

Iron and Alloys of Iron

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All lunar soil contains iron in the metallic form, mostly as an iron-nickel alloy in concentrations of a few tenths of 1 percent (Nozette 1983). See figure 1. Some of this free iron can easily be separated by magnetic means (Shedlovsky et al. 1970; Goldstein, Axon, and Yen 1972). It is estimated that the magnetic separation of 100 000 tons of lunar soil would yield 150-200 tons of iron. Agglutinates (glass-bonded aggregates of soil fragments) contain metallic iron which could be extracted by melting and made into powder-metallurgy products (Romig and Goldstein 1976, Criswell 1981). However, agglutinate metal is so finely dispersed that it may be difficult or impossible to separate.

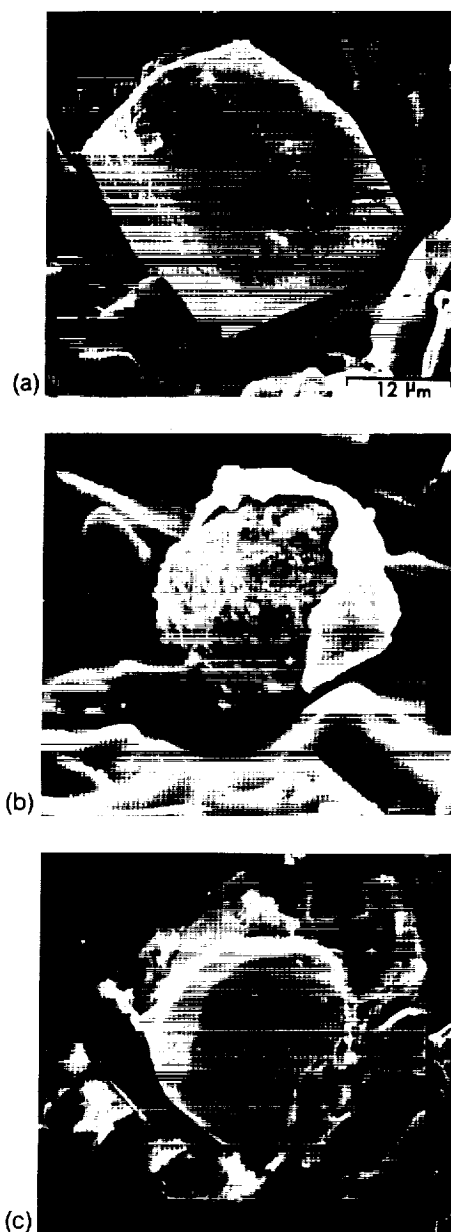


Figure 1

Iron in Lunar Soil

Many of the highly recrystallized breccias from Apollo 14 contain vugs with well-developed crystals that extend from the vug walls and bridge open spaces. Many of the larger vugs contain metallic crystals of iron or nickel-iron.

a. This photograph taken with a scanning electron microscope (SEM) shows a euhedral iron crystal. The tetrahedron has an axis of four-fold symmetry projecting toward the upper right of the photograph. The crystal contains no detectable nickel (less than 1 percent).

b. This SEM photograph shows a nickel-iron crystal that contains about 12 percent nickel. Because the tetrahedron was photographed along an axis of three-fold symmetry, it appears to be hexagonal. The crystal is partially covered with a coating of iron sulfide, presumably troilite. The rough texture of the nickel-iron crystal may have been caused by a former coating of troilite.

c. The crystal habit of such nickel-iron particles commonly is not obvious. Only at magnifications above 1000X can crystal face development be observed. The near spheroidal shape of this particle is typical of those photographed with the scanning electron microscope. This nickel-iron crystal contains about 4 percent nickel. These crystals are thought to have been deposited from a hot vapor during the cooling of the large ejecta blanket from the impact that formed the Imbrian Basin on the Moon. Such a process is only one source of the metallic fragments in the lunar soil. Other iron-nickel fragments are pieces of meteorites that have crashed into the Moon.

Photographs and their interpretation taken from McKay et al. 1972, pp. 745-746.

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The basalts in the lunar maria contain up to 17 percent chemically combined iron, primarily in ilmenite, olivine, and pyroxene. And ilmenite (FeTiO_3) concentrations in lunar soil are of fairly high grade compared to deposits on Earth. A variety of extraction schemes have been proposed for recovering metallic iron from these silicates and oxides: electrolysis of molten lava (Lindstrom and Haskin 1979), a carbochlorination process (Rao et al. 1979), solar furnace evaporation (King 1982), a carbonyl process (Meinel 1985), a hydrofluoric acid leach process (Waldron 1985), and hydrogen reduction of ilmenite (Williams 1985). Even though

considerable work is needed to evaluate and test these processes for feasibility in a lunar environment, the abundance of iron and its relative ease of separation suggest that metallic iron and its binary alloys may find wide application in large-scale space operations.

Characteristics and Potential Uses

Table 1 provides a list of the characteristics and potential uses of the pure iron and iron alloys which might be readily produced from lunar materials.

Casting Iron Parts

Iron parts are cast on Earth by pouring liquid metal into molds. Many intricate parts that would be difficult to machine can be made in this manner. The lunar equivalent could use iron or iron alloy produced as a byproduct of oxygen extraction and poured into "sand" molds made from lunar soil.

Courtesy of the Association of Iron and Steel Engineers, reprinted from *The Making, Shaping and Treating of Steel*, 10th ed., fig. 40-6.

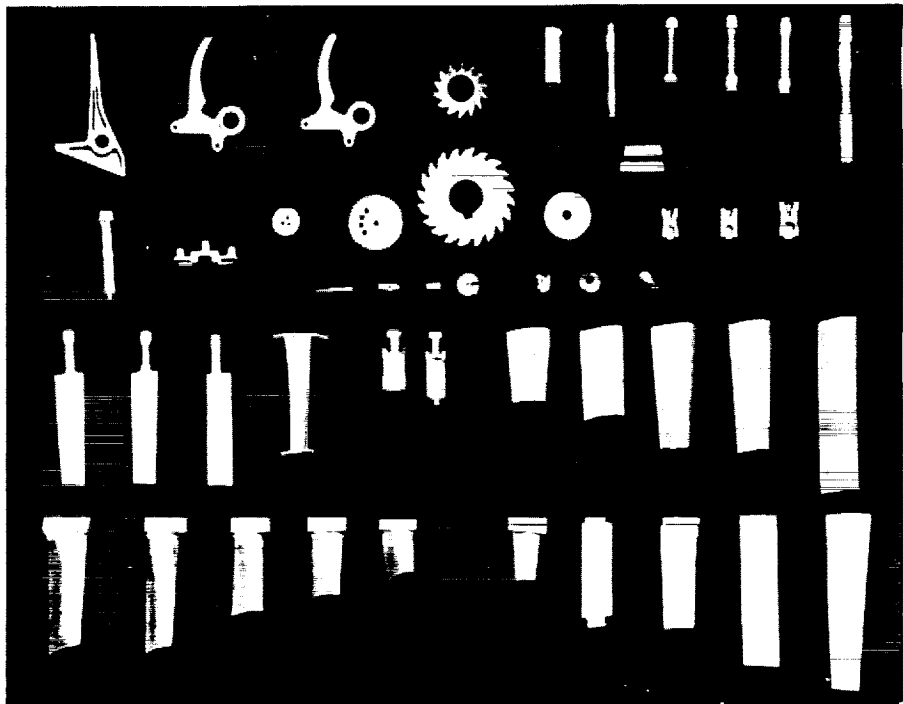


TABLE 1. *Applications of Iron and Alloys of Iron*

Name	Composition	Characteristics	Uses
Ingot iron	Pure iron (industrial grade)	Ultimate tensile strength (UTS) 290-331 megapascals (MN/m ²) or 42-48 x 10 ³ psi Elongation (el) 22-28%	Structures, beams, plates
Iron whiskers	Single-crystal pure iron fibers	0.00004-in. diameter UTS as high as 3448 MN/m ² (500 x 10 ³ psi)	Structures Electronics parts
Iron powder	Free of carbon and sulfur	10- to 40-micron powder	Propellants, Small powder-metallurgy parts—mechanical, electrical, and magnetic
Carbonyl iron powder		UTS 193-275 MN/m ² (28-40 x 10 ³ psi) el 30-40%	Propellants Powder-metallurgy parts Coatings for containers, walls
Iron-silicon alloy	Fe and Si form a solid solution up to 4.5% Si	UTS 345-414 MN/m ² (50-60 x 10 ³ psi) el 8-22%	Structures, beams, Motor transformer parts
Iron-nickel alloys	Fe and Ni form a continuous series of solid solutions	For 47-55% Ni, UTS 483-621 MN/m ² (70-90 x 10 ³ psi) and el 30-50% Ni increases UTS without loss of ductility	Structures Containers
Iron-titanium alloys	Fe and Ti form a eutectic solution	Ti increases hardness and strength	Structures Containers
Iron-manganese alloys	A range of Fe-Mn alloys are possible	For 1% Mn, UTS 414 MN/m ² (60 x 10 ³ psi) and el 40% Mn increases strength, hardness, and hardenability	Structures, beams
High-purity iron	Ultra-pure	Extremely difficult to produce on Earth High corrosion resistance Can produce high-strength, defect-free single-crystal or directionally solidified parts	Pressure vessels Solar mirrors Sheets Containers

The simple alloys described in table 1 may be relatively straightforward products of lunar metallurgy. Little is known, however, of the composition of the metal phase that forms directly from each of the processes described above. Process technology needs to be defined to establish the feasibility of providing the alloys.

Processes for Working Iron

A list of terrestrial manufacturing processes that might be used on iron and iron alloys in a nonterrestrial facility is shown in table 2. Criswell (1980) evaluated 200 manufacturing techniques and found more than 40 of them appropriate for a near-term, evolutionary space manufacturing

facility. We consider all of the processes given in table 2 to be plausible for early application; however, when evaluated using the ground rules of our exercise, the processes that I discuss after the table appear to be the most feasible.

Casting

Casting, one of the oldest processes in the world, involves pouring liquid metal into a mold and allowing it to solidify in that shape (fig. 2). The casting process has to be modified for application in free space because gravity is so limited. Casting at a lunar facility in 1/6 gravity should be straightforward; however, mold construction techniques require study, particularly if indigenous materials are to be used for the molds.

TABLE 2. *Terrestrial Manufacturing Processes That Might Be Used on Lunar Iron*

Casting	Powder metallurgy	Hot working and cold working	Joining
Sand casting	Compaction and sintering	Forging	Welding
Shellmolding	Hot isostatic pressing	Rolling	Brazing
Die casting		Extrusion	Soldering
Investment casting		Wire drawing	Fastening
Permanent molding		Machining	
Centrifugal casting			

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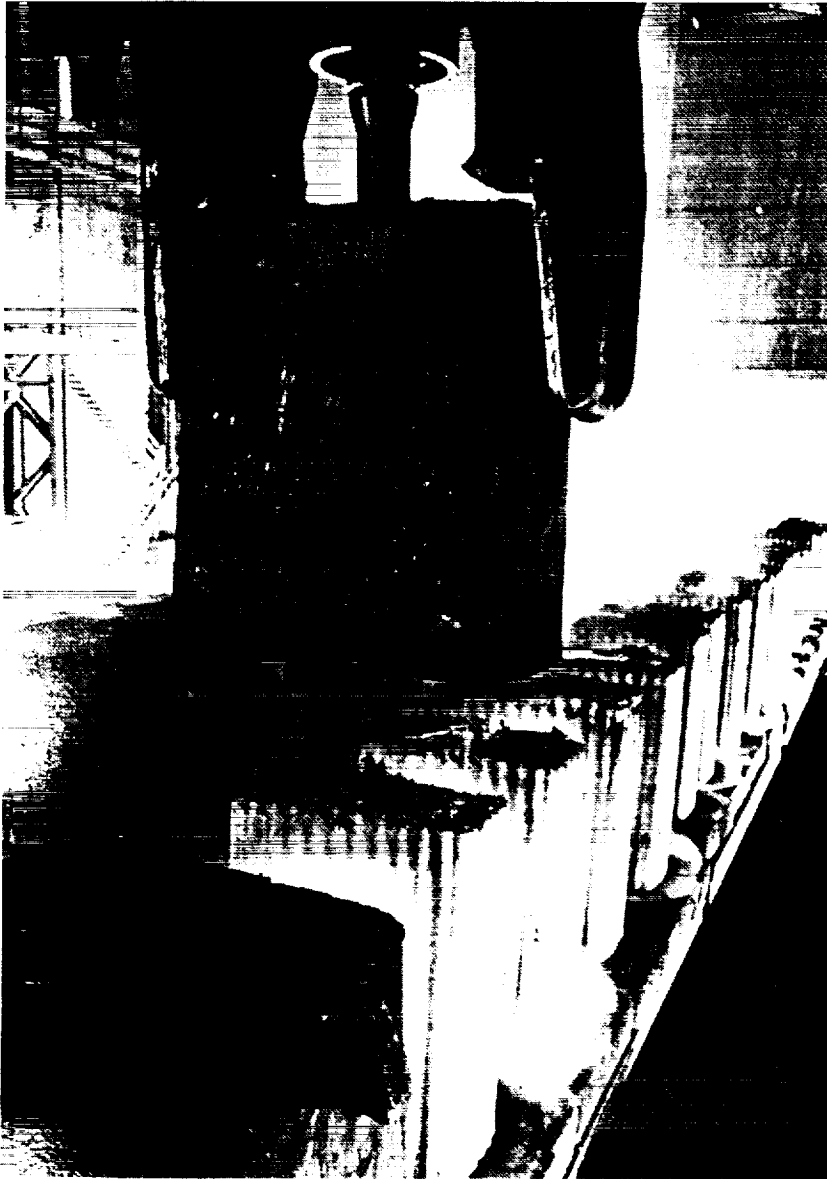


Figure 2

Casting of Metal Ingots

Refined steel is poured from a refractory-lined ladle into molds of the desired size. The casting operation depicted is a continuous process, where large quantities of metal are being produced. A lunar operation would be on a much smaller scale and could produce castings that are directly usable, as well as the starting materials for rolled or extruded products. The ingot molds would be maintained at elevated temperature, waiting transfer to a rolling facility, in which they would be formed into bars or sheets.

Courtesy of the Association of Iron and Steel Engineers, reprinted from The Making, Shaping and Treating of Steel, 10th ed., fig. 20-2.

Powder Metallurgy

Powder metallurgy consists of compacting fine metallic powder into a desired shape and sintering the shape (fig. 3). 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.

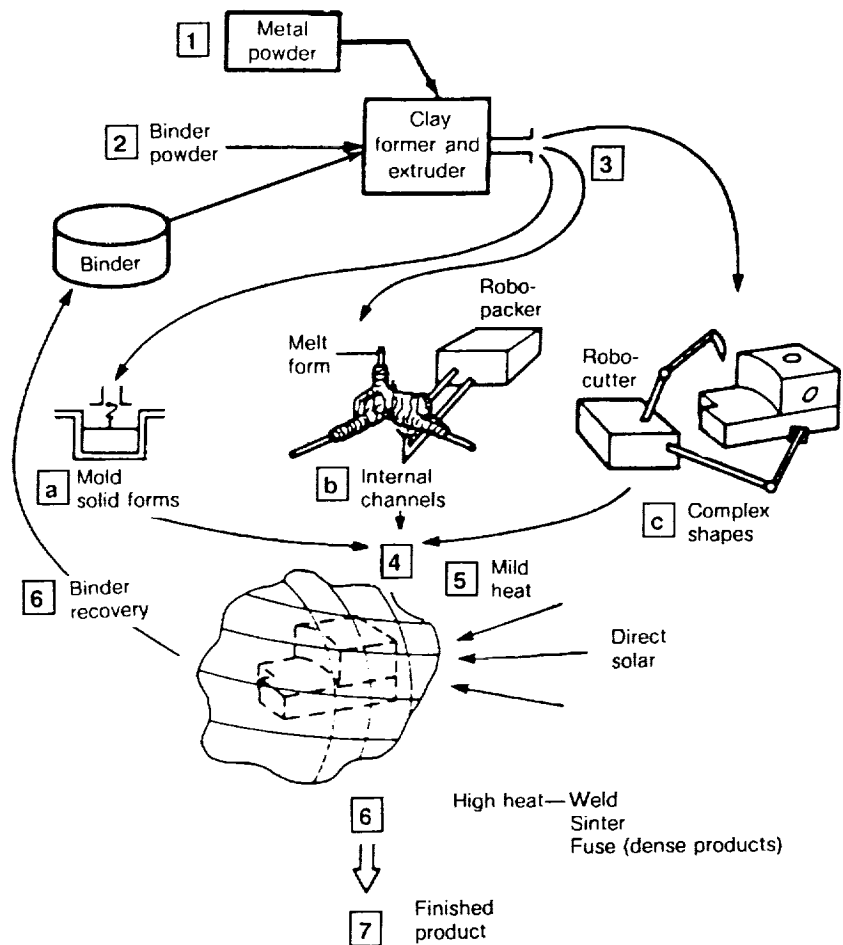


Figure 3

Powder Metallurgy

An alternative process for forming objects of metal is to compress and heat a metal powder in a mold. 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.

Here we see three ways in which the technique might be used. A metal powder [1] and a binder powder [2] are formed into a "clay" and extruded [3]. This clay is then used to create solid forms in a mold [4a], to shape intricate internal structures by molding metal powder around a meltable form [4b], or to make complex shapes [4c], which are then heated [5]. Similar techniques could be used for ceramics.

Taken from Criswell 1981, p. 397.

Rolling

Rolling consists of passing a metal between two rolls which revolve in opposite directions, thereby decreasing the cross sectional area and increasing the length of the feedstock (fig. 4). Larger ingots are rolled into blooms

having a cross section of more than 6 inches and finally into shapes such as plates, bars, rods, I-beams, and angles (fig. 5). Rolling should be readily adaptable to the space environment, as it does not depend on gravitational forces.

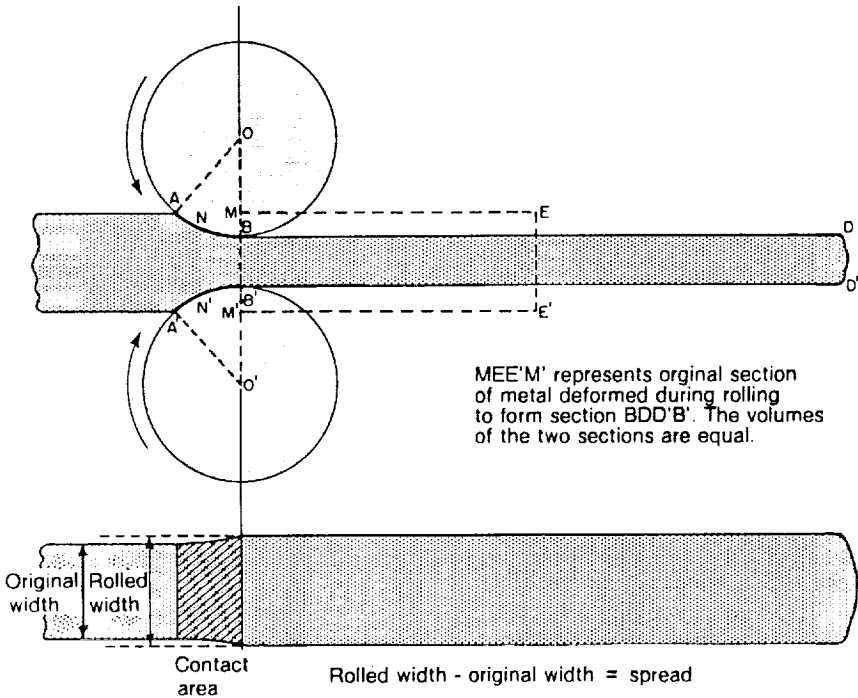


Figure 4

Rolling Steel

Hot steel in a plastic state can be rolled into a variety of products. Various types of rolling mills have been designed, depending on the type and properties of the desired product. Typically, an ingot of steel will pass through a series of rolls that gradually shape the steel. This diagram shows the basic principle.

Courtesy of the Association of Iron and Steel Engineers, reprinted from The Making, Shaping and Treating of Steel, 10th ed., fig. 22-9.

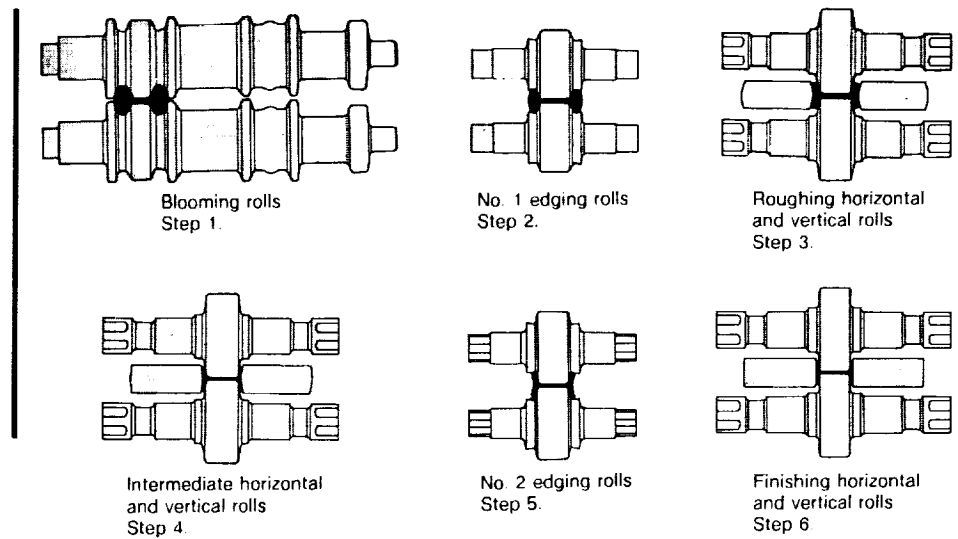
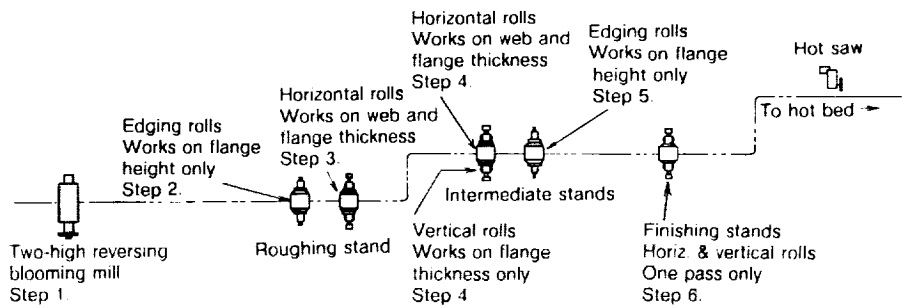


Figure 5

Shaping Bars

Rolling mills can produce a variety of shapes. Here, the rolled bar passes through several shaping steps on its way to becoming an H-bar.

Courtesy of the Association of Iron and Steel Engineers, reprinted from *The Making, Shaping and Treating of Steel*, 10th ed., fig. 23-3.



Extrusion

Extrusion is essentially a hot working operation where a metal is extruded through a die or orifice that controls the cross sectional shape (fig. 6). Some common extruded shapes are rods, tubing, and window frames. Extrusion should be easily adapted to space operation.

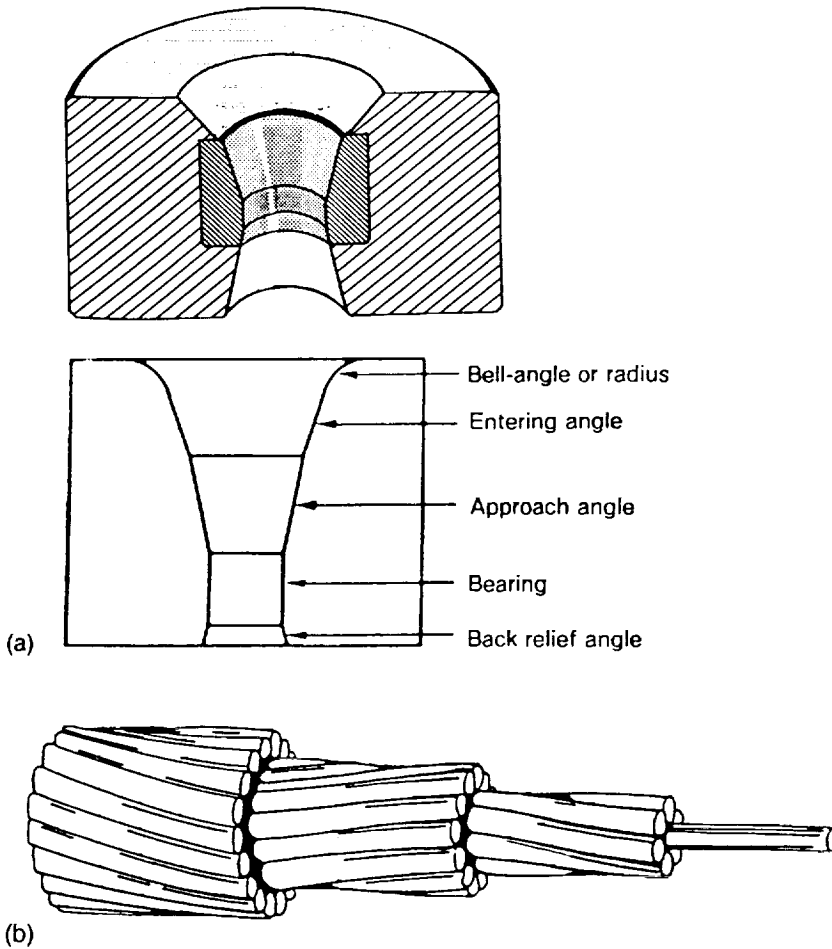


Figure 6

Wire

a. Die for Wire Pulling

b. Arrangement of Wires in a Cable

When bar stock has been produced, one of the further fabrication processes is the pulling of wire. In this process, a heated bar is pulled through a die, reducing its cross-sectional area by 10-45 percent. Several successively smaller dies may be necessary to produce wire of the appropriate diameter. Wires have a variety of uses. Two principal ones at a lunar base may be in cables used to prestress concrete structures and as supporting cables for structures.

Courtesy of the Association of Iron and Steel Engineers, reprinted from *The Making, Shaping and Treating of Steel*, 10th ed., figs. 31-13 & 31-14, and 9th ed., fig. 30-43.

Cold Welding

Cold welding consists of joining two flat, clean surfaces of a metal by contact and application of pressure. Cold welding works by joining the surfaces at the molecular level. In space and on the Moon, where oxide layer formation is retarded (if not eliminated), cold welding has high potential. In particular, using ceramic rollers to cold roll ultra-pure metals may result in a low-cost way of cold welding.

On the other hand, extreme care has to be exercised to keep the surfaces of high-purity metals separate so that undesired cold welding does not take place spontaneously.

Vapor Deposition

Vapor deposition involves allowing vapors of a metal to contact a surface in a closed chamber. On the surface metal layers build up atom by atom. The presence of vacuum makes this process a viable one in a space manufacturing facility. It is particularly suitable for applying thin coatings, such as making highly reflective mirrors.

Although these procedures are plausible for space manufacturing, all are in need of testing and demonstration to ensure that they can be used with typical nonterrestrial metals.