Austenitic Manganese Steel

A Complete Overview

By
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Abstract:

Manganese steel is used in harsh applications that require high levels of toughness. Its total production is small, however, at least when compared to carbon and alloy steels. John Tasker describes manganese steel by saying “it is the only material that will survive in most of the large crushing equipment used today.” When one of my colleagues said that “manganese steel was a metallurgist’s dream,” he was extolling all of its good properties while completely ignoring its weaknesses. A more accurate statement might be: “manganese steel is the best alloy for any application where all other alloys fail.” This statement illustrates that even though some materials might outwear manganese steels, many times they will catastrophically fail in the harsh service conditions in which manganese steels excel. This paper will cover many of the uses and properties of manganese steels and the production methods that produce high quality castings. In addition, some of the modifications to the alloy system will be presented.
Acknowledgments:

This paper is dedicated in memory of Phil Belding. Phil was a mentor and a dear friend. His enthusiasm and knowledge of metallurgy and manganese steel greatly affected my career during the nearly two decades we spent together.

I would also like to thank Mike Holt who is also a great friend and mentor. Mike’s knowledge of manganese steel is immense and I have greatly appreciated his input and advice over the years, including his review of this paper.
History:

Manganese steel was discovered by Sir Robert Hadfield in 1882. Figure 1 shows an image of Hadfield cast in manganese steel. Earlier experiments with manganese additions to produce steels that were sound and free of cavities had been conducted by the Terre Noire Company. At the time of this work manganese alloys containing 5% carbon and 20% manganese were all that was available. This composition, due to its low manganese and high carbon content, prevented its use in the production of low carbon steels, and therefore sound low carbon steels could not be produced at this time.

Due to this problem, work was begun on the concept of producing a manganese alloy with higher manganese content. Alexander Pourcel is credited with producing the first ferro-manganese alloy with 80% manganese and 6% to 7% carbon. This achievement opened the way for producing low carbon steels with manganese contents that improved soundness and ultimately Hadfield’s work.

Previous work had only investigated manganese contents up to 2.46% in the steel, so above this is where Hadfield’s experiments started. He produced a series of steels using a ferro-manganese alloy of 80% manganese and 7% carbon. Due to using this alloy an approximate 10 to 1 ratio of the manganese to the carbon was set up. Hadfield found that in the range of 2.5% to 7.5% manganese the steels were extremely brittle, but once the manganese content exceeded 10% the steels became remarkably tough. He also found that the toughness was further enhanced by quenching in cold water after heating to approximately 1832°F. As Hadfield continued to work on his newly discovered material the nominal composition settled in at 1.2% carbon and 12.5% manganese, this composition is nicely set up by the ferro-manganese alloy that was available (10 to 1, Mn/C ratio). This composition is still to this day called Hadfield’s Manganese Steel. In 1883 Hadfield was granted British Patent number 200, the first patent related to manganese steel.

Figure 1. Commemorative Plaque of Hadfield cast in manganese steel
Applications:

Manganese steel’s ability to work harden from impact loading along with its exceptional toughness make it the best wear material choice for many demanding applications. These applications include gyratory crusher mantles shown in Figure 2; concaves, jaw crusher dies shown in Figure 3; cone crusher bowl liners and mantles shown in Figure 4; track pads for large mining shovels; and hammers for many different types of impact crushers including automobile shredders. Manganese steel also develops a favorable wear pair with alloy steels so manganese steels can be used as a bushing material in demanding mining applications. Frogs and switches for the railroad are also produced from manganese steel. Various conveyor links, flights, buckets and pans are also made from this material. Armor plate and even soldiers helmets have been produced from manganese steels in the past.

Recently, new lightweight alloys with very high manganese and aluminum contents for armor applications are being developed. Due to its austenitic structure, manganese steel has no magnetic response and therefore makes good wear plates for the bottom of electro-magnets.

Manganese steel also finds applications at extremely low temperatures due to its persistent toughness even at these temperatures. One application of manganese steel that is not a wear component is in the construction of safes. This material resists many of the normal break-in methods used by thieves so manganese safes are quite robust. Manganese alloys will work well in most situations that involve impact or gouging abrasion where other alloys fail.

One final consideration when selecting manganese steel is the section thicknesses of the desired part. As section thicknesses increase it becomes harder to obtain good properties in manganese steel castings and to avoid casting flaws. Manganese steel has a low thermal conductivity when compared to other steels and in order to obtain good toughness it requires a fast quench after solution annealing. Therefore, it is desirable
to keep section sizes less than 6 inches, but with alloy modifications greater thicknesses are possible. These heavier sections will typically have diminished properties.

Austenitic Manganese Steel

Figure 4. Cone Crusher Liner Set

Grades of Manganese:

The standard grade of manganese steel (Hadfield’s Manganese) used today has roughly 12% manganese and 1.15% carbon. This approximate 10 to 1 ratio from Hadfield’s work is the basic target for much of the manganese steel produced even to this day. The chemistry has not changed much since the alloy’s discovery. Most manufacturers do offer similar materials with some variations to the carbon level, with or without other added elements, but these alloys are still roughly 12% manganese. By varying the carbon level the desired properties can be optimized.

In the late 1970’s a second new family of manganese steels with elevated manganese and carbon levels emerged. The first was patented by Raufoss from Norway. This alloy had a manganese level near 19% and carbon around 1.45%. This combination of carbon and manganese was found to improve the wear resistance by a considerable amount. Due to the success of this alloy in service, other high manganese content alloys were developed. Manganese contents of 18%, 20% and 24% can now be found in the offerings of many producers. These higher manganese grades require elevated carbon levels in order to achieve the desired increase in service life.

A third family of manganese steels with relative low manganese levels called “Lean Manganese Steel” has found various levels of success over the years. This alloy was first introduced and patented in 1963 by the Climax Molybdenum Company. It has manganese levels of 5% to 7% and carbon levels near 1%. Molybdenum is also added to this alloy at a fairly high level, up to 1.5%, to help stabilize the austenite. This composition of manganese steel has never been produced in the tonnages of the other grades. One reason seems to be the variable performance in service of this alloy. Many producers have invested considerable effort to achieve repeatable results from this grade, but most have reverted back to the more typical grades in order to achieve consistent service life. Due to the composition of this grade, which is a less stable austenite, this alloy experiences less material flow while in service. It can also offer superior service life in certain wear situations, such as those that have higher amounts of abrasive wear.

ASTM A128 governs many grades of manganese steels that are produced, but many suppliers have proprietary formulations that may not fit entirely within the limits set by the grades in this specification. In addition the high manganese grades, those with manganese levels above 16% are not covered by ASTM A128 at all.
Work Hardening:

The hardness of manganese steel in the solution annealed and water quenched condition is normally around 220 HB. It is possible to strain harden this material to approximately 500 HB. In order to achieve this high hardness level, the impact loading must be high while the material wearing away from gouging abrasion is limited. It is typical in crushing applications where the main wear mechanism is gouging abrasion that the manganese steel will harden to some intermediate level, typically 350-450 HB.

The mechanisms by which hardening occurs include twinning, stacking fault formation and dynamic strain. See Figure 5 for a work-hardened microstructure of manganese steel; clearly visible slip lines are the result of the work hardening to the grains. It has also been suggested that a deformation based martensitic transformation also plays a part in the hardening, but no evidence has been found to support this theory.

Manganese steel’s rate of work hardening is dependent primarily on two variables. The first factor is the rate and intensity of impacts being received by the material. This is not a property of the material, but a result of the service conditions. More impacts and those of larger magnitude speed the material along to its maximum hardness level. The next factor is the amount of carbon in the material. The higher the carbon level the faster the material will work harden in any given service.

In order to increase dimensional stability or add additional wear life to manganese steel parts, they can also be pre-hardened by explosive hardening. In this process the surfaces to be hardened are covered with sheet explosives and the pressure created by the explosion deforms and hardens the surfaces. Sometimes this process is repeated two or three times to obtain a greater hardness to a greater depth. Railroad track work castings are an example of manganese steel castings that are often explosively hardened.

Note:

The information presented in the rest of this paper will be based on alloys with manganese levels near 12%. This will cover the standard Hadfield grades and the common modifications to these materials. When information is presented for materials with other manganese levels it will be specifically stated as such.
Production:

Manganese steels can be produced by any of the conventional steel making processes. In the early days of its production molten ferro-manganese was added to essentially carbon free iron to produce the manganese steel. This process required two different melters and was known as the duplex process to some. Modern production of manganese steel is carried out in electric arc furnaces or electric induction furnaces. Due to the attack of manganese oxides on acid type furnace linings, a basic or neutral lining must be used in the melting furnace to produce manganese steels. The furnace charge is typically made up of returns (gates and risers), worn castings, ferroalloys and steel scrap. Most producers dead melt the charge to produce the manganese steel, but it is also possible to perform a silicon burn in the electric arc furnace. The silicon burn helps to stir the metal, remove oxides and lower gas levels. Arc furnace heats will normally employ a single slag practice to protect the metal during melting. This slag will be produced from lime (CaO) and should be kept basic in nature to prevent excessive attack of the basic furnace lining.

The fluidity of manganese steel is quite high, approaching that of cast iron, which makes it is possible to fill intricate shapes and pour at low superheats. The mechanical properties of manganese steels are greatly enhanced by a fine grain size. Strength and ductility can be as much as 30% greater for fine-grained material.

See Table 1 for data on the reduction in properties due to changes in grain and section size. See the appendix for a more thorough listing of the properties of manganese steel.

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Table 1. Average mechanical properties of manganese steel composed of 12.7% Mn, 1.1% C, 0.5% Si, 0.043 P

In order to achieve a fine-grained material it is necessary to use low superheats when pouring manganese steel alloys. Grain refiners for manganese steels do exist, some of which are proprietary to various manufacturers and others of which are commercially available. Some producers have had some success implementing the various grain refinement techniques, but the most reliable method to obtain a fine grain structure is to pour the metal with low superheat.
Figures 6 and 7 show the fracture surfaces of 2 inch by 2 inch bars that were broken as-cast to reveal the grain size. Both bars are from the same (12% Mn) heat with Figure 6 being poured at 2510°F and Figure 7 being poured at 2707°F. In practice, pouring temperatures below 2600°F are typical for the 12% Mn grades and can be much lower as carbon and alloy levels are increased. Temperatures near 2500°F are desirable for pouring the higher manganese and carbon grades.

In order to successfully pour at these low superheats it is important to have a well-insulated and preheated ladle. Ladles are typically lined with a basic or neutral (alumina based) lining system to avoid attack from the manganese oxides. It is also normal to pour at a fairly high volumetric rate to prevent laps and wrinkles. Care does need to be taken to avoid excessive air entrainment due to turbulence when pouring at low superheats. When these gases are entrained they will likely be trapped at the cope surface of the casting. This can lead to costly weld repairs or scrapped castings.

Molding:

Molds for manganese steel castings, just like the furnace and ladle, are subject to reaction with the manganese oxides. In order to avoid this problem many producers use olivine sand to make their molds. This sand is basic in nature and does not react with manganese steel. It is possible to use silica sand for the molds, but the mold will either need to be faced with olivine or heavily mold washed with an appropriate coating. Even properly coated silica sand molds can produce poor quality surface finishes. Any of the standard sand bonding systems will work with manganese steels, but not all systems will work with olivine sand. Other details of the mold are similar between manganese steels and carbon or alloy steels.

Manganese steel is a wide freezing range alloy which leads to dispersed micro-shrinkage and micro-porosity. This makes it difficult to feed to high levels of solidity and thus allows for the use of smaller risers than an equivalent casting poured in carbon steel.
Yields can reach 65%+ in some cases. The pouring temperature also affects the required amount of risering. Low pouring temperatures allow for minimal risering. This methodology will produce adequate internal soundness for most applications except armor plate. When manganese steel is to be used for armor plate it is essential to heavily riser the casting. This will produce the soundest casting and a high quality armor plate.

Heat Treatment:

Ideally heat treated manganese steels will have a fully homogenized fine-grained austenitic microstructure. The grain size is a function of pouring temperature and heat treatment typically does not influence the grain size. Some have tried to develop strategies of heat treatment that would first transform the structure to a pearlitic structure, which would then allow for grain refinement in the final heat treatment. These strategies have not been widely accepted or implemented for various reasons. One reason is that these cycles become expensive due to the high furnace temperatures and long hold times required. In addition the alloy was often not significantly improved by these cycles.

The typical heat treatment cycle for most manganese steels consists of a solution anneal followed by a water quench. This cycle may start off at room temperature or at an elevated temperature depending on the starting temperature of the castings. The starting temperature in the heat treat furnace is set to be near the castings temperature and is then raised at a slow to moderate rate until the soaking temperature is reached. Soaking temperatures are typically high in order to facilitate the dissolution of any carbide that might be present. Temperatures at or near 2000°F are typically used to achieve the desired homogenizing effect. The chemical composition of the alloy will ultimately set the soaking temperature.

Figure 8. Microstructure of properly quenched manganese steel magnified 100X

Manganese steel castings require a rapid water quench following the high temperature soak. This quench needs to occur immediately after the castings are removed from the heat treatment furnace. The rate of this quench needs to be high enough to prevent any precipitation of carbides. Figure 8 shows the microstructure of properly quenched manganese steel. A slack quench can reduce the toughness of the material dramatically. In the toughened condition manganese steel castings can be final processed with little special care.
The one item to avoid with heat-treated manganese steel castings is reheating above 500°F. Temperatures at or above this level will cause the precipitation of acicular carbides, which can dramatically reduce the toughness. This effect is time and temperature based with longer times and higher temperatures both causing greater losses of toughness.

Cleaning:

The removal of gates, risers and vents can be accomplished in a few different ways for manganese steel castings. If the castings are allowed to cool to room temperature after shakeout, most of the rigging can be broken or flogged off of the casting. The casting will be fairly brittle at this point and removal of these items with an impact force can be quite effective. Once heat-treated, however, it will no longer be possible to break anything of size off of the casting. Cutting will be required to remove rigging from the casting once it has been heat-treated. This can be accomplished by abrasive cutting, torch cutting, or arc air gouging. Torch cutting is somewhat difficult and produces high volumes of smoke, due to the high alloy content of manganese steels. It is typical to use torch tip sizes that are much larger than what is needed for carbon steel. Properly designed dust and smoke collection systems are required when using hot methods to cut manganese steels. Care must also be taken not to overheat the manganese steel when doing hot work. Fast cuts and moving around the casting to avoid concentrating the heat are advisable in order to minimize the damaging effect of overheating.

Welding:

Manganese steels are weldable and many different alloy compositions are available for joining or repair welding. Just like for any other hot work on manganese steel the welding interpass temperature must be kept below 500°F to avoid embrittlement. No post weld stress reliefs are required or desirable for manganese steel alloys. Heavy peening of each weld bead is recommended to setup compressive stresses in the weld. Before welding begins, proper surface preparation is required. It is typical to have a decarburized surface on castings that must be removed before welding. Worn manganese steel parts will have a work-hardened layer that also must be removed to facilitate welding. For joining or fabrication it is typical to use a stainless steel welding consumable. This material adheres well to many different base metals including manganese steels. Weld filler materials that are also manganese steels are available and are often used for repair welding of castings. Few, if any, of these materials will be able to match the base metals wear resistance. High carbon contents are critical to allow manganese steels to resist the wear that they typically encounter in service. Carbon levels are somewhat limited in weld filler materials so that the produced welds do not crack after being deposited.

It is also possible to use welding to deposit manganese steel onto other steels. This allows a wear resistant manganese steel surface to be created. This layer can greatly increase the life or performance of the overlaid part in certain situations.
Machining:

Manganese steel’s unique wear resistant properties also make it very difficult to machine, at best. In the early days of manganese steel production it was thought to be unmachineable and grinding was used to shape the parts. Now with modern cutting tools it is possible to turn, bore and mill manganese steels. Manganese steel does not machine like other steels and typically requires tools that are made with a negative rake angle. In addition, relatively low surface speeds with large depths of cut produce the best results. This arrangement produces high cutting forces and the equipment and tooling must be robust to withstand these forces. Any chatter of the tooling can add to the work hardening of the surface being machined. Most cutting is typically done without any sort of lubrication. During the machining of manganese it is important to continuously remove the work-hardened zone with the next cut. Small finishing cuts or tool chatter will cause the hardness to build and make the remaining surface virtually unmachineable.

Drilling of manganese steels, while possible, is very difficult and required holes should be cast into the part versus drilled. If drilled holes are required, mild steel inserts are often cast into the part so that the machineable insert can be drilled or drilled and tapped.

Effects of various elements:

**Carbon** is one of the two most important elements in manganese steels along with manganese. Manganese steels are a supersaturated solution of carbon. For most standard manganese steel grades the carbon and manganese are in an approximate ratio of Mn/C=10. These steels therefore are typically 12% Mn and 1.2% C. This ratio was mainly setup by early steel making limitations and the fixed ratio has no real significance. Increasing the carbon content raises the yield strength and lowers the ductility. See Figure 9 for the effects of increasing carbon content on the properties of 13% manganese steel.

![Figure 9. Effect of carbon upon the tensile properties of manganese steel, 1-inch section test bars (13% Mn, 0.6% Si, 0.035% P)](image)
The main significance of increased carbon content though is to increase the gouging wear resistance, see Figure 10. Most manganese steels are used in gouging abrasion and high impact wear situations so manufacturers try to maximize carbon contents. Practical limits do exist and as the carbon content exceeds 1.3% cracking and undissolved grain boundary carbides become more prevalent. The premium grades of manganese steels, those with high manganese contents, have pushed the upper carbon limit well beyond 1.3%.

Increasing manganese levels tend to increase the solubility of nitrogen and hydrogen in the steel. Premium alloys with higher carbon contents and additional alloy elements exist with manganese levels from 16-25% manganese. These alloys are proprietary to their manufacturer.

Silicon contents up to 1% are typically considered safe in manganese steels, but the silicon exerts no noticeable influence on the mechanical properties. At 2.2% silicon content, Avery has shown a sharp reduction in strength and ductility. Most of the reported experimentation has been done with small section sizes of less than 1 inch, when considering silicon content and heavier section sizes the impact strength can be severely decreased with increasing silicon contents. See Figure 11 for the effect of adding 1.5% Si to a 6-inch section size.

Manganese is an austenite stabilizer and makes this family of alloys possible. It decreases the austenite to ferrite transformation temperature and therefore helps to retain a fully austenitic structure at room temperature. Alloys with 13% Mn and 1.1% C have a martensite start temperature below -328°F. The lower limit for manganese content in plain austenitic manganese steel is near 10%.

**Figure 10. Gouging wear ratios of austenitic 12% manganese steel vs. carbon content**

**Figure 11. Effect of 1.5% silicon addition on the Izod impact energy and tensile elongation of 6-inch section manganese steel. (Base composition 13% Mn, 0.6% Si, 0.035% P)**
The data shows a 75% reduction in impact energy when the silicon is increased to this level. It is recommended to keep the silicon levels in manganese steel low, to less than 0.6% silicon when producing section sizes over 1 inch.

**Chromium** is used to increase the tensile strength and flow resistance of manganese steels. Additions of up to 3.0% are often used. Chromium increases the solution-annealed hardness and decreases the toughness of the manganese steel. Chromium does not increase the maximum work hardened hardness level or the strain hardening rate. Chromium bearing grades require higher heat treatment temperatures as chromium carbides are more difficult to dissolve into solution. In some applications chromium can be beneficial, but in many applications there is no benefit to adding chromium to manganese steel.

**Nickel** is a strong austenite stabilizer. Nickel can prevent transformations and carbide precipitation even at reduced cooling rates during quenching. This can make nickel a useful addition in products that have heavy section sizes. Increasing nickel content is associated with increased toughness, a slight drop in tensile strength and has no effect on the yield strength. Nickel is also used in welding filler materials for manganese steels to allow the as-deposited material to be free from carbides. It is typical to have lower carbon levels in these materials along with the elevated nickel to produce the desired result.

**Molybdenum** additions to manganese steels result in several changes. First the martensite start temperature is lowered which further stabilizes the austenite and retards carbide precipitation. Next, molybdenum additions change the morphology of the carbides that form during reheating after the material has had a solution treatment. Grain boundary films of acicular carbides typically form, but after adding molybdenum the carbides that precipitate are coalesced and dispersed through the grains. The result of these changes is that the toughness of the steel is improved by the addition of molybdenum. Another benefit of molybdenum additions can be improved as-cast mechanical properties. This can be a real benefit during casting production. In higher carbon grades molybdenum will increase the tendency for incipient fusion, so care must be taken to avoid this as the resulting mechanical properties will be severely diminished.

Molybdenum is beneficial when very heavy section thicknesses are to be produced in manganese steel. These are sections that are in excess of 6 inches and especially those that are over 10 inches in section size. These section sizes can be found in large primary gyratory crusher mantles and thick jaw die castings. For these castings it is recommended to add molybdenum in the range of 0.9% to 1.2% while reducing the carbon content to 0.9% to 1.0%.
Aluminum is used to deoxidize manganese steel, which can prevent pinhole and other gas defects. It is typical to use additions of 3lbs/ton in the ladle. Increasing aluminum contents decreases the mechanical properties of manganese steel while increasing brittleness and hot tearing. In practice it is advisable to keep aluminum residuals fairly low for most grades of manganese steel.

New materials that contain high levels of aluminum and approximately 30% manganese are being developed for high-strength, weight-sensitive applications. In these cases the low density of the aluminum is being used to lower the density of the resulting alloy.

Titanium can be used to deoxidize the manganese steel. In addition, titanium can tie up nitrogen gas in titanium nitrides. These nitrides are stable compounds at steel making temperatures. Once tied up the nitrogen is no longer available to cause pinholing in the castings. Titanium can also be used to refine the grain size, but the effect is minimal in heavier sections.

Cerium can be used to refine the grain size of manganese steels. The compounds of cerium have a lower disregistry with austenitic manganese steel than other compounds and therefore should make it a better grain refiner for this alloy. It also suppresses the grain boundary carbide precipitation, which strengthens the grain boundaries. Impact strengths are also reported as being improved for manganese steels alloyed with cerium.

Phosphorus is very damaging to manganese steel. It forms a weak phosphoid eutectic film at the austenite grain boundaries. Phosphorous is difficult to remove from manganese steels and the most effective method to control it is careful selection of charge materials. ASTM A128 calls out a phosphorous maximum of 0.07%, but it is recommended to keep the phosphorous level well below this level when producing high quality manganese steel.

Sulphur, while not a benefit in most steels, causes few problems in manganese steels. The high manganese levels keep the sulphur tied up in manganese sulphide inclusions of the spheroidal type.

Boron has been used to try to produce grain refinement in manganese steels. As boron levels increase, however, a brittle boride carbide eutectic is precipitated at the grain boundaries. Boron also accelerates the decomposition of the austenite if the manganese steel is reheated, which makes the material un-weldable. It is not recommended to use boron in manganese steels.
Conclusion:

Manganese steel is used extensively in the mining industry and in other applications that require extreme toughness. Much work has been done since the discovery of the combination of elements that produce manganese steels. Some of the possible alloy modifications enhance certain properties of the steel, but many of these alloy modifications severely deplete the normal high reserve of toughness. Regardless of the enhancement that was achieved, if the part fails early in service, the gain was likely not useful. Section thickness must always be considered when evaluating the properties of manganese steels and the results of any enhancements. Laboratory section sizes (<1-inch) will often mask the true effect of any given change on normal working section sizes (approximately 6-inches). It is critical to test any new formulation or processing step on actual section sizes before implementing the change. Work is still progressing on specialty versions of manganese steel alloys to this very day.

Figure 12. Pouring 44,000 pounds of manganese steel into a large wear part mold
Appendix:

The property values below refer to Hadfield’s manganese steel in the properly heat treated condition.

Physical properties:
- Melting Point: Liquidus 2552°F, Solidus 2462°F
- Specific Gravity: 7.87 at 59°F
- Density: 0.285 pounds per cubic inch

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Mean Thermal Expansion Coefficient:

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<th>752°F (400°C)</th>
<th>932°F (500°C)</th>
<th>1112°F (600°C)</th>
<th>1292°F (700°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^-6 (in/in°F)</td>
<td>10.2</td>
<td>10.6</td>
<td>11.1</td>
<td>11.9</td>
<td>12.6</td>
<td>13.4</td>
<td>13.6</td>
</tr>
<tr>
<td>10^-6 (cm/cm°C)</td>
<td>18.4</td>
<td>19.1</td>
<td>20.0</td>
<td>21.4</td>
<td>22.7</td>
<td>24.1</td>
<td>24.5</td>
</tr>
</tbody>
</table>

(The thermal expansion of manganese steel is 1.5 to 2 times that of carbon steel)

Thermal Conductivity:

<table>
<thead>
<tr>
<th>Temperature</th>
<th>32°F (0°C)</th>
<th>392°F (200°C)</th>
<th>752°F (400°C)</th>
<th>1112°F (600°C)</th>
<th>1472°F (800°C)</th>
<th>1832°F (1000°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Btu/(hr<em>ft</em>°F))</td>
<td>7.50</td>
<td>9.43</td>
<td>11.13</td>
<td>12.58</td>
<td>13.55</td>
<td>14.76</td>
</tr>
<tr>
<td>(cal/(cm<em>sec</em>°C))</td>
<td>0.031</td>
<td>0.039</td>
<td>0.046</td>
<td>0.052</td>
<td>0.056</td>
<td>0.061</td>
</tr>
</tbody>
</table>

(The thermal conductivity of steel is approximately 3 times greater than that of manganese steel)
Tensile Properties: (Data compiled from various sources)

<table>
<thead>
<tr>
<th></th>
<th>Yield (ksi)</th>
<th>Tensile (ksi)</th>
<th>Elongation (%)</th>
<th>Reduction of Area (%)</th>
<th>Brinell</th>
<th>Impact Data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cast</strong></td>
<td>44/54</td>
<td>80/130</td>
<td>15/40</td>
<td>15/40</td>
<td>185/220</td>
<td>Izod: 100ft-lbs</td>
</tr>
<tr>
<td><strong>Wrought</strong></td>
<td>44/56</td>
<td>110/130</td>
<td>40/60</td>
<td>35/50</td>
<td>185/220</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Cast</strong></td>
<td>55</td>
<td>140</td>
<td>50</td>
<td>30/40</td>
<td>190</td>
<td>Charpy V 125ft-lbs</td>
</tr>
<tr>
<td></td>
<td>50/57</td>
<td>100/145</td>
<td>30/65</td>
<td>30/40</td>
<td>185/210</td>
<td>Charpy V 90/220ft-lbs</td>
</tr>
<tr>
<td><strong>Casting Sample</strong></td>
<td>62.4</td>
<td>101.3</td>
<td>26.5</td>
<td>24</td>
<td>NA</td>
<td>Charpy V 80ft-lbs</td>
</tr>
<tr>
<td><strong>Casting Sample</strong></td>
<td>60.9</td>
<td>120.2</td>
<td>37</td>
<td>30</td>
<td>NA</td>
<td>Charpy V 76.5ft-lbs</td>
</tr>
</tbody>
</table>

The two tensile specimens shown in Figure 13 are a manganese steel bar on the top and an alloy steel bar on the bottom. The alloy steel bar necked and failed with the classic cup-cone fracture. The manganese steel bar on the other hand necked along its entire length. Each time the bar starts to yield, the work hardening of that area increases the strength and prevents further necking until the whole length has necked. This progression is repeated until failure.

**Figure 13. Manganese and alloy steel tensile bars**

Compression:
Manganese steel is capable of supporting a compressive load of 700 ksi without rupture.

Fatigue:
The fatigue limit of the wrought material is 60 ksi, based on 10 million cycle reversing stress. Another source states the fatigue limit as 39 ksi, but does not state if the material was a casting or forging. Due to its high level of toughness, manganese steel is resistant to overstress crack propagation, but cyclically loaded parts like crusher liners can succumb to fatigue if not properly supported.
References:

2. Austenitic Manganese Steel-Fact and Fallacy, John Tasker, Intermountain Minerals Symposium, 1982
3. A Literature Survey on Certain Aspects of Austenitic Manganese Steels, R. Molnar, Steel Castings Institute of Canada, 1974
6. Austenitic Manganese Steels, Subramanyam, Swansiger, Avery, Specialty Steels and Heat-Resistant Alloys
8. ASTM specification A128/A128M-93 (Reapproved 2017)