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Advanced Lightweight Metallic Fuselage Project Manufacturing Trade Study

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Abbreviations and Acronyms

AATT	Advanced Air Transport Technology
AFS	Additive friction stir
AHP	Analytical hierarchy process
AM	Additive manufacturing
ASE	Additional structural elements
CMM	Coordinate measuring machine
CMT	Cold metal transfer
DED	Directed energy deposition
FOM	Figure of merit
FSW	Friction stir welding
GMAW	Gas-metal arc welding
IML	Inner mold line
ISC	Integrally stiffened cylinder
LaRC	Langley Research Center
LMD	Laser metal deposition
LHW	Laser hot wire
LW	Laser welding
MDA	Manufacturing demonstration article
MRL	Manufacturing readiness level
NASA	National Aeronautics and Space Administration
NDI	Non-destructive inspection
OML	Outer mold line
RFSSW	Refill friction stir spot welding
TRL	Technology readiness level
WAAM	Wire arc additive manufacturing

Abstract

Recent advances in large-scale flow forming of integrally stiffened cylinders (ISCs) have motivated evaluation of available technologies for rapid manufacturing of metallic fuselages. The current state-of-the-art in flow forming of ISCs produces 10-ft. diameter, 5-ft. long barrels with integral longitudinal blade stiffeners, and these single-piece ISCs are produced in approximately 1.5 hours. While other manufacturing processes are required to incorporate additional structural elements (ASE) such as circumferential ring frames, reinforcements around window and door cut-outs, and floors to the ISCs to complete the fuselage structure, flow forming technology may assist the aerospace industry in meeting manufacturing rate demands. In order to evaluate this technology, a fuselage manufacturing demonstration article (MDA) fabricated from two ISCs is scheduled for fabrication and delivery to NASA Langley Research Center (LaRC) by the end of 2022.

In this study, eight manufacturing technologies were assessed to downselect candidate manufacturing processes for adding ASE to complete the MDA. A literature review and evaluation of contractor-produced panels covering a spectrum of welding and additive manufacturing (AM) processes were conducted at NASA LaRC. The analytical hierarchy process (AHP) was used to evaluate figures of merit (FOMs) for selecting manufacturing process(es) to integrate ASE with the ISCs to form a fuselage MDA. The AHP results revealed that scalability, structural performance, and distortion control were the most valued criteria for downselecting the manufacturing process to construct the internal stiffening structures. Based on the FOMs, this study concluded that a welding process is best suited for integrating the majority of the ASE, namely the circumferential ring frames. All of the welding processes received higher scores than AM processes due to higher maturity, higher structural performance, fewer post-processing requirements in machining and heat treating, and faster deposition rates.

Among the welding processes, cold metal transfer (CMT) welding was ranked the most favorable process for assembling the MDA, with the other welding processes (laser welding (LW), friction stir welding (FSW), and refill friction stir spot welding (RFSSW)) scoring slightly lower. This was a consequence of the perceived maturity of the CMT welding process and its relatively high structural performance and low distortion resulting from the low heat input.

Among the AM processes, CMT AM showed the greatest promise due to benefits derived from its scalability, lower 1st order process complexity, and low distortion. The AM processes may have potential for select applications, such as adding structural reinforcements around window and door cut-outs, but are not considered optimal for integrating the entire MDA.

1. Introduction

1.1 Advanced Lightweight Metallic Fuselage Background and Objectives

The Aeronautics Research Mission Directorate (ARMD)'s Advanced Air Transport Technology (AATT) project is developing technologies for ultra-efficient commercial transport vehicles. In response to a US industry challenge, the AATT project is seeking to develop technologies to enable high rate manufacturing while simultaneously reducing weight and cost. The objective is to advance the Manufacturing Readiness Level (MRL) of a suite of next-generation metallic manufacturing technologies that enable production of commercial transport-scale aircraft in the 100,000 to 250,000 pound class (commercial aircraft for passengers and/or cargo). The goals of the project are to achieve a two-fold increase in manufacturing rate to 100 aircraft per month without building additional production facilities, a 10-20% structural weight reduction, and a 25% reduction in manufacturing cost compared to state-of-the-art riveted aluminum fuselage structures.

One task under the AATT project is the Advanced Lightweight Metallic Fuselage for Subsonic Transport Vehicle Technologies, which is exploring the use of metallic integrally stiffened cylinder (ISC) technology to fabricate single-piece aluminum cylindrical sections for fuselage applications. The ISC process is a single-step flow forming process for creating a seamless, thin-walled cylindrical shell with integral longitudinal stiffeners on the inner mold line (IML). The current state-of-the-art in ISC development at large scale for aluminum alloys is 10-ft diameter which is close in scale to current production single isle commercial subsonic transports such as the Boeing 737, hence the rationale for evaluating ISCs for fuselage applications. Using ISCs as the starting point for fuselage structure reduces fixturing and the time for assembly of stringers and skins, eliminates lap joints and fasteners, and reduces part count, thereby offering significant reduction in cost, weight, and manufacturing time. Studies replacing conventional multi-piece, machined and welded launch vehicle structures with ISCs estimate cost savings of up to 50% and reductions in manufacturing time by 40% over the conventional manufacturing processes (1), thereby motivating the exploration of the ISC process for high-rate, low-cost fuselage manufacturing.

The ISCs form the foundation of the fuselage section consisting of the skin and integral longitudinal stiffeners; however, additional structural elements (ASE) such as circumferential ring frames, floors, and local reinforcements around cutouts (doors and windows) are still required to support airframe mechanical and pressure loads. Select welding and additive manufacturing (AM) processes may be better suited for integrating these ASE with the fuselage section compared to the conventional assembly processes (riveting and adhesive bonding) and have the potential to improve structural performance, assembly rate, and/or damage tolerance of fuselage segments. This prompted the need for a trade study to evaluate candidate processes for integrating ASE with the ISC-based fuselage structure.

A manufacturing trade study was conducted to screen candidate welding and AM processes for integrating ASE with the prototype ISC-based fuselage. The first phase of this trade study focused on assessing candidate manufacturing processes specific to integrating the circumferential structural ring frames. Seven candidate manufacturing processes spanning solid-state and fusion welding and AM were evaluated. To compare the processes, NASA issued contracts with vendors specializing in each of the candidate manufacturing processes to produce single-blade stiffened test panels representative of ring frame structure and a data package detailing the manufacturing equipment, production steps and times, primary and ancillary equipment, tooling, fixturing hardware, and unique process environments. The test panels were subjected to post-fabrication secondary operations (heat treatment, machining and non-destructive inspection (NDI), microstructural evaluation, and mechanical property testing (hardness, tensile, and pull-off tests). The data packages were used to assess scalability, manufacturing steps and rates, first and second order process complexity, and applicability for fuselage structure. The results were used by the NASA team to aid in the downselection of manufacturing processes for integrating ASE.

The second phase of the manufacturing trade study used the analytical hierarchy process (AHP) to compare the candidate manufacturing processes for integrating ASE. The AHP used select data generated from the first phase of the study and literature to numerically score and rank the processes based on eight figures of merit (FOMs) specific to the MRL of the near-term assembly of a prototype ISC-based fuselage manufacturing demonstration article (MDA). The weighted scores were used to downselect and recommend manufacturing process(es) suitable for integrating ASE with an MDA.

1.2 Integrally Stiffened Cylinder (ISC) Technology

The integrally stiffened cylinder (ISC) process is an adaptation of the backward flow forming process for manufacturing seamless longitudinally stiffened barrels in a single forming operation (2), (3), (4), (5). As shown in Figure 1, a thick-walled cylindrical preform is placed over a mandrel that has machined grooves that define the longitudinal stiffener geometry and spacing. The mandrel and preform are rotated in tandem by a series of inner idler rollers while the outer drive rollers impart radial and axial compression forces to the preform as they translate along the length of the rotating preform. These compression forces, when above the yield strength of the preform material, cause the material to plastically flow in both the radial and axial directions to reduce the wall thickness and axially elongate the preform, while simultaneously forming material into the mandrel grooves to create integral longitudinal stiffeners on the IML of the ISC.

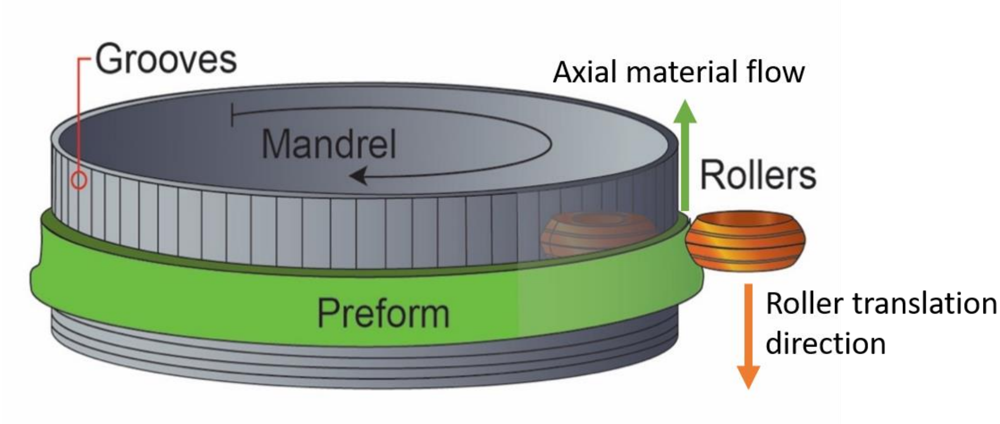
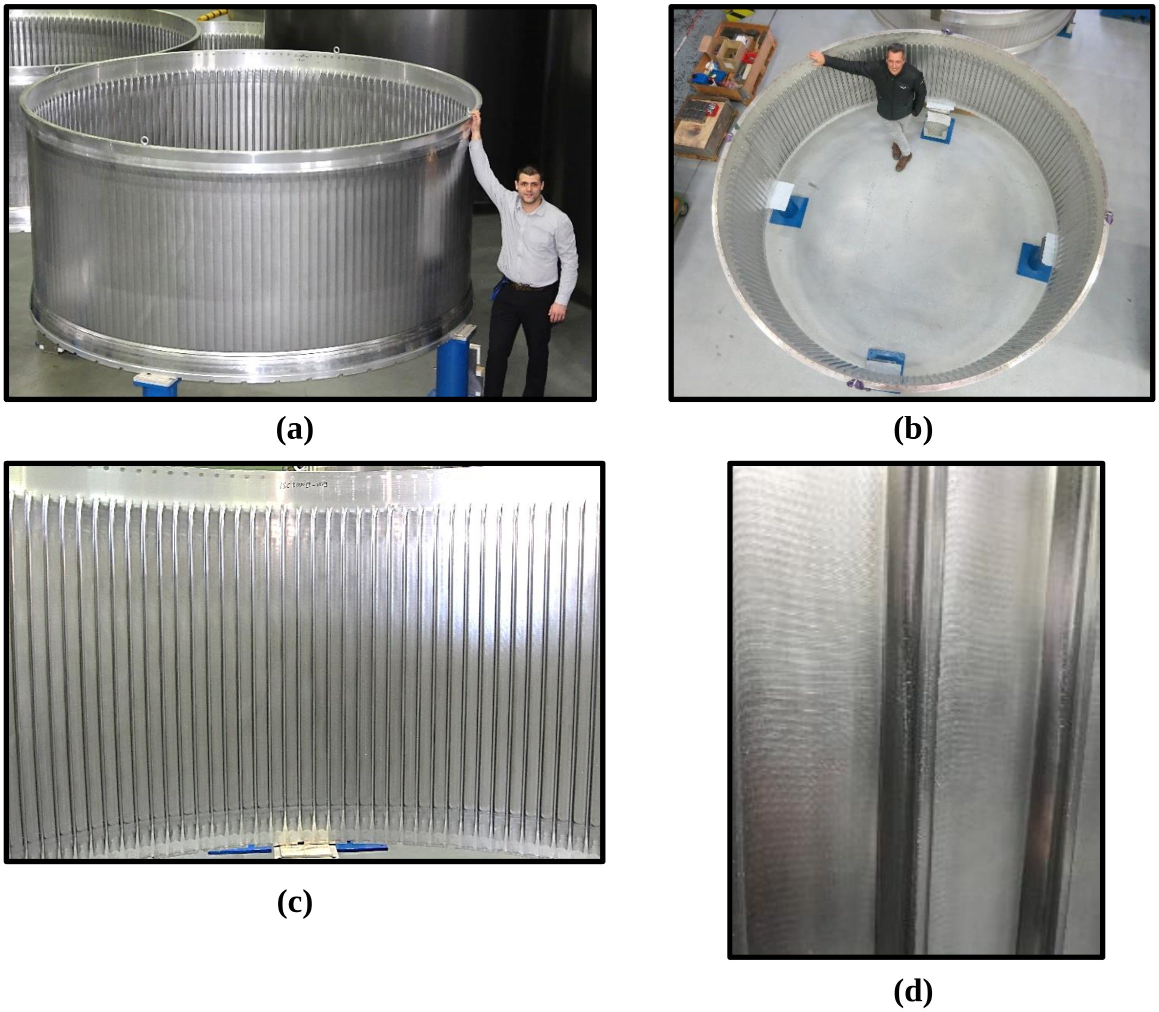


Figure 1. Schematic of the ISC flow forming process.

The current state-of-the-art in ISC development at large scale for aluminum alloys is 10-ft diameter, 5-ft long ISCs with the longitudinal blade stiffener geometries and spacings based on the mandrel design used during forming. The total forming time for these large-scale ISCs is ~ 90 min and thus directly supports the AATT goals for high rate manufacturing. Figure 2 shows an Al alloy 6061 ISC formed at MT Aerospace (Augsburg, Germany) and shows the outer mold line (OML), IML, and close-up views of the longitudinal stiffeners. The nominal wall thickness, stiffener geometry and stiffener spacing for the stiffened region of the ISCs are shown in Figure

3. This ISC design produces 0.5-inch tall stiffeners spaced every 2.3 inches about the IML, resulting in a total of 164 longitudinal stiffeners. The ISC stiffener geometry shown is the current and most successfully fabricated material / geometry combination to date, but the cylinder wall (skin) thickness, stiffener geometry and spacing have been sized for producibility. A structural design trade study was conducted in parallel with this manufacturing trade study to explore fuselage designs that capitalize on the benefits of ISC technology to achieve the high rate manufacturing and weight reduction goals of the AATT project (6).



(a)

(b)

(c)

(d)

Figure 2. Full-scale Al alloy 6061 ISC (10-ft. diameter by 5-ft. long); (a) OML, (b) top view of IML, (c) IML, and (d) close-up of stiffeners. (Image used with permission from MT Aerospace)

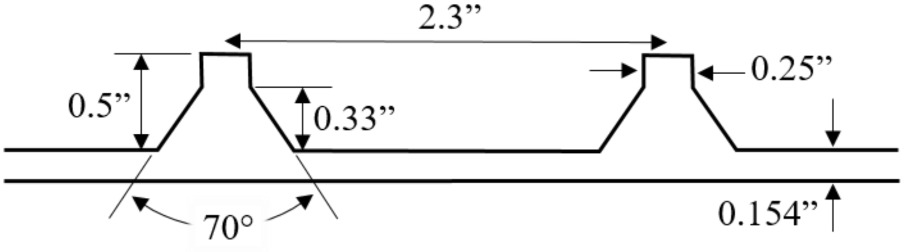


Figure 3. As-formed ISC stiffener geometry with associated dimensions.

The ISC technology has been demonstrated at different scales on a number of Al alloys, including 2219, 2195, 2050, and 6061. Al 6061 was selected for the 10-ft diameter ISCs to be used in the manufacture of the prototype ISC-based fuselage MDA based on its enhanced formability and heritage in ISC development activities. To ensure commonality with the ISC, Al 6061 was also selected as the base plate alloy in this manufacturing trade study. While Al 6061 is not a traditional fuselage alloy, it is being used a baseline for the fuselage MDA development. A separate study is evaluating the flow forming characteristics of potential airframe aluminum alloys with higher strength and damage tolerance more suitable for airframe applications.

1.3 Challenges of Integrating ASE with the ISC-based Fuselage

The ISC process represents a possible paradigm shift in fuselage manufacturing; however, it brings with it a number of new challenges. One of the principal challenges is associated with the overall scale of the single-piece, thin-walled 10-ft diameter ISC. Under this category, challenges include heat treating large structures to develop service properties; post-processing considerations such as machining, aligning, and joining ISCs end-to-end under tight tolerances; and integrating ASE with the ISC-based fuselage structure. The challenges associated with the overall scale and ancillary processing (heat treatment, machining, and joining) of the 10-ft. diameter ISCs are beyond the scope of this trade study. The focus of this trade study will be on those challenges pertinent to the candidate manufacturing processes used to integrate ASE with the ISC-based fuselage MDA.

Since candidate manufacturing processes will likely involve welding / AM rather than mechanical fastening (riveting), the properties in the weld zone or AM stiffener may be lower than desired due to factors such as dissolution of strengthening phases, in-situ annealing, or overaging during welding / AM. However, the scale of the built-up cylinders at different stages in the fuselage assembly process may prevent heat treating of the final structure to correct property knockdowns, thus promoting manufacturing processes that reduce mechanical property degradation.

Another challenge is the versatility of manufacturing processes to navigate the existing ISC geometry (e.g. stiffener shape and spacing, shown in Figure 3) to integrate the ASE. The ability to attach ASE to the skin for the closely spaced stiffeners makes process versatility a difficult challenge regardless of which manufacturing process is used. AM processes that have bulky print heads or welding processes with strict atmospheric requirements may not be compatible with ISCs, in spite of excellent performance when fabricating single-piece flat blade stiffened panels in controlled environments. As a result, the downselected manufacturing process should be versatile and adaptable to a fuselage production environment.

A related challenge for assembling fuselages from ISCs is the manufacturing rate for integrating the ASE. Selected welding / AM processes for integrating the ASE may require significantly longer production times than the baseline conventional manufacturing (riveting) or require additional post-processing steps (machining), thereby lessening the manufacturing rate benefits of the ISC technology. Thus, high-rate, low impact manufacturing processes are important to fully realize the benefits of ISC technology in fuselages assembly.

2. Candidate Manufacturing Processes for Integrating ASE

Eight candidate manufacturing processes spanning solid-state and fusion welding and direct energy deposition (DED) AM were considered in this trade study (Table 1).

Table 1. Candidate manufacturing and assembly processes for integrating fuselage ASE

Welding Processes	Friction Stir Welding (FSW)
	Refill Friction Stir Spot Welding (RFSSW)
	Laser Welding (LW)
	Cold Metal Transfer (CMT) welding
AM Processes	Additive Friction Stir (AFS)
	Laser Metal Deposition (LMD)
	Laser Hot Wire (LHW) AM
	Cold Metal Transfer (CMT) AM

A brief summary of each manufacturing process describing an overview of the process, its advantages and disadvantages, and maturity level are presented in the following sections to inform the reader as to the rationale for selection in this manufacturing trade study.

2.1 Conventional Manufacturing Processes

To assist in benchmarking the evaluation of alternative manufacturing processes for integrating ASE with the ISC-based fuselage structure, it is useful to begin with an overview of the processes for current state-of-the-art fuselage construction. Note that these conventional processes are described with respect to multi-piece construction of aircraft skins, stringers, and frames and are not specific to ISC-based fuselage manufacturing.

2.1.1 Riveting

The rivet is a simple but highly specialized type of fastener used to join, attach, or reinforce various types of structural materials including fabric, wood and metal. The rivet is a relatively tamper-proof, permanent fastener, unlike machine screws or bolts generally designed for easy removal and replacement. The riveted joint can carry both tension and shear loads, although the latter is the preferred loading. Further information covering a broad array of common aerospace rivet types may be found in Reference (7), and diagrams and discussion of riveting and its automation are found in Reference (8).

An advantage of the riveting process is ease of inspection, with the quality of the riveted joint being assessed simply by ensuring that the factory head is flush with the aircraft skin and that the shop head is symmetric and deformed as expected. An additional advantage is that the process can be performed at room temperature in a typical factory environment since it is a mechanical, non-reactive joining process. Typically no post-processing steps are required in terms of post-machining since the joint is mechanically fastened and forged to be flush with the aircraft skin. A further advantage is that rivets develop strength through cold working and subsequent natural aging, requiring no further heat treatment to perform at full-strength. However, riveting is labor-intensive, not in the installation of a single rivet but the large number (tens of thousands for a transport category aircraft) of rivets required (9). Also, the high number of rivets results in a weight penalty and increased part count and complexity. Each rivet hole is also a potential stress riser, crack initiation site, corrosion reservoir, and leak point for pressurized air or fuel, though practical solutions to each of these drawbacks have evolved over many decades

The technology readiness level (TRL) / manufacturing readiness level (MRL) of the riveting process is considered to be a 9, i.e. “full production process qualified for full range of parts and full metrics achieved.” The tooling and technology already exist, and riveting can be performed manually or robotically. Riveting is the most prevalent manufacturing process for assembling aircraft structures and serves as the baseline of comparison for assessing the benefits of the candidate manufacturing processes in this trade study.

2.1.2 Adhesive Bonding

Adhesive bonding is the primary alternative assembly process to riveting aircraft structures. Compared to riveting, which uses tens of thousands of parts and fasteners in the assembly of a passenger aircraft, adhesive bonding requires fewer and simpler parts. Aerospace adhesives include liquids, pastes, and films, each with its own specific curing requirements (10). Generally, aerospace adhesives require cure temperatures of at least 248°F to achieve full strength under a range of thermal and chemical operating conditions (11). Cold cure systems are available, requiring longer times (up to a week) to achieve full strength, although slight heating can speed up this process (10). The interested reader should see References (10) and (12) for more details. In order to cure, parts can be put into an industrial autoclave or heated with localized devices.

Adhesive joints offer beneficial, large stress-bearing areas compared to point (riveting) or linear (welding) joints and exhibit excellent fatigue strength, dampen vibrations and absorb shock, and yield an attractive strength-to-weight ratio compared to structures with metallic fasteners (11), (13). In addition, adhesive joints require little post-processing and are sealed, making cabin pressurization straightforward and preventing water penetration as opposed to a riveted structure, which has many access points (13). However, joint preparation requires strict requirements for cleanliness, or the performance of the bond will suffer irrevocably (14). In addition, adhesive bonding requires specialized facilities for surface cleaning and autoclaves to cure the adhesive joints, as well as the time required for the cure.

The TRL/MRL of the adhesive bonding process is considered fully mature, i.e. a level of 9, since the process has been implemented on full-scale aircraft for over 50 years (10). Adhesive bonding represents the second largest joining process used in the aircraft industry after riveting. Based on the drastically reduced part count compared to riveting and the unique requirements for surface cleaning and adhesive curing, the process is a useful alternative baseline for comparison for the proposed candidate manufacturing processes.

2.2 Welding Processes

Four welding processes were selected for this trade study to evaluate alternative joining methods that are commonly used for structural applications in the space and automotive industries. These processes would be used to attach pre-manufactured ASE directly to the ISC skin and/or stiffener. Solid-state welding processes such as friction stir welding (FSW) and refill friction stir spot welding (RFSSW) are of interest since they do not reach the melting point of the material, thereby avoiding common fusion welding issues such as hot cracking. The fusion-based laser welding (LW) and cold metal transfer (CMT) processes were also evaluated due to their slightly higher maturity and smaller weld process zone than FSW.

2.2.1 Friction Stir Welding (FSW)

Friction stir welding (FSW) is an established, solid-state joining method that has been replacing conventional, fusion-based welding for more than a decade. In FSW, a non-consumable tool consisting of a shoulder and a profiled pin that extends from the shoulder is used to join mating work pieces in either a butt or lap joint configuration. The tool is rapidly rotated and plunged into the mating work pieces which produces dynamic frictional heating that locally plasticizes the material at the joint interface. As the tool traverses along the joint seam, it mechanically intermixes and forges the hot and softened material by mechanical pressure that is applied by the tool and backing anvil. The interested reader is referred to References (15), (16), and (17) for FSW process schematics and in-depth discussion of FSW of aluminum.

One of the primary advantages of FSW is that it is a solid-state joining process that combines high temperature and strain in the weld zone which leads to a fine-grained recrystallized microstructure and improved mechanical properties compared to fusion welding processes (15), (18), (19). FSWs have smaller heat affected zones, less shrinkage and distortion, and lower risk of melting-induced cracking or porosity than fusion-based processes (15). This allows for the welding of a wide range of alloys including Al, Ti, and Ni alloys (18) and dissimilar materials (20), and offers more design flexibility for joints. In addition, operational costs for FSW are lower than fusion-based processes due to lower energy requirements, and the process is easier to automate. However, a disadvantage is that FSW equipment and tooling costs are typically higher due to structural requirements driven by higher loads and stresses associated with the FSW process (21).

FSW is a mature technology that has been used in commercial production since the late 1990s. Initially, FSW was first applied in the shipbuilding industry and has since grown into aerospace. FSW has been commercially demonstrated at scales relevant for fuselage structures, including welding of Space Shuttle external tanks (~27 ft. diameter) and FSW of skin panels for the Airbus A380 (22). This technology can be readily adapted for high-rate fuselage manufacturing needs in the commercial transport aircraft industry. For these reasons and in combination with the maturity of the process, FSW is a highly regarded candidate process for the manufacturing trade study.

2.2.2 Refill Friction Stir Spot Welding (RFSSW)

Refill friction stir spot welding (RFSSW) is a solid-state joining process derived from conventional FSW; however, during RFSSW no linear translation of the tool occurs. This results in a localized "spot" weld. Although one continuous process, RFSSW occurs over four stages: clamping, plunging, stirring, and extraction. The RFSSW process uses a tool comprised of two rotating components - a pin tool probe and shoulder - assembled concentrically within a static clamp ring. The pin tool probe and shoulder move independently in the vertical direction during the plunge and extraction stage. This tool design enables the material contained within the weld nugget to "refill" the exit hole as the pin tool probe is extracted following weld completion and avoids leaving an exit hole typically associated with conventional FSW or friction stir spot welding (FSSW). The interested reader should see References (23) and (24) for more details about the process and relevant schematics and microstructures.

The principal driver for RFSSW is to replace mass-adding fastening processes, such as riveting, and to join a wide range of dissimilar materials, which are currently difficult to join using fusion welding processes. In comparison to fusion welding processes, the RFSSW process advantages include the lack of inert gas shielding requirements, porosity, or metal spatter. RFSSW has been demonstrated for a wide range of dissimilar materials. The process complexity is relatively low; therefore, it is amenable to automation and favorable for production environments. In comparison to resistance spot welding, RFSSW has lower energy demands and a lower sensitivity to contamination effects. In comparison to riveting, RSFFW is less complex since it does not involve fasteners, pre-drilling of fastener holes and is less expensive. One of the primary disadvantages of the RFSSW technique is that it creates a non-continuous joint, making it less robust. Additionally, the RFSSW can be susceptible to hook and bonding ligament defects, which can degrade mechanical properties (25).

RFSSW is a relatively new adaptation of FSW but is a mature joining technology that has been used in commercial production in the shipbuilding, railway, and automotive industries. Reference (26) details the application of RFSSW for fuselage and wing construction along with skin-stringer joining. This technology would be readily adaptable for high-rate fuselage manufacturing needs in the commercial transport aircraft industry. For fuselage construction, RFSSW is of interest as a replacement for riveting because it is faster, easier to automate, and less expensive. Conceptually, the strategy and equipment staging for RFSSW will be similar to riveting technology. Therefore, RFSSW likely can be implemented into current production lines as a more direct substitution for riveted construction. The maturity of the process and clear advantages over other fusion-based processes make RFSSW a desirable candidate for the manufacturing trade study.

2.2.3 Laser Welding (LW)

Laser welding (LW) is a fusion welding process that uses a high-energy laser to join metal work pieces. The beam provides a concentrated heat source, which allows for narrow, deep welds, and high welding rates. LW can be autogenous or used in conjunction with filler wire of a special composition to weld hot-crack sensitive materials. A laser welding system is comprised of four primary subsystems: the laser, the wire feed subsystem, the shield gas delivery subsystem, and the motion subsystem, which controls the location of the laser beam relative to the work piece. The laser subsystem often consists of a direct diode laser that uses multiple wavelengths of light resulting in larger focused laser spot sizes that are more amenable to aluminum processing. The motion subsystem often consists of a robotic arm that controls the position of the laser with respect to the work piece. The reader is referred to Reference (27) for a thorough description of LW and process variables.

LW offers several advantages for aircraft manufacturing, including that it can be used with crack sensitive aerospace-grade aluminum alloys when used with an appropriate filler material, exhibits good weld repeatability, and can be readily automated using robotic positioning systems. These systems can be adapted to large-scale manufacturing environments for joining components in-situ at high rates. One key disadvantage for LW aluminum aircraft structures is the difficulty in transferring the energy from the laser beam to work piece weld location due to the high reflectivity and high thermal conductivity of aluminum alloys. This issue can be overcome by using lasers with shorter wavelengths of light and resistively heating the weld wire. Another issue associated with laser welding is the highly localized heat input that can result in distortion and/or residual stresses in the welded structure.

LW is widely used in the automotive industry (28). The use of LW is not as widespread in the aircraft manufacturing industry but is emerging as a highly desirable process. LW was selected as a candidate joining process for this trade study due to its industrial maturity and its amenability to automation. This process is readily scalable due to its utilization of robotic controls for laser and wire positioning. It can be integrated into the fuselage manufacturing stream and used to rapidly weld large-scale components in-situ within the manufacturing environment.

2.2.4 Cold Metal Transfer (CMT) Welding

Cold metal transfer (CMT) welding is a modified form of gas-metal arc welding (GMAW) based on short-circuit transfer of weld metal. The process was invented by Fronius in 2004 and was specifically designed to reduce heat transfer to the substrate during welding. CMT works under the same principal as GMAW, with the primary differences being control of the wire feed motion and the physical characteristics of the metal droplet detachment and transfer to the melt pool. Instead of the wire moving continuously forward into the melt pool, as in GMAW, the CMT process control system incorporates rapid back and forth wire feed motion to separate droplets in phase with the arc, thereby lowering the overall heat input. Through use of the sophisticated control and weld robotics, the CMT process can be utilized in both the weld and AM modes. The reader is directed to References (29) and (30) for more information about this process.

The principal advantage to the CMT process is reduced heat input, which leads to a multitude of benefits including reduced residual stresses and part distortion due to lower heat conduction and the ability to use thin-gage sheet products (as thin as 0.118 inches, or 0.3 mm) (31). However, at thicknesses greater than 0.39 inches (10 mm), the conventional GMAW process is favored. CMT does offer improved weld quality and reduces post-production rework, leading to an increase in manufacturing and efficiency. However, due to process complexity, CMT requires precise control of the weld parameters hence it requires a sophisticated computer and robotics for industrial application. It can be more expensive than conventional GMAW processes unless incorporated into an overall large-scale production facility to amortize costs.

CMT was originally developed for joining thin-gage sheet metal in the automotive industry but has since expanded to thicker gage sheet products where structural integrity of the weld is important. CMT was selected for the manufacturing trade study based on the need for depositing material on thin-gage aluminum airframe structure, as most of the blade stiffeners and ISC skin components will be in the range of 0.040 to 0.080 inches thick. In addition, the process is readily adapted to weld robots or gantry systems, which would facilitate airframe manufacturing.

2.3 Additive Manufacturing Processes

Additive manufacturing (AM) processes represent a class of fabrication technologies that are classified as either non-beam based (solid-state) or beam-based fusion (direct energy deposition, DED) techniques that result in near-net shape structural elements. The solid-state process described as additive friction stir (AFS) deposition is capable of precise, site-specific fabrication of deposits (32). This process was considered as a possible candidate for this project given its ability to generate near-net shape geometry required for an airframe stiffener with low heat input. Ultrasonic additive manufacturing (UAM) was briefly considered but omitted from this study due to scalability issues in building up structures from thin foils.

Directed energy deposition (DED) AM processes utilize high energy beam or arc-based energy sources to selectively deposit wire or powder feedstock in the molten state and build structural elements by fusion of the deposited layers (33). These methodologies are capable of rapidly fabricating near-net shape geometries with tailored properties, and the processes evaluated include laser metal deposition (LMD), laser hot wire (LHW), and cold metal transfer (CMT) AM. These processes are candidates for this project given their ability to generate near-net shape geometry by selective melting of wire or powder feedstock in-situ on a substrate to achieve the required geometry for an airframe ASE.

2.3.1 Additive Friction Stir (AFS)

Additive friction stir (AFS) deposition is a solid-state metal deposition process that uses a non-consumable hollow tool through which feedstock material (solid rod or powder) is delivered. The tool rapidly rotates and sits above the substrate surface, which defines the layer height of the deposited layer. The feedstock material is fed through the tool and plunges into the substrate where the contact dynamic friction at the tool / feedstock material interface generates heat that locally plasticizes the feedstock material by severe plastic deformation. Heated and softened, the feedstock material metallurgically bonds with the substrate. The transverse motion of the tool results in a single track of feedstock material being deposited on the substrate surface. Selectively adding subsequent layers results in the generation of a 3D part. An excellent overview of this process is presented in References (32) and (34) with property information available in References (35) and (36).

The primary advantages of the AFS process stem from the fact that it is a solid-state deposition process compatible with most metals and metal matrix composites. It has a high deposition rate compared to other AM processes (5.95 lbs / hour for Al 6061 alloy (32)), and typically uses 3/8 in. square rod as the feedstock. Additionally, AFS is performed in atmosphere so is not restricted by environmental chamber size and is therefore readily scalable to support large parts. However, the AFS process does require a backside support to react the forces required to promote metallurgical bonding. The AFS process generally is expected to produce minimal distortion due to the lower heat input as compared with fusion-based AM processes. However, a disadvantage of the AFS process is the amount of excess deposited material (flash) that is produced, likely requiring extensive machining to achieve the final geometry.

This process is relatively new but has a sustained record of developmental research efforts for certain applications. NASA has utilized the process to fabricate stiffener structures on flat panels and fabricate curvilinear stiffened panels, confirming the ability to fabricate stiffened structures with complex geometries. Also, a demonstration reinforced window frame for the Orion crew module geometry was successfully fabricated, representing applications with potential benefit for fuselage structure. These potential benefits of AFS for fuselage structures stem from the demonstrated high deposition rate and compatibility with aluminum alloys that are of potential interest for fuselage applications.

2.3.2 Laser Metal Deposition (LMD)

Laser metal deposition (LMD) is a laser-based DED process in which a laser beam is used to form a molten pool on a metallic substrate. A nozzle injects metal powder from a hopper into the path of the laser at the molten pool via an inert gas stream. This process is differentiated from the powder bed fusion (PBF) process in which the powder is pre-deposited on a bed for selective melting (33). During LMD, the laser and powder interact, preheating the particles to below their melting point, and the preheated particles are absorbed into the laser-induced melt pool. The absorbed powder particles quickly melt and then re-solidify into a deposit as the motion system translates the laser across the substrate surface. The size of the melt pool, the speed at which the laser moves, and the powder feed rate dictate how much powder is captured in the melt pool, and thus the overall deposition rate. Reference (37) provides an overview of LMD and contrasts it with the more common laser PBF process.

An advantage of the laser DED process over continuous wire arc AM (WAAM) processes is lower overall heat input into the process zone. This process offers low controlled heat input and rapid cooling rates which result in a reduced heat affected zone and minimal residual stress and distortion within the deposit as well as improved microstructures (38). The mechanical properties for some nonferrous metals have been found to be close to wrought (39), though no reported properties for aluminum were found. Additionally, the use of powders allows for graded material compositions as well as omnidirectional printing (38). However, distortion becomes an issue in large-scale LMD builds as the build height increases (40). The deposition rates vary greatly depending on the application, with a high rate of 39.9 lbs / hour reported for cladding cylinders down to 0.001 lbs / min for jet engine repair (41). Despite advances in the technology, reliability issues remain for 2xxx and 7xxx aluminum (32). In terms of the fuselage MDA, scale up of the LMD process for production of a large structure would be difficult due to the requirements for an inert gas environmental chamber in order to prevent hydrogen pore formation, yet recent work has shown the ability to deposit aluminum in atmosphere with gas shrouding (40).

LMD is considered to be an emerging technology and, as such, has a low TRL. LMD has been widely implemented as a repair technology in the aerospace sector and used for two-dimensional cladding in other industries (39), only recently being implemented as an AM technique for 3D structures. LMD was selected as a candidate process for the manufacturing trade study due to fast cooling and a small heat affected zone resulting in good mechanical properties as well as the ability to create complex geometries.

2.3.3 Laser Hot Wire (LHW) AM

The laser hot wire (LHW) AM process is similar to the LW process with resistively-heated filler wire (see Section 2.2.3). In the case of the LHW AM process, the wire is fed into the molten pool on the substrate surface created by the laser. The wire melts and is deposited as a single bead along a programmed path. A robotic arm increments the laser and wire in the Z-direction for subsequent deposition layers, resulting in a multilayered deposited structural feature (such as a blade stiffener) on the substrate. There are numerous references available for more detailed information about the LHW AM process and resulting material properties (42), (43), (44), (45).

LHW AM can have deposition rates on the order of 10-15 lbs / hour, depending on the wire size and the feed rate, making this deposition rate high compared to other additive manufacturing processes. However, LHW AM has the same disadvantages as does LW where high localized heat input that can result in distortion and/or residual stresses in the deposited structure. In addition, the LHW process results in a rapidly solidified, as-cast microstructure and will contribute to lower mechanical properties than wrought materials. Finally, LHW is a near-net shape process and requires post-deposition machining to produce the final dimensions.

This fabrication technique has been reportedly used for deposition of small, near-net shape structural features that can be easily machined to final shape and heat treated to the required property levels (43). However, with respect to fabricating large structural items similar to an airframe structure, the LHW process has a low maturity level. That said, LHW was selected for this study due to its high deposition rate compared to other additive manufacturing processes and potential scale-up and incorporation of the robotically-controlled laser positioning system into an industrial manufacturing environment.

2.3.4 Cold Metal Transfer (CMT) AM

Cold metal transfer (CMT) AM is classified as a wire arc additive manufacturing (WAAM) process and is similar in principal to the CMT welding process (see Section 2.2.4). CMT AM is a low heat input variant of the gas metal arc welding process (GMAW) process in which the current carrying wire is mechanically oscillated to provide controlled dip transfer. The CMT AM process produces metal parts layer by layer, with the layers formed by the melting wire electrode. This WAAM technique is particularly suited to deposition of aluminum alloys due to the high reflectivity of aluminum making it a difficult material to deposit with laser processes. The mechanical wire control leads to continuous, spatter-free deposits, which aid in preventing flaws while the low heat input of the process results in minimal melting of the substrate material and prior deposited layers. More detailed information of the CMT AM process is provided in References (46), (47), (48), (49), (50).

CMT AM offers a relatively high deposition rate, which helps to reduce production times and enables the production of high volume structures. TWI reports that CMT AM used to generate a 5183 aluminium structure using a 0.039 in. diameter wire resulted in a deposition rate of 2.07 lbs / hour (51). In the future, multi-wire solutions could give rise to even higher deposition rates. Compared to powder-based processes, CMT AM benefits from the immediate availability of a range of AWS-certified filler metal wire compositions. There are relatively few powder-based compositions to choose from, and it can take years to acquire the necessary certification and material data sheets.

The use of traditional welding processes for WAAM aluminium is limited by solidification defects such as porosity and solidification cracks, which negatively impact mechanical properties. The use of CMT AM in various pulse and polarity modes in Al 2139 build deposits resulted in a refined equiaxed microstructure, elimination of porosity, reduction in cold and hot cracking, and improved mechanical properties as compared to the O-tempered alloy (50).

The CMT AM process advantages include low equipment costs, high arc deposition rates, high precision forming, ultra-low heat input, stable arc and droplet transition without splash. The process is designed for use on a robotic system and therefore is well suited for AM, where a pre-determined path is used to generate complex structures in large scale manufacturing. Based on these process attributes, the CMT AM process was selected for this trade study

3. Manufacturing Process Downselection

The analytical hierarchy process (AHP) was used for downselecting the manufacturing processes to integrate ASE with the ISC-based fuselage MDA. The AHP is an analytical tool developed by R. Saaty (52) to assist with the decision making process when both quantitative and qualitative criteria are under consideration. The AHP models the decision problem through a hierarchical structure of the evaluation criteria, or figures of merit (FOMs). Through use of pairwise comparisons, weights are allocated to the FOMs and the value of the benefits achieved by the various FOMs methods is quantitatively determined. Scores on a standard scale are then assigned to the candidate manufacturing processes to determine how well each process fulfills FOM requirements, and the scores are multiplied by the FOM weighting factors and summed to achieve a final weighted score. These weighted scores form the basis of comparison among the manufacturing processes and were used to downselect processes for adding ASE to the ISC-based fuselage MDA.

3.1 Figures of Merit for Downselection

In this study, FOMs were chosen to represent important aspects for the manufacture of the fuselage MDA and were used to judge the capability of the candidate manufacturing processes for integrating ASE such as circumferential ring frames or stiffening elements around window and door cut-outs. The following eight FOMs were selected to model the decision problem on which manufacturing process(es) to downselect:

- Scalability
- 1st order process complexity
- 2nd order process complexity
- Post-processing requirements
- Deposition rate / joining rate
- Structural performance
- Distortion / distortion control methodology
- Inspectability / repairability

It should be noted that these FOMs are specific to the decision of which manufacturing process(es) to use for the prototype ISC-based fuselage MDA. External commercial airframe stakeholders for a future advanced metallic airframe would likely have alternative or additional FOMs. The FOMs and associated definitions are outlined in Table 2 and were provided along with the survey of pairwise comparisons to a group of researchers at NASA LaRC for performing the AHP.

Table 2. Figure of Merit (FOM) definitions

Figure of Merit	FOM Definition
Scalability	• 8” x 18” flat plate to 120” diameter cylinder with 2” tall stiffeners (~25 ring frames) • Access to inside surface of cylinder • Build feature size vs. process zone size • Feedstock utilization efficiency • Process automation capability • Manufacturing readiness level (MRL) / technology readiness level (TRL)
1st order process complexity	• Process-specific considerations (hardware/infrastructure requirements) • Unique tooling (e.g. gas shielding, powder handling, fixtures/jigs) • Unique facilities (e.g. environmental control, clean room)
2nd order process complexity	• Piece-by-piece consideration (required for each part) • Surface prep/preservation/environmental control requirements • Critical times (e.g. adhesive cure, pot life, protective coatings) • Number and order of major operations (e.g. avoid multiple heat treatments)
Post-processing requirements	• Mechanical properties (e.g. hardness, tensile) • Microstructure and properties dictate whether heat treatment is required • Machinability (as-deposited and after direct age heat treat)
Deposition / joining rate	• Process-specific, may be variable; affects throughput
Structural performance	• Defined as stiffener pull-off load per unit weight of sample • All samples machined first; some as-deposited and some with direct age heat treatment
Distortion / distortion control methodology	• Distortion and distortion control methods
Inspectability / repairability	• Inspectability and repairability during fabrication

Figure 4 depicts the complexity of the decision making process in downselecting a manufacturing process that best represents the values placed by the surveyed researchers. The FOMs are applied to every manufacturing process, with the quantitative value of the FOM based on the weights assigned during the AHP survey process.

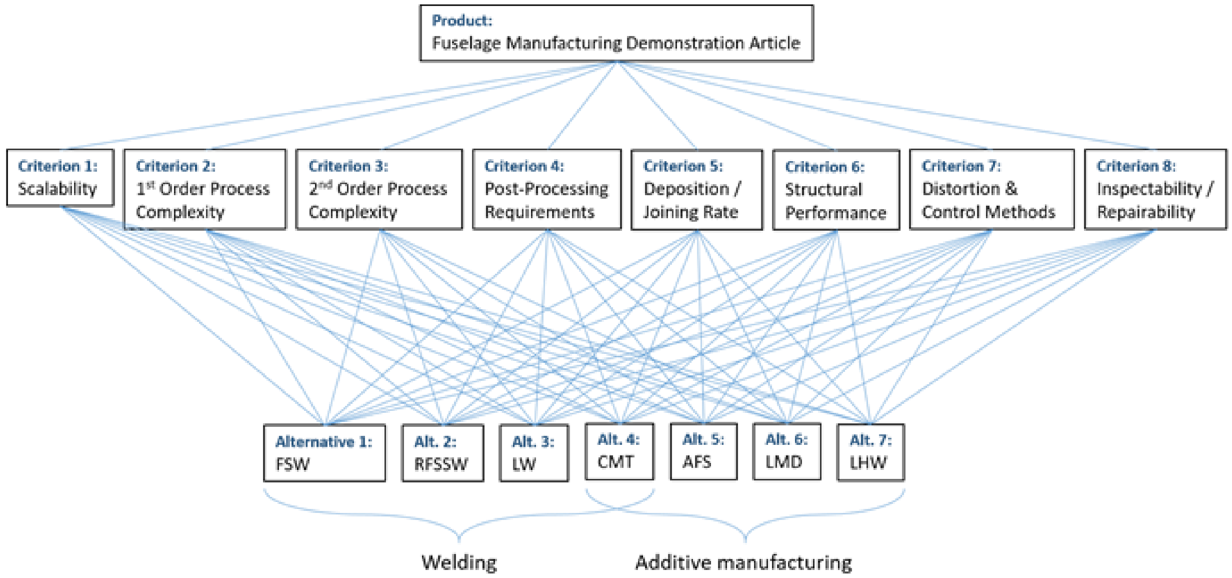


Figure 4. **Schematic showing the decision making process addressed by the AHP analysis, where the criteria (FOMs) are applied to each of the manufacturing processes to compare their relative value for the fuselage MDA**

3.2 Weighting of the Figures of Merit

Sixteen researchers in the materials and structures fields at NASA LaRC formed the survey group and were provided with the AHP survey, FOM definitions, and manufacturing trade study overview. The survey group was instructed to compare the FOMs based on their individual assessment of each FOM's value in manufacturing the fuselage MDA.

The AHP pairwise comparison tool was not specific to any particular manufacturing process. For each pairwise comparison of two FOMs, the reviewers were instructed to consider how much more important one FOM was relative to the other FOM. Higher rankings were given to those FOMs, which would make it easier, faster, and/or would provide better performance (properties) for manufacturing the fuselage MDA.

The AHP survey covered 8 FOMs, resulting in 28 pairwise comparison questions (Table 3). For each pairwise comparison of FOMs, the reviewer was required to rank the FOMs on a scale of 1 to 9, with 1 being "equally important" and 9 being "absolutely more important". Macros contained within the AHP survey spreadsheet calculated the relative weights placed on each FOM after all the pairwise comparisons were completed.

Table 3. Summary of the FOMs and pairwise comparisons required by the survey. FOMs are not listed in any particular order.

FOM #	FOMs	Pairwise Comparisons	# of Pairwise Comparisons
1	Scalability	1 vs. 2-8	7
2	First-order process complexity concerns	2 vs. 3-8	6
3	Second-order process complexity concerns	3 vs. 4-8	5
4	Post-processing requirements	4 vs. 5-8	4
5	Deposition rate / joining rate	5 vs. 6-8	3
6	Structural performance	6 vs. 7-8	2
7	Distortion and distortion control methodology	7 vs. 8	1
8	Inspectability / repairability	------	0
Total			28

At the completion of the survey, a consistency ratio was calculated by a background macro to ensure a consistency ratio below 0.1. Ratios above 0.1 triggered an error message that highlighted the inconsistent FOMs, and the reviewer was required to adjust his or her rankings to lower the consistency ratio to an acceptable level.

Through pairwise ranking of the FOMs, the reviewer implicitly creates a hierarchy based on his or her individual assessment of each FOM's relative importance. When multiple reviewers complete the AHP survey, the results may be aggregated to summarize the group's collective ranking of the FOMs. The results of the AHP analysis were applied to the candidate manufacturing processes to assist in their downselection for completing the ISC-based fuselage MDA.

AHP Results: FOM Prioritization and Weights

The results of the AHP surveys were obtained from the individual reviewers of the survey group in the form of normalized priority vectors (i.e. weighted FOM rankings). These were aggregated using the row geometric mean method to obtain a group priority vector, with the normalized FOM rankings shown in Table 4.

Table 4. Aggregated FOM rankings and normalized prioritizations from the survey group.

Figure of Merit (FOM)	**Normalized Prioritization**
Scalability	0.296
Structural performance	0.166
Distortion / distortion control	0.139
1st order process complexity	0.122
Post-processing requirements	0.115
2nd order process complexity	0.060
Deposition / joining rate	0.051
Inspectability / repairability	0.051

The AHP results showed that scalability was the most valued FOM for integrating ASE on the fuselage MDA. This emphasized that the welding or AM process downselected for the MDA should be readily scaled and implemented on the 10-ft. diameter ISCs. Two other FOMs that were given significant value were structural performance and distortion/distortion control methodology; this meant that a process may not be downselected if it resulted in the MDA exhibiting low structural performance, e.g. process-induced property knockdowns. Similarly, if the manufacturing process produced large distortions in the MDA from the heat of deposition or joining and/or residual stresses, the manufacturing process would be less likely to be downselected.

In contrast to the most valued FOMs, 2nd order process complexity, inspectability/repairability, and deposition/joining rate were given the lowest prioritization by the surveyed researchers. Despite the low normalized FOM rankings, a process should not be discounted if it requires more joining time, additional surface preparation, curing time, or complicated inspection and repairs, provided that it has acceptable scalability, structural performance, and low distortion. While certain FOMs may be given greater value in commercial, serial production of aircraft fuselages (e.g. deposition/joining rate), they were given low prioritization for the production of a singular fuselage MDA.

3.3 Manufacturing Process Scoring

Teams were formed for each FOM to develop a scoring metric for evaluating the candidate manufacturing processes. The scoring metric consisted of numerical score definitions and scores assigned on a 1-5 scale, with 5 being the best and 1 the worst. The scores for each manufacturing process were derived from data generated from internal tests and analyses of manufacturing demonstration panels, data packages produced for each candidate manufacturing process, engineering judgment, and reference literature. The definitions of the 1-5 rating scale, the assigned scores, and the rationale for the given score are provided in Appendix A, Table A- 1 to Table A- 9 for each FOM and manufacturing process.

A summary of the assigned numerical scores for each FOM and manufacturing process weighted scores is shown in Table 5 and Figure 5. The weighted score and ranking of each manufacturing process is determined by multiplying the numerical score for each FOM by the FOM normalized prioritization factor (in parentheses beneath each FOM in Table 5). It should be noted that the inspectability/repairability FOM was split for scoring and the two components evaluated separately (see Table A- 8 and Table A- 9), since inspectability and repairability have distinct requirements for scoring. After scoring, these two FOMs were recombined and the numerical scores averaged in the manufacturing process ranking and downselect analysis.

Although a test panel was not fabricated using CMT welding, it was deemed a promising candidate manufacturing process after the benefits of CMT AM were realized. Much of the FOM scoring relied on qualitative assessments, thus scores were developed for CMT welding for each FOM using engineering judgement and adopting the rationale from similar processes (e.g. LW and CMT AM). CMT welding was thus included among the candidate processes for downselection shown in Table 5 and Figure 5.

A final note is required to understand the conventional manufacturing scores. The conventional manufacturing processes were scored under the assumption that state-of-the-art fuselage assembly methods using skin-stringer panel sub-assemblies were being used to serve as a baseline using real world, in-use large-scale manufacturing data. As a result, direct comparisons between the scores for conventional processes (riveting and adhesive bonding) and those for welding and AM processes cannot be made, since scores for the latter processes were assigned with the ISC-based fuselage concept in mind.

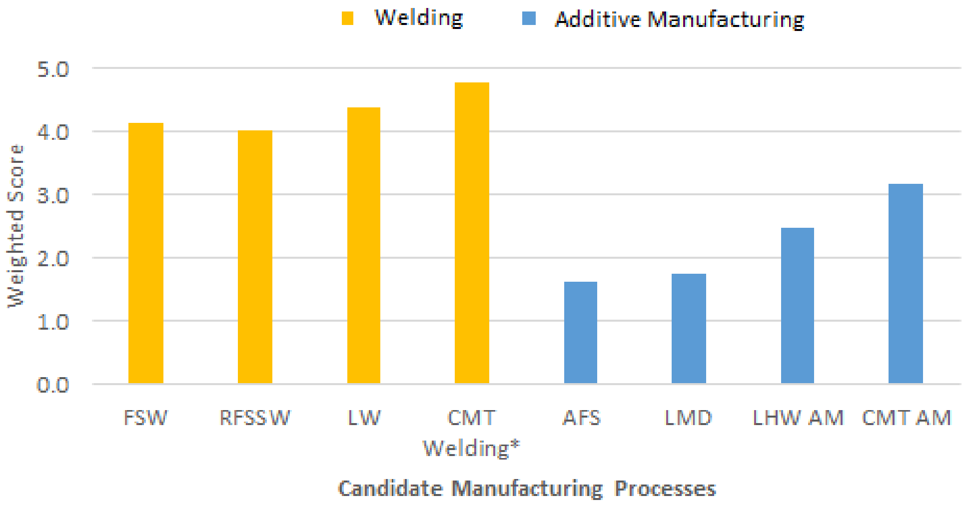
Table 5. Summary of FOM numerical scores and resulting manufacturing process weighted scores.

Manufacturing Process	Figures of Merit (FOMs)									Total Weighted Score
	Scalability (0.296)[1]	Structural Performance (0.166)	Distortion/ Distortion Control (0.139)	1st Order Process Complexity (0.122)	Post-Processing Requirements (0.115)	2nd Order Process Complexity (0.060)	Deposition / Joining Rate (0.051)	Inspectability (0.026)[2]	Repairability (0.026)[2]	
FSW	5	4	3	4	4	4	4	4	4	4.16
RFSSW	4	3	5	4	4	5	4	3	5	4.03
LW	5	5	3	3	5	4	5	5	3.5	4.38
CMT Welding[3]	5	5	5	4	5	4	5	5	3.5	4.78
AFS	2	1	2	1	1	3	1	3	2	1.63
LMD	1	1	5	1	1	3	1	2	3	1.75
LHW AM	3	1	3	3	1	4	3	2	3	2.47
CMT AM	4	1	5	4	1	4	3	2	3	3.17

[1] Values in parentheses under the FOM headings are the normalized prioritization of each FOM (see Table 4)

[2] Weighting results from halving the joint Inspectability / Repairability FOM weight

[3] Process did not have a data package or characterization



*CMT Welding did not have a data package or characterization

Figure 5. Comparison of the total weighted scores for candidate welding and additive manufacturing processes.

To compare the candidate manufacturing processes, a discussion and comparison of the weighted score for each manufacturing process is presented. The four highest prioritized FOMs (scalability, structural performance, distortion/distortion control, and 1st order process complexity) are discussed in detail as they had the largest impact on the downselection decision, followed by a brief discussion of the remaining FOMs.

The lowest ranked processes, LMD and AFS, will not be discussed in detail, given that each process has considerable challenges to overcome for implementation in large-scale manufacturing. LMD received the lowest scalability score due to the need for an environmental chamber to maintain an inert atmosphere in this study, severely limiting the size of the build envelope (currently 5 ft x 5 ft x 7 ft.). Gas shielding has shown some promise in printing aluminum alloys (53; 44), though more study is needed to be able to reliably print aluminum in a manufacturing setting. Additionally, LMD requires low-porosity, spherical powders to maintain consistent flow to make high quality parts, which would be expensive for large scale manufacturing. In order to form complex shapes or maneuver around obstacles such as stringers, the robotic assembly equipment would need significant development. While LMD scored highly for distortion, its low performance across most other FOMs, particularly scalability due to low TRL and issues with reliability, justified its removal from the downselection of candidate processes.

The AFS process also scored poorly across the prioritized FOMs. In terms of scalability, AFS has also not been proven on larger scales, although the process is performed in ambient atmosphere compared to the strict environmental requirements for LMD. Additionally, AFS modifies standard FSW tooling and continuous feeding of the rod feedstock is not yet widely implemented. In order to be a viable large-scale manufacturing process, this issue would need to be addressed, as well as integrating AFS tooling to a gantry system capable of reacting the forces generated during deposition. The remaining manufacturing processes are discussed in detail below and were considered for downselection.

Scalability

The scores for scalability mirror the maturity (TRL/MRL) and implementation level of these processes in current large-scale manufacturing. The process should be readily adapted, integrated, and scaled to current production practices without requiring significant new production facilities. It follows that those processes already adopted by the aerospace industry, like some of the welding processes, received higher marks, while the less mature AM processes scored lower.

FSW received a high score given that it is already being employed in the aerospace industry. While RFSSW is gaining popularity with usage in skin-stringer joining, itis at a slightly lower TRL level. FSW has been adopted by the aerospace industry for large-scale production, seeing usage in the welding of the Space Shuttle external tanks (~27 ft. in diameter) and of skin panels for the Airbus A380 (22). LW has been implemented in large-scale aerospace manufacturing on the Airbus A318 to simultaneously weld both sides of the skin-stringer joints using a dual-beam robotic laser system to achieve a ~ 20x increase in joining rate compared to riveting (54). Furthermore, CMT welding is fully automated in the automobile industry, giving it a higher TRL rating if used as a welding technology. Accessibility to the inside surface of the ISC between stringers could be a concern for LW, CMT (welding and AM), and LHW given out-of-plane weld paths and tight spacing between stringers (~2.3 in.). The programmable path could be complex in order to properly position the energy source, material feedstock, and gas shielding.

CMT and LHW AM received higher scores for scalability due to their similarity to welding processes; however, both processes have low maturity levels when dealing with large-scale manufacturing. CMT AM equipment used in this study had a build envelop of 3 x 3 x 3 ft., though this could be expanded by integrating the robotic system on a single axis rail or three-axis gantry. Similarly, LHW AM could be integrated with a robotically-controlled system with laser positioning, and thus is also amenable to scale-up. The potential for large-scale airframe manufacturing is possible for CMT and LHW AM, but neither has been proven in production.

The welding and AM processes discussed above all show promise in scaling up to (or are already used in) large-scale manufacturing. While there are no barriers preventing their implementation in terms of scalability, innovation is still needed to achieve consistent access to the inner skin between stringers to complete welds or deposition given bulky tool heads, energy sources, material feedstock, and gas shielding.

Structural Performance

Tensile, microhardness, and microstructural characterization were conducted on specimens excised from the panels to infer the structural performance of the candidate processes. Al 6061 was chosen as the alloy for the base plate for each of the manufacturing process. The test data of the joint interface / built-up regions was collected and compared to wrought Al 6061 base plate properties to assess the impact of these processes on the parent material. The results may not reflect the true potential of each process because (1) the selection filler/feedstock materials may be different than the 6061 base plate material, and (2) process parameter optimization was not performed.

LW and FSW received the highest scores, 5 and 4 (respectively), due to the small tensile property knockdowns, with the fusion zone of the weld retaining roughly 80% of the hardness of the Al 6061 T6 baseplate measured at a remote location. In addition, LW and FSW are the only two processes which have been used in large-scale aerospace production, and thus are known to be able to provide adequate structural performance.

Based on the lower heat input of CMT welding compared to LW, it was assumed that CMT welding would have similar or better performance to LW. Adding to the evidence, CMT AM has a lower tensile property knockdown than LHW, suggesting the weld variant of the processes would follow suit. For these reasons, CMT welding was ranked a 5. RFSSW scored a 3 and had the greatest decrease in hardness of the three welding processes accessed, with 61% of the hardness of the base plate in the weld. Also, the weld cross sectional area for RFSSW is the largest of three processes. RFSSW is a discrete weld, whereas the other processes are all continuous deposition, thus the differences in local microstructure could serve as stress concentrators under load.

LHW and CMT AM used ER5356 weld wire as the feedstock and thus direct comparison of the deposit with the 6061 Al base plate is not possible. The LHW and CMT AM deposits exhibited similar hardness values and tensile properties and were approaching 6061-O properties. This was not unexpected and is within the norm for welding processes. These reductions in strength result from the fusion AM processes depositing material in an as-cast state, with re-heating from subsequent deposition layers further overaging the material. This results in a stiffener with properties closer to the annealed (O temper) condition than the wrought T6 baseplate material. The annealed AM stiffener material has significantly lower strength than the wrought stiffeners used in the welded skin/stiffener joint configurations, decreasing the overall structural performance and resistance to buckling. Additionally, the layer-by-layer deposition in AM processes creates boundaries that could be prone to failure compared to homogeneous wrought microstructures. Due to the low hardness and yield strength throughout the as-deposited stiffener, all the AM processes were given scores of 1 for structural performance.

Without more mechanical testing to probe the performance of each process and test panels made of more realistic aerospace aluminum alloys, it is unclear if any process is unsuitable for integrating ASE with the ISC-based fuselage structure. However, careful selection of the alloy and possible heat treatments must be made before adopting AM processes for ASE in order to achieve adequate material properties. The welding processes show promise in being able to meet the structural performance requirements of a fuselage, especially given that many of them have been implemented in large scale aerospace and automobile production. The AM processes will need more development to optimize the alloy and processing parameters in order to achieve adequate material properties without subsequent heat treatment.

Based on the experimental constraints of this study, the welding processes were ranked higher than the AM processes. There are opportunities for improvement in structural performance / material properties for both welding and AM processes. It is understood that process parameter optimization and material selection can result in change of these rankings, thus this particular FOM is more dependent on the available experimental results.

Distortion / Distortion Control

Distortion / distortion control was prioritized by the survey group due to the application of the ISC technology to fuselage structure. Manufacturing processes that cause large distortion of the ISC skin when integrating ASE could result in improper fit-up between adjacent ISCs and could disrupt the aerodynamic flow over the fuselage skin. Distortion measurements were conducted on the test panels using coordinate measurement machine (CMM) analysis and characterized by 3D contour plots to assess out-of-plane distortion with respect to the original base plate. The magnitude of the distortion range (the average positive distortion plus the absolute value of the average negative distortion) was used as an indicator of the degree that each manufacturing process met the FOM requirement. While it is currently unknown whether the additional constraint from the barrel geometry and the longitudinal stringers of the ISC would reduce the distortion, the distortion manifested in flat plates is a good indicator of the thermal input of various processes and the degree of residual stresses that may result if the test panels are constrained. A summary of the measured average distortion of the welded and AM panels is given in Figure 6. The RFSSW panels were not measured due to minimal distortion levels based on visual inspection.

For the welding processes shown in Figure 6, RFSSW was assigned the highest score of 5 for the distortion FOM even though the panel was not measured since it showed little distortion. This is likely due to the minimal heat input of the process compounded with the fact that it is a spot weld. FSW and LW each scored a 3, although LW panel exhibited more distortion than the FSW panel based on visual observation. The LW panel had mid-level distortion with slight bowing in the skins across the width of the panel. This higher distortion in the LW panel was likely due to the process involving melting and solidification, while FSW and RFSSW are solid-state processes. In large-scale manufacturing, the existing fuselage structure should act as a heat sink and constraint, thereby mitigating distortion and residual stress.

Among the AM processes, CMT and LMD exhibited the lowest average panel distortion magnitudes and thus were given scores of 5. LHW AM exhibited mid-level distortion, slightly worse than CMT and LMD, but close to the distortion of the two welded panels. Finally, the AFS-produced panels showed the worst distortion in spite of being a solid-state process. These high levels of distortion could be due to the larger deposition volume of the AFS process, which may have allowed for greater heating of the base plate and residual stress or the clamping used during fabrication. The distortion also varied between the two AFS companies/panels studied, in spite of similar deposition techniques, although the tooling, fixturing, and deposition parameters were not necessarily the same. It is expected that process and parameter refinement would reduce the distortion in AFS. It should be noted that these distortion measurements were made on stand-alone panels whereas the stiffened ISC fuselage structure with ring frames produced via AM or advanced joining concepts would mitigate some of the observed distortion.

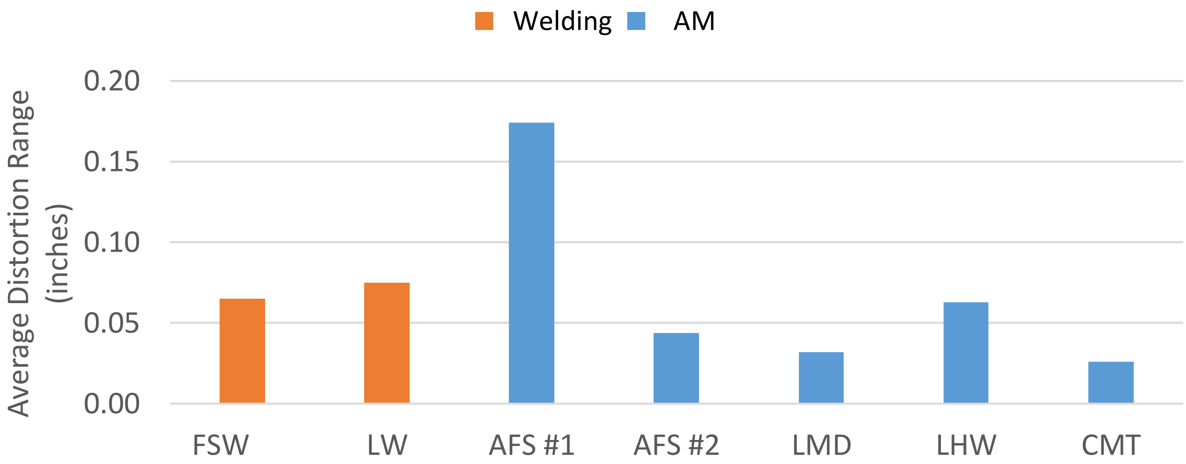


Figure 6. Comparison of average magnitude of distortion of the measured welded and AM test panels (average positive distortion plus the absolute value of the average negative distortion).

Based on CMM measurements of the panels conducted, it was found that the welding and AM processes exhibited overlapping regimes of distortion. In fact, the CMT AM and LMD test panels showed less distortion than FSW and LW panels. While the RFSSW panel was not measured and no CMT welding panel was produced, it is expected that these processes would have similar low distortion levels as the CMT AM and LMD processes. The general trend seen across all processes was that as the heating level and manufacturing cycle time increased, distortion also increased. However, other factors such as degree of constraint in fixturing may have played a role in the distortion results and would require further testing to elucidate the effects on distortion and residual stress. Future work in the area of distortion and residual stress is required for many of the candidate manufacturing processes, especially when considering the differing constraint conditions of the ISC geometry.

1st Order Process Complexity

From the AHP results, the survey group also prioritized 1st order process complexity, which is defined by the degree of complexity introduced by the process and ancillary equipment, fixturing, and tooling, and process requirements of a given manufacturing process. Processes with greater limitations on equipment, tooling, and fixturing, such as LMD, were given low scores for this FOM. Such complexity would limit the ability to integrate this manufacturing process into the fuselage assembly manufacturing cell.

Within the welding processes, RFSSW earned a high score given that it can be implemented with some additional development into automated riveting machines with appropriate end effecters, requires little fixturing, and is being evaluated by Boeing for fuselage construction (55). FSW also received high scores since it can be automated via a robotic gantry system. For fuselage structure, the conventional FSW process would require a backing anvil to react the high forces generated during welding and would leave an exit hole from retraction of the pin tool at the end of the weld that requires filling with a plug weld. The use of self-reacting FSW tooling and adaptive (AdAPT) techniques enables adjustment of the gap between the tool shoulders during the welding operation to fill the extraction hole (56). It also lowers the normal downward force required by conventional FSW, as the reactive forces within the weld are contained between the tool shoulders, thereby eliminating the need for a backing anvil. LW was given the lower score of 3, since it requires the laser tool, laser shielding, and auxiliary equipment such as a power supply, chiller, and robotic welding unit. Further increasing process complexity is the need to incorporate the wire feed and resistance heating system as part of the automated robotic or gantry system.

Among the AM processes, the 1st order process complexity of CMT and LHW AM are more easily retrofitted than the other AM techniques and thus received higher FOM scores than AFS and LMD. Similar to LW, LHW AM will require retrofitting of the laser weld system and auxiliary equipment. CMT AM requires similar retrofitting, including a power source, robotic control and positioning system, welding torch, and wire buffer and reel.

When comparing welding and AM processes scores for the 1st order process complexity FOM, the processes had overlapping regimes based on their power source, feedstock, and fixturing requirements. LW and LHW AM received median scores of 3 due to the various requirements for laser power source support, gas shielding, and wire feedstock handling. The best ranking processes were CMT AM, RFSSW, and FSW – a mix of AM and welding – and received a 4 due to their minimal atmospheric requirements and/or the lack of feedstock.

Lower Ranking FOMs

The remaining FOMs – post-processing, 2nd order process complexity, deposition / joining rate, and inspectability / repairability – were given lower priority by the survey group. It should be emphasized that the weights assigned through the AHP were determined for a single fuselage MDA and not serial production of fuselage structures. It is likely that the prioritizations and weights for the latter would differ for serial production. Given the goal of increased manufacturing rate, the importance of both post-processing requirements and deposition / joining rate would likely be prioritized.

The possible post-processing operations include machining and heat treatments, which could reduce the manufacturing rate and increase costs. Machining is likely not needed for the welding processes, while AM processes required machining in this study to achieve net shape and are anticipated to require some degree in the future, even if simply to achieve the proper surface finish. Welded joints do not require significant heat treatment due to the small process zone and relatively high hardness retention, while the AM processes would likely require a multistep heat treatment given the volume of material in the as-deposited/as-cast condition. While this could be reduced by proper alloy design and control of heat flow through processing parameters to achieve optimal microstructures, it is likely that stiffeners made from AM processes will still require a T6 heat treatment to achieve properties required for stiffening fuselage structures.

The deposition / joining rates of the manufacturing processes were scored based on the calculated fabrication rate per inch of stiffener. The calculations were made only for “beam on” time, excluding times required for unclamping and rotating the panel for welding or interlayer cooling times for AM, to better mimic large scale manufacturing rates. For welding processes, this is twice the joining rate of a 1-in. length (due to a weld on each side of the prefabricated stiffener). For AM processes, this is the time to build a 1-in. long, 1-in. tall, and 0.125-in. minimum thickness stiffener. The scores for AM depend on stiffener height, so ASE designs requiring taller stiffeners will result in lower deposition rates and scores for AM. The welding processes all ranked higher than AM processes, with fabrications rates ranging from 0.038 to 0.22 min/in. of stiffener, with LW and CMT welding showing the highest rates. Two of the AM processes – LHW AM and CMT AM, had deposition rates on the order of 0.4 min/in. for a 1-in. tall stiffener, only twice that of the slowest welding process. LMD and AFS scored the lowest with deposition rates on the order of 5 min/in. due to low traverse speeds and/or a high number of layers to achieve the build height. Given the lower deposition rates and the dependency on stiffener height for AM processes, a welding process would be better suited for larger ASE, while smaller-volume ASE with unique geometries, like reinforcement around cut-outs, could be performed by AM processes.

For 2nd order process complexity, there were common trends between fusion and solid-state processes. When a DED source is required, modifications to the manufacturing floor are needed to protect workers with laser shielding. Additionally, for fusion-based processes, there is often surface preparation required such as removing an oxide layer. The solid-state welding processes have low 2nd order process complexity since they do not require environmental shielding or surface preparation, and thus are ranked highly.

Inspectability / repairability FOM scores were split along the welding and AM divide, with welding processes receiving slightly higher scores. AM processes inherently have a larger build volume to inspect compared to the fillet joints for welding methods, which makes detection of defects with techniques such as ultrasonic transmission (UT) more challenging. Additionally, deposits from all the AM processes have a rough as-built surface texture, which adds further complexity to the inspection process. The welding processes are well-established processes that have well-defined inspection techniques. Additionally, RFSSW has the added benefit of discrete weld locations, further reducing the volume of material to inspect. For repairability, all the AM processes will tend to have more variable defects in terms of type, number and location as compared to welding, making repairs more complicated.

3.4 Manufacturing Process Downselect

Based on the FOM scores, rationale, and manufacturing process weighted scores, the recommended candidate processes for integrating ASE with the fuselage MDA are LW, CMT welding, FSW, and RFSSW. These processes are well-understood, more readily incorporated in current fuselage production lines than the AM processes, and create structurally sound joints. At this time, the AM processes are not competitive with the welding processes across a number of valued FOMs, including structural performance, post-processing requirements, and deposition / joining rate. For the AM processes, CMT AM shows the most promise for its lower heat of deposition, higher maturity, and lower complexity; however, significant development is still required to justify its use for all ASE on the fuselage MDA, and likely the production floor.

Despite the maturity of FSW with its use in large scale manufacturing processes and being well suited for circumferential welds for joining ISC barrel sections, it ranked lower than CMT welding and LW for integrating the ASE. FSW has additional programming complexities, as the process leaves pin tool extraction holes at the end of each discrete weld segment. To prevent crack initiation sites, FSW plug welds or a FSW adaptable adjustable pin tool (AdAPT) weld head are used to refill these holes. Additionally, the fixturing requirements entail specialized large tooling to react the loads and maintain geometric accuracy that could require significant installation time and cost.

RFSSW scored very similar to FSW, with a comparable deposition rate and lower 2nd order process complexity due to the ability to retrofit existing riveting robots to RFSSW. Furthermore, the spot welds result in lower distortion and easier repairability. Major aerospace companies are investigating the use of RFSSW as an alternative to riveting, highlighting the advantages this welding technology possesses.

The top-ranked processes, LW and CMT welding, are summarized together because CMT welding largely adopted the scoring of LW. The greatest benefit is that they are both well-understood processes that are incorporated in large-scale manufacturing via weld robots and gantry systems. The existing manufacturing processes for laser systems can be retrofitted for LW, requiring no major changes to existing facilities; however, the laser head is a large component to navigate the tight spaces in an ISC-based fuselage structure. Both processes require gas shielding during welding; however, the LW process requires additional ancillary equipment and safety protocols. The laser welds showed the highest hardness values of all the studied processes, and the lower heat from CMT welding is expected to exhibit even better structural performance and very low distortion. The deposition rate of LW and CMT welding were the highest of the studied processes, with rates on the order of 0.05 min/in. (3 sec/in.). This good performance across most of the FOMs resulted in the highest ranking of the LW and CMT welding processes.

All of the welding processes have high TRL/MRLs, lowering the barrier to incorporate the technologies into the large-scale fuselage manufacturing. The welding processes have the added benefit of weight savings as compared to riveting and reduced process complexity as compared to adhesive bonding, although the former was not explicitly assessed. Despite the attention AM has received in recent years, the advanced welding practices, specifically LW and CMT welding, are the best route forward to integrating ASE on the ISC-based fuselage MDA.

4. Concluding Remarks / Future Direction

Recent advances in large-scale flow forming of ISCs have motivated evaluation of the technology for constructing metallic fuselages at rapid manufacturing rates. A manufacturing trade study was conducted to screen eight candidate welding and AM processes for integrating ASE with a prototype ISC-based fuselage MDA. The AHP was used to prioritize FOMs critical to the production of an ISC-based MDA, and the performance of each manufacturing process with respect to the FOMs was scored to yield overall rankings that guided the downselection of the processes.

From the rankings, it is clear that the welding technologies assessed are more mature and capable to meet the demands of adding ASE to a large-scale, ISC-based fuselage MDA. The best welding processes studied are two high-TRL processes, LW and CMT welding. The scale-up process would be more readily implemented into the fuselage manufacturing cell given that there are existing robotic and gantry systems available for large-scale manufacturing. For LW, there exists challenges with the use of a laser as the energy source for personnel shielding. Additionally, for either LW or CMT welding, the large laser head or welding torch, wire feeder, and gas shielding must be able to navigate between the tightly spaced stiffeners in the ISC-based fuselage structure. Overall, LW and CMT welding are recommended for both the production of a fuselage MDA and serial production of ISC-based fuselages.

The other two highly ranked welding technologies, FSW and RFSSW, are both solid-state joining techniques that are being pursued by commercial aerospace companies as an alternative to riveting. RFSSW can be retrofitted to use current state-of-the-art riveting automation equipment and is a discrete joining method that could be valuable in avoiding complex tooling paths needed to navigate the stiffener geometry in an ISC-based fuselage design. FSW is well suited for circumferential welding of ISC barrel sections although it may require additional development for ASE integration.

The AM processes each have individual issues, although CMT and LHW AM are recommended over AFS and LMD. CMT and LHW AM can be retrofitted to the robotic infrastructure already available in large-scale manufacturing production facilities, as these processes are similar to arc welding and laser welding, respectively. AFS would require further development to incorporate the AFS deposition head with pre-existing manufacturing weld robot / gantry positioning systems and a backing anvil to react the forces during deposition. Furthermore, all AM processes suffer from lower deposition rates compared to welding due to the layer-wise nature of the process to build ASE and greater post-machining requirements. Another detractor for all AM processes is that the in-situ NDI techniques to assure the quality of deposition for AM processes is not sufficiently developed to implement in large-scale manufacturing.

AFS and LMD received the lowest FOM weighted scores due to scalability and process complexity concerns. While similar to FSW in requiring additional equipment to react forces generated during deposition, AFS also faces challenges in the manual and non-continuous nature of feedstock insertion, as well as some distortion concerns. LMD has the largest issue of all AM processes because it requires an inert gas chamber in this study. The cost in both time and facilities to operate an inert gas chamber large enough to accommodate an ISC is a significant disadvantage. . The LMD process also requires powder feedstock, which adds cost and increases handling complexity. The other AM processes can operate in atmosphere but are not realistic options to build up ring frame structures for to the MDA due to the time consuming, layer-by-layer building process and need for post-machining.

AM processes are not recommended for large-scale manufacturing of circumferential ring frames due to concerns over scalability, process complexity, long deposition times and low structural performance. However, these processes could be a reasonable choice for selective reinforcement around window and door cut-outs given the customized shape and lower build volume required. While AM techniques continue to show rapid, promising developments and could be implemented in small-volume builds, the MRLs of the AM processes are currently not mature enough to be recommended for the majority of the ASE for the MDA.

To advance the MRL of this suite of technologies for future metallic fuselages, the AATT project is funding an effort for the design, manufacture, and integration of a prototype ISC-based fuselage MDA. The planned construction of the fuselage MDA in 2022 will likely employ one (or more) of these advanced manufacturing technologies. The implementation of these technologies in the MDA will provide further insight into the challenges at-scale that must be overcome in order to reach the high rate fuselage manufacturing goal while simultaneously reducing weight and cost. The potential structural benefits of the ISC technology opens up the design space, allowing for innovation in the final design and ideally leading towards a more efficient structure in terms of mass, production times, and cost.

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6. Appendix: Criteria and Rationale for FOM Scoring

Table A- 1. Numerical score definitions, scores, and rationale for the scalability FOM

Scalability FOM Definition:

- 8” x 18” flat plate to 120” diameter cylinder with 2” tall stiffeners (~25 ring frames)
- Access to inside surface of cylinder
- Build feature size vs. process zone size
- Feedstock utilization efficiency
- Process automation capability
- Manufacturing readiness level (MRL) / technology readiness level (TRL)

Numerical Score Definition (1-5 scoring scale):

5:	Already used on large structures, fully autonomous process, high MRL/TRL
3:	Can work on large diameter structure, mostly autonomous process, mid MRL/TRL
1:	Cannot work on large structure, minimally automated process, low MRL/TRL
2 or 4:	Interpolate if a process does not closely match the definition for 5, 3, or 1

Manufacturing Process	Score (1-5)	Rationale
FSW	5	Incumbent industrial process for launch vehicle structures (butt joints), TRL 9; already scaled to this diameter, ideal for circumferential welds. Issue with starts/stops for discontinuous seam welds – will require further development. Lap joints are feasible but will require tight controls with thin gage product forms.
RFSSW	4	Can readily be scaled to fuselage, small pin tool head can be incorporated into existing riveting / FSW setup; TRL/MRL ~6-8; weld robot, gantry, rail system; Boeing interested in technology and actively researching replacement for riveting; further development required. Could be adapted as an end effector on an existing automated riveter.
LW	5	Readily scaled to fuselage via welding robots & gantry systems; fully autonomous & automated. Direct diode laser with resistance heating ideally suited for Al; Airbus using for wing structure; TRL 9
CMT welding	5	Can be scaled to fuselage structure; high TRL/MRL, 9 in auto industry; fully automated; weld robots, single rail, or 3-axis gantry, may require further development for ISC-based airframes. GMAW is incumbent welding process in many industries.
AFS	2	Not proven at this scale, TRL/MRL 3; adapt AFS deposition head to weld robot / gantry; (feedstock mechanism is discrete, needs development for fully automated feeding: 1st order issue).
LMD	1	Restricted by chamber size, must be conducted in inert atmosphere to prevent oxidation and hydrogen pores, may require specialized powder, used for repair / detailed parts.

		Easily incorporated onto 5-axis machine, require portable enclosure.
LHW AM	3	Unsure if it is being implemented in production applications, cladding / repair on existing structure. TRL/MRL ~4, readily applicable to welding robots.
CMT AM	4	Can be scaled to fuselage structure; high TRL/MRL 9 in auto industry (welding); fully automated; weld robots, single rail, or 3-axis gantry, may require further development for airframe. GMAW is incumbent weld process in many industries. Lower TRL for AM, most applications are for welding.

Table A- 2. Numerical score definitions, score, and rationale for 1st order process complexity FOM

1st order process complexity FOM Definition:

- Process-specific considerations (hardware/infrastructure requirements)
- Unique tooling (e.g. gas shielding, powder handling, fixtures/jigs)
- Unique facilities (e.g. environmental control, clean room)

Numerical Score Definition (1-5 scoring scale):

5: Does not require unique facility, minimal unique tooling, easily retrofitted to current manufacturing processes
3: Does not require unique facility, some unique tooling, can retrofit current manufacturing processes
1: Requires unique facility, requires numerous unique tooling, cannot/difficult to retrofit current manufacturing processes
2 or 4: Interpolate if a process does not closely match the definition for 5, 3, or 1

Manufacturing Process	Score (1-5)	Rationale
FSW	4	Limited FSW applications are currently used in aerospace industry to join large components. The fixturing requirements include specialized large tooling to react the loads and maintain geometric accuracy.
RFSSW	4	RFSSW is very similar to riveting. The primary modification to current processes is the hardware to provide backing force.
LW	3	Requires some additional facility and tooling requirements, possible to retrofit current manufacturing processes for laser systems. The laser head is a relatively large component which may require additional space for incorporation. Laser shielding is also required during operation to protect the operator. Protecting workers in the vicinity of operations from the welding fumes is also required.
CMT welding	4	CMT is a form of GMAW so the supplies (equipment, feedstock, PPE) are readily available and the safety requirements such as weld shielding are common. Protecting workers in the vicinity of operations from the welding fumes and light is the primary difficulty.
AFS	1	Hardware is potentially difficult to retrofit. The fixturing required to react the loads is significant.
LMD	1	There are some major facility modifications required for use of LMD systems. The laser head is a relatively large component (as noted for the LHW process.), also requires coaxial powder spray. Laser shielding is required during operation. Blown powder systems required specialized powder handling and recovery processes. The LMD process requires controlled environment or gas shroud. Powder feedstock is expensive and critical applications may not permit use of recaptured powder.

LHW AM	3	LHW AM scores the same as LW with filler material, see above.
CMT AM	4	CMT is a form of GMAW welding so the supplies (equipment, feedstock, PPE) are readily available and the safety requirements such as weld shielding are common. Protecting workers in the vicinity of operations from the welding fumes and light is the primary difficulty.

Table A- 3. Numerical score definitions, score, and rationale for the 2nd order process complexity FOM

2nd order process complexity FOM Definition:

- Piece-by-piece consideration (required for each part)
- Surface prep/preservation/environmental control requirements
- Critical times (e.g. adhesive cure, pot life, protective coatings)
- Number and order of major operations (e.g. avoid multiple heat treatments)

Numerical Score Definition (1-5 scoring scale):

5: Low critical times, no or minimal major operations, minimal extra prep
3: Medium critical times, couple major operations required, some extra prep
1: Long critical times, multiple major operations required, large amount of extra prep
2 or 4: Interpolate if a process does not closely match the definition for 5, 3, or 1

Manufacturing Process	Score (1-5)	Rationale
FSW	4	FSW requires very little preparation. Installation of specialized fixturing to react the loading is required. Specialized fixturing to react the loads induced by the process may interfere with other secondary operations.
RFSSW	5	RFSSW requires very little preparation. Specialized fixturing to react the loads induced by the process may interfere with other secondary operations.
LW	4	The primary requirement for fusion-based welding operations involving Al is the removal of the oxide layer, which is normally performed with a wire brush.
CMT welding	4	The primary requirement for fusion-based welding operations involving Al is the removal of the oxide layer, which is normally performed with a wire brush.
AFS	3	The AFS process requires unique feedstock. Specialized fixturing to react the loads induced by the process may interfere with other secondary operations.
LMD	3	A secondary operation is required to clean the powder from the components upon completion.
LHW AM	4	The primary requirement for fusion-based additive operations involving Al is the removal of the oxide layer from the substrate, which is normally performed with a wire brush.
CMT AM	4	The primary requirement for fusion-based additive operations involving Al is the removal of the oxide layer from the substrate, which is normally performed with a wire brush.

Table A- 4. Numerical score definitions, score, and rationale for the post-processing FOM

Post-processing requirements FOM Definition:

- Mechanical properties (e.g. hardness, tensile)
- Microstructure and properties dictate whether heat treatment is required
- Machinability (as-deposited and after direct age heat treat)

Numerical Score Definition (1-5 scoring scale):

5:	High tensile strength (AM only), high hardness, no heat treatment required, little to no extra machining needed
3:	Medium tensile strength (AM only), medium hardness, one heat treatment step required, some machining needed
1:	Low tensile strength (AM only), low hardness, multiple heat treatment steps required, substantial extra machining needed
2 or 4:	Interpolate if a process does not closely match the definition for 5, 3, or 1

Manufacturing Process	Score (1-5)	Rationale
FSW	4	Minor machining may be required, possible heat treatment step.
RFSSW	4	Minor machining may be required, possible heat treatment step.
LW	5	No heat treatment or machining required due to small process zone size.
CMT welding	5	CMT welding test panel not produced, but follows LW score due to similar process zone size.
AFS	1	Extensive machining required due to excess flash. Low strength and hardness, requires multistep heat treatment.
LMD	1	Small amount of machining required due to higher tolerance of powder-fed system. Low strength and hardness due to as-cast microstructure, requires multistep heat treatment.
LHW AM	1	Requires machining of overage for stiffeners. Low strength and hardness due to as-cast microstructure, requires multistep heat treatment.
CMT AM	1	Requires machining of overage for stiffeners. Low strength due to as-cast microstructure, requires multistep heat treatment.

Table A- 5. Numerical score definitions, score, and rationale for the deposition / joining rate FOM

Deposition / joining rate FOM Definition:

- Process-specific, may be variable; affects throughput
- Here calculated as the time required to integrate a 1 in. long stiffener segment to a substrate and using rates given in the manufacturers' data packages.
  - For welding, this works out to be the time to weld two 1 in. lengths, one on each side of the premanufactured stiffener.
  - For AM, this is the time to build a 1 in. long segment of a 1 in. tall, 0.125 in. minimum width stiffener.
  - Note that the deposition rates of the AM processes will increase if the stiffener height requirement is increased, while the joining rates of the welding processes will remain the same.

Numerical Score Definition (1-5 scoring scale):

5: Fast = 0.05 min/in. of stiffener length
3: Moderate = 0.5 min/in. of stiffener length
1: Low = 5+ min/in. of stiffener length
2 or 4: Interpolate if a process does not closely match the definition for 5, 3, or 1

Manufacturing Process	Score (1-5)	Rationale
FSW	4	Prefabricated stiffener (J, T, L). Manufacturer used a joining rate of 60 ipm and reported 3 mins to complete two 24" welds, working out to a rate of 0.13 min/in.
RFSSW	4	Prefabricated stiffener (J, T, L). Manufacturer reported the total spot welding rate was 12 sec/weld, assumed 1 sec travel between 2" spot spacing = 0.22 min/in.
LW	5	Prefabricated stiffener (J, T, L). Manufacturer used a 40 ipm joining rate and reported 27 sec required to complete each 24" length = 0.038 min/in.
CMT welding	5	CMT welding test panel not produced. Using CMT AM traverse speed of 28 ipm (likely an underestimation), this would require 39 sec to complete each 18" length = 0.071 min/in.
AFS	1	25 layers to build a 1" tall stiffener. Traverse speed of 5 ipm, resulting in 90 mins to complete 18" long, 1" tall stiffener (not including feedstock reload) = 5.0 min/in.
LMD	1	55 layers to build a 1" tall stiffener. Manufacturer reported a total build time without stops of 95 min. Chamber evacuation time excluded from calculation, but significant. 5.3 min/in.
LHW AM	3	17 layers to build a 1" tall stiffener at 40 ipm. Manufacturer reported 12 mins of "beam on" time for a 32" long stiffener, in addition to a significant 20 mins of cooldown per layer (not included in calculation). Rate = 0.38 min/in.
CMT AM	3	14 layers to build a 1" tall stiffener at 28 ipm. Manufacturer reported 10.5 mins of "beam on" time for a 24" long stiffener, with interlayer cleaning passes not included in calculation. Rate = 0.44 min/in.

Table A- 6. Numerical score definitions, score, and rationale for the structural performance FOM

Structural performance FOM definition:

- Defined as joint penetration and joint / base metal hardness ratio
- All samples machined first; some as-deposited and some with direct age heat treatment

Numerical Score Definition (1-5 scoring scale):

5: Meets industry standard
3: Potential to meet industry standard
1: Unlikely to meet industry standard
2 or 4: Interpolate if a process does not closely match the definition for 5, 3, or 1

Manufacturing Process	Score (1-5)	Rationale
FSW	4	Penetration of skin material ≈ 20% (0.7 mm). Width = 5 mm. Some hardness loss; H_V(Weld)/H_V(6061-T6) = 83%, and H_V(HAZ)/H_V(6061-T6) = 89%. Incumbent industrial process for launch vehicle structures.
RFSSW	3	Penetration of skin material ≈ 35% (1.1 mm). Width = 7 mm. Some hardness loss; H_V(Weld)/H_V(Skin) = 61%, and H_V(HAZ)/H_V(Skin) = 73%.
LW	5	Penetration of skin material ≈ 20-35% (0.6-1.1 mm). Diagonal width = 3.2-3.8 mm. Some hardness loss; H_V(Weld)/H_V(Skin) = 80%, and H_V(HAZ)/H_V(Skin) = 94%. Incumbent industrial process for aircraft structures
CMT welding	5	CMT welding test panel not produced, but follows LW score due to similar process zone size
AFS	1	Large effect on skin material, hardness, and strength. As-built strength is too low for use in circumferential stiffeners without heat treatment. Penetration of skin material ≈ 80-100%. Hardness loss; H_V(Build)/H_V(Skin) = 41-48%, and H_V(HAZ)/H_V(Skin) = 45-47%. Strength loss; σ_Y(Build)/σ_Y(6061-T6) = 28%.
LMD	1	Large effect on hardness and strength. As-built strength is too low for use in circumferential stiffeners without heat treatment. Penetration of skin material ≈ 16%. Hardness loss; H_V(Build)/H_V(Skin) = 66%, and H_V(HAZ)/H_V(Skin) = 47%. Strength loss; σ_Y(Build)/σ_Y(6061-T6) = 41%.
LHW AM	1	Large effect on skin material, hardness and strength. As-built strength is too low for use in circumferential stiffeners without heat treatment. Penetration of skin material ≈ 60%. Hardness loss; H_V(Build)/H_V(Skin) = 63%, and H_V(HAZ)/H_V(Skin) = 56%. Strength loss; σ_Y(Build)/σ_Y(6061-T6) = 45%.

CMT AM	1	Large effect on hardness and strength. As-built strength is too low for use in circumferential stiffeners without heat treatment. Penetration of skin material ≈ 30%. Hardness loss; H_V(Build)/H_V(Skin) = 67%, and H_V(HAZ)/H_V(Skin) = 81%. Strength loss; σ_Y(Build)/σ_Y(6061-T6) = 43%.

Table A- 7. Numerical score definitions, score, and rationale for the distortion / distortion control FOM

Distortion / distortion control FOM Definition:

- Distortion and distortion control methods

Numerical Score Definition (1-5 scoring scale):

5: Low distortion, or average of < 0.02” (+/-)
3: Mid-range, or average of 0.02” - 0.04” (+/-)
1: High distortion, or average of 0.04” and higher (+/-)
2 or 4: Interpolate if a process does not closely match the definition for 5, 3, or 1

Manufacturing Process	Score (1-5)	Rationale
FSW	3	Mid-level distortion. Nowhere near as bad as AFS panels, but slightly worse than LMD and CMT AM processes. Slightly better than LW.
RFSSW	5	Not measured, but due to it being a spot welding process, there should be minimal heat input and thus low distortion. Visually, there seemed to be minimal distortion.
LW	3	Mid-level distortion. Nowhere near as bad as AFS panels, but slightly worse than LMD and CMT AM processes. Slightly more distortion than FSW.
CMT welding	5	CMT welding test panel produced, but distortion is expected to be minimal due to the low heat of welding.
AFS #1 AFS #2	2* *=avg of AFS #1 and #2 panels	Mixed results between the AFS panels but both showed some of the highest distortion. While AFS may experience lower peak temperatures, it is suspected that the larger volume deposited leads to high heat input combined with high mechanical stresses due to FS process.
LMD	5	Second best among the measured panels and quite comparable to the CMT AM (best) panel. Low distortion.
LHW AM	3	Mid-level distortion. Nowhere near as bad as AFS panels, but slightly worse than LMD and CMT AM processes. Roughly equivalent to the two welding processes.
CMT AM	5	Best of the measured panels. Likely more distortion than riveting, adhesive bonding, and RFSSW; however, those panels were not measured.

Table A- 8. Numerical score definitions, score, and rationale for the inspectability FOM

Inspectability FOM definition:

- Inspectability during fabrication

Numerical Score Definition (1-5 scoring scale):

5: Manufacturing process is well established and resultant geometries and surfaces are suitable for NDE during all stages of manufacturing. Process generates indications / defects that are *detectable* and well understood by traditional NDE methods. Process results in a homogenous microstructure.

3: Manufacturing process is established and resultant geometries and surfaces are suitable for NDE during some stages of manufacturing (i.e. not as-deposited or only after machining). Process generates indications / defects that may be difficult to *detect* and may require additional NDE test methods or evaluation to understand and resolve. Process results in relatively homogenous microstructure.

1: Manufacturing process is not well established (or is a low TRL) and generates indications / defects that are either *not detectable* or understood by traditional NDE methods and would require advanced or new NDE method development. Resultant geometries and surfaces may not easily inspectable at any stage of manufacturing and/or the microstructures are not homogenous.

2 or 4**:** Interpolate if a process does not closely match the definition for 5, 3, or 1

Manufacturing Process	Score (1-5)	Rationale
FSW	4	While the cracks and voids of friction stir are similar to, or even more pronounced than, traditional welding, the low-fusion, or "kissing-bond" fusions deep in the weld can be more difficult to detect than the similar, but more pronounced low-fusion areas of traditional welding. The medium is generally homogeneous.
RFSSW	3	Defects are similar to the single-stage continuous version; however, with the joint existing only in "spots", the method of UT is limited to mostly perpendicular evaluation. A pro of the "spot" evaluation is that if the UT signal shows a defect of some kind, one knows within the size of the "spot" the defect location and the location of the needed repair. In this case, a pass/fail criteria would most likely be utilized with minimal concern for exactly the "where" or "type" of defect.
LW	5	Due to the limited area of inspection and degree of experience in the discipline related to this more traditional assembly methodology. The types of flaws associated with this type of welding are well understood. Even the rough-finished laser weld would most likely be preferable over a friction stir weld, once again due to the well-established expectations of this more traditional method. The homogeneity of the medium is also favorable.
CMT welding	5	Score follows LW score due to small volume of interrogation and similar types of flaws.

AFS	3	Large volume of interrogation, more consistent and homogeneous grain structure of those two compared to other AM processes.
LMD	2	Due to large volume of interrogation, the need for extensive surface finishing, and the varying grain structure/UT propagation constants of layered methods.
LHW AM	2	Due to large volume of interrogation, the need for extensive surface finishing, and the varying grain structure/UT propagation constants of layered methods.
CMT AM	2	Due to large volume of interrogation for AM, the need for extensive surface finishing, and the varying grain structure/UT propagation constants of layered methods.

Table A- 9. Numerical score definitions, score, and rationale for the repairability FOM

Repairability FOM Definition:

- Repairability during fabrication

Numerical Score Definition (1-5 scoring scale):

5: "Excellent" repairability:
- Repair methods well established.
- Methods can be performed at any time during the process.
- Does not significantly affect microstructure, mechanical performance, or additional distortion.
- Does not require secondary process operations (e.g. finishing) to achieve form/fit/function.

3: "Moderate" repairability:
- Repair methods well established.
- Methods difficult to perform at any time (in-situ) during the process.
- Does affect microstructure, mechanical performance (i.e. some possible knock-down) or distortion.
- Does require minor secondary process operations (e.g. finishing) to achieve form/fit/function.

1: "Poor" repairability:
- Repair methods not well established or will require development.
- Methods cannot be performed at any time during the process.
- Does significantly affect microstructure, mechanical performance or cause significant distortion.
- Does require significant secondary process operations (e.g. finishing) to achieve form/fit/function.

2 or 4: Interpolate if a process does not closely match the definition for 5, 3, or 1

Manufacturing Process	Score (1-5)	Rationale
FSW	4	Well-established manufacturing, can be performed in-situ and on top the original weld without microstructural impact, no additional distortion.
RFSSW	5	Discrete point process, can add additional spot welds nearby, can even overlap them (no restrictions for rivet spacing).
LW	3.5	Based on provided fillet welds, this would be more like a traditional weld repair – grind and reweld. Thin gauge – from heat and microstructural standpoint – may cause issues.
CMT welding	3.5	Score follows LW score due to similar weld geometry.
AFS	2	Type, number, and location of defects can vary more than in welding. Fine microstructure and properties could be significantly affected by MIG/TIG repairs, may need to add additional reinforcement to compensate for property knock-downs.
LMD	3	Type, number, and location of defects can vary more than in welding. Similar reasons to LW.
LHW AM	3	Type, number, and location of defects can vary more than in welding. Similar reasons to LW.

CMT AM	3	Type, number, and location of defects can vary more in AM than in welding. Similar reasons to LW.