed for scientific study of relevant physical phenomena and development of welding and joining processes to technical maturity. Such data will enable integrated computational materials engineering (ICME) to elucidate the underlying physical and metallurgical processes needed to achieve critical space welding and joining operations.

1. Introduction. In this white paper we discuss relevant background, problems, challenges, opportunities, identify areas of research and development, and suggest paths forward in a plan that will aid in steering research and development activities at NASA (and other agencies), academia, and industrial aerospace companies. This plan will guide efforts within the aerospace community towards fulfilling the goals of commercialization of space through successful space welding, joining, and allied processes such as additive manufacturing.

Understanding the relationship between the melting and solidification physics and joint integrity during welding, brazing, and soldering in microgravity and reduced gravity environments is critical for the safety and viability of NASA's exploration missions. The future market for on-orbit servicing, assembly, and manufacturing (OSAM) is projected to be large and will benefit the broad space community including space exploration, commercial, and national security missions [1]. A number of manufacturing technologies are captured under the OSAM umbrella including welding and joining [2]. Indeed, welding, joining (such as brazing, diffusion bonding, soldering, additive manufacturing, solid-state welding, etc.), and allied processes make up a significant portion of terrestrial manufacturing. A 2002 study by the American Welding Society estimated that these processes enable over 50 % of the U.S. manufacturing sector's Gross Domestic Product [3]. Certainly, given their profound importance within terrestrial manufacturing, welding and joining processes will be enabling technologies for the OSAM mission success of NASA's exploration missions. The International Space Station (ISS) conference held in 2019 in Atlanta Georgia attended by NASA leadership, as well as industry and academic experts, issued the view: "*The consensus of the participants was that* ***further investigation of joining technologies for in-space use*** was of ***critical importance****…*" [4].

Fortunately, welding is not new to space. The first space welding experiments performed by the U.S.S.R aboard Soyuz-6 in 1969 [5], followed by the first U.S. welding experiments on Skylab in 1973 [6], demonstrated that welding techniques are readily adapted to space. The U.S.S.R performed welds in open space outside Salyut-7 in 1984 and additional experiments on the Mir space station in 1988 [5]. In addition to these pioneering in-space welding experiments, ground-based high-vacuum and airborne-based high-vacuum reduced-gravity welding experiments have been conducted [7–9]. However, no further welding and/or brazing efforts have been performed in space since the initial low earth orbit experiments and current aluminum brazing (BRAINS) joint NASA and Roscosmos project work [10]. The experiments above and related work (parabolic flight, drop tower, vacuum chamber, controlled atmosphere furnaces) have demonstrated that space welding and joining are viable technologies for orbital manufacturing efforts. Yet data from these experiments falls short of describing fundamental structure-property-processing relationships needed for development of robust welding processes and process models that will enable critical one-shot space joints necessary for space hardware.

Fusion welding by definition is the formation of a metallurgical bond between two or more pieces of material into a single piece by melting and solidification. The physics of terrestrial fusion welding have been studied widely for 100 years and physics-based predictions of resulting weld structure and properties are robust. Key physical processes include: the transfer of energy from a heat source to the weldment, melting, evaporation and fume formation, convection (natural, electromagnetic, and Marangoni), solidification of the weld pool, formation of defects (such as porosity and cracking) during and after solidification, metallurgical transformations to the parent material around the melted region, and accumulation of non-uniform residual stresses. Each of these influence the properties and performance of the final weldment [11]. The numerous physical processes mentioned above can be drastically altered relative to terrestrial behavior by introducing microgravity, extreme temperature fluctuations, and the reduced pressure of space. Therefore, welding processes developed *in terra* to achieve certain design criteria (weld penetration depth, strength, etc.) would require significant adjustment to ensure success in space. The same holds for other joining processes, e.g., brazing. For this reason, a permanent welding and joining laboratory is needed in space to understand physical changes to aforementioned physical processes, to generate relevant data for calibration and validation of computational joint models, and to aid in development of welding parameters for OSAM. Such a system must accommodate various joining processes and metallic materials while ensuring safety for astronaut operators.

2. Problem Statement. Space presents an extreme environment that requires novel welding and joining solutions to fully deploy and expand human exploration, enable colonization, and to make possible the exploitation of in-situ resources. Welding in space is subject to 1) reduced gravity, 2) vacuum/reduced pressure, and 3) large temperature variations compared to terrestrial welding. Currently, there are no weld process parameters that account for these physical changes, and thus, critical in-space welds cannot be performed. Figure 1 establishes anticipated differences of 1), 2), and 3) on key physical processes that occur during e.g., a laser beam weld, and demonstrates how a well-defined welding process window determined on earth becomes uncertain for space conditions.

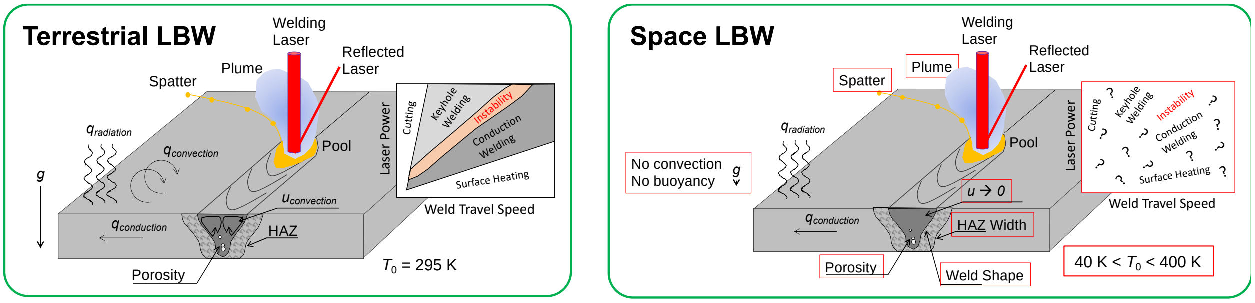

Fig. 1. Comparison of Terrestrial Laser Beam Welding (LBW) and Space Laser Beam Welding physics and modeling opportunities (in red) required to improve space welding predictions.

2.1. *Reduced gravity* in space mitigates buoyancy which influences natural convection of liquid metal in the weld pool. The development of the weld pool solidification grain structure and shape is altered due to elimination of mass transport via natural convection [6]. Surface tension (Marangoni) is thought to be the dominant flow mechanism for liquid mixing in absence of gravity-induced natural convection although others exist including electromagnetic (Lorentz) forces, beam force, thermal expansion induced dilation [12]. Cooling of welds occurs via convection, conduction, and radiation. Weld cooling on earth is often dominated by natural convection, a mode that is not possible in space due to the presence of microgravity and lack of heat transport medium (air). Weld shape, heat-affected zone (HAZ) shape, metallurgical transformations, and subsequent weld properties will be influenced by changes to the weld cooling mechanism.

2.2. *Reduced pressure* in space eliminates air that aids in weld convective cooling and enhances evaporative heat transport and mass transport from the weld pool. Reduced pressure drives liquid metal evaporation of species with higher vapor pressure, thus altering weld pool chemistry and subsequent metallurgical transformations and properties. Furthermore, the lack of atmospheric pressure typical *in terra* will alter stability of welding heat sources. Welding arcs require ionization of (usually) inert gas to carry the electron current, and transfer heat to the weld pool by conduction of the gas itself [13]. Laser beam and Electron Beam keyholing, a phenomenon that results in deep weld penetration and intermittent formation of gas pores within the solidifying weld, is influenced by atmospheric pressure head [14]. Welding heat source instabilities such as those described for arcs and energy beams induce weld defects and reduce properties and performance.

3. Topical Areas for R&D. Basic and applied research studies of welding and joining processes benefit from the classic material science approach of understanding structure-property-processing relationships. Such understanding provides a way to rapidly diagnose off production problems or forward project work into e.g., new spaces of unknown chemistry or processing conditions while maintaining a degree of certainty in the positive outcome of weld behavior. Furthermore, infusion of computational weld and materials modeling into the approach presents tremendous insight into the expected properties of the weld. Therefore, opportunities to improve knowledge and ability to weld in space with these four areas (modeling, processing, structure, and properties) are highlighted below.

3.1 Modeling. Weld modeling was in its infancy when the first space welding experiments were performed in the 1960s and 70s. With the advent of tools like computational thermodynamics and fluid dynamics, and finite element analysis, the coupling of process and metallurgical modeling under the umbrella of Integrated Computational Materials Engineering (ICME) will enable technology for critical one-shot space welds. Connecting the micro-, meso-, and macro-scales with various computational packages provides a toolbox with which to perform virtual welding and joining experiments to bound processing envelopes. As such, space effects such as gravity and pressure are readily incorporated within the commercially available computational framework. Opportunities for research include:

- Model input data is scarce, particularly thermophysical properties at high temperatures [15] where metals are between their melting and boiling point and in equilibrium with metal vapor. Such properties are generally unavailable for complex alloys. This data is needed to accurately model the region between a metal and a fusion welding heat source. State of the art sensors are needed to fine tune the models to take care of dynamic changes in boundary conditions.
- There are no robust algorithms to predict metal vaporization rates from a molten weld pool [15].
- The reduced pressure and gravity in space, and lack of thermophysical property data and vaporization models under those conditions, further complicates needs.
- Phase-field modeling provides an opportunity to simulate melting and solidification of liquid metal driven by surface tension, impacted by viscosity, in microgravity environments.

3.2 Processing. Development of terrestrial aerospace hardware welding processes is driven by costly, time-intensive empirical approaches where many variables are tuned until satisfactory weld quality is achieved. Processing parameters are often driven by input from a welder or operator and are adjusted and tuned to optimize a weld property of interest (typically strength and ductility). The complexity of in-space operations increases associated cost and time requirements, and as such, the welding process studies in the original space joining experiments resulted in nothing close to a hypothetical welding process window for laser beam welding, such as the one shown in Figure 1. A variety of process physics are needed to model welding processes included in space welding efforts including: electron beam welding [5,6], plasma arc welding [5], consumable arc welding [5], brazing [5,12,16], laser beam welding [7], and hollow cathode gas tungsten arc welding [17] (as well as solid-state welding). Further research opportunities include:

- Complete parametric studies with various welding and joining processes, on materials of interest, through thoughtful experimental design approaches coupled with real-time data collection of key processing variables and simultaneous feedback such as the spatio-temporal evolution of temperature and strain. Such data will be critical for calibration and validation of ICME modeling efforts.

- Real-time monitoring and adaptive control of welding and joining processes to optimize in-situ critical characteristics such as seam position, weld penetration depth, and defect formation. Adaptive process controls to adjust parameters to increase the joint quality is a longstanding "holy grail" of the welding and joining research communities and now the additive manufacturing community.

3.3 Structure. Most of the structural metals used in space are lightweight aluminum and titanium alloys. Other alloys are selected for unique properties such as corrosion resistance (stainless steels) or high temperature resistance (nickel-based and refractory alloys). The focus of the Soyuz-6 experiments evaluated welding of stainless steel, an aluminum-copper alloy, and a titanium alloy. Similar alloys were studied in the Skylab welding experiments with the addition of a nickel base alloy [18]. These alloys represent a broad grouping with varying metallurgical transformations and strengthening mechanisms. Characterization of the microstructure of in-space joints, while rudimentary, revealed profound differences in solidification and grain structure relative to terrestrial joints. The textures of such welds, strengthening mechanisms, and their chemical homogeneity have not been explored in the seminal studies of space joints.

- Advanced characterization methods on space joints samples is required to determine effect of microgravity on e.g.: non-destructive characterization of defects, joint microstructure, texture evolution and phase transformation, all of which have profound influence on properties.
- Space joint chemistry changes and homogeneity as a result of vaporization and chemical segregation patterns during microgravity solidification should be investigated. Strengthening and corrosion (where applicable for environmental/life support or fuel systems) are likely to be influenced by such changes.

3.4 Properties. Compared to the three areas above, the least work has been published on characterization of mechanical properties and performance of space joints. Weld mechanical properties of space vehicles built on earth must carry launch loads that include atmospheric drag and modal vibrations. Structures produced in space, which might include hermetic habitats and truss assemblies for solar arrays, will have entirely different mechanical design requirements than those produced on earth. Such requirements are largely unknown or undefined at this point and need to be explored to populate mechanical property handbook data for OSAM designers. In addition, OSAM is expected to produce critical inhabited structures, therefore characterization of fatigue and fracture properties and damage tolerance of in-space welds is also needed.

- Many of the space vehicles in orbit transmit numerous telemetry signals (including temperature, strain, and pressure) that could be used for development of joint properties requirements due to e.g., non-uniform solar heating.
- Basic mechanical properties of space joints such as hardness, strength, ductility, and fatigue performance with the relevant temperatures and environment should be determined to populate handbook data for designers of future OSAM efforts, requiring sample return.
- Damage tolerance and associated repair should be explored. Volumetric defects produced for space flight hardware are among the costliest problems encountered in manufacturing since their implications on fatigue initiation and life are so critical. A hermetic joint for a habitat may have requirements close to those for earth-based welding whereas a truss welded in space may accommodate large defects as long as it provides intended rigidity.
- Non-destructive techniques that provide insight into structure/defects/properties through direct observation *in situ* and in real-time, or via new correlations could mitigate costly sample return.

4. Suggested Path Forward. It is advantageous to develop partnerships between government, industry, and academia for the pursuit of a rigorous and innovating robust research and development approach that encompasses the materials and manufacturing challenges of NASA and OSAM, and that seeks to overcome these challenges while advancing the state-of-the-art.

The methodology being adopted is one that seeks to design novel materials adapted to space environments, synthesize and characterize these materials, and then implement process engineering for in-space manufacturing. ICME approaches have become the accepted methodology for material development in research and across industry. The various steps of alloys design and discovery, synthesis and testing, process development and manufacturing are enhanced by computational methodologies, supported by experimental, laboratory-testing-based data collection. Computational and experimental methods complement each other by insisting on feedback at every step and scale of the approach. The result is that the ICME approach promises to accelerate alloys discovery and deployment from the traditional decade or so to a year or two. Additionally, ICME is able to accommodate both terrestrial environments as well as extreme in-space environments. ICME is material agnostic in that the methodologies can be applied to materials development, and rapid optimization of welding and joining of lightweight alloys, ceramics, superalloys, high entropy alloys and even refractory alloys. Terrestrial ICME workflow applies to space ICME workflow.

Initially, feedstock for space based welding, brazing and additive manufacturing trials must be designed, optimized and fabricated *in terra* using an ICME approach with e.g. optimization via a performance function using machine learning. These optimized feedstock alloys will be used in both terrestrial and space-based manufacturing. Synthesis of alloys, however, must also be performed in relevant space environments. This requires the capability to perform materials synthesis on board a module of the ISS or similar space-based ‘laboratory’ platform. Samples testing should include on-board testing as well as sample return for terrestrial and more thorough testing and characterization.

Process development for welding and joining will have to be performed in-space as well as the terrestrial equivalent in order to establish (terrestrial) baselines for the former and in order to fully adapt the processes to the in-space environments. Therefore, it will be advantageous to deploy an in-space laboratory capable of performing welding, brazing, soldering and even additive manufacturing. Here it is envisioned that a new orbital platform or ISS module is to be deployed that can weld, join, additively manufacture or repair structures such as scaffolds, trusses, or girders for satellites, space craft, and additional platforms. It will be advantageous to develop partnerships between civic, defense, commercial and academic participants in order to best develop and deploy such a capability.

An in-space manufacturing platform, complementing materials science platforms such as the ISS, is key to the rapid and successful commercialization of space.

5. Conclusions In-space extreme environments require novel materials and manufacturing methods. We discuss some materials and process physics challenges for in-space welding and joining. We suggest a permanent space welding and joining platform to enable both the scientific study of relevant physical phenomena and to provide the ability to evaluate and develop welding and joining processes to technical maturity. Further, we suggest an expandable system that would enable full-scale manufacturing demonstration articles with the welding or joining process matured for space conditions. Lastly, we suggest that these approaches are to be developed under the guidance of the ICME approach to enable earth-based predictions of welding and joining process windows for critical one-shot joints. These are needed, and necessary, in order to fulfill the mission goals of NASA as mandated by US policy towards the commercialization of space.

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