Space manufacturing Techniques: A Review

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Abstract- Space Manufacturing is the production of materials in the outer space, away from the atmospheric and gravitational disturbances of earth. The space consists of complete vacuum and zero gravity that can be employed for carrying out various manufacturing processes with much ease and greater efficiency, which cannot be performed on earth. In past few decades, space researchers and astronauts have explored number of ways in which space environment can be utilized by the manufacturing industries to greater economic feasibility. This concept is still in its initial stages and currently many research and experiments are being carried out at the International Space Station (ISS).

Current paper describes the process of extraction of minerals and manufacturing of products from available resources in space. Different potential products that can be obtained through space manufacturing are also elaborated. It has been concluded that feasibility of space manufacturing on large scale depends on the fact that how effectively challenges of cost capitalization will be reduced.

Index Terms- space manufacturing, lunar soil, near earth objects, vaccum

I. Introduction

Space manufacturing is the process of production of commodities outside earth's atmosphere. This involves collection of raw materials from earth, moon or near earth objects, carrying these materials to manufacturing sites, processing and separating them into their pure form and then utilizing them for production of various products. Manufacturing of certain products on earth has few limitations in their methodology. Factors such as gravity, air tolerance, contamination, wind etc. are not present in outer space. These factors affect extensively the processes carried out on earth.

Ultra clean vacuum, absence of gravity, infinite heat sink and endless source of energy are advantages of manufacturing in space. Ultra clean vacuum makes it possible to manufacture highly pure pharmaceutical products, crystals and alloy, which are impossible to produce on earth. Zero gravity and the absence of air turbulence facilitate the handling of very large components and their assembly into giant structures, which is a challenging feat in earthly conditions. It also provides large sink for heat rejection. Abundance of heat energy is available from sun. Potentially hazardous processes can be performed in space with minimal risk to the environment of the Earth or other planets.

The unique environment of space is employed in various ways to carry out manufacturing efficiently. Microgravity helps in controlling convection in liquids and the gasses, that is, heat transfer in gases and liquid by the circulation of currents due to the difference in the densities. This eliminates the phenomenon of mixing due to sedimentation. Hence diffusion is the primary method of material mixing and allowing immiscible materials to sufficiently intermixed. Microgravity also debars the use of supporters used for holding things like mold, etc. Surface tension is a contractive tendency of the surface of a liquid that allows it to resist an external force. The absence of the gravity results in formation of perfectly round spheres of liquids as shown in the figure. This is helpful in applications requiring perfect liquid spheres, e.g. manufacturing through droplet deposition

Never ending shades in space aids with temperatures as low as reaching absolute zero. Storing of materials is easy in these cold shades. They can also be used for condensation of vapors in electrophoresis to obtain pure separated out metals.

Manufacturing in the space environment is expected to be beneficial for production of a variety of products. This process, in order to be self-sustaining and beneficial to society, needs to be economically profitable. The most significant cost is overcoming the energy hurdle for boosting materials into orbit. Once this barrier is significantly reduced in cost per kilogram, the entry price for space manufacturing can make it much more attractive to entrepreneurs.

Economic requirements of space manufacturing imply a need to collect the required raw materials at a minimum energy cost. The economical movement of material in space is directly proportional to the change in velocity required to move from the mining sites to the manufacturing plants. Near-Earth asteroids and the lunar surface have a much lower change in velocity as compared to launching the materials from the surface of the Earth to Earth orbit.

Significant work has been done on space manufacturing at international space station and various mission conducted by NASA. During the Soyuz 6 mission, Russian astronauts performed the first welding experiments in space. Three different welding processes were tested using a hardware unit called Vulcan. The tests included welding aluminum, titanium, and stainless steel. The Skylab mission, launched in May 1973, served as a laboratory to perform various space manufacturing experiments. The station was equipped with a materials processing facility that included a multi-purpose electric furnace, a crystal growth chamber, and an electron beam gun. Among the experiments to be performed was research on molten metal processing; photographing the behavior of ignited materials in zero-gravity; crystal growth; processing of immiscible alloys; brazing of stainless steel tubes, electron beam welding, and the formation of spheres from molten metal. In February 1994 and September 1995, the Wake Shield Facility was carried into orbit by the Space Shuttle. This demonstration platform used the vacuum created in the orbital wake to manufacture thin films of gallium arsenide and aluminum gallium arsenide.

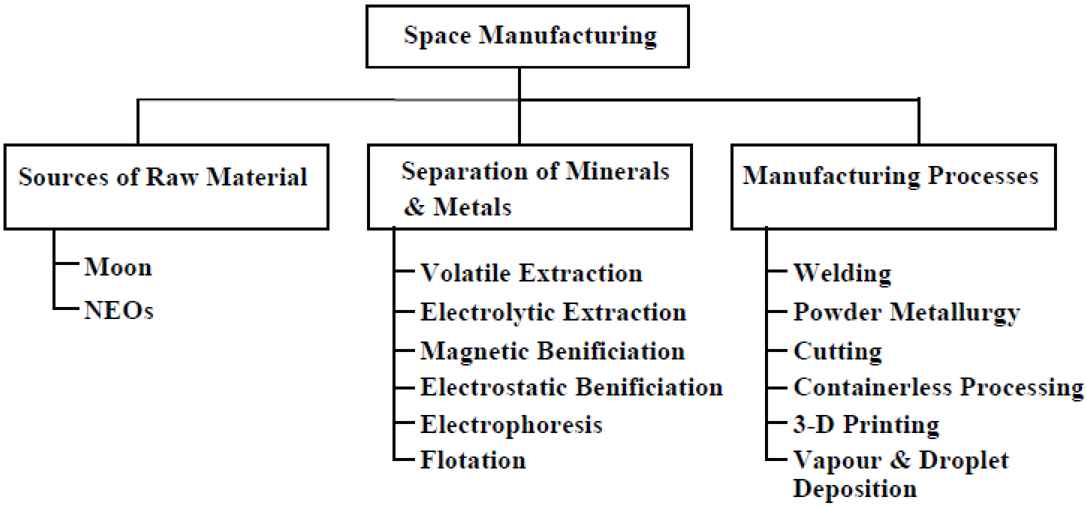

Chart . Various Stages in Space Manufacturing

Through this review paper, concept of space manufacturing has been discussed in detail. Various sources of raw materials available for manufacturing in outer space are described. The advantages offered by space in processing and separation techniques are also reviewed. Different potential products that can be obtained through these techniques are also elaborated in the present work.

II. SOURCES OF RAW MATERIAL

Manufacturing requires raw materials as a primary input to be processed and give out desired output. Manufacturing processes when carried out in space will also require such feedstock to be performed on. Since, transportation of mass from earth's surface is a challenging task in terms of cost and energy. other alternative sources needs to be explored to provide raw material discussed below-

1. Raw material from moon-The analysis of samples brought back from moon and a comparison of the physical and chemical processes operating on the Moon and on the Earth provides a basis for predicting both the possible types of material resources (especially minerals and rocks) and the physical characteristics of ore deposits potentially available on the moon [1]. The main mineral present on the lunar soil is Anorthite ($CaAl_2Si_2O_8$), "Olivine" (predominantly magnesium and iron silicates,Mg_2SiO_4 and Fe_2SiO_4), ilmenite ($FeTiO_3$) and pyroxenes ($MgSiO_3$, $CaSiO_3$, $FeSiO_3$) [2]. Metals (Fe, Ti, Al, Mg and Ca) are found as metal oxides. Oxygen is the main constituent of all minerals which is mainly present in form of oxides of metals and non-metals (SiO_2).

Anorthite can be considered to be a potential aluminum ore from which it may be economically feasible to extract the metal. Calcium is the fourth most abundant element in the lunar highland. Titanium and iron can be commercially extracted from ilmenite. Oxygen and silicon can be extracted from Olivine, Pyroxenes and Anorthosite.

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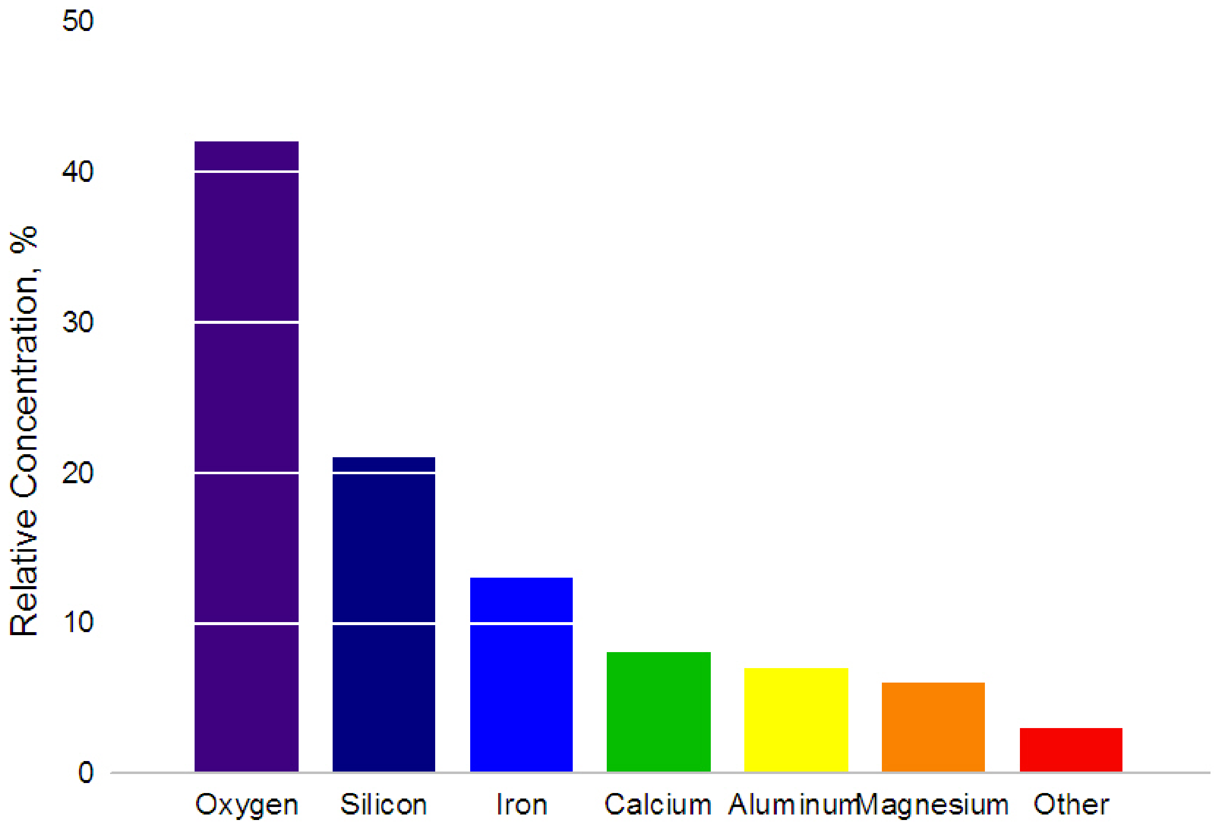

Figure 1. Composition of Lunar Soil

2. Material from Near Earth Objects (NEO's) - These are objects that have been nudged by the gravitational attraction of nearby planets into orbits that allow them to enter the Earth's neighborhood**.** They include a few thousand near-Earth asteroids (NEA's), near-Earth comets, a number of solar-orbiting spacecraft, and meteoroids large enough to be tracked in space before striking the Earth.

Composed mostly of water ice with embedded dust particles, comets originally formed in the cold outer planetary system while most of the rocky asteroids formed in the warmer inner solar system between the orbits of Mars and Jupiter. The composition of an NEO depends upon its origin, but almost all asteroids contain some free metals, Predominantly Nickel-Iron-Cobalt ally and platinum which can be used as construction material**.** Water from asteroids is a key resource in space**.** Water can be converted to rocket propellant or supply the need of humans living on Earth. In addition to water, other volatiles such as N_2, CO, CO_2 and Methane exist in quantity sufficient to warrant extraction and utilization. The composition of an NEO can be determined by telescopic reflectance spectroscopy [3].

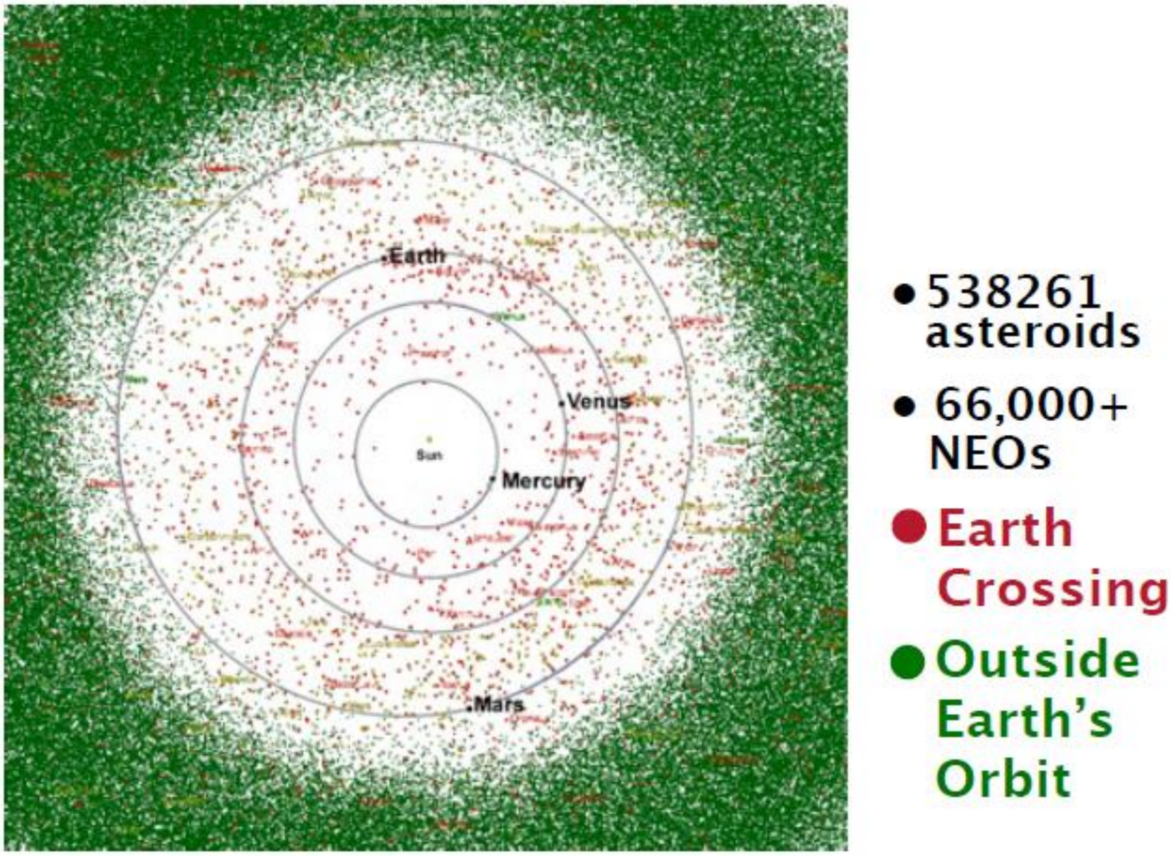

Figure 2. NEO population data as of 2006[4]

III. SEPARATION OF MINERALS AND EXTRACTION OF METALS

Raw materials obtained from moon or NEO's are then further subjected to separation processes, which separate different constituents of raw material. Minerals can be separated on the basis of difference in their magnetic, physical, chemical, electrical or metallurgical property. Various processes that can be used in space for separation are described below.

Thermal Extraction of Volatiles - This process can be used for the extraction of Water, Oxygen, Sulphur, Carbon and other volatile elements. Raw material is heated in large solar ovens by concentrating solar energy using mirrors which evaporates volatile component. These volatiles are in turn refrozen (no need for refrigeration - just a shadow will do it in space) in tanks put in series such that furthest one away is coldest. So the component freezes in different tanks depending upon the difference in the freezing point[5].

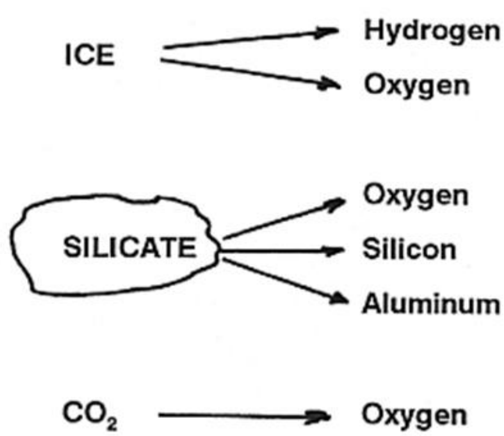

Figure 3. Thermal Extraction of Volatiles

Electrolytic extraction - Electrolysis is a process which uses electric voltage and current to separate minerals into metals, oxygen, and any desired oxides. In this process, two electrodes are placed in molten mineral and a potential difference is applied. The metals move towards the negative electrode (cathode) and the oxygen towards the positive electrode (anode). Electrolysis can also be used to split up a mineral into metal oxide rather than pure metal, e.g., for making special ceramics. Careful selection of electrode voltages, currents, temperature, and optional additives to the melt can tune the process to extract certain desired substances. Researchers have successfully electrolyzed a variety of synthetic lunar materials with no additives whatsoever, as well as by adding small quantities of salts (e.g., calcium carbonate, sulfides).

Because of the effects of vacuum on the vapor pressures of metals at various temperatures, metals will be liberated at the cathode in solid, liquid and vapor form. Aluminum, calcium, sodium, potassium and manganese would be in vapor form, iron and silicon may be liquid or solid depending on bath temperature, while titanium will deposit on the cathode in solid form."

Electrophoresis - Electrophoresis is defined as migration of charged ion in external electric field. In a solution electric current is passed between electrodes and is carried by ions. The negative electrode - cathode donates electrons and positive electrode - anode takes up the electrons to complete the circuit. Cations (positively charged ions) move toward cathode and anions (negatively charged ions) move toward anode due to presence of external electric field.

Now, if mineral grains (to be separated) are placed in between the electrodes, then they will get suspended due to zero gravity environment. Electric charges will pass through the fluid from one electrode to the other, and the minerals will collect electric charge. Due to the differing molecular natures of the different mineral types, each will accumulate a different net electric charge with respect to the fluid. The different minerals will migrate through the fluid to a certain position between the two walls and between other types of minerals of higher and lower "isoelectric" values. Each type of mineral will form a plane of material parallel to the two walls and parallel to planes of the other mineral types.

Electrophoresis on Earth is limited to very lightweight materials. When it is used, it is performed with difficulty and limited effectiveness because of Earth's gravity, which causes convection currents, as well as Gravitational settling, but in space it can be conveniently used as a process for separation of different mineral.

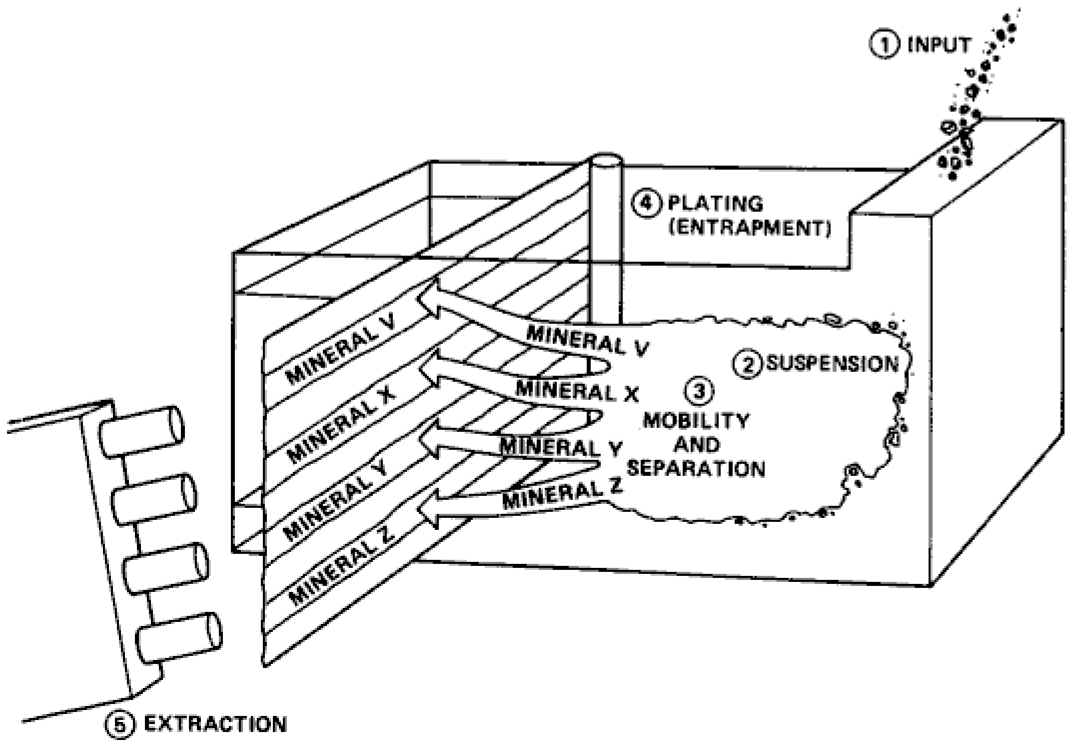

Figure 4: Electrophoresis

Magnetic beneficiation - Grinding of the material is done in order to break it into smaller parts. After this streams of material are passed through a magnetic field to separate out the magnetic granules such as nickel and iron from the silicate and other non-magnetic particles. Even after grinding some silicate particles are still attached to the magnetic particles, impact grinders and repeated cycling is used to separate out all silicate particles and obtain a pure form of nickel-iron particles [1].

The stream of particles is dropped on magnetic drums as shown. The silicates and other non-magnetic particles deflect off from the drums whereas magnetic particles and particles holding magnetic grains stick to the drum and finally removed away by a scrapper.

'Impact grinder' is an equipment which consists of a very rapidly spinning wheel that accelerates the scrapped off materials through the spokes and hurl forcibly on an impact block. Magnetic particles containing scrap attached to silicate materials are shattered off to free metal. Most of the shattered silicate particles are small enough which can be sieved away.

These fine particles are again passed over through a magnetic drum where the silicate particles get separated out from the magnetic particles and giving highly pure nickel iron metal.

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The use of this technique is dependent on the gravity. Hence, in order to utilize this for the separation of materials in space, an artificial gravity will be required which can be easily developed by centrifuges and of any required sensitivity. The vacuum of space is beneficial since no air turbulence is present that can disturb the stream of materials dropping on the drum.

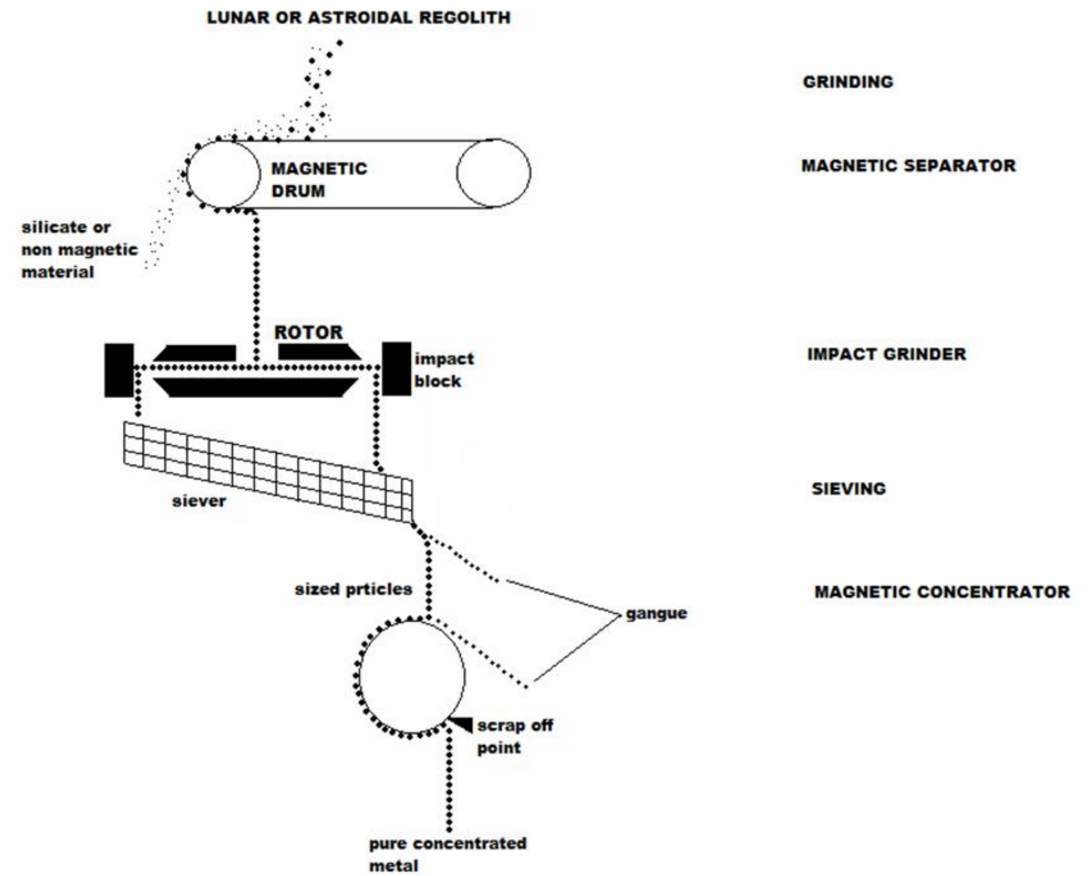

Figure 5. Magnetic Beneficiation

Electrostatic beneficiation -

The material will be initially sieved by screens to separate grains by size. Optionally, the grains of each given size can be passed through the appropriately sized mechanical grinders and sieved again for uniformity.

The next step is to separate the mineral grains by a process called "electrostatic beneficiation", which means charging them with static electricity and separating them by passing them through an electric field[6].

The working principle of an electrostatic beneficiator is the different minerals have different electrostatic affinities, that is, they absorb different amount of electric charge depending upon their composition, and hence are deflected to different amounts by an electric field. After sieving by size, they are placed in beneficiator and passed through it number of times to obtain pure separated minerals.

Grains are dropped freely through the electric field in the beneficiators. Different methods are also utilized such as passing the grains down a ramp or putting them across rotating drums with certain electrostatic charge. Grains with certain affinity sticks to the drum and other fall to the ground due to centrifugal force or gravity.

Different minerals respond differently to different processes, hence, charging of grains depends on mineral to be separated. The grains are charged using following methods;

1) Charging the sieve through which they are passed
2) Charging the ramp on which they are passed.

The separated material in collected in different bins kept at the bottom.

Use of electrostatic separation in space is very efficient since vacuum in space means no air turbulence in the drop chamber and no tolerance to the electric field. No moisture is present to make the grains stick together. The microgravity greatly effects the fall of materials through the electric field, thereby greatly enhancing the separation. If the beneficiation is carried out in orbit, artificial gravity by using centrifuges can be created.

Floatation - Just vibrating a bed of same sized grains will separate mineral grains into layers fairly well based on their "weight" in a centrifuge or in lunar gravity. The denser grains fall to the bottom.

Pouring material into a liquid of intermediate density will quickly separate a desired grain by floatation, though it must be dried thereafter and the fluid recycled. Floatation can be fine-tuned based on the theory discussed below.

In orbital space, zero gravity helps in this process, as a centrifuge can provide different levels of artificial gravity as different minerals settle at different rates[3].

IV. MANUFACTURING PROCESSES

Micro Gravity and contamination free environment of space make it possible to perform various unique manufacturing processes such as Containerless processing and droplet deposition that can't be done on earth's surface. Welding and Cutting operations give better results when performed in space. Manufacturing processes that can be performed in space are discussed below.

Welding - Welding in space is very effective process for joining material because of zero gravity and vacuum. In addition to initial construction task, long term operations in space will require performance on maintenance task such as repair of micrometeoroid damage, leaking fluid line etc. These tasks will require welding[7]. Since no contamination is present in space, hence no oxidation of material will take place which result less porous and brittle material formation. There is no need of using inert gas for shielding in space. The main benefit is in the welding of chemically reactive metals such as titanium. Titanium is so reactive that it cannot be welded on earth even using an inert gas blanket (TIG and MIG). The only way to weld titanium on earth is to completely encase it in an inert atmosphere.

Welding in space is not a revolutionary concept. Since the 1960s the former USSR and the United States have been conducting experiments in space welding. In 1969 the "Vulcan" automatic welder was launched on Soyuz 6 to compare three types of welding for potential space application: Electron beam, low-pressure constricted plasma jet, and consumable electrode (stick welding). As a result of the Vulcan project, the Soviets concluded that electron beam welding was the most promising process due to its versatility and low power consumption

Electron Beam Welding (EBW) is a fusion joining process that produces a weld by impinging a beam of high energy electrons to heat the weld joint. EB welding requires only an electron gun and a source of electricity for the fusion .It can weld massive thicknesses and works BEST in a vacuum.

Friction stir welding also possesses a great potential to be used in space as a joining process. It is a solid state welding process where a machine rotates, plunges, and then traverses a special shaped FSW Tool along a joint to form a weld. The rotation action and the specific geometry of the FSW tool generates friction and mechanical working of the material which in turn generate the heat and the mixing necessary to transport material from one side of the joint line to the other[9]. Friction stir welding results in ductile and strong joint and it is almost perfect for space application**.** There is no splatter, it is utterly insensitive to the atmosphere and can weld thick or thin pieces at excellent production rates.

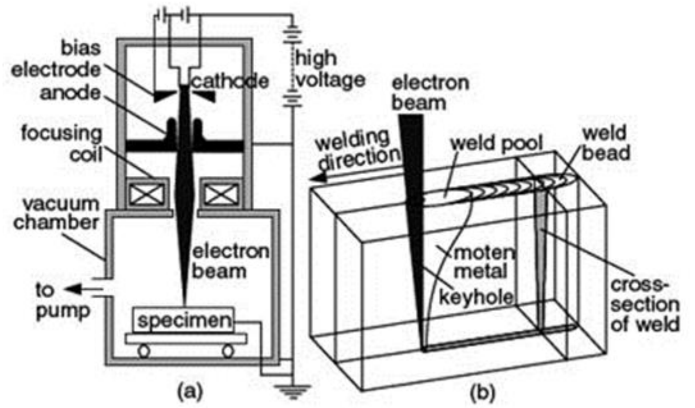

Figure 6. Electron beam welding: (a) process; (b) keyhole

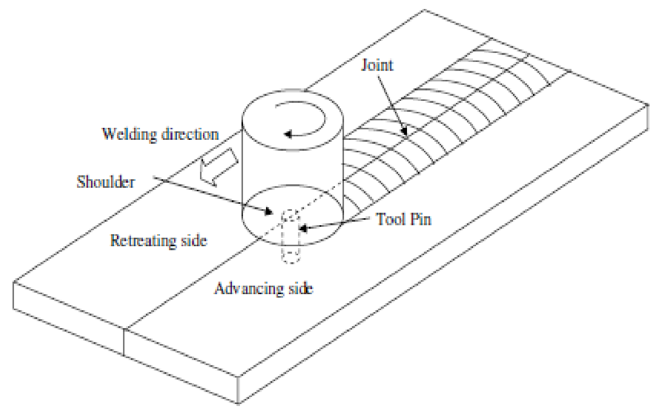

Figure 7. Friction Stir Welding

Powder metallurgy - Powder metallurgy is the process of blending fine powdered materials, pressing them into a desired shape or form (compacting), and then heating the compressed material in a controlled atmosphere to bond the material (sintering). The powder metallurgy process generally consists of four basic steps: powder manufacture, powder blending, compacting, and sintering. Lubricants may be required to separate pressed parts from the die. The absence of atmosphere in space prevents the formation of oxides or other contaminating layers on the powders and thus may promote the formation of high quality parts.

An alternating process for forming object of metals is to compress and heat a metal powder in a mould. Iron powder derived from the metal in lunar soil or from byproducts of oxygen extraction may be molded in this manner for small manufactured items.

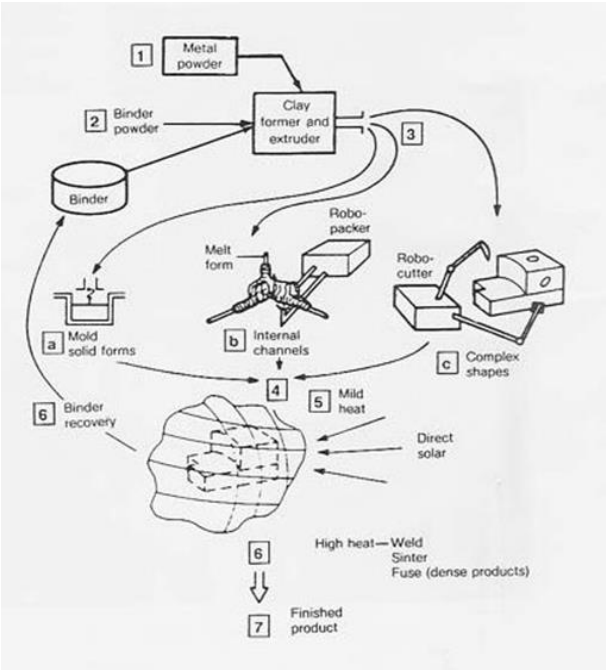

Figure 8. powder metallurgy

As shown in figure 8 we use three ways in which the technique might be used. A metal powder and a binder powder are formed into "clay" and extruded. This clay is then used solid forms in a mold to shape intricate internal structures by molding metal powder around a meltable form, or to make complex shapes ,which are then treated .Similar techniques could be used for ceramics.

Cutting in Space - Machining in space can be done either by electron beams or particle beams [5].Electron beam machining involves a highly energized and focused beam of electrons heating the metal and vaporizing it. It uses a cathode of titanium or tantalum to produce free electrons and a pattern of electrostatic and magnetic fields to focus the beam at a spot. Vacuum is favorable for this process since the collision of electrons with air molecules and the oxidization of cathode is minimized. Since there is no mechanical contact between tool and work piece the process is favorable in space as there is no tool wear and no occurrence of "cold welding" between tool and work piece – which can be a problem with other conventional machining processes [11]. Particle beam and ion beam machining processes are similar processes which use neutral particles or charged ions in a similar setup to for machining.
Figure 9 shows the schematic diagram for such a setup. The electron beam generated from the cathode is first focused by the focusing coil and then deflected by the deflecting coil to a particular point in the workpiece where machining is to be performed.

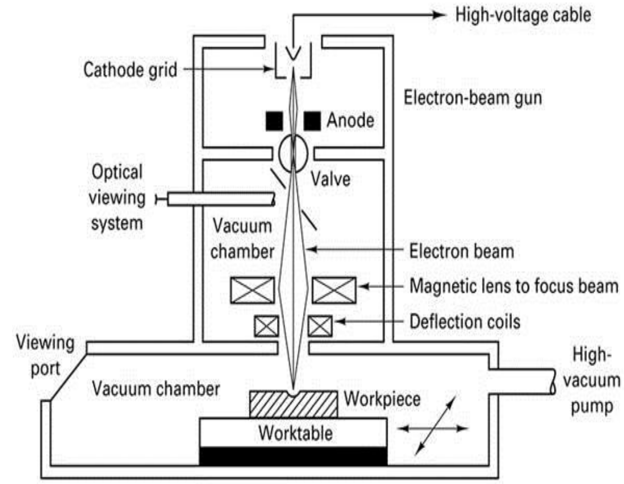

Figure 9. Electron Beam Machining [12]

Containerless Processing - The virtual absence of hydrostatic pressure in microgravity allows liquids to be confined solely by their surface tension without any contact with the container walls eliminating contaminants that may be introduces by these walls and thus giving ultrapure materials. This is an important process for materials prone to corrosion in the melt. Elimination of container-induced nucleation also permits melts to be deeply undercooled before solidification thus offering possibility of studying homogeneous nucleation and solidification of undercooled melts. Such solidification can be extremely rapid and may produce unique microstructures or amorphous phase in metals. The range of glass formation may be extended to borderline glass formation systems, which may result in new glasses with unusual properties formed by melts confined only by surface tension having perfectly pristine surfaces undamaged by grinding or other shaping processes [13].

A metal sample was processed by TEMPUS (Tiegelfreies Elektromagnetisches Prozessieren Unter Schwerelosigkeit), an electromagnetic levitation facility developed by German researchers and flown on the IML-2 and MSL-1 and 1R Spacelab missions. Electromagnetic levitation was used to form a spherical sample of 1 cm (2/5 inch) in diameter (Figure10) [14]. Acoustic levitation is another technique being developed for the manipulation and control of melt in case of non-magnetic material [15].These techniques can be used to position the melt in enclosures for zone melting, casting, and crystal growing, casting of composites and casting materials with dispersed voids.

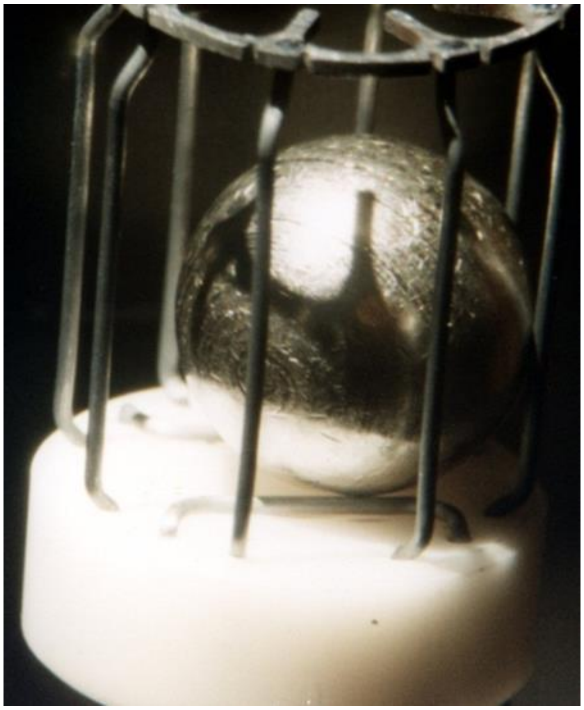

Figure 10. Sample from TEMPUS

3-D Printing - Also known as "additive manufacturing" is the process of making 3-dimensional objects of virtually any shape from a digital model. It is achieved by an additive process where successive layers of material are laid down in different shapes. Since there is no wastage of material as in other "subtractive machining" processes much energy can be saved in transportation of raw materials from their sources. Also, microgravity is favorable for 3-D printing since gravity has adverse effects on the process of layer formation. Currently, NASA is conducting tests for sending a 3-D printer to ISS where it will be useful in making basic items such as hand tools and other "on demand" complicated devices. Rocket parts made by 3-D printers have passed tests on high temperatures. A printer that can print food items is also being developed. This will provide food for long manned missions and future space colonies.

Vapor and Droplet deposition-Vapor and droplet deposition comes under additive manufacturing. This technique is used to build solid parts by deposition of layers of materials on over the other.

Droplet-based manufacturing (DBM) processes are promising production techniques for metallic pans and coatings with unique properties. In DBM processes, molten metal droplets are produced and deposited onto a substrate where they solidify to form near-net-shapes [16]. The quality of parts formed using such processes depends on the precise control of droplet size, flux, velocity and temperature.

Droplet deposition is a technique for producing unique parts by melting metals and without using a mold. This is carried out by small increments of material to a structure and building it up into any desired shape. This process is also called as rapid prototyping. Droplet deposition employs a computerize system to move the droplet depositor. Creating a new part will require just reprogramming the computer.

Vapor deposition uses electron beam to vaporize a metal sheet and these vapors are sputtered off onto a mold. A magnetic field is employed to control and paint the mold. Parts of any shapes and sizes can be created with easy and purity.

Recent researches have showed that utilizing these techniques in outer space to produce various parts are very beneficial and efficient due to the unique environment provided by the space. The energy for the vaporization and melting of the metals can be obtained directly by solar ovens trapping rays from the sun using huge mirrors [5]. When Vapor deposition carried out on earth, oxygen hinders the process and results in embrittlement in the part produced, hence necessitating the development of special environments. In space there is no such need since it provides pure vacuum. Under zero gravity there is no need of using a supporter to support the mold and the part during the process of deposition.

V. PRODUCTS FROM SPACE MANUFACTURING

Space manufacturing technique has opened a new avenue for manufacturing of ultrapure product that cannot be easily manufactured on earth. There are a number of useful products that can potentially be manufactured in space and result in an economic benefit. Research and development is required to determine the best commodities to be produced, and to find efficient production methods. Potential products that can be obtained from space manufacturing technique are semiconductors, pharmaceutical products, metal alloy and MEMS.

Semiconductors - Manufacturing of semiconductor require clean environment that is available in space. Mostly semiconductors are made from extremely pure silicon. Raw material (silicon) require for manufacturing of semiconductor can be obtained from lunar soil (Silica is the second abundant material found on lunar soil)[1].semiconductor can be used for manufacturing of large solar arrays that supply power to continue various operations in space.

Pharmaceutical products - Observation and experiments in space have provided crucial medical insights and breakthroughs, as well as revolutions in medical monitoring. Continued breakthroughs are to be expected, especially with respect to the human aging.

Over the last 20 years, experiments done onboard NASA's shuttles have proven that pharmaceuticals produced in space have purities far higher than any produced on Earth. The new medicines developed and manufactured on Space Island Stations and Geodes will completely change the way we treat illness. Lives could be saved and the pain and suffering which could be eliminated could become our greatest gift to Mankind's future [17].

The products formed in the pharmaceutical industries such as medicine or drugs are formed easily and are free from contamination in space which results in high accuracy and better quality products.

The current potential products in pharmaceutical industries are protein crystal, bacterial growth, microencapsulation, zeolites and aerogels. Protein crystal is the best developed application; bacterial growth is faster in space whereas zeolites are widely used in chemical industries. Microencapsulation is widely used technique on earth for delivering cells and also drugs into the body for medical treatment which is much efficient in space. Aerogels are usually made on earth but there has been research going how their formation differ in microgravity.

Metal alloys - Alloys are produced by melting and mixing different substances into new combinations, then cooling and solidifying the resulting blend. Formation of alloy is affected by gravity because heavier elements in alloy sink and occupy lower position. This is why manufacturing alloy of varying densities such as gold and germanium is not possible on earth. Also, crystal structure of some alloy form imperfectly on earth. This problem can be completely eliminated by manufacturing alloy in space.

VI. Conclusion

Although there is a vast scope of space manufacturing in various fields related to pharmaceuticals, alloy manufacturing, semiconductors, MEMS and space exploration as discussed in this paper but still it faces a challenge of cost capitalization of commencing such a self-sustaining facility. Once set, raw materials can be then mined from sources like moon and other near earth objects like asteroids and comets. The compositions of these sources have been studied by various probes in the past.

Raw materials which are not available on non-terrestrial sources pose a great difficulty to be transferred to the orbit. Biggest hurdle being the substantial amount of energy required to boost materials into orbit. Advancements in the direction of reducing the energy barrier for this are required. Strategies are required for reuse and recycle of fragments of satellites and space which can otherwise be deleterious for other satellites and shuttles. Development of a completely self-sustaining human habitat in outer space is required in case of facilities with a human crew. Use of telecheric devices as labor is also an alternative but the speed-of-light constraint on communication needs to be worked on.

The resources on earth are limited and the needs of humankind are constantly increasing, space manufacturing can play a vital role in fulfilling these demands and also providing for technological advancements and our future space endeavors.

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