THE PERFORMANCE OF HADFIELD’S MANGANESE STEEL
AS IT RELATES TO MANUFACTURE

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Abstract

In 1992 AREMA introduced solidity standards for austenitic manganese steel (AMS) castings, due to complaints by the Railways of the presence of gas, shrinkage and porosity in special trackwork castings. Between 1992 and 1995 the North American Class 1 Railways increased their gross car loading (on 4 axles) from 263,000 lb. (119,295 kg.) to 286,000 lb. (129,727 kg.). In 1996 CN began to see a marked increase in the failure of its railbound manganese frogs (RBM’s). Subsequent investigation and research has revealed that AMS is extremely sensitive to section size, heat treatment and the apidity and effectiveness of quenching. Poor quench compounded by large section size results in an unstable, in-homogenous structure, subject to transformation to martensite under increased loading and strain rate.

Keywords: austenite, martensite, annealing, quenching, transformation, segregation, grain size, carbides, grain boundaries, mechanical twinning.

Introduction

Hadfield’s manganese steel was invented by Sir Robert Hadfield in 1882. The first British patent for AMS, number 200 was granted to Hadfield in 1883. The first US patents, numbers 303150 and 303151, were granted in 1884.
This austenitic steel contains approximately 1.2% carbon and 12% manganese in a 1 to 10 ratio. It was unique in that it exhibited high toughness, high ductility, high work hardening ability and excellent wear resistance. Because of these properties Hadfield’s austenitic manganese steel (AMS) gained rapid acceptance as a useful Engineering material. It is still extensively used in the following heavy industries, in the form of castings or rolled shapes:

- Earthmoving
- Mining
- Quarrying
- Oil and gas drilling
- Steel making
- Dredging
- Logging and lumber
- Railways

In the railway industry AMS has been used successfully in special trackwork, namely frogs, diamond crossings, guardrail wear bars and replaceable switch point tips.

**Mechanical Properties**

AMS has a yield strength between 50,000 psi (345 MPa) to 60,000 psi (414 MPa). Although stronger than low carbon steel, it is not as strong as medium carbon steel. It is however, much tougher than medium carbon steel. Yielding in AMS signifies the onset of work hardening and accompanying plastic deformation.
The modulus of elasticity for AMS is $27 \times 10^6$ psi. (186 x $10^3$ MPa) and is somewhat below that of carbon steel, which is generally taken as $29 \times 10^6$ psi. (200 x $10^3$ MPa).

The ultimate tensile strength of AMS varies but is generally taken as 140,000 psi (965 MPa). At this tensile strength, AMS displays elongation in the 35 to 40% range. The fatigue limit for manganese steel is about 39,000 psi. (269 MPa).

Nevertheless, the mechanical properties of AMS listed above vary significantly with section size. Properties affected are tensile strength, elongation, reduction of area and impact resistance. For example, a 1 inch (25.4 mm) thick section properly heat treated, will display higher mechanical properties than 4 inch (102 mm) section.

Grain size is the primary reason for these mechanical differences. Fine-grained specimens exhibit tensile strengths and elongations up to 30% greater than course grained specimens. The effect of section size on grain structure and therefore mechanical properties will be discussed later.

The ability of AMS to work harden up to its ultimate tensile strength is its main feature. In this regard AMS has no equal. The range of work hardening of AMS from yield to ultimate tensile is approximately 200%. This however is accompanied by large dimensional instability. See Figure 1 for a typical stress strain curve for austenitic manganese steel.
Composition

Essentially, AMS is a solid solution of carbon and manganese in iron. Figure 2 indicates a phase diagram for steel containing 13% manganese.

While the nominal composition of AMS is 1.2% carbon and 12 to 13% manganese, in commercial AMS products, the carbon will range between 1.0 and 1.4%, while the manganese will range between 10 to 14% in accordance with ASTM–A128 specification.

Carbon content affects the yield strength of AMS. Carbon levels below 1% cause yield strengths to decrease. The optimum carbon content has been found to be between 1 and 1.2%. Above a 1.2% carbon content, yield strength is unaffected. Other alloying elements such as chromium will increase the yield strength, but decrease ductility. Silicon is generally added as a de-oxidizer. Carbon contents above 1.4% are not generally used as the carbon segregates to the grain boundaries as carbides and is detrimental to both strength and ductility [1].

Manganese has very little effect on the yield strength of AMS, but does affect both the ultimate tensile strength and ductility. Maximum tensile strengths are attained with 12 to 13% manganese contents. Although acceptable mechanical properties can be achieved up to 20% manganese content, there is no economical advantage in using manganese contents greater than 13%.
Manganese acts as an austenitic stabilizer in AMS and delays isothermal transformation. For example, a carbon steel containing 1% manganese begins isothermal transformation about 15 seconds after quenching to 700°F (371°C), whereas a steel containing 12% manganese begins isothermal transformation about 48 hours after quenching to 700°F (371°C) [1], [2].

Essentially, AMS structure is one of carbon in solution in austenite. The practical limit of carbon in solution is about 1.2%. Thereafter, excess carbon precipitation to the grain boundaries results, especially in heavier sections.

**As Cast Properties**
AM5 in the as-cast condition is too brittle for normal usage. As section thickness increases, the cooling rate within the molds decreases. This decreased cooling rate results in increased embrittlement due to carbon precipitation. In as cast castings, the tensile strength will range from approximately 50,000 psi (345 MPa) to 70,000 psi (483 MPa) and will display elongation values below 1%.

Heat treatment is used to strengthen and increase the mechanical properties of AMS. The normal heat treatment method consists of solution annealing and rapid quenching in a water bath.

Solution annealing generally consists of re-heating the steel to a high enough austenitizing temperature above 1850°F (1010°C) for a sufficient time period of time
to complete the solution of carbon. Usually railway frogs and crossings are heat treated at 2000°F (1093°C) and held for 2 hours for each inch (925 mm) of thickness before quenching.

Quenching is accomplished by immersion in a water bath agitated by air, as agitation reduces the tendency for the formation of a vapour coating (known as the Leidenfrost effect) on the casting surfaces, and therefore a more uniform rate of cooling is obtained. The speed of quench is an important factor in the final mechanical properties. The maximum rate of quench is fixed by the heat absorption from the casting surface by agitated water and by the rate of thermal conductivity of the AMS. AMS has low thermal conductivity.

A lower rate of quench, results in lower mechanical properties in the centre of heavier section. This results in a practical maximum thickness for castings of about 6 inches (152 mm). Another reason for limiting casting size to 6 inches (152 mm) is that castings larger than 6 inches (152 mm) develop large residual stresses upon cooling in the mold. Such stresses acting on a brittle steel structure are prone to cause cracking in heavier sections prior to heat treatment [3].

Heat treatment at high temperature causes surface decarburisation and some loss of manganese. This decarburisation layer can be as much as 1/8 inch (3 mm) and can be slightly magnetic. This is not usually a problem, as most railway frog and crossing
running surfaces are machined by either milling or grinding, which removes this decarburisation layer.

As treated AMS has an as cast as heat-treated hardness of approximately 190 to 200 brinell. It also possesses relatively low yield strength. As hardness is a measure of resistance to plastic flow (yielding), work hardening of the cast wear surface of railway castings for frogs and crossings is required. This hardness increase in turn increases the yield strength and results in a surface more resistant to impact and flow. The current generally accepted practice is to explosive depth harden railway castings for heavy haul use. This process results in surface hardness of 370 to 385 brinell.

**Early Problems with AMS**

In the mid to late 1980’s, the Class 1 Railways were experiencing problems with AMS castings, primarily frogs. Castings were not 100% homogenous with respect to internal discontinuities. These were in the form of solidification shrinkage cavities, gas, porosity and sand inclusions and were the result of riser and gating practice and moulding and pouring methods employed by the foundries. Also contributing, but not to the same degree was the difference in pouring rate, poring temperatures, mold strength and type of sand used. Such defects were shortening the life of the castings. Resulting repair welding by Railway welders was both time consuming and uneconomical.
To counter this, both CN and BN (now BNSF) introduced their own solidity specifications in the late 1980’s, based on ASTM reference radiographs, namely ASTM E–186, E-280 and E-446.

Subsequently AREA Committee 5 (now AREMA Committee 5) undertook to develop an industry radiographic standard for solidity of ASMS castings. An ad-hoc committee consisting of Class 1 Railway Engineers, manufacturers and foundry experts was formed. The Committee developed the standard based on a compromise between the CN and BN specifications. The AREMA Solidity specification was introduced in 1992 and can be found on drawings 100-96 and 1012-03 to 1017-03 inclusive in the AREMA Portfolio of Trackwork Plans [4].

In order to achieve the higher solidity levels required by the Railways and AREMA, the manufacturers decreased the spacing between risers and consequently increased the number of risers in the castings. These risers act as a secondary feed source and reservoir of molten steel from which the casting is fed as it shrinks during solidification. This practice achieved the desired results and the solidity of casting improved markedly. This worked well from about 1988 to 1995. Figure 3 and 4 show a recently de-molded RBM casting as viewed from the underside prior to and after the removal of the knock-off risers.
Between 1992 and 1995, the North American Class 1 Railways increased their axle loading from 65,750 lb. (29,823 kg.) to 71,500 lb. (32,432 kg.). With this increase in wheel loading, CN noted a sharp increase in the failure rate of its frogs.

The failure mode of the frogs was predominantly in the point and wing area. In the point, subsurface cracks, about 1/4 inch (3 mm) below the surface of the point, starting approximately 2 inches (51 mm) from the ½ inch point of frog, ran towards the heel of the frog. Cracks propagated parallel to the running surface and towards the heel of the frog until a 4 (102 mm) to 6 inch (152 mm) piece broke out. The surfaces of the cracks were serrated indicating a start-arrest nature of the propagation. Further examination at high magnification revealed crack propagation with “pools of ductility” characteristic of fatigue cracking [5]. Figure 5 and 6 indicate typical point failures. Note the depth and the surface texture of the failed surface.

**Magnitude of the Problem**

The type and appearance of the failures was consistent and indicative of a systemic problem with the manufacture of the castings. CN monitored the situation and determined the magnitude of the problem to be as follows [6]:

- 10% of its mainline frogs were failing and required weld repair before reaching 40 MGT.
- An additional 40% of its mainline frogs were failing and required weld repair before reaching 100 MGT.
- Relatively few (less than 10%) of its mainline frogs were able to carry in excess of 200 MGT. Of those that did, 250 MGT appeared to be the maximum attainable life in a mainline.

- At the tonnages being carried by CN at that time, this meant that the average life expectancy of a mainline frog was approximately 4 years.

- Compounding the original failure problem of the AMS castings was that weld repairs on these failed castings were short lived.

**Failure Investigation**

Originally it was thought that either poor foundry practice or repair welding at either the foundry or trackwork manufacturer was the source of the problem. Metallurgical investigation and quality assurance traceability indicated that only a small percentage of the castings had been repair welded by the foundry or trackwork manufacturer.

More frustrating were the results of numerous metallurgical investigations that indicated the manganese structure was considered acceptable (although not optimum) [7], and the best achievable given the section thickness of these castings [5], [7]. Generally, these metallurgical reports indicated an austenitic grain structure with small continuous grain boundary carbides. At much higher magnification a continuous lamellar phase was seen. Cracking as seen under scanning electron microscope, was along grain boundaries with carbide precipitation and consistent with inter-granular fracture [14].
A theoretical investigation on the contact stresses on the points and wings of the frogs was carried out at McGill University in Montreal [8]. This investigation indicated that the Hertzian stresses in the point would be in the order of 500,00 psi (3,447 MPa) and on the wings 475,000 psi. (3,275 MPa). Such stresses exceed the ultimate tensile strength of AMS, however due to confinement of the material in the contact area, the material does not fail immediately. Nevertheless, under such loading, rapid straining would exist. Strain rate may play a more important role than the magnitude of the Hertzian stresses in the failure of AMS.

As deformation under such service loading continues, the yield strength of the AMS rises to equal the imposed service stress creating a condition of equilibrium. Given current casting practice, it may well be that the imposed loading has now exceeded the ability of AMS to reach a stable condition and fatigue cracking results. Avery [2] predicted such behaviour in AMS in 1981.

**Discussion**

The desired result after quenching is a fully austenitic structure, carbide free and completely homogenous with respect to both carbon and manganese. This however, is the ideal and can only be achieved in lighter sections. More often than not, carbides will exist at the grain boundaries. Grain size at the outer skin of the casting is fine while towards the centre of heavier sections it becomes coarser grained.
In many cases, in heavier sections only partial transformation at the centre due to an ineffective quenching. If homogeneity of the matrix with respect to carbon and manganese is not achieved, the inner matrix may contain, pearlite, acicular carbides, martensite, meta-stable austenite and other unstable austenitic compositions. Also carbide precipitation due to ineffective quenching has a marked effect on reducing the toughness of AMS. Figure 7 indicates a cross-sectional view through a casting removed from track for examination. Note the size of the cross-section and impaired ability for proper quench towards the centre.

It has been commonly accepted that AMS subjected to rapid work hardening is stable during plastic strain. However, there is now evidence to suggest that under rapid work hardening and plastic deformation, AMS undergoes strain induced stress transformation from $\gamma$ austenite to $\alpha$ ferrite or $\varepsilon$ martensite. It has been shown that the transformation from $\gamma$ austenite to $\varepsilon$ martensite is dependent on the strain rate. For example increasing the strain from $6 \times 10^{-3}$ to $60 \times 10^{-3}$ min.$^{-1}$ at room temperature has been shown to cause martensite transformation on unstable austenite [9].

There appears therefore to be a fundamental relationship in the transformation of $\gamma$ austenite (an fcc structure) to $\alpha$ ferrite (a bcc structure) or to $\varepsilon$ martensite (an hcp structure) between strain rate, temperature and the stability of the $\gamma$ austenite. Strain induced transformation of austenite to martensite is primarily caused by the localized segregation of both carbon and manganese during quench, leading to unstable austenitic compositions. It has been shown that stress induced transformation only
occurs on these unstable compositions [10], [11]. It has been found that segregation can cause local variations in carbon from 0.2 to 0.3% and manganese from 4 to 6%. It is these local segregations that lead to unstable austenitic compositions.

The widely accepted theory of the mechanism for work hardening in AMS is fine mechanical twinning [2], [10], [11], [13]. Twinning is not driven by chemical reaction but rather applied stress or strain energy. It is this strain energy that provides the driving force towards complete transformation from $\gamma$ austenite to $\varepsilon$ martensite. The two types of steels most susceptible to type of transformation are Hadfield’s manganese and austenitic stainless steel [13]. The transformation to martensite is not large scale, however, if enough twins are produced, localized transformation products throughout the crystal can coalesce and act as initiation points for fracture planes.

**Conclusion**

In an attempt to correct problems associated with manganese castings in the 1980, such as shrink, porosity, gas and inclusions, manufacturers decreased the distance between risers and increased the number of risers on any given frog or crossing casting. In so doing, the steel within the castings stayed hotter for longer leading to both larger grain size and dendritic structure upon cooling. In addition, the cross-sectional size was increased at the riser locations resulting in an ineffective quench and consequently reduced mechanical properties.
Ineffective quench results in partially transformed austenite and metastable austenite and other compositions. Such constituents are non-stable and will transform to martensite. This transformation from austenite to martensite is not driven by chemical reaction but rather applied stress or strain energy. The increased rate of strain due to increased loading also plays an important part in spontaneous transformation of austenite to martensite.

Some manufacturers have already recognized this problem and have or are working on finding the optimum placement of risers to prevent gas, shrink, and porosity, while at the same time obtaining a rapid and effective quench.

If foundry and casting design practice cannot obtain an effective quench of castings, it may well be time to start looking at other materials or compositions.
REFERENCES


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Figure 1  Stress-strain curve for austenitic manganese steel

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