METALLURGICAL PROPERTIES OF LUNAR AND ASTEROIDAL STEELS

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Abstract

The first step in any space industrialization project and in some conceivable exploration projects will be site preparation and plant construction. It is economically desirable to use local materials for this. Metals are the engineering materials of choice in most situations. Native iron is readily available on the moon and on many asteroids. In addition, iron is a likely byproduct of oxygen manufacture on the moon. The engineering use of extraterrestrial steel is discussed, and its properties are compared to those typical of terrestrial steels and to other engineering materials. Typical methods of production and difficulties expected in the space environment are discussed. Steel may also be a valuable product for export to LEO or other locations. If its economy is recognized during preliminary design definition, very attractive savings can be realized by using steel instead of more expensive materials. The purpose of this paper is to make the Space Industrialization research community aware of the economy and utility of steel in the space context, so that space manufacturing system startup costs can be kept to a low level.

Introduction

The purpose of this paper is to make the Space Industrialization research community aware of the ease and economy of using locally derived iron and steel as one of the basic engineering materials in many possible space based projects. This paper is more of a proposal or an invitation to thought than a research paper presenting real results. Most of the material herein can be found in or inferred from basic ferrous metallurgy books. The interested reader is encouraged to refer to such books for a more detailed discussion of the treatment and properties of iron and steel.

Metals form the most important group of engineering materials. They have desirable mechanical and physical properties. They can be easily fabricated into various shapes by a variety of techniques. They are hard, tough, ductile, strong and temperature resistant, a combination of properties not available in any other materials. The properties of metals can be controlled by heat treatments so that fabrication is much easier, since the work piece can have properties much different than those needed in the final product. Reference 1 gives an introduction engineering materials and ferrous metallurgy.

There is free, native iron on both the moon and the asteroids which is suitable for many engineering uses. For uses on site or at the point of final delivery, some amount of non locally available alloying additions can be used to control properties. The only large penalties paid for using imported alloying additions are when a very large amount of metal is being processed, or when alloying and forming is carried out far from the final destination. One possible problem with native iron of chondritic origin is that it is usually intimately associated with sulfides. Sulfur has very detrimental effects on the properties of the metal and must be kept to low levels in the finished product. Low levels are typically below .05%.

Terrestrial practice in forming steel has been to cast it and then to deform it to final shape. Some steel is used as cast, but castings have poorer mechanical properties than wrought (processed by deformation) products do. Casing and working is followed by heat treatment to give it the desired final properties. The processes of casting, working and heat treating are described in referecne 2. Intricate shapes or large items are formed by machining and welding basic stock formed from wrought products. There is no reason to assume that other methods will prove more advantageous in the space environment. For example, carbonyl processing requires large, heavy pressure vessels, a large inventory of carbon monoxide and has a low throughput per mass of process equipment. It is incapable of producing most alloy compositions of interest. Ultrapure nickel and iron do not have particularly desirable mechanical properties. Powder metallurgy also has a low throughput, and requires careful control to acheive good mechanical properties in the parts produced. On earth powder metallurgy is usually used for small, intricate parts - something there will not be a large mass demand for in space for some time.

There are two basic ways to control the properties of steels. These are to control the composition and to control the thermomechanical history. Composition can be controlled by carefully selecting the native metal fraction with the most desirable composition, equilibrating the molten metal with appropriate slags before casting, and making alloying additions of other materials from various sources. The thermomechanical history is controlled by performing specific deformations, then heating the solid metal and cooling it at a controlled rate. This rate is often rapid, requiring the use of a quenchant.

While special alloys of aluminum and titanium have properties superior to steel on a mass basis, the superiority is small. The best aluminum alloys are about 20% stronger per unit mass than are the best steels. Titanium alloys are about twice as strong as steel. In the easier to produce low grade alloys, these differences are less marked. Low grade steels usually have a higher specific strength than low grade titanium or aluminum. Aluminum and titanium do not occur as free metals on the moon or asteroids, and they are difficult to win. Titanium is also difficult to form. If high specific strength is the only criterion for materials selection, graphite, kevlar or polyethylene fibers are the materials of choice. These have specific strengths many times that of any metal. It is unlikely these will be fabricated in space in the near future.

Discussion

Sources of Iron There is free native iron on the moon and on some asteroids of interest as resources. Asteroidal iron typically has >2% cobalt and >7% nickel. There is an extremely low level of other materials in the metallic phase. For metal recovered from carbonaceous chondrites, there is likely to be some adhering carbonaceous material, as well as adhering sulfides. Lunar native iron is in two forms - that coming from meteoritic impacts and that actually occuring in lunar minerals. The meteoritic iron has a typical bulk composition similar to that found on the asteroids. The metal in lunar minerals is fairly pure iron, without substantial amounts of nickel and cobalt. This allows the nickel and cobalt content of lunar steel to be adjusted by controlling the ratio of meteoritic to nonmeteoritic metal in the feed. In manufacturing oxygen on the moon, iron is a likely byproduct. Iron produced by slag reduction will contain some manganese, silicon or titanium (depending on the feed composition) and chromium. Any carbon in the lunar iron will be derived from imported materials, due to the low level of carbon available on the moon.

Properties Typical mechanical properties of selected steels are shown below:

Material	Yield Strength (MPa)
Ultrapure Iron	4,800
Heavily drawn pearlitic wire	4,800
8% Nickel steel	1,400
4% Nickel steel	1,050
Carbonyl formed Nickel alloy	1,380
Annealed HSLA steel	700
Hardened HSLA steel	1,400
Annealed Carbon steel	400
Hardened Carbon steel	1,100

The change in properties with increasing temperature for steel is much more desirable than for other metals. Depending in the exact composition, heat treatment is not spoiled until a temperature of from 300 to 800°C is reached. Creep (slow deformation under load) is not a problem until about 650°C, while aluminum starts to have creep problems at about 175°C. At low temperature, steel is subject to brittle failure. This is a problem aluminum alloys are not subject to. They typically remain ductile at cryogenic temperatures. Nickel additions to steel lower the brittle failure temperature range substantially. Since nickel is readily available on the moon and asteroids, it can be used to reduce brittle failure problems. Typical nickel concentrations in lunar and asteroidal steels lower the ductile to brittle transition temperature to -50° to -100°C. The transition temperature for plain carbon steel is about 60°C. Certain commercial 9% nickel steels are ductile at cryogenic temperatures. It should be possible to obtain this low temperature ductility in practice in space.

Metal fatigue is a major source of failure in engineering. Steel has unique fatigue resistance, shared by very few other metals. On the strain - number (S/N) curve, steel exibits an endurance limit. That is to say that for strains less than about half the yield strength of the part, an infinite number of excursions may occur without any fatigue effect. Other metals, such as aluminum, have no endurance limit. These metals will eventually fail from fatigue no matter how arbitrarily low the strain excursion is. This behavior is illustrated in figure I below.

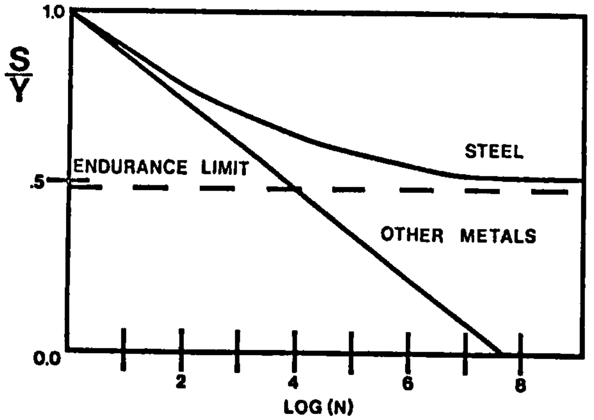

Figure I. Fraction of test item yield strength versus cycles to failure for steel and other metals. S is stress, Y is yield strength and N is the number of cycles.

Composition There are a few elements which are important in determining the engineering properties of commercial steels. These are carbon, nitrogen, nickel, chromium, manganese and molybdenum. Aluminum, titanium and silicon are also useful, but are typically less used. Boron can be used and has a great mass advantage in space. The effects of various alloying additions is discussed in more detail in reference 3.

Carbon and nitrogen control the microstructure of the steel, and are the major determiners of strength and hardness. Since there is very little carbon on the moon, any carbon needed in the steel will have to be imported. Typical useful carbon contents are .1 to .77 weight percent, so this is not a major disadvantage for steel for local use. Carbon in the form of garbage and scrap (composite materials, plastic wrappers, etc.) is likely to be available wherever there are people, so the carbon needed to make lunar carbon steels may not have to be imported solely for that purpose. Asteroidal iron will typically be associated with carbon.

The addition of chromium to plain carbon steels improves hardenability, strength and wear resistance. Improving mechanical properties typically requires ~1% chromium. Imparting corrosion resistance typically requires 10-25%. Corrosion resistance is much less necessary in the space environment than it is on earth. Where it is needed, aluminum has been found to impart superior corrosion resistance to steels, and can be used to produce an aluminum bearing series of stainless steels. There are available sources of aluminum, such as spent stages and scrap (for example, the space shuttle external tank) which should prove to be adequate sources of low cost aluminum for making aluminum bearing stainless steels. Low levels of chromium for strength improvement may be available from equilibrating steel melts with chromium containing minerals or with partially re-reduced steelmaking slags. Since chromium improves strength by forming a strong carbide, it is of limited utility in strengthening ultra low carbon steels.

Nickel is used in low alloy steels to increase strength and slow the rate of the austenite to ferrite phase tranformation. This allows relatively thick parts to be fully hardened by quenching. For parts of equal size, a nickel bearing steel can be quenched more slowly, leading to lower distortion and better tolerances in the finished part. In many respects, the effects of nickel are similar to those of manganese. The major constraint on the use of nickel on earth is its high cost relative to iron and to other alloying additions. Since nickel is readily available on both the moon and asteroids, this is not a factor in its use in space. Nickel strengthens steel by solid solution hardening, and its effect is not dependent on carbon. Nickel also lowers the temperature of the phase transformation from austenite to ferrite. Many nickel steels remain austenitic if slowly cooled to room temperature. Nickel steels also form a martensitic structure on cooling which does not depend on carbon for its existence. This allows a certain amount of heat treatment hardening and strengthening in nickel steels with no carbon addition. A more complete description of the properties of nickel steels is given in reference 4.

Manganese is used to strengthen steels and retard the rate at which as quenched microstructures change on heating. This allows heat treated parts to be used at relatively high temperature without losing their properties. These uses require .25 to 2% manganese. Manganese is also used to produce hard facing steels. These steels retain austenite when cooled to room temperature. When mecanically deformed, this austenite is transformed to martensite. Thus manganese bearing steels used for rock drills, shovels, etc. have an extremely hard and wear resistant surface, while retaining a strong, tough and ductile core. There is no adequte substitute known for hardfacing steel in such applications. 10-14% manganese is needed for such hardfacing steels. These levels of manganese would probably have to be obtained by reducing steelmaking slags from many steelmaking heats. Manganese would only be available in significant amounts from won steels. It can not be derived from native metal.

The major use of molybdenum in steels is to enhance the properties of other alloying elements. It is typically used in concentrations of .15 to .60%. Since there is no source of molybdenum on the moon or asteroids, it seems likely that it will not be used in significant amounts due to the cost of importing it.

Aluminum, titanium and silicon are used primarily as deoxidants to remove oxygen from steel which has been purified by oxidation of the melt. As mentioned above, aluminum can also be used as a corrosion inhibiting addition. Titanium is may also be used to form carbides to enhance mechanical properties. It is available as ilmenite on the moon, but titanium is difficult to win, and would probably be imported as metal if it were needed. Silicon in the range of 0.5 to 4.5% finds use in transformer cores and magnetic alloys. It is particularly important that silicon alloys for magnetic applications be wrought, since deformation is used to enhance their magnetic properties. Silicon is relatively easy to win as ferrosilicon. Any process which was winning iron from a melt could probably be designed so that occaisional heats of ferrosilicon could be produced.

Boron is an alloying addition of great interest for space use. It increases strength and hardenability. The amount needed is a few thousandths of a percent, making it a very attractive choice when alloying additions must be imported. There has been extensive work on how to substitute boron for other alloying additions in commercial steels, making this a well understood process.

Phosphorus and sulfur are undesirable impurities in steel. These are present in the native metals in very low concentrations. Care must be taken not to introduce them, for instance by equilibration with a slag containing one or the other in substantial quantity. This is particularly important since these impurities are removed best by highly basic (calcia containing) slags, which are not available on the moon or asteroids. Sulfides are associated with native iron of asteroidal origin. Care must be taken not to introduce sulfur from these sulfides into the metal upon melting. The extent of sulfide association with lunar and asteroidal iron, and methods to separate sulfides from the metal bear further study.

Copper is an undesirable impurity, as it has a very detrimental effect on ductility. The only source of copper in space is external tank aluminum. If this is used as an alloying addition, care must be taken to account for the detrimental effect of the copper content.

Hardenability Lunar steel will likely be of low carbon content. Most of the increase in hardness of alloy steels is due to carbon (or nitrogen) in solid solution or in various phases. The hardness of pure iron can only be increased about a factor of two by adding metallic alloying elements. When this steel must be hardened, case hardening by nitriding or carburizing the surface is desirable. Case hardening keeps the consumption of imported carbon or nitrogen to a low level. These processes typically would require heating in a pressure vessel. Carburizing by packing the part in solid carbon powder could be done without a pressure vessel, but this requires a relatively large inventory of carbon. Nitriding with ammonia is preferable, since this is done at a lower temperature.

Most uses of lunar and asteroidal steels will require that they be quenched to acheive desirable mechanical properties. Quenching is usually done in water or oil on earth, as these are cheap and readily available. In space it would be desirable to recover the quenchant, leading to complex condensers and to rejecting large amounts of heat at the boiling points of the quenchant. Water or hydrocarbon might be abundant enough in asteroidal materials that they could be expended. This is certainly not the case on the moon. In order to obtain adequate cooling rates on quenching, oil or water baths must be strongly agitated. This makes them difficult to contain and control under reduced gravity.

The problems listed above imply that it may be desirable to use alternative quenchants in space. Some possible materials are gallium, gallium-indium alloys or sodium-potassium alloys. These do not boil at the heat treating temperatures, so heat transfer into the bath is rapid and heat rejection is relatively simple. Gallium and indium have a low enough vapor pressure at the temperatures of interest that the quenching bath might not have to be enclosed. This would lead to some very desirable plant simplification.

Processing in Space There are several basic steps which are used in producing steel products. These are casting, rolling, forging, drawing, welding and machining. The final parts are often heat treated to produce the desired properties. A discussion of some aspects of these basic processes in the space environment follows.

Casting requires that the steel be melted and poured into a mould. In melting the steel it is desirable to preheat it as much as possible with concentrated sunlight before electrical heating commences. There are two practical forms of electrical heating. These are arc heating and induction heating. In arc heating the electrodes must be cooled so that they are not consumed, while in induction heating the inductor must be cooled. Thus both methods require some heat rejection at relatively low temperature. One possible way around this is to use a semiconducting ceramic such as titania as part of the refractory lining, and heat the bath directly as is done in glass melting furnaces. It is not clear that this is feasible. The melting furnace must be lined with a refractory. There are few materials on the moon or the asteroids which would be suitable. Some possibilities are rutile from partial reduction and subsequent liquation of ilmenite, or calcium - aluminum rich inclusions in chondrites. Casting into the mold requires that the steel be poured or moved into the mold. This could be a potentially hazardous operation in microgravity. Since steel shrinks by 8-12% on solidification, voids can be expected to occur in objects cast in microgravity. Assymetrically would induction heating coils will exert a net force on the charge theya re heating. This can be used to control the melt pool in microgravity, or (at low power) to suppress voidage in castings.

Once cast, relatively heavy parts are forged. Forging requries large, heavy presses and dies. These can be cast from locally derived steel, so forging does not require much imported equipment. Drop forging is desirable due to its operational simplicity and reliability. This is only possible on the moon, where there is substantial gravity.

A variety of useful objects can be produced by extrusion. The presses used in extrusion can serve double duty as presses for forging. Rods, angles, I beams, tubes and pipes can be made by extrusion in substantial lengths.

A variety of shapes are made by rolling. Sheet, plate, angles, channels, bars and rods are all made this way. The rolls and roll stands can probably be cast from locally derived steel and machined to final form. Most rolling is done with the workpiece hot (800-900°C) to reduce the energy needed to deform it and to prevent work hardening. This requires that the rolls be cooled in some manner. On earth the rolls are cooled with a water spray - probably not a desirable way to do it in space. Some form of lubricant is usually used to keep the work from sticking to the rolls. It would be desirable to find a locally available material which can serve this function.

Terrestrial rolling mills which produce wide plate or sheet (greater than 1 meter in width) typically have a capacity of 1 to 3 million tons per year. It is unlikely that there will be a demand for this much rolled steel in space for some time to come. The rolling mill plant envisioned here is likely to be one or two two or four high adjustable gap reversing roll stands. Even a single four high reversing roll stand would have such a large throughput that it would not have to operate at a particularly high duty cycle to fill all needs for rolled steel products.

Sensing, control and maintaining surface finish are three problems which could benefit from R&D. Sensing and controlling the figure of sheet or plate as it is being rolled is a difficult problem on earth, which has usually been solved empirically. Since production runs in space are likely to be very small by terrestrial standards, it is desirable to have positive control, thus keeping the scrap rate down. Surface finish deteriorates rapidly as the rolls start to wear. In order to maintain good surface finish, either the microstructure of the roll surfaces must be carefully controlled when they are made, or a separate finishing stand must be available.

Drawing is used to make wire, and requires very little in the way of massive equipment. Substantial amounts of wire and cable can be produced with a very small investment of terrestrial equipment. Wire drawing machines are quite simple, and most of their components could be fabricated if simple machine tools were available. Motors and drawing dies would have to be imported for some time. Drawing depends on controlled work hardening of the material. Frequent annealing is needed to turn rods into wires. The annealing is very well suited to using direct solar heat, since it requires heating to about 800°C, then slow cooling. it is worth noting that while iron is not a particularly conductive metal, impurities do not lower its conductivity very much. This differs from the behavior of other metals such as copper and aluminum.

Machining will probably require using machine tools imported from earth. It is possible that massive ways, tables and braces for lathes and mills will be among the first items cast. These machine tools can be looked upon (along with a melter and caster) as the first bootstrapping operation in space industrialization. Among other things, these machines will be be used to produce many of the heavy components of the initial mill, such as rolls and forging dies. The availability of basic machine tools also greatly enhances reliability, since parts needed for unanticipated repairs can be produced on site. The basic requirements are a milling machine and a lathe, or a lathe with an attachment that allows it to be used as a milling machine. These will behave essentially as they do on earth with one important exception - in microgravity chip control will be a problem. Loose chips could be very destructive. Microgravity chip control will have to be studied.

Welding is a very basic process in metals fabrication. Welding in the vacuum of space would have the great advantage that there is no oxygen to dissolve in the weld pool. Electron beam welding has been demonstrated on skylab, and would probably be the method of choice. Arc welding would probably be impossible due to the unstable behavior of the arc in vacuum. Gas welding would be very wasteful of gas, and laser welding would require sophisticated, inneficient power conditioning equipment (the laser). Welding requires low carbon steels. Since these are the most economical steels in the space context, all welded construction is particularly easy and economical in space.

Uses There are many possible uses for steel in initial industrial activities in space. Large portions of a lunar (or martian, or asteroidal) base could be made out of locally produced steel sheet. This would remove a number of design constraints on the base. There is no particular reason for bringing many large, pressurizable structures from earth at great expense. Once one or two get there, they can house a crew to build a steel mill and make the rest. Walkways and roads can be made by laying textured steel sheet on a partially smoothed surface, greatly increasing mobility and decreasing the amount of dust that gets in and on things to ruin them. Baseplates, foundations and protective housings could be produced locally, greatly increasing the number of experiments which could be performed for a given mass sent to the destination. Much of the structure and foundation for a second (possibly more complex) factory could be made from locally produced steel, substantially reducing the initial investment.

Steel would also be very useful for producing large space structures and factories of various types in earth orbit. Items such as solar power satellites could be designed to make maximum use of whatever materials were most economically available at their intended location. In a solar power satellite, this would mean having steel structure, steel mirrors (with a surface coating of aluminum, coming to a few thousand pounds per satellite) to focus sunlight on steel receivers which heat an imported working fluid to run steel motors which turn steel generators (using iron wires and silicon steel magnets) sending current through thick (for adequate conductivity) steel wires or steel waveguides to a steel antenna for power transmission to earth. Heat rejection could be by steel radiators blackened by controlled surface oxidation. The major imports would be a working fluid and a bit of electrical insulation (perhaps lunar or asteroidal ceramic).

Production of large space structures (such as solar power satellites in the example above) from extraterrestrial steel would make them much cheaper and more economically feasible than is currently envisioned by reducing the up front capital costs for the factory (steel mills are relatively simple and cheap compared to most other factories envisioned for extraterrestrial resource utilzation) and by reducing the technical and cost uncertainties in plant performance (since a lunar, asteroidal or earth orbiting steel mill would not be doing things a lot differently than they are done in a mill on earth). This is important as capital costs and technical risk have not been given adequate weight in most prior studies of space resource utilization.

One prospective large space project that could benefit from the inexpensive availability of large amounts of steel is the Strategic Defense Initiative (SDI). The key to a space based defensive system is in having satellites which are tough enough to survive the attacks which could be made on them. Since satellites can not hide in any practical way, this means they must be made very strong. Steel is the obvious material of choice for this. While nothing can be made indestructible, history shows that thick pieces of steel are capable of withstanding destructive forces on the order of those which the satellites in a space based defensive system could be exposed to.

Conclusions

Iron and steel are useful materials which are available onmost bodies which are of interest for space resource exploitation. This steel has a composition which makes it quite useful if simply melted and cast. A space steel mill could be built which is light, cheap, and has low technical risk and very predictable cost and performance. Steel is thus a readily available engineering material for various space projects. Most large space projects could make almost all of their massive components out of steel if properly designed at the systems level. When considering space structures and factories, the ready availability, economy and utility of steel should be kept in mind.

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