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Joining Technologies for Space Structures

Spojovací technologie kosmických konstrukcí

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Ondřej Hladík

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Supervisor: Mgr. Jaroslav Kousal, Ph.D.

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Pokyny pro vypracování:

Pro vypracování proveďte:
1) Definujte specifika požadavků na spojovací prvky a technologie pro kosmické konstrukce
2) Proveďte rešerši spojovacích technik kosmických konstrukcí
3) Zhodnoťte vhodnost různých spojovacích technologií pro tvorbu velkých struktur v kosmickém prostředí

Seznam doporučené literatury:

Charles D. Brown: Elements of Spacecraft Design, AIAA, 2002, ISBN 1-56347-524-3
Malcolm Macdonald, Viorel Badescu (ed.): The International Handbook of Space Technology, Springer, 2014, ISBN 978-3-642-41101-4
+ další literatura dle doporučení vedoucího

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Mgr. Jaroslav Kousal, Ph.D., ústav letadlové techniky FS

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Mgr. Jaroslav Kousal, Ph.D.
podpis vedoucí(ho) práce

Ing. Robert Theiner, Ph.D.
podpis vedoucí(ho) ústavu/katedry

prof. Ing. Michael Valášek, DrSc.
podpis děkana(ky)

III. PŘEVZETÍ ZADÁNÍ

Student bere na vědomí, že je povinen vypracovat bakalářskou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací. Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v bakalářské práci.

30.04.2020
Datum převzetí zadání

Podpis studenta

Declaration

I declare that presented thesis called "Joining Technologies for Space Structures" made under supervision of Mgr. Jaroslav Kousal, Ph.D., was written by me using literature listed in the chapter "Sources".

In Prague 07. 08. 2020 Ondřej Hladík ....

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Abstract:

In this thesis we are looking for technologies best suited to manufacture and construction of large-sized structures in space. A lot of research has been conducted in this field during the height of the Space Race into welding and brazing using various technologies, primarily electron beam welding. At the same time various systems for assembly using integrated locking mechanisms, and systems for foldable structures using mobile hinges were developed. Ultimately most technologies provide their own benefits and drawbacks that have to be considered and can best be mitigated by developing wide range of readily available technologies. For now, the best available technologies are the ones in use, namely integrated locking mechanisms and foldable structures, but for further progress we need to finalize development of welding and additive manufacturing technologies.

Keywords: space technologies, in-space construction, large-sized structures, in-space manufacturing, welding, in-space assembly

Anotace:

V této práci hledáme nejlepší technologie pro stavbu velkých konstrukcí ve vesmírném prostoru. Na toto téma probíhalo mnoho výzkumu během vesmírných závodů. Především se zaměřením na sváření a pájení za využití nejrůznějších technologií, především elektronového svazku. Ve stejné době také docházelo k vývoji systémů založených na integrovaných zámkových mechanismech a systémů rozložitelných konstrukcí s pohyblivými klouby. Ve výsledku většina technologií má své výhody a nevýhody, které mohou být zmírněny vývojem široké palety technologií připravených k použití. V současné době jsou nejlépe vyhovující dnes aplikované technologie sestávající z rozkládacích konstrukcí a zámkových mechanismů, ale pro další postup je nezbytné dokončit vývoj svařovacích technologií a technologií aditivní výroby.

Klíčová slova: vesmírné technologie, vesmírné konstrukce, velké vesmírné konstrukce, výroba ve vesmíru, svařování, montáž ve vesmíru

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1. Introduction

During the Space Race there were grand plans of expansion beyond Earth which were swiftly thwarted by how difficult this task has proven. For the longest time space stations were lifted as one compact structure but these have proven to be too small. This has changed with Mir, the first modular space station. International Space Station is its direct descendant, incorporating modules originally intended for Mir-2, and it is nearing the end of its lifespan and is planned to be replaced by Lunar Gateway. There are also new projects by private companies to exploit resources present in our solar system and to set up commercial space stations in Earth’s orbit. Furthermore, Elon Musk is open about his plans to colonize Mars. So how do we build vessels for these new tasks? As was shown previously with space stations, we will need vessels and stations bigger than what can be lifted in one piece, this is what we will be in this work referring to as large structures. These large structures will need to then be assembled or entirely constructed in space. For this we will need to assess what technologies are available and what technologies can be adapted for in-space use.

2. Technological Requirements

To properly set our requirements for technology we first must take a look at what types of joints we will need to produce. One of the structures that are commonly proposed are truss structures. There are already examples of these being erected in space, plans were outlined for both mechanical joined structures (STS 61-B ACCESS [1]), transformable foldable structure (Topol-CB truss deployer [2]), and welded structures. Although these elements can be and are load bearing the true challenge are pressurized structures. In none of the sources there was mention of pressurized compartments assembled or built in orbit, closest to this is assembly of modular space stations which are built from monolithic modules, which have their plumbing connected together to some degree after docking. This is time proven technology, but it has its limits. Firstly the weight, size, and shape of the module is still limited by launch vehicle, and secondly the docking ports of modules do not provide same rigidity and strength as monolithic body would provide, thus they are less viable for use when we are expecting high loads to be exerted. To be able to exceed weight and shape limitations of launch vehicle and create pressurized large structure we would need to create or finish its shell after it was already placed into orbit. This obviously presents its own host of problems but developing such technology would allow us to build larger stations and vessels with shape and weight independent of capabilities of our launch vehicles.

Another important thing to take into account are the materials commonly used in space industry. These materials are mainly various steels, light metal alloys (primarily titanium and aluminium based alloys), and composite materials (Kevlar and ceramic based composites).

It is important to also note that the sources of the stress place upon structure are different than in ground-based structures. Unlike ground-based structures have high amount of stress imposed on them by their own weight, in orbit we are mostly dealing stresses imposed by inertia, thermal expansion, inside pressure, and engine thrust. This means that if we assemble structures in orbit we can design them with only these sources of stress, while structures lifted from ground must be designed to bear their own weight and allows spin stabilized structures

Now that we have outlined what joints were envisioned for this study, we can look at further requirements and limitations stemming from the environment in which these technological processes will be taking place.

One of the very pressing problems is logistics. All materials and equipment available must be lifted into orbit. This constrains volume and weight of items that can be delivered into orbit for further construction. This means that every delivery will need to contain necessary consumables (feeder wire, inert gas, bolts, nuts, etc.) to erect the structure that was delivered. This means the less consumables we use the bigger structure can be created from single material delivery. Obviously, another problem can be presented by waste material created by technologies, although that is most profound problem with machining which is not one of technologies considered for this application. Furthermore, if our tools were to break replacement would not only be expensive but it could also take too long and lead to further complications. This means we will need tools that are exceptionally reliable and durable.

Another problem we might encounter is energy consumption. Under normal circumstance high energy consumption only increases cost, but in our case, it can make it complicated to use certain technologies efficiently. If we consider output of about $250\ \mathrm{Wm}^{-2}$ for solar panels in orbit [3] and compare it to power necessary for operation of welding laser, which itself can have output upwards of $5\ \mathrm{kW}$. While not ruling out use of more energy demanding technologies, especially due to their high productivity and high quality of final product, we have to plan accordingly with power available on site, which can vary case by case. Energy consumption goes hand in hand with waste heat, which also poses additional problems. This means we have to look for efficient technology, not only to reduce demands on size of solar array but also to prevent either overheating or need for excessive size of heatsinks.

Last but no least is accuracy of given technology. It is undeniable that spaceflight is one of the greatest achievements of humanity and it became only possible thanks to use of highly sophisticated machines and same goes for our devices in orbit. It is important that we take into account that these technologies should remain viable for use in creating as precise instruments as space telescopes [4].

In Table 1 we have summarized parameters we are looking for in technology for use in in-space construction.

Table 1 - Parameters for technologies for in-space construction

Parameter	Description
Equipment reliability	In temporary structures ability to repeatedly disassemble and assemble them without damage, in operations requiring tools this translates to length of service life of tool, increases with reduction in amount of moving parts, optimal reliability for given technology is when same reliability as on the ground is achieved
Technology reliability	Percentage of successfully created joints, current pinnacle upon which many companies aim is so called "Six Sigma" which seeks over 99% success rate, in emergent and immature technologies as well as in technologies with low technology readiness level.
Energy efficiency	Efficient transformation of input energy, usually electricity, into output energy in desired location, usually heat, hard to compare dissimilar technologies as their power consumption may differ wildly and therefore energy efficiency might prove misleading, therefore only similar technologies will be compared against one another based on efficiency and these groups of technologies will be compared by overall energy consumption
Energy density	High values of this parameter allow faster welding speeds, deeper penetration, and thinner fusion zone and heat affected zone
Material efficiency	Higher values mean less wasted material and material that doesn't become part of the joint, due to specific properties space environment we should aim for 100% or nearly 100% material efficiency as vacuum prevents burning of the material and therefore prevents material loss
Quality joints	Exact requirements may wary depending on location of the joint, but in general joints need to be strong, rigid, and in some applications airtight joints
Able to work with various materials	Optimally chosen technology should work with majority of materials used in space industry. This includes steel, aluminium, titanium, and various composites.
High accuracy	We need to be able to create joints of at least same precision as those produced on the ground.

3. Specific properties of space environment

To selected right technology, we need to understand in what environment we will be utilizing it. This becomes even more important when dealing with environment with which we have as little experience as with the environment of space. Let us start by breaking down the various characteristics of it.

First one is very low pressure which presents double-edged sword. On the one hand such environment provides great protective atmosphere, as there is very few atoms for metal to react with. On the other hand, the atmosphere at common spaceflight heights contains high percentages of atomic oxygen [5] and oxygen ions [6]. Furthermore, space vacuum has pressure low enough, that in accordance to Paschen's law the necessary voltage to create an electric arc is immensely high. And obviously near absence of gas means that heat transfer to environment from material is nearly non-existent.

Second important aspect of space environment is microgravity. This leads to changes in mode of melt solidification, convection, and more [5][6]. Furthermore, the lowered buoyancy means that gas evolving from the melt separates slower and it can lead rather high porosity of the weld [7]. Possible solution to this issue was found in introduction of oscillation into the pieces [7]. It also means that the most powerful force applied to the melt is the surface tension, which on Earth is being suppressed by gravity, its absence leads to several effects in orbit [5]. Most profound one being that flow of matter can establish itself swiftly due to surface forces due to thermo-capillary convection. This together with melt pool being up to several times the thickness of the piece [5] can lead to re-joining of pieces during cutting, which necessitates correct temperature gradient [5].

Another peculiar property of space environment are extreme temperature differences between sunlit and shaded sides [5]. There are several modes in which space vehicles are exposed to thermal cycling. First of them being orbit around Earth, where save for few orbits (SSO), space vehicle passes through Earth's shadow. The second mode of thermal cycling can be caused by the rotation. If vehicle is not rotating temperature differences can reach up to hundreds of degrees Celsius. If vehicle is rotating this difference is substantially decreased [8], this reduces thermal stresses but leads to increase in thermal cycling, which together with exposition to space gas plasma, ultraviolet radiation, and high-energy particles can lead to changes in material structure and composition [8]. In assembly requiring high precision of parts thermal expansion can pose problems, which is why insulants like Kapton are being used [1].

The last specific characteristic to mention is presence of hard ionizing radiation far above standard. This leads to embrittlement of metal over time. Along with the effects on electronic parts and organic life this poses potential danger to any machinery and personnel alike.

As we can see, most of these properties affect mainly processes that utilize heat and create melts, like standard welding operations. Only real effect on mechanical assembly using various locking mechanism is possibility of irregular heating of illuminated and shaded sides leading to deformation of locking mechanism and thus problems properly connecting parts of various temperatures.

4. Effects of thermal cycling on steel and alloys in orbit

Thermal cycling can present problem as it can lead to deterioration of mechanical properties of material which together with cycling load from thermal expansion and contraction can have serious effect on service life of machinery. Because of this, series of test was performed by Ukrainian scientists [8].

Tests were conducted on 12Kh18N10T steel, chrome-nickel stainless steel, and VT1-0 titanium alloy with over 99% of titanium. Tests were conducted on plates with dimensions 9x9x1 mm for steel and 9x9x0.6 for titanium alloy which were affixed in special holder heated by tungsten Archimedean spiral from below. From above the samples were irradiated by flow of electrons, from Auger electron spectroscopy, photons, due to X-ray-electron spectrometry, and or ions due to cleaning of the surface by argon ions. Before the experiment started all the samples were subjects to desorption treatment by thermoflash method. [8]

In several studies they determined that main changes of properties take place during no more than 10 thermal cycles. Furthermore cycles simply accumulated these effects further.

Results for 12Kh18N10T steel showed that with cycles content of carbon in surface layer is increasing. Dissolved oxygen was reacting with metals creating oxides, first $(Fe,\ Cr)_2O_3$, then later also oxides of nickel and various compounds containing titanium. Concentration of all elements have strong periodicity due to the wave mass-transfer of elements. [8]

In VT1-0 oxygen, carbon, and titanium form stable oxide and carbon-oxide films which are hard to remove from the surface of material. Considerable amount of impurities was found in very thin layer beneath the film. During the thermal cycling chlorine is being removed from surface layer and only oxygen and carbon adsorption is present. Chemical composition of fracture contained deeply penetrated impurities, some of which were not explainable by diffusion. Because of this, another method of impurity element sorption was proposed. It was proposed that due to the cyclic load from heating and cooling intergranular space metal acts as sorption pump of sort. Penetrating gases then induce additional stress further accelerating the process and promoting penetration of other impurities. This then leads to metal embrittlement. [8]

5. Mechanical Joints

Assembling premade parts has proven to be useful and versatile ability, be it assembling modular space station or assembly of truss structures used as support for various equipment like antennas and solar panel arrays. From wider perspective truss structures were connecting and holding in place inner and outer shell of Mir space station. It is also notable that there is minimal difference to the creation of mechanical joint in orbit and on the ground. The notable difference is lack of gravity which therefore can't be used to lock the joint, although that is not common mechanism used even for similar structures on the ground and therefore presents minimal change. Mechanical joints are less reliable than welded joints, especially with stresses present in orbit. [9]

5.1. ACCESS

Assembly Concept for Construction of Erectable Space Structures, ACCESS, was NASA experiment which aimed to study possibly of manual assembly of long truss structures. ACCESS was designed to be lightweight, compactly stowed, and simple to assemble. ACCESS was flown onboard Space Shuttle Atlantis during STS-61-B. [1]

Trusses and nodes (as seen in Figure 1) were made from aluminium. For thermal stability trusses were covered in Kapton for thermal insulation and dimensional stability. Once a truss was locked to node, spring loaded sleeve would then be extended to cover the joint. There were several types of struts, namely longerons, diagonals, and battens. All of them interchangeable with like parts. Locking mechanism, as seen in Figure 1, is protected by spring-loaded sleeve. [1]

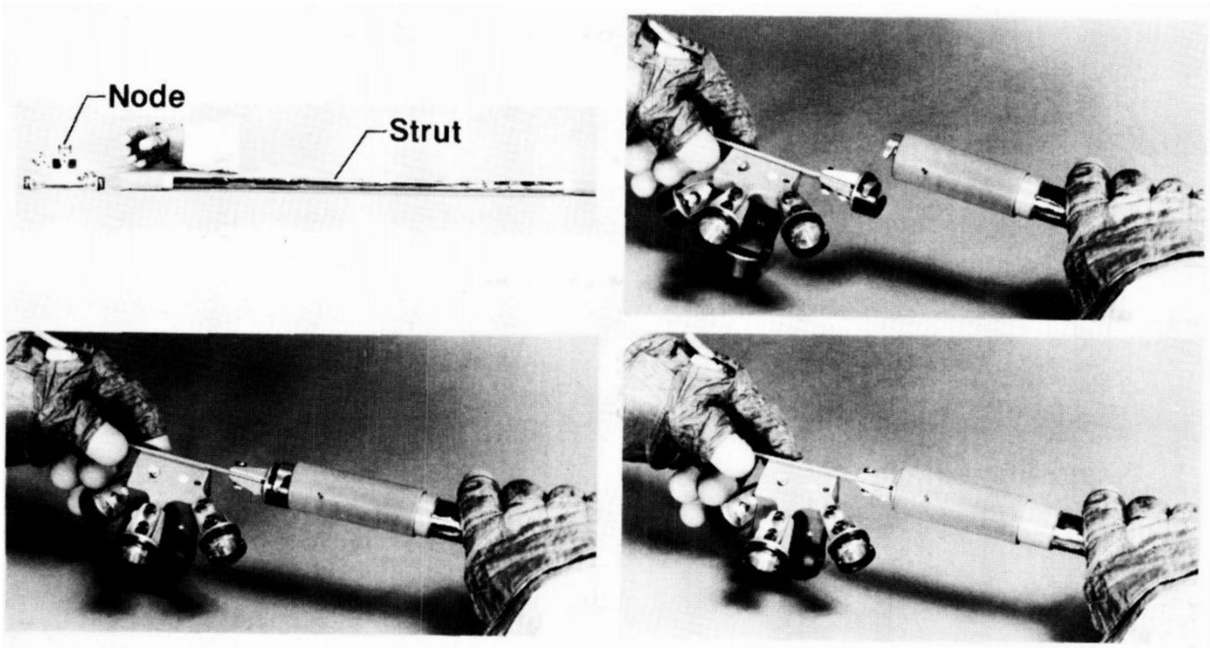

Figure 1 - Locking system of ACCESS truss structure [1]

During EVA astronauts first built nine bays using assembly line method, where one worked the upper side of the bay making all connections at the upper side, while the other installed nodes on the guide rails and made all connections at the bottom edge of the bay. This process can be seen in Figure 2. Once the bay was completed, they pushed it upwards so that the work on next bay could be started. Both astronauts were locked into foot-restraints while assembling these bays. For the final bay one of the astronauts used Remote Manipulator System with Manipulator Foot Restraint as a mobile platform for the construction of final bay. For this purpose, it was outfitted with component carrier and moved to the top of truss structure where the final bay was built. Next part of the experiment consisted of various tasks to study manipulation, possibility of structural repair, extending cable through the truss structure, and finally disassembly of the whole structure and its stowage for return to Earth [1].

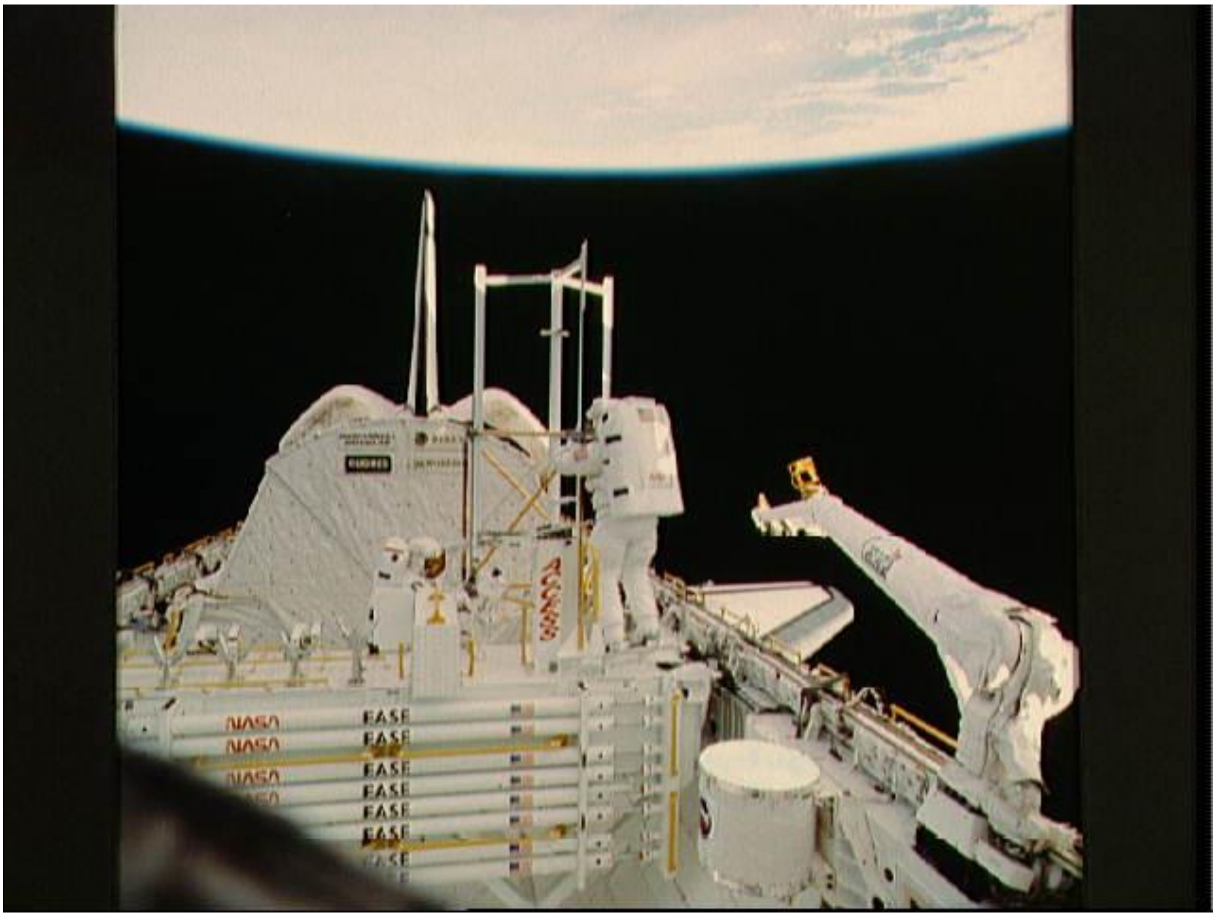

Figure 2 - Astronauts Jerry Ross and Sherwood Spring during first stage of ACCESS truss assembly [10]

The results of the experiment were encouraging as all the parts of experiment were performed successfully. No effect from vernier engines of orbiter were detected, although it is unclear whether they fired during the experiment. Astronauts even reported that mass of truss structure could be much increased. The only negative thing to report was numbness of the fingers that occurred. This was attributed to pressure points in gloves [1]. Nevertheless, this experiment confirmed possibility of truss structure assembly in orbit by astronauts.

5.2. Soviet Research

Soviet Union was not behind in research of orbital erectable structures although they had different approach. Part of this stems from Soviets having fully developed electron beam welding capabilities for in-space use, which can be seen for example in Mayak experiment. The difference is usage of various folding truss structures, where folding is made possible by various hinged joints. This means that truss structure is lifted already assembled and is only extended to its full size and allows for increase in rigidity by welding the hinges in position [2]. Lifting already finished structure that deploys to its full size in orbit is most common technique used to deliver large structures.

Mayak truss, which can be seen in Figure 3, was unfolded in orbit aboard Salyut-7. The truss structure was based on hinge-rod and created tetrahedral structure. The deployment time for 15 meters long truss was 15 minutes. All longitudinal rods are 1 meter long and have hinge which allows for them to be folded in half, this means that whole structure can be folded into 0.5 meter tall transport position. Mayak experiment was considered success, as the truss was not only successfully deployed but also data was collected to allow use of this system in a next generation of space vehicles, namely Mir space station. Even though the data was considered enough to green-light this, it was acknowledged by experts that it didn't contain enough information regarding dynamics of variations in temperature conditions on deployer, manipulator, and truss proper, and small number of telemetry channels.[2]

Figure 3 - Truss mast Mayak in its deployed state [2]

Another extendable truss structure was used to support solar batteries onboard the Kristall module, part of Mir. They were deployed using Topol-CB truss deployer. It is also stated that after docking with Mir an additional truss was extended using a truss deployer, like the one in Figure 4 which has been spaceborne for two years [2] prior to deployment and no problems with the process were noted. This is ascribed to use of special lubricant and materials. In comparison to manually assembled structures, the deployment time of these truss structures was exceptionally fast too and to reinforce its rigidity the hinges could be welded in place [2].

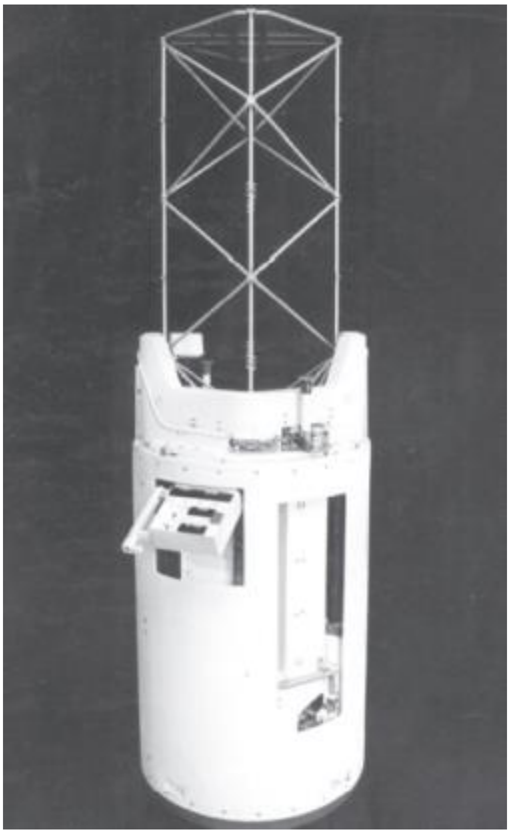

Figure 4 – Truss deployer [11]

Even though clear advantages in favour of the truss deployment systems, manual assembly still remains more reliable and simpler. For that reason Stapel device was put into development. Process of assembly of truss structures using this device was tested in neutral buoyancy. Primary focus of this research was on brazed and welded joints, although it would also allow for mechanical joints to be made. [2]

6. Riveted and Threaded Joints

Riveted joints are permanent joints used to join plates as either lap joints or butt joints using one or two straps [12]. Rivets have been used to build first pressure vessels and they did not entirely lose their use in this field. They have been used in various space vehicles as they provide great versatility in shapes of the pressure vessels. Rivets are also prominent in joints carrying shear load. In catalogues of companies we can easily find blind rivets that are marketed as being able to create airtight and pressure-tight joints with use of additional seal, for example in form of sealant preapplied to the rivet. [13]

There were no experiments found regarding riveting in space. For this there can be several reasons speculated. One of the first is the minimal impact of environment on the technology itself as there is no melt present. Second is that forces applied to the rivet, and reactions in accordance with Newton's Third Law forces applied to the riveting tool, were expected to be too high to easily balance them. It is also of note that rivets were mostly replaced by welds in pressure vessels. Therefore, rivets were not widely considered later in this work because of lack of research on riveting in weightless environment, complications brought by both logistical supply and forces utilized during riveting process, and rivets being replaced in some of applications by other technologies which already underwent development for in-space use.

Threaded joints are much like riveted joints very old and very common. And much like riveted joints are being used in space industry. But much like riveted joints they face same problems as riveted joints when considering their manufacturing in space. Common force bearing joint must be preloaded with force, sometimes this force can be rather high. This together with fact that space environment has virtually no effect on creation and function of these joints means there is little to no research regarding their creation during spaceflight. In creating these joints it is important to manage the forces and their reactions, if these are properly countered then there is no further change to how threaded joints are made or how they work

7. Permanent Assembly Using Metal Joining Technologies

Permanent joining of material is basis for welding and brazing and is common manufacturing practice all around the world, especially for pressure vessels. So it comes as no surprise that considerable amount of research was conducted to develop and adapt these technologies for usage in space.

7.1. Effect of space environment on crystallization and structure of metals

Most commonly used materials in space industry are age-hardenable aluminium alloys, namely alloy 1201 [14]. During welding these materials can incur defects not detectable by X-ray. These defects can lead to lowering of its strength, toughness, loss of corrosion resistance, and loss of tightness of joints. Tests were conducted onboard reduced-gravity aircraft, referred to as flying laboratory in source material, with electron beam with output of 1.5 kW. Under microgravity welds had increased number of pores but there was no detectable change in weld metal composition under various overloads. Connection was found between temperature and composition, with lower temperatures more copper remained dissolved in solid solution increasing the strength of joint.

Additionally, heat affected zone is thinner at lower temperatures further increasing quality of such weld. Strength of joint was rising with decrease in temperature and increase in overload. Heat affected zone porosity was also investigated but no connection was found to overload, although welds should be spaced out enough to prevent growth of micro-porosity in base material. [14]

In further study the effect of dissolved hydrogen was studied on non-hardenable aluminium alloys, AD00, AMg6, AMg3 and IMV-2. During welding of AMg3 there was high amount of splatter and the melt pool was unstable independently on overload and IMV-2 cause magnesium contamination of cathode leading drop in current. Most stable alloys were AD00 and AMg6 with $0{,}2\ \mathrm{cm}^3$ / $100\ \mathrm{g}$. Once again, the composition of weld metal was unaffected by overload, gas content, or starting temperature. Lowest porosity was found in alloys with hydrogen content of $0{,}2\ \mathrm{cm}^3$ / $100\ \mathrm{g}$. AMg6 with higher hydrogen content was creating considerably more porous welds, especially at lower overloads, with pores reaching the size of 3 to 3.5 mm. Welds made in lower overloads had on average 3-5% lower strength. This was attributed to micro-porosity. Sample temperature before welding had no effect on strength of weld. [15]

Next experiment was aimed at comparing welds made under standard conditions with the ones made in microgravity. Microgravity was simulated in reduced-gravity aircraft. As with previous experiments electron beam welding was performed on samples from alloy 1201 and AMg6, depth of welds ranged from 2 to 4 mm. This experiment once again confirmed that gravity has no effect on weld composition. Macrostructure of welds made in microgravity is slightly coarser. Microstructure of alloy 1201 is solid solution of copper in aluminium with coarse and fine precipitates of intermetallic phase of $\mathrm{CuAl_2}$. Precipitates of hardening phase are evenly dispersed. In microstructure of AMg6 elongated grains of solid solution of magnesium in aluminium with intermetallic phase along the grain boundaries. Welds made in microgravity had increased number of pores. Hardness of the weld of alloy 1201 ranged from HRB 75 to HRB 90, with alloy 1201 having HRB 80 in annealed state. From these experiments it was concluded that welds made by electron beam in microgravity do not create principally different welds than under normal circumstances and welds made in microgravity can be only characterised by their higher porosity. [16]

Some studies reported that solidification texture was different depending on temperature gradient vector relative to vector of gravity. Both ground and flight experiments were conducted in Isparitel-M unit which uses defocused electron beam to heat the molybdenum radiator which then heats the sample. Samples of aluminium and aluminium alloy with 0.2% of copper were placed in graphite crucibles which were further inserted into quartz ampoules. After horizontal experiment, there was no texture in direction of temperature gradient, but there was noticeable texture in vertical experiment. These results were similar for both pure aluminium and alloy. In experiments with perpendicular temperature gradient vector and gravity vector only convection related to gravity was found in solidification, namely thermal convection and concentration convection. Impurity ousting in alloy was also observed leading to copper accumulating ahead of the solidification front. For perpendicular vectors of gravity and thermal gradient convective flows not related to gravity, concentration capillary and thermal capillary convection, were observed in addition to previously mentioned gravitation related effects. It was concluded that thermocapillary convection is responsible for the absence of predominant orientation of grains. Thermocapillary convection, also known as Marangoni effect, causes the destabilisation of convective flow and its transition into turbulent mode. [17]

All the previously mentioned experiments studied only the results of melting and crystallization but not the process itself. That later prompted Soviet scientists to conduct experiments using salt melts of $\mathrm{NaNO_3}$ and $\mathrm{KNO_3}$ which have similar properties to molten metals, namely they form two component alloys that have equilibrium diagram similar to metals. Salt melt is optically transparent and so the entire process can be observed. Disadvantage of this method is high sensitivity to overheating which leads to decomposition of chemical compounds from which these salts consist while releasing oxygen and potentially nitrogen. Experiments were conducted onboard the reduced-gravity aircraft which means the duration of about 30 seconds of free fall. Studied melt was produced in thin salt plates (0.5 mm to 1.5 mm) by 60 W electric heater coil. Studies of both free cooling and forced heat removal were conducted. The rate of free cooling was found to be severely reduced in free fall due to the abrupt reduction of convection heat removal. Furthermore convective stirring of melt near solidification boundary appears to be altered. This was concluded from observation of oxide particles dispersed in the melt. Another observed difference was in direction of growth and shape of crystals. [18]

7.2. Arc Welding

Arc welding is one of the most basic methods of welding. It relies on creating electric arc between electrode and base material. Greatest benefit of arc welding is the simplicity of tools and great amount of knowledge from extensive application in industry. Moreover, arc welding does not need overly complicated electronic equipment, which can be damaged by gamma radiation and in comparison with electron beam welding doesn’t produce gamma radiation itself. Another big advantage is low demand on surface preparation before welding. Downside is mostly on the logistic side. Some of arc welding methods need specific gases, and all of them need gas to light the electric arc, as the necessary voltage quickly rises to extreme values when pressure is too low, as per Paschen’s law. With consumable electrode methods you also need to provide enough electrode material for the operation. Various types of arc welding have been studied by both USA and USSR.

Research conducted by USSR into arc welding was revolving around consumable electrode method and plasma arc welding. In reduced-gravity aircraft tests were conducted on stainless steel 12Kh18N10T, titanium alloy VT1, and aluminium alloy Al-6.2Mg. Filler was identical to the base metal. With low currents the drop of filler material that accumulates on the electrode can reach substantial size. Furthermore, surface layer of the drop is moving at slightly lower speed than is the speed of supplied filler wire. Matter transfer occurred only once the drop touched melt pool. To better control size of the drop arc gap had to be shortened or it is necessary to introduce current pulses. Minimal current to separate the drops from 1 mm diameter electrode was measured to be 32 A. With accordance to other measurements the parameters used for arc welding in microgravity and vacuum have to be set higher than under normal circumstances. In the melt pool there was noticeable mass transfer from edges to the centre, but the shape of the weld remained satisfactory. The most severe issue that has been present for all arc welding is lowered stability due to the rate of gas evacuation and subsequent destabilization of arc. Instability was severe enough that it led to damage to the Soyuz 6, aboard of which Vulkan welding unit was tested. Same tests were conducted on plasma arc welding. Both micro- and macrostructure had no visible defects cause by microgravity. Small increase of strength of the titanium welds. Although, just as with consumable electrode welding, due to high rate of gas evacuation the arc was unstable. [19]

American research was revolving primarily around non-consumable electrode arc welding, namely TIG. To introduce gas into the welding area hollow electrode was used and through it the gas was pumped. This led to problems with erosion of electrode that through subsequent development was reduced. Experiments that took place in reduced-gravity aircraft showed that there is no spatter of weld pool and consumption of inert gas was reduced to 28 l/h. [20]

As the erosion of electrode was not fully solved and introduction of foreign particles, especially with as high melting point as tungsten, can have severe negative impact on quality of the weld. This combined with the instability experienced during experiment on board Soyuz 6, leads me to lean towards not considering arc welding as the safest and most reliable technology for in-space welding.

7.3. Welding and Brazing Using Solar Radiant Energy

Attractiveness of technology utilising Sun as its energy source for welding and brazing is undisputable. There are several obstacles in the way though. First one being the high energy density necessary for welding and cutting, which already complicates using solar energy for this purpose. It does not appear to be such problem for brazing. Another issue that remains unsolved is cases of materials having higher reflectivity or if surface layer of oxides has particularly high temperature of melting, which are exactly the materials used in space engineering. Despite these drawbacks there was a series of experiments conducted in Soviet Union to study this technology. [21]

The welding experiment was conducted in enclosed chamber with controlled atmosphere. Radiant flow was concentrated on sample by reflector and brought into the chamber through quartz window and water-cooled aperture. The chamber was able to operate with both vacuum and mixes of various gases. Sample material was aluminium-copper alloy 1201. Prior to welding layer of 0.1 mm was scraped from the edges of samples. Energy density was $1200 - 1300\ \mathrm{W/cm^2}$. Samples were preheated and in protective argon atmosphere. Results showed that this energy density allows welding samples of thickness up to 2.0 mm at speed of 4 m/h. Higher speeds led to lack of penetration and discontinuities in the weld. Short welds were uniform enough but there was discernible non-uniformity in longer welds where defects were periodically observed. Large amount of inclusions with origin in oxide layer permeated the weld. Tight joint could not be obtained. There was no significant difference in composition of weld metal and base metal. Metallographic structure of weld metal was coarse with globular precipitation of $\mathrm{CuAl_2}$. On the edges of weld there was dendritic structure with dendrites growing out of partially melted grains. Heat affected zone has gone through grain coarsening and formation of discontinuities. Mechanical properties were just as severely impaired. Tensile strength dropped to little more than 50% of original value. Even on first look the weld is visibly thick and rather crude as can be seen in Figure 5. Thus, the results of the experiment proved that at the time it was not possible to create satisfactory welds using this technology. [22]

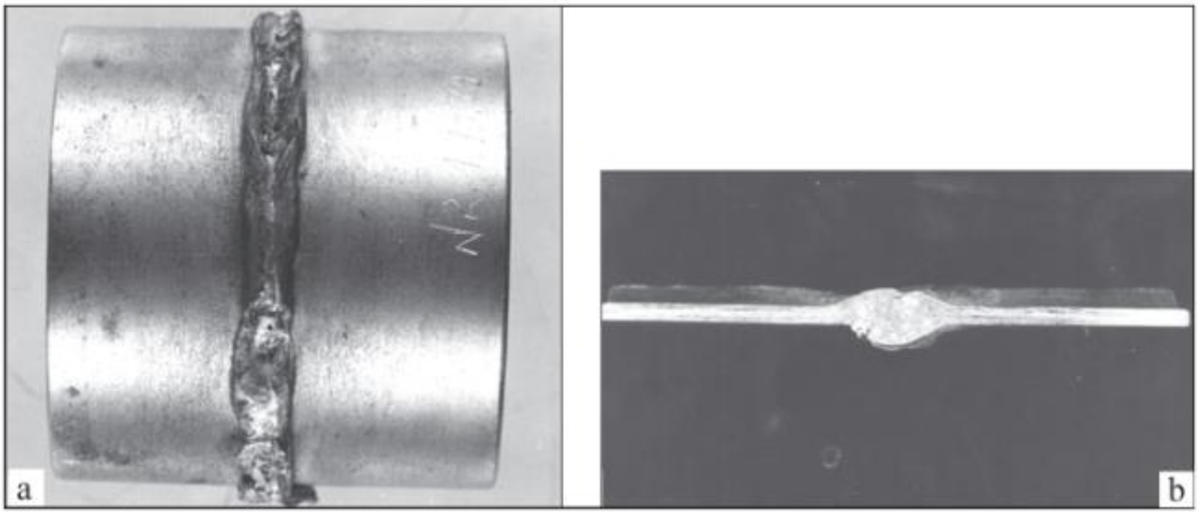

Figure 5 - Appearance of welded joint on a cylindrical sample (a) and its cross section (b). [22]

Experiments in brazing using radiant solar energy were from the beginning expected to be more successful as necessary energy concentration is lower than in welding. Experiments were conducted in testing chamber which was mounted aboard reduced-gravity aircraft. This allowed for experiments to be conducted in free fall and vacuum closely resembling conditions in Earth's orbit. Source of light was xenon arc lamp which was concentrated using elliptic mirror. Brazed materials were VT1 titanium alloy and steel 12Kh18N10T. Materials used as filler were copper and braze alloys POS-40, POS-61, and PSr-72. Brazing speed was between $0.2 - 16\ \mathrm{m/h}$. Samples were in form of plates with thickness of 0.3-0.8 mm and 1.0-2.5 mm high flanged edges. In ground experiments with larger gaps between plates root sagging was observed in steel samples with copper filler. At free fall gap was uniformly filled with braze alloy. Composite structure formed in braze metal due to dispersion of particles from base metal. At free fall these particles are dispersed uniformly with increasing concentration towards interface With VT1 plates and copper filler there was incomplete melting of the copper filler in lower parts of the joint which led to inclusion of needle-like structure in direction of heating. Due to high solubility of copper in titanium the weld consists mainly of Ti-Cu system with amount of eutectoid being higher closer to the heating surface. Intermetallic interlayer was found on the interphase and has microhardness of $300 - 400\ \mathrm{kg/mm^2}$. In using braze alloy POS-40 no structural differences were found, although alike in copper, in free fall there was no root sagging. [21]

7.4. Friction Stir Welding

Friction stir welding is solid state welding technique using friction between the tool and joined pieces to generate heat, which together with pressure joins the pieces together. This technology is utilised heavily in space industry for example by NASA in manufacturing of SLS. The joints are much more defect-free than welds made using conventional methods thanks to the fact that they are created in solid state. [23]

But despite its popularity in space industry, it is not believed that this technology is well adaptable for in-space use. The main problem is presented with the speeds of rotation and the resulting reaction forces from the friction along with the pressure needed means that while friction stir welding is very beneficial technology for use on the ground, it might be very hard to adapt for in-space use. Together with lack of research this means that friction stir welding is not further considered as viable candidate for in-space construction technology at the time.

7.5. Electron Beam Welding

Electron beam has many advantages over the other heat sources. Namely it is high effectivity of transforming electricity into heat, very high level of energy concentration reducing energy consumption, and the welds it creates have small dimensions of HAZ. It is also already adapted for use in vacuum which makes it ideal candidate to adapt for in-space use. The downside is that electrons produce bremsstrahlung radiation. This led to design decision in Paton Welding Institute to use accelerating voltage of 10 kV. Overall power of the beam was $0.5 - 1.5$ kW. This meant that it was sufficient for welding and cutting of materials up to 3 mm thick as well as effective evaporation of metals. [7]

First experiments with electron beam welding were conducted alongside arc welding and plasma-arc welding onboard reduced-gravity aircraft. Electron beam used had output of 1 kW and supplied current was 70 mA. Samples being welded were made from aluminium alloy Al-6.2Mg, titanium alloy VT1 and steel 12Kh18N10T. Welds made using electron beam were of sufficient quality. Electron beam welding was the least impacted of the processes used as both arc welding and plasma arc welding were showing decreased stability due to fast evacuation rate of gases. More experiments were conducted in Vulkan unit on board Soyuz 6 in 1969. Experiments were conducted in orbit inside depressurized habitation module of the vehicle. These experiments confirmed previous results and thus it was decided that further development would focus on electron beam welding in USSR. [19]

First and foremost, aim of the program in USSR was to create equipment for repairs on space stations [24]. This development culminated in Versatile Hand Tool, VHT, which was able to not only weld, braze, and cut, but also for depositing various coatings. VHT is made of two diode electron guns with indirectly heated cathode, one for brazing, welding, and cutting and the other equipped with crucible for deposition of coatings. The handheld part is then connected to backpack which contains secondary power source and control panel. Focusing system gives focal distance in order of hundreds of millimetres. Accelerating voltage was 10 kV due to bremsstrahlung radiation not exceeding set limits. VHT as whole consisted of container with secondary power source and control panel, sample board, and working tool as can be seen in Figure 6. The working tool has two electron beam guns, one for welding, brazing, and cutting, and the other one with crucible for surface coating deposition. These two electron beam guns are covered in screen protecting operators hand from heat emissions of metal being treated. The tool further consists of supply cable, high-voltage converter, and handle with trigger, which all can be seen in Figure 7. [25]

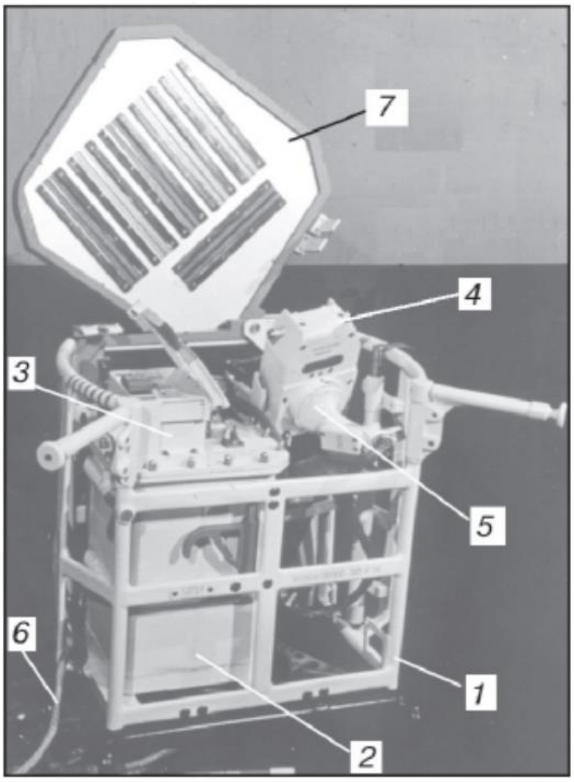

Figure 6 - VHT, 1—container; 2—secondary power source; 3—control panel; 4—working tool; 5—handle with a trigger; 6—cable; 7—6-sample board [25]

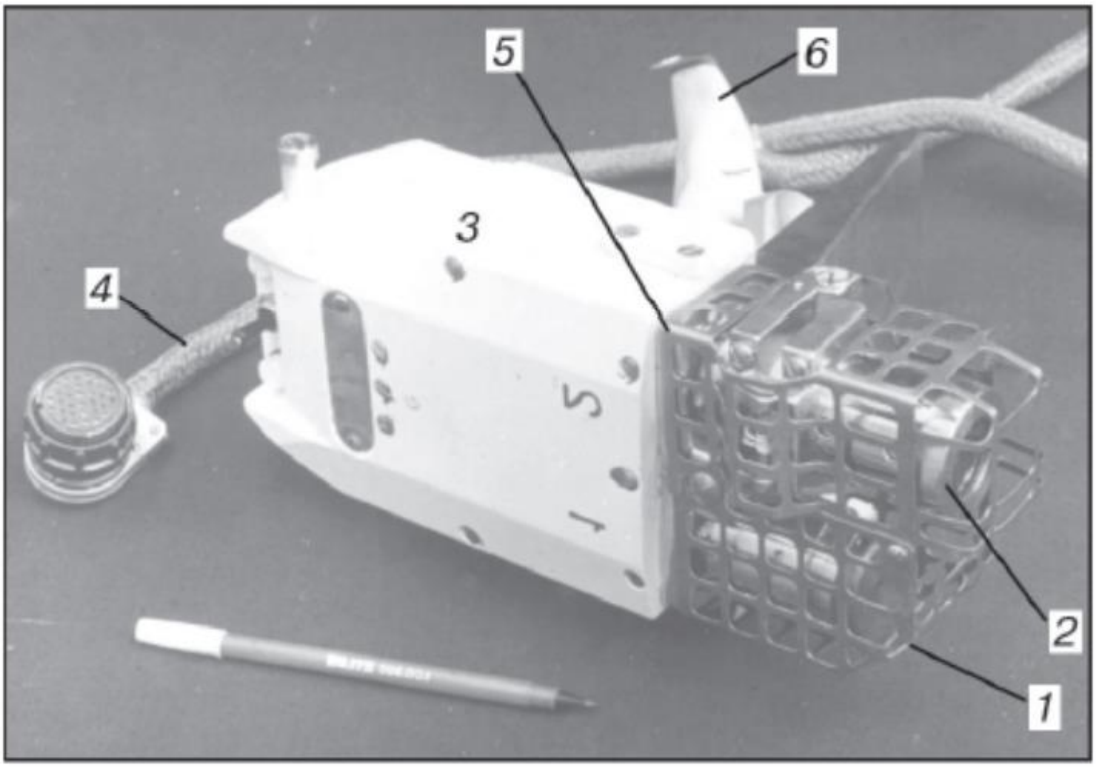

Figure 7 - Working tool, 1—electron beam gun for welding, cutting and brazing; 2—electron beam gun (with a crucible) for coating deposition; 3—high-voltage converter; 4—supply cable; 5—screen, protecting hand from heat emission of metal being treated; 6—handle [25]

This tool was tested during spacewalk on station Salyut 7 on June 25th 1984 [26]. Samples being welded ranged in thickness from 1.5 mm to 3.0 mm from distance of 200 mm to 220 mm. Current supplied was between 55 mA and 75 mA. As with every manual operation welding speed varied, in this case it was between 7 m/h and 10 m/h. Results of these experiments showed that the variation in distance did not have any detectable impact. Most important thing was welding speed which when increased severely decreased depth of penetration. Defects were attributed to insufficient training of operator. During manual welding operator managed to make welds of width equal to up to 50% of sample’s thickness. [27]

After these experiments VHT was revised and new welding tool was crated, this one was called Universal. Power was increased and they added automatic filler wire feed. Increase in power solved problems with low penetration of weld and problems when working with aluminium. [28]

Further Soviet experiments in orbit were focused on welding of sheet metal in open space. Samples were 47 by 180 mm and made from titanium alloy VT1-0 of 0.8 mm thickness and stainless steel 12Kh18N10T of 1.0 mm thickness. Experiments were conducted in open space where pressure was $10^{-3} - 10^{-4}$ Pa with welding speed of $5 - 7\ \mathrm{mm \cdot s^{-1}}$. For comparison experiment was conducted in simulation chamber with same parameters save for pressure, which in this case was $5 \cdot 10^{-2}$ Pa. Welds made in orbit were no different from those made on Earth in shape or appearance. Continuity of welds was checked by liquid penetrant inspection. No discontinuities were discovered this way, although space samples lacked penetration in several places. This was blamed on the operators and their lack of experience. Tensile strength of welded pieces was tested. Due to apparently low amount of samples these data are not statistically significant and therefore drawing wider conclusions from them could lead to inaccurate assumptions The results showed that welds of VT1-0 were of higher or equal strength compared to those made on the ground and that welds of 12Kh18N10T were comparable to those made on the ground. Microhardness was comparable for both welds made in space and those made on the ground. When it came to the fracture, brittle fracture area was bigger in welds made in space. Soviet scientists believed that this was caused by higher content of sulphur. In total weld was enriched by alloying components while HAZ was deprived of them. Diffusion zone was clearly visible in both ground and space samples. Microstructure of steel welds was dendritic with α phase along the boundaries. In space samples α phase is less present and γ phase is more finely dispersed. Amount of dislocations was higher in welds from orbit. Titanium welds were made of fine needle precipitates. In weld from orbit the were finer than in the weld from ground due to higher solidification speed. This result contradicts other results that claimed that welds made in orbit have in fact courser grain. This result was acknowledged by source material without any further explanation. In welds from space there was visible cellular substructure where dislocations are concentrated outside of the cells. Auger electron spectroscopy showed that the samples did not exceed limits for hydrogen, carbon, oxygen, and nitrogen according to GOST. [29]

Notable feature of design base on application of EBW are spherical flanged joints which allow for repeated welding operations in case of unsatisfactory welds as seen in Figure 8. This allows repeated welding in case of unsatisfactory welds.[30]

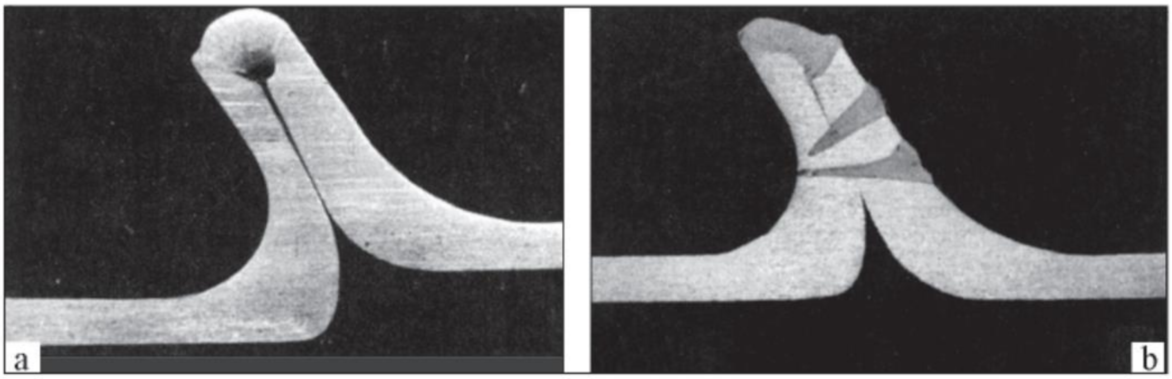

Figure 8 - Macrosections of joints made by EBW in one pass over the edges flanging (a) and after application of the second and third repair slot welds (b). [30]

When all the experiments conducted using handheld electron beam welding in orbit are taken into account lack of penetration seems to be one thing they have in common. Together with high demand for efficiency of chosen process and previously stated power limitations I believe it is entirely possible that equipment used was underpowered for the parameters of process. Whether this was result of too high welding speed chosen for process or error on operator's side cannot be clearly discerned. Results from the research conducted by Soviet and later Russian and Ukrainian scientists shows that EBW is one of the technologies that can be employed for use in space to great benefit from space environment which provides vacuum necessary for the process and turns one of the greatest disadvantages of EBW into an advantage.

7.6. Laser welding

Even though USSR was primarily focused on development and use of electron beam welding. During experiments in USSR they estimated necessary power output for to be 2 to 5 kW. Lasers with such output were at the time judged to be far too big and energy inefficient to be used. Furthermore, there were concerns about safety of using lasers as some metals might be reflective in the wavelengths of the lasers. The upside compared to the EBW is better focus which caused better results when welding titanium pipes, but the laser was lacking power to reliably weld aluminium, which would require not only higher energy output but also continuous operation instead of pulsed one which was utilised in experiments conducted in USSR. [31]

Research into in-orbit metal joining technologies began later in USA. The first avenue of research was laser welding. Laser welding was chosen due to big advancements technology has seen since USSR decided laser welding was not the best alternative, although many drawbacks have persisted. Unlike electron beam welding the laser welding equipment is harder to scale down into handheld tool which still grants electron beam welding advantage, there is also a lot of advantages in laser welding. For example the laser can theoretically be delivered using optical fibre, thus negating the small size advantage of EBW equipment. This compounds with need for short power connections for EBW equipment to avoid loss of voltage. Furthermore EBW, and all arc welding technologies can affect sensitive electrical equipment onboard space stations and EBW also releases X-ray radiation. The last, but probably the biggest advantage of laser welding over EBW is that it can be used both in vacuum and in atmosphere. There is also theoretical advantage of solar pumped lasers not needing electric power, but there is lack of experiments regarding their viability, although the concept itself seems more than promising. Lasers were also used to weld other materials than metals. This combined with optic fibre delivery system puts laser welding as one of the most versatile options for in-space welding. Equipment used in the flight experiments was Q-switched diode pumped Nd-YAG laser array from which the laser was delivered using fibre optics to the welded piece. Array was powered by 10 kW power supply, double that of power supply for Soviet EBW experiments. Nd-YAG laser was chosen for its wavelength and diode pumping for its efficiency and low heat generation. Samples used were comprised stainless steel 304 (EN 1.4301) and 301 (EN 1.4310). The experiments were conducted onboard KC-135 flying on parabolic trajectory. The welded specimen was held in small vacuum chamber. Variety of tests were conducted at various pressures and at various overload levels. Welds created during these experiments were then further studied. It was noticed that while all the welds were of high quality, the experiments conducted in atmosphere comprised of air had cracks and oxide deposits on surface. Welds were relatively clean when pressure of air was below $0.5\ \mathrm{Torr}$ (roughly $66.7\ \mathrm{Pa}$). When comparing penetration between flight experiments and experiments conducted on the ground it was found that the flight experiments had better penetration which was not achieved on the ground even after increase in laser’s power output. Low-g welds have radially emphasized microstructure, heat flow is radial as well as solidification. This is attributed to the reduction in convective flow. It also stated that the removal of gravity should cause the weld pool width to diminish as higher curvature of the liquid surface of the bead becomes sustainable. The reduction of width seems more profound for partial penetration welds. In longitudinal section of partial penetration weld we can see increase in penetration in low-g compared to high-g. Low-g welds also showed thinner HAZ, although there was still steep drop in strength of material in HAZ but it was lower than in high-g welds. [32]

American in-flight experiments showed promise for laser welding as the results show that they are at least comparable to the EBW if not better thanks to the advancements in lasers. Moreover possibility of electricity independent solar pumped laser is enticing prospect as circumventing need for oversized solar array to power the laser could theoretically allow for more powerful laser to be used further improving the results we can achieve using it.

7.7. Diffusion welding

All the previously mentioned methods were to a certain degree experimented and test results were promising to a certain degree, all of these technologies produced joint that was inferior to base material. There is technology, that at least in theory, produces joints of same quality as base material and does not seem to be thoroughly investigated for its possible use for in-orbit construction, only as mode of failure. Diffusion welding shares some of the properties with EBW, namely the need for vacuum and big impact of surface quality on quality of the joint.

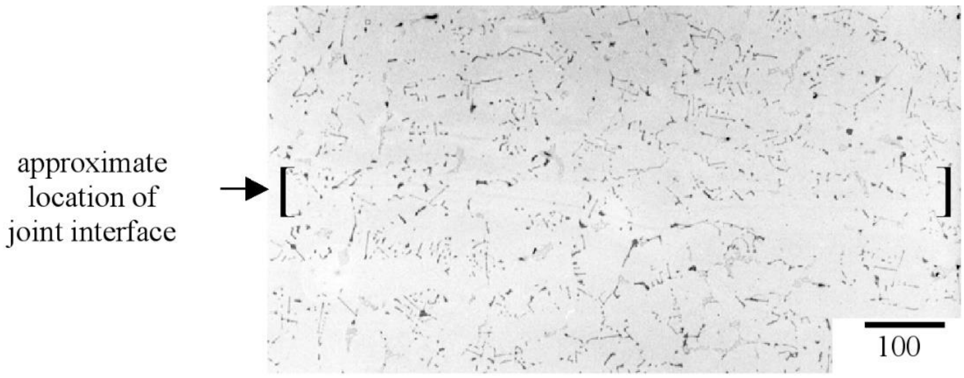

Figure 9 - Diffusion weld of cobalt superalloy, without flaws or loss of alloying elemnts [33]

Diffusion welding can produce the highest quality joints where the joint itself is indistinguishable from the base material, as seen in Figure 9. These joints are can be made not only between metals, even those that would not be weldable any other way, but also non-metallic materials like ceramics. Final products from diffusion welding can also be far more complicated than and way more detailed than those produced by other technologies. The main problems are the need to dispose of oxide layer on the joined surfaces. Most common method is heating the pieces to be joined to simply dissolve the oxide layer. [33] Search reveals an alternative proposition for cleaning the surface of the oxide layer, ion bombardment. Patent from 1981 for diffusion welding contains description of using ionised argon, xenon, or similar gas to clean the contamination layer from surface of the material [34]. This obviously would allow to bypass the need of high temperatures to dissolve the oxide layer therefore reducing the chance of deterioration of mechanical properties of age hardened alloys but presents problem of logistics. Although it is my belief that it might be possible to develop tools and system that would allow retention of ionized gas, but for now this technology must be judged as is, and that is without option of gas retention. Further issue can be seen with the time this process takes. Diffusion welding is not fast process and in furnace it takes several hours, this time will only increase with lower temperatures. Advantage is that the time needed for the process to take place is not related to the size of the weld therefore big complicated welds can be done as fast or faster than with other technologies. [33]

Because of absence of melt some of the specific effects of space environment are negated. Most important effect for diffusion welding technology is presence of vacuum which protects material from oxidation once the oxide layer is removed or dissolved. Oxide layer takes considerable time to reform in vacuum and therefore it should be possible to diffusion weld the materials in the meantime, although tests are needed to ascertain this.

Experiments conducted pertaining to these phenomena were mostly aimed at discovering how likely random occurrence of diffusion bonding is and what problems it would present. NASA tested over forty different combinations of metals in sliding contact. There was always resting period between the movements for the diffusion to occur. Results showed that if the point of resting contact remains the same, then there is sharp growth of coefficient of breakaway friction. This coefficient stabilises swiftly and does not seem to grow beyond second cycle. Other experiments conducted consisted of partial rotation of disc in contact with metal pellet after each resting period. There was noted some increase in coefficient of breakaway friction which was ascribed to disruption of oxidic layer due to sliding motion. Tests with change in length of resting period did not show any correlation between the increase in breakaway friction coefficient and length of resting period. It was considered result of randomness of the phenomena. [35]

7.8. New Assembly Paradigm

In the 2012 paper published by American Institute of Aeronautics and Astronautics we can find proposition for advancement in use of assembled structures over deployable structures. As deployable structures quickly add to the complexity of the craft and therefore lower its reliability. This would be far less of a problem if there was option of on-orbit servicing and repair but as things stand now, there is no such option. As this article is specifically talking about James Webb Space Telescope, the main focus is on truss structures that would support large precision segmented reflector.

The aim of the paper was to propose a way in which diameter of main aperture would not be dependent on launch vehicle dimensions and still maintain high reliability. This led to proposition of in-orbit assembly using either manual assembly by astronaut or automated assembly by robots. Both options were successfully tested in neutral buoyancy. So far welded structures were not commonly used despite experiments regarding them being performed by both USA and USSR. [4]

Table 2 Comparison of assembly methods [4]

Feature/Attribute	Mechanical/Erectable Structure	Welded Structure
Joint (Nodes/connectors) Mass	High	Minimal
Connection Complexity (and cost)	High: many mechanical features with high tolerances	Simple: butt joint that is welded
Truss strut complexity (and cost)	High: must have mechanical joints on each end, precision lengths set for each individual strut	Simple: tubes with sliding plunger or strut sleeve allows length setting and welding on orbit
Manufacturing Cost	High: for precision node balls and connector components	Low: simple balls, tubes and end fittings
Application Versatility	Low: all components must be manufactured and geometries set for a particular application being built. Infrastructure to support assembly is application dependent.	High: simple balls and struts allow different geometries and scales to be built from a few common elements. Assembly infrastructure adaptable to different geometries and scales. IPJRs can be programmed to build different systems
Location of assembly complexity	Each individual structural element (nodes, joints) are complex; assembly infrastructure requires astronaut positioners, manipulators, tools, and end effectors.	IPJRs are complex, and require auxiliary manipulators, tools, and end effectors. Requires welding process equipment, inspection equipment.
Location of jigging	Built into each individual strut (lengths preset at high precision)	Separate IPJRs, which are reusable and versatile

Table 2 shows that welded joints have many advantages over mechanical joints. Due to the electron beam being able to not only weld but also to cut it is also possible to disassemble these joints which mitigates one of the two major complications with welded joints. Second issue is the assembly itself. In mechanical joints high precision is ensured via the high precision of parts, in welded joints there is need for higher precision of assembly, both when automated and done by hand. Once the position of strut and nodes is set, they would be welded together using electron beam. [4]

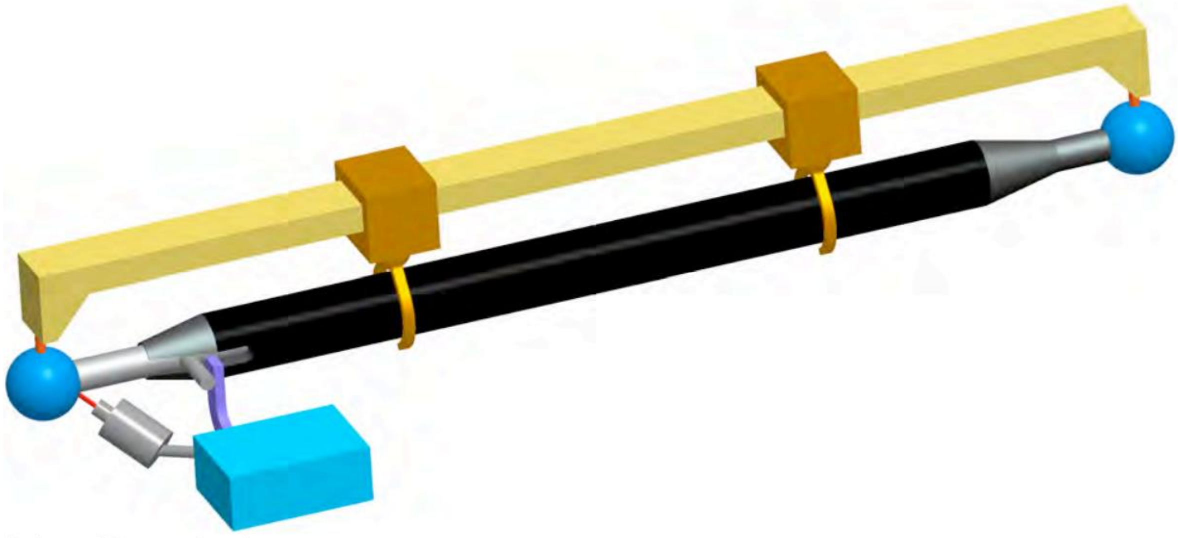

Figure 10 - Weldable truss strut and assembly [4]

8. Additive Manufacturing

In the last years 3D printing has been gaining on popularity and research into this emergent technology has been on the rise, so it comes as no surprise that possibilities of its in-space utilization have been explored. NASA has stated that in-space manufacturing capabilities are critical for future exploration missions [36].

Research into this technology comes not only from state sponsored space programs but also from private company Made in Space which has developed in-space manufacturing capability using additive manufacturing. Made in Space has developed manufacturing platform Archinaut which will be launched as NASA's OSAM-2 (On-Orbit Servicing, Manufacturing and Assembly). It will be technological demonstration in which the platform assembles and deploys its own solar arrays [37]. Even though the swiftness of development of this technology shows that it harbours great potential, it is still too early to entirely compare it to the previously explored technologies. If technical demonstration succeeds additive technologies might become dominant technology for in-space manufacturing.

9. Discussion

In the previous paragraphs we have discussed what technologies are being investigated or could be investigated for their application in in-orbit constructions. In this work we were concerning ourselves with large structures, both pressurized and unpressurized, that can't be delivered using commonly used single launch system. Currently used systems for such structures are transformable structures and docking systems aboard ISS and although these systems are well developed and well familiarized technologies but the limitations stemming from launch vehicles dimensions and power are still present.

First, we must compare mechanical joints and welded/brazed joints. Mechanical joints present way better option for temporary structures, erectable structure, transformable structures, and mobile joints. They cannot really be replaced in these cases. When it comes to permanent structures and fixed connections welded joints can be preferable due to overall lower weight of structure and due to allowing for simpler creation of airtight joints. Also reliability of welded joints is higher than of mechanical joints [9]. Soviets have developed VHT to repair damage to various structures and help erect weldable truss structures and their experiments confirmed that this technology can be used [25]. Further the development in robots and automatization that was documented in AIAA paper means that we are close if not beyond point where we can automate such technological process using robots [4]. NASA’s own research into laser for in-space welding purposes shown that we can also replace electron beam with it, although electron beam still remains most developed technology for in-space use and allows a plethora of technological processes to be performed. Additionally, laser welding can be performed not only in vacuum as electron beam welding but also in atmosphere inside pressurized module [32]. Diffusion welding could prove to be promising if studied and further developed as even though it lacks versatility of laser or electron beam it offers joints of superior quality over any other technology. It is also of note that developed welding technology can allow for more extensive and readily available repairs to be performed in case damage to structural integrity. Of note is the development in field of additive manufacturing as at the time it seems to be only in-space manufacturing and construction project moving forward. Additive manufacturing also opens possibility for on-demand production of specific parts in space and thus can play crucial role in further development of our spaceflight capabilities. Main benefits and drawbacks of various technologies are listed in the Table 3

Table 3 - Benefits and drawbacks of various in-space construction technologies

Technology	Benefits	Drawbacks
Mobile mechanical joints	Simplicity and speed of deployment of structure, can be automated, low weight compared to other types of truss structure, can be reinforced by welding various hinges shut	Can't be used for airtight joints, lower rigidity compared to other options
Integrated locking mechanisms	Simple and easy to assemble, can be automated, higher rigidity than structures with mobile joints	Complex locking mechanisms, need of high precision, low versatility
Threaded joints	Simple, relatively cheap, strong, high reliability, able to achieve high rigidity	High mass, needs additional steps to achieve airtight seal, reaction forces when tightening bolts need to be considered in weightless environment
Riveted joints	Simple, reliable, cheap, strong, in use currently	No experiments with riveting in space environment
Electron beam welding	Most developed of welding technologies for in-space construction, surface cleanliness is not as important as with other welding technologies, extraordinary versatile tools (used for brazing, welding, cutting, and coating deposition), joints of good mechanical properties, possible to automate, can work with or without wire feed, airtight joints	Cannot work in atmosphere, emits X-rays and can interfere with sensitive equipment
Laser welding	High quality of joints, airtight joints, laser can be delivered using optical wire without the need to move device itself, works both in atmosphere and vacuum, theoretical prospect of solar pumped laser	High energy demand, even with optimal type of laser, the wavelengths emitted are not completely absorbed by materials and besides energy loss this also can pose danger to operator
Diffusion welding	Same properties of joint as of base material, can be used to make extensive and complex welds, size of weld does not increase the length of the process	Untested in space environment, logistically complicated due to need of extremely clean surfaces of the joint (possible to solve through further development), very slow
Solar radiant energy welding and brazing	Does not rely on electricity, experiments confirmed feasibility of brazing	Not high enough power density for welding or cutting, solar doped laser allows same advantages
Additive manufacturing	Can be used to create complex shapes on demand from various materials, even creating exactly specified alloys using powder metallurgy as well as creating light-weight structures using other materials, like composites and plastic	Being the youngest in terms of development of all the technologies discussed, makes it fall short in terms of amount of experiences gathered using this technology, although at the moment it is the only technology being developed

We have to also discuss how various technologies fit the criteria we have outlined in the begining. It is without surprise that currently used technologies, meaning various integrated locking mechanisms and mobile mechanical joints, are satisfactory in all relevant parameters. This does not necessarily mean they are the optimal choice as there are other parameters to consider, but those are often specific to particular types of structures (these are outlined in Table 5).

When considering riveted and threaded joints, it is important to consider that while these technologies are essentially same in space as on the ground, you have to counter reactive forces. Additionally, parts that are being connected need to already have the needed holes as drilling and other machining technologies require equipment not available in the orbit and are problematic with regard to the forces used during the process. Therefore while they can be used with any other material, they are not entirely versatile in their application as they need precisely premade parts delivered from the Earth, much like integrated locking mechanisms.

On the other side of versatility spectrum sits additive manufacturing which can produce any structure from source of material (metallic powder, spool of material, etc.). This means that if manufacturing device is stocked, then it can produce items on demand. This can mean both complete structures and replacement parts. This means that while additive manufacturing can play important role for in-space construction, it should be paired with appropriate development of other technologies to take full advantage of its capabilities.

Welding has proven to be most affected by the environment of space. Some of the technologies like arc welding became unstable and unreliable due to evacuation rate of gasses. Other welding technologies were affected positively, for example electron beam welding is done in vacuum which limits its use to outside of pressurized areas. Laser welding has no such limitations but compared to EBW it is far less developed for in-space use. Laser welding also needs more power, this could be remedied by developing solar pumped lasers. As it currently stands, EBW is the only successfully tested and fully developed technology for in-space welding. All the tested and welding technologies adapted for in-space use had one disadvantage that caused them to be more affected by the microgravity, which caused increased porosity in some cases, and that was the presence of melt. Even though amount of melt is limited when using electron or laser beam it was still enough to potentially affect the operation. Solid state welding would counter this and offer better results, just like it does on the ground. Friction stir welding is widely use in space industry and if was not for the forces occurring during the process it would be endorsed for adaptation, but the forces needed put it into disadvantage. Another solid-state welding technology available is diffusion welding which can create joints that are nearly indistinguishable from base material. Major disadvantage of this technology is the need for completely clean surface without contaminants or oxides which is challenging even on the ground. This means that diffusion welding is less energy efficient, and may even require consumable materials that will not become part of the joint, therefore decreasing its material efficiency.

Attempts at directly using sunlight to weld and braze parts were less than successful. Even though both experiments successfully joined material, neither of experiments produced as high quality of the joint as other technologies. That can potentially be solved by using bigger mirror to collect the light and increase energy density, but this could make the whole process too unwieldy. But from the experiments conducted in USSR, this technology does not seem reliable enough. All welding processes, save for diffusion welding, also have problem with joining dissimilar materials.

Information from previous paragraphs are condensed in the Table 4, where each parameter is either marked Y, if the technology is satisfactory in this parameter, N, if the technology is not currently satisfactory at this parameter, or /, if the parameter is irrelevant to the technology.

Table 4 - Technologies in relation to technological requirements

	Equipment reliability	Technology reliability	Energy efficiency	Energy density	Material Efficiency	Quality joints	Workable material diversity	High Accuracy	Reaction forces
Mobile mechanical joints	Y	Y	Y	/	/	Y	Y	Y	Y
Integrated locking mechanisms	Y	Y	/	/	/	Y	Y	Y	Y
Riveted joints	Y	Y	Y	/	Y	Y	Y	Y	N
Threaded joints	Y	Y	Y	/	Y	Y	Y	Y	N
Welding and brazing using solar radiant energy	Y	N	Y	N	Y	N	N	N	Y
Electron beam welding/brazing	Y	Y	Y	Y	Y	Y	N	Y	Y
Laser welding	Y	Y	N	Y	Y	Y	N	Y	Y
Diffusion welding	Y	Y	N	/	N	Y	Y	Y	Y
Additive manufacturing	Y	Y	Y	/	Y	Y	Y	Y	Y

From the Table 4 we can conclude that most of the technologies can be used in space under the right circumstances and for the right purposes. We can split these structures into 3 main groups (as seen in Table 5). For temporary structures or structures with mobile joints, like solar arrays or various extendable antennas. It is advantageous to use either mobile mechanical joints, which can be folded and unfolded rather quickly, but also can be individually actuated. For temporary structures there is also an option of various integrated locking mechanisms. Less optimal but still viable option are threaded joints using either threaded pieces or nuts and bolts. Obviously wrong choice are technologies that form permanent joints, although in some cases they can be used, for example to increase rigidity in extended structure by welding hinges in position, which blocks it from folding turning it into permanent structure. For permanent truss structures without mobile joints, or in places where mobile joint is not needed, welding and brazing provide best solution due to simplicity and strength of the joints. Integrated locking mechanisms are heavier and while still usable, they are at disadvantage in comparison to welded joints

Very specific in their manufacturing are pressure vessels. The need for airtight joint immediately rules out most of integrated locking mechanisms, only exception are docking and berthing systems used by ISS. Welding and riveting are obvious choice for pressure vessel manufacturing with welding being preferred as it is also the technology used for vast majority of pressure vessels manufactured on the ground. Very interesting option is also Additive manufacturing which can, at least theoretically, produce pressure vessels too, as well as parts for all the other structures.

Table 5 - Advantageous technologies depending on type of structure

Structure	Examples	Advantageous technologies	Disadvantageous technologies
Temporary truss structures / truss structures with mobile joints	Solar arrays, extendable antennas	Integrated locking mechanisms – assembled by robot or by astronaut, long assembly, heavy, does not directly require electricity Mobile mechanical joints – can be extended quickly, needs electricity, lighter, actuated joints	Any form of welding or brazing as they form permanent joints,
Permanent truss structures / truss structures without mobile joints	Support structures, load bearing structures, antennas,	Welding – both EBW and laser welding are viable choice, if fully developed solar pumped laser will not require electricity Brazing – simpler, requires prepared sleeves to connect elements of structure	Integrated locking mechanisms, diffusion welds
Pressure vessels	Inner shell of habitable modules, plumbing, various tanks, and reservoirs	Welding – EBW, laser, and diffusion welding, as the joints must be of highest quality and airtight Riveting – rivets have been used for this application in space industry, old method of creating pressure vessels, but it was never tested in space environment Additive manufacturing – pressure vessel can have any shape that the manufacturing unit can make and does not need any premade parts delivered, only material for manufacturing unit	Integrated locking mechanisms (with exception of docking and berthing systems used onboard ISS)

10.Conclusion

To conclude, large structures that require completion in orbit can use wide array of technologies and it is impossible to choose one single technology that would fit every purpose best. This being said it is my belief that it would be very beneficial from long term perspective to finalize development and start utilizing more technologies for permanent joining of metals in space as that will not only open up more possibilities for larger constructions, like large telescopes, to be erected but also for habitable structures to be built for the nascent industry of space tourism. If paired with successful development in additive manufacturing for in-space use, it would simplify and reduce price of in-space manufacturing in long run. Furthermore, the lessons learned while developing and utilizing these technologies, like knowledge of behaviour of molten metals and how to utilize space as technology environment to our benefit, will benefit us if we ever start exploiting resources found in asteroids.

Sources

[1] HEARD, Walter L. Jr and Judith J. WATSON. Results of the ACCESS Experiment. In: *NASA Technical Reports Server* [online]. NASA, November 04, 1995 [cit. 2020-07-01]. Available at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19880001498.pdf

[2] BALUTSEV, A. R., E. S. MIKHAJLOVKSAYA, A. A. ZAGREBELNY, V. P. NIKITSKY, A. V. MARKOV and I. V. CHURILO. Truss Structures in Orbital Complexes. PATON, B. E. *Space Technologies, Materials and Structures: Welding and Allied Processes*. London: Taylor & Francis, 2003, pp. 484-495. ISBN 0-415-29985-3.

[3] BROWN, Charles D. *Elements of spacecraft design*. Reston: AIAA American Institute of Aeronautics, 2002. ISBN 15-634-7524-3.

[4] DORSEY, John T., William R. DOGGETT, Robert A. HAFLEY, Erik KOMENDERA, Nikolaus CORRELL and Bruce KING. An Efficient and Versatile Means for Assembling and Manufacturing Systems in Space. *NASA Technical Reports Server* [online]. NASA, October 03, 2012 [cit. 2019-02-02]. Available at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120014279.pdf

[5] PATON, B. E. Technological Aspects of Space Welding. PATON, B. E. *Space Technologies, Materials and Structures: Welding and Allied Processes*. London: Taylor & Francis, 2003, pp. 35-40. ISBN 0-415-29985-3.

[6] SLICHTER, William P., Richard A. ORIANI, Robert BRAGG, et al. *Materials Processing in Space* [online]. Washington, DC: The National Academies Press, 1978 [cit. 2020-07-24]. ISBN 978-0-309-33596-6. Available at: https://doi.org/10.17226/20033

[7] OKHOTIN, A. S., V. F. LAPCHINSKY and G. S. SHONIN. Some Results of Works Made by the Soviet Scientists in the Field of a Space Technology. PATON, B. E. *Space Technologies, Materials and Structures: Welding and Allied Processes*. London: Taylor & Francis, 2003, pp. 52-56. ISBN 0-415-29985-3.

[8] SMIYAN, O. D., G. M. GRIGORENKO, E. S. MIKHAJLOVSKAYA, L. M. KAPITANCHUK and S. O. ANTONOV. Features of Chemical Element Migration in the Subsurface LAyers of Metals and Alloys During Thermal Cycling. PATON, B. E. *Space Technologies, Materials and Structures: Welding and Allied Processes*. London: Taylor & Francis, 2003, pp. 220-226. ISBN 0-415-29985-3.

[9] TAMIR, David, Dr. Thomas A. SIEWERT, Dr. Koichi MATSUBUCHI, Lee FLANIGAN, Dr. Renjeng SU and Dr. Thomas W. EAGAR. In-Space Welding: Visions & Realities. *MIT - Massachusetts Institute of Tehcnology* [online]. April 30, 1993 [cit. 2020-07-24]. Available at: https://eagar.mit.edu/Publications/Eagar136.pdf

[10] NASA JSC Digital Image Collection. STS61B-45-005 [image] STS61B [online]. Avalable at: https://science.ksc.nasa.gov/mirrors/images/images/pao/STS61B/10062564.jpg

[11] BULATSEV, A. R., M. I. MOREJNIS, S. A. SKOROBOGATOV, V. I. MOTRIJ, V. N. SAMILOV and D. V. BELETSKY. Assembly and Welding of Large-Size Structures in Space. PATON, B. E. Space Technologies, Materials and Structures: Welding and Allied Processes. London: Taylor & Francis, 2003, pp. 474-484. ISBN 0-415-29985-3.

[12] CHAKRABORTY , G, B. MAITI and S. K. ROYCHOWDHURY. Design of Pertmanent Joints: Riveted Joints, Types and Uses [lecture]. Kharagpur: IIT Kharagpur. [cit. 2020-07-24] Available at: https://nptel.ac.in/content/storage2/courses/112105125/pdf/mod10les1.pdf

[13] TITGEMEYER [online]. POP Closed END Blind Rivets. [cit. 2020-07-24]. Available at: https://www.titgemeyer.com/fileadmin/titgemeyer/downloads/befestigungstechnik/blindniete/katalog/en/10019EN1019_1_POP_Becher_Blindniete.pdf

[14] RABKIN, D. M., V. F. LAPCHINSKY, E. G. TERNOVOJ, A. V. LOZOVSKAYA, S. V. MNYSHENKO, A. A. BONDAREV and I. Ya. DZYKOVICH. Investigation of the Properties and Structures of 1201 Alloy Joints Electron Beam Welded at Different Gravity Levels and Low Temperature. PATON, B. E. *Space Technologies, Materials and Structures: Welding and Allied Processes*. London: Taylor & Francis, 2003, pp. 229-236. ISBN 0-415-29985-3.

[15] TERNOVOJ, E. G., A. A. BONDAREV, V. F. LAPCHINSKY and A. V. LOZOVSKAYA. Influence of Gravity Forces, Dissolved Hydrogen and Initial Temperature on the Properties and Tightness of Joints in EBW of Light Structural Alloys. PATON, B. E. *Space Technologies, Materials and Structures: Welding and Allied Processes*. London: Taylor & Francis, 2003, pp. 236-240. ISBN 0-415-29985-3.

[16] BONDAREV, A. A., V. F. LAPECHINSKY, A. V. LOZOVSKAYA and E. G. TERNOVOJ. Investigetion of the Structure and Element Distribution in Welded Joints, Made by the Electron Beam on Alloys 1201 and AMg6. PATON, B. E. *Space Technologies, Materials and Structures: Welding and Allied Processes*. London: Taylor & Francis, 2003, pp. 240-245. ISBN 0-415-29985-3.

[17] PIMENTOV, V. N., V. F. SHULYM, S. A. MASLYAEV and S. Ya. BETSOFEN. Experiments on solidification of Aluminium Melts in Isparitel-M Unit. PATON, B. E. *Space Technologies, Materials and Structures: Welding and Allied Processes*. London: Taylor & Francis, 2003, pp. 401-406. ISBN 0-415-29985-3.

[18] ZAGREBELNY, A. A., V. F. LAPCHINSKY, V. V. STESIN and Yu. M. CHERNITSKY. Study of the Features of Melt Solidification at Zero Gravity Using Optically Transparent Models. PATON, B. E. *Space Technologies, Materials and Structures: Welding and Allied Processes*. London: Taylor & Francis, 2003, pp. 395-398. ISBN 0-415-29985-3.

[19] PATON, B. E. and V. N. KUBATSOV. Experiment on Metal Welding in Space. PATON, B. E. *Space Technologies, Materials and Structures: Welding and Allied Processes*. London: Taylor & Francis, 2003, pp. 154-160. ISBN 0-415-29985-3.

[20] TAMIR, David. A Path to In-Space Welding: and to other In-Space Metal Processing Technologies Using Space Shuttle Small Payloads In: *NASA Technical Reports Server* [online]. October 23, 1992 [cit. 2019-02-01]. Available at: https://ntrs.nasa.gov/search.jsp?R=19930003977

[21] KASICH-PILIPENKO, I. E., V. S. DVERNYAKOV, V. V. PARSICHNY, V. F. LAPCHINSKY, V. S. NOVOSADOV, L. B. BELOBORODOVA and A. A. ZAGREBELNY. Some Features of Formation of Brazed Joints with Radiant Heating under Conditions of Gravity and Zero Gravity. PATON, B. E. *Space Technologies, Materials and Structures: Welding and Allied Processes*. London: Taylor & Francis, 2003, pp. 212-217. ISBN 0-415-29985-3.

[22] BONDAREV, A. A., V. S. DVERNYAKOV, I. E. KASICH-PILIPENKO, A. A. KOROL, V. F. LAPCHINSKY, A. V. LOZOVSKAYA and E. G. TERONOVOJ. Welding Aluminium Alloy 1201 by Radiant Energy of the Sun. PATON, B. E. *Space Technologies, Materials and Structures: Welding and Allied Processes*. London: Taylor & Francis, 2003, pp. 217-220. ISBN 0-415-29985-3.

[23] BURKEY, Martin. A (much) Closer Look at How We Build SLS. NASA Blogs: Rocketology: NASA's Space Launch System [online]. June 2, 2016 [cit. 2020-08-05]. Dostupné z: https://blogs.nasa.gov/Rocketology/2016/06/02/a-much-closer-look-at-how-we-build-sls/

[24] PATON, B. E. and V. N. KUBATSOV. Ten Years of Space Technology. PATON, B. E. *Space Technologies, Materials and Structures: Welding and Allied Processes*. London: Taylor & Francis, 2003, pp. 8-11. ISBN 0-415-29985-3.

[25] PATON, B. E., V. A. DZHABENIKOV and S. E. SAVITSKAYA. Tested in Orbit. PATON, B. E. *Space Technologies, Materials and Structures: Welding and Allied Processes*. London: Taylor & Francis, 2003, pp. 11-18. ISBN 0-415-29985-3.

[26] NIKITSKY, V. P., V. F. LAPCHINSKY, A. A. ZAGREBELNY, V. V. STESIN and V. D. SHELYAGIN. Testing of Manual Electron Beam Welding Tool in Open Space. PATON, B. E. *Space Technologies, Materials and Structures: Welding and Allied Processes*. London: Taylor & Francis, 2003, pp. 178-184. ISBN 0-415-29985-3.

[27] PATON, B. E., D. A. DUDKO, V. N. BERNADSKY, V. F. LAPCHINSKY, A. A. ZAGREBELNY, V. V. STESIN and V. I CHALOV. Perofrmance of Manual Electron Beam Welding in Space. PATON, B. E. *Space Technologies, Materials and Structures: Welding and Allied Processes*. London: Taylor & Francis, 2003, pp. 174-177. ISBN 0-415-29985-3.

[28] PATON, B. E., S. S. GAVRISH, V. F. SHULYM, et al. Work on manual Electron Beam Technology in Space. PATON, B. E. *Space Technologies, Materials and Structures: Welding and Allied Processes*. London: Taylor & Francis, 2003, pp. 190-212. ISBN 0-415-29985-3.

[29] PATON, B. E., V. F. LAPCHINSKY, E. S. MIKHAJLOVKSAYA, V. F. SHULYM, S. S. GAVRISH, G. N. GORDAN and V. P. NIKITSKY. *Manual Electron Beam Welding of Sheet Metal in Open Space*. PATON, B. E. *Space Technologies, Materials and Structures: Welding and Allied Processes*. London: Taylor & Francis, 2003, pp. 289-296. ISBN 0-415-29985-3.

[30] BONDAREV, A. A. and E. G. TERNOVOJ. Design, Based on EBW Application under Extreme Conditions. PATON, B. E. *Space Technologies, Materials and Structures: Welding and Allied Processes*. London: Taylor & Francis, 2003, pp. 227-229. ISBN 0-415-29985-3.

[31] LAPCHINSKY, V. F., U. RIECK, G. SOBISCH and S KEITEL. Bases of Orbital Joining Technologies. Requirements for Equipment for Welding in Space. PATON, B. E. *Space Technologies, Materials and Structures: Welding and Allied Processes*. London: Taylor & Francis, 2003, pp. 297-304. ISBN 0-415-29985-3.

[32] WORKMAN, Gary L. and William F. KAUKLER. Laser Welding in Space In: *NASA Technical Reports Server* [online]. November 07, 1995 [cit. 2020-07-26]. Available at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19910018227.pdf

[33] SHIRZADI, Amir. Diffusion Bonding. In: *University of Cambridge: Phase Transformations & Complex Properties Research Group* [online]. Cambridge: University of Cambridge [cit. 2020-07-26]. Dostupné z: https://www.phase-trans.msm.cam.ac.uk/2005/Amir/bond.html

[34] SATER, B. L. Method of Cold Welding Using Ion Beam Technology In: *NASA Technical Reports Server* [online]. November 14, 1995 [cit. 2020-07-26]. Available at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19810010928.pdf

[35] MOELLER, C. E. and M. NOLAND. Cold Molecular Welding Study Final Report: Jun. 15, 1966 - Jun. 14, 1967 In: *NASA Technical Reports Server* [online]. February 1996 [cit. 2020-07-26]. Available at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19670022172.pdf

[36] GASKILL, Melissa. Solving the Challenges of Long Duration Space Flight with 3D Printing. *NASA: Space Station Research* [online]. December 16, 2019 [cit. 2020-07-27]. Available at: https://www.nasa.gov/mission_pages/station/research/news/3d-printing-in-space-long-duration-spaceflight-applications

[37] HARBAUGH, Jennifer, ed. OSAM-2. *NASA: Technology Demonstration Missions* [online]. April 23, 2020 [cit. 2020-07-27]. Available at: https://www.nasa.gov/mission_pages/tdm/osam-2.html

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