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An Overview on high manganese steel casting

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ABSTRACT

Hadfield steel invented in 1882 has an enormous capacity for work-hardening upon impact and it is commonly used for railroad components such as frogs and crossings and for rock-handling equipment. It has nominal composition of iron, 1.0 to 1.4 % carbon and 10 to 14% manganese in a 1 to 10 ratio. The present paper deals with a comprehensive analysis on the overview of high manganese steel casting. The effect of chemical composition was analysed highlighting how different alloying element can affect the final mechanical properties of high manganese steel casting. Good and bad practices were reviewed, looking at how high melting temperature can course micro and macro segregation at the grain boundaries resulting in uneven wear rate and loss of strength and impact of the said steel. A Proper heat treatment cycle was discussed and typical mechanical properties and work hardening rate of the steel was also emphasised on, so as to know on which application is the steel best suited for.

Keywords: Austenitic Manganese steel, Melting temperature, Work hardening rate

INTRODUCTION

Manganese increases the ductility of the metal and adds greatly to its toughness and resistance to abrasive action. Sir Robert Abbott Hadfield was an English metallurgist noted for his 1882 discovery of manganese steel, one of the first alloys steel. His invention was based on adding large percentage of manganese to molten iron whereby producing a steel that have good toughness and hardness while possess distinguished characteristics [8].

After a number of experiments performed by sir Hadfield, a conclusion was made that a steel having good toughness and hardness while possess distinguished characteristics can be found when the Mn content is between 11-13% Mn and 1-1.3% carbon with a Mn\C ratio of 10:1. The table below shows the effect of different manganese content on the mechanical properties of Hadfield steel.

Table 1: Mechanical properties for different Mn content [16]

Mn (%)	YS (MPa)	TS (MPa)	El (%)	Hardness
Mn13	414	995	40	225Hv
Mn16	335	740	53	178Hv
Mn26	250	610	67	130HV

Hadfield manganese steel has a high capacity for work-hardening upon impact. Due to its unique service properties, it has been used widely in a number of applications like rail tracks, dredge buckets, jaw crushers and a number of high impacts and wear resistance operations [2]. In the as-cast condition, the steel contains carbides and embrittling transformation product [17]. Carbides form in castings that are cooled slowly in the moulds regardless of mould cooling rates. These carbides can also form when the as-cast contains more than 1.0 %C or the addition of alloying element such as Cr, V, Ti, etc. They form in heavy section castings during heat treatment if quenching is ineffective in producing rapid cooling throughout the entire section thickness [17].

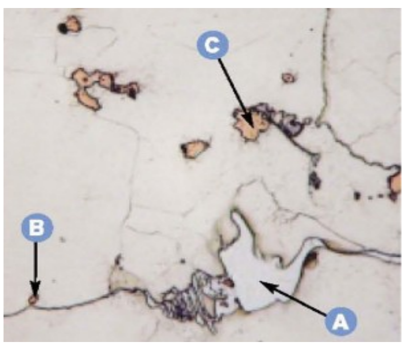

Figure 1 : As-cast structure of Hadfield steel, containing carbides at grain boundary [20]

A full solution treatment can be used to remove unwanted carbides; this can be obtained between 1000 °C and 1100 °C with soak times appropriate for the section thickness of the part. Higher solution treatment temperature (STT) should be avoided because carbon segregation may cause incipient melting thus decarburization may occur [17]. Although some grain growth may occur during solutioning, it is the pour temperature and solidification rate that strongly influence the final austenitic grain size.

Other points which determines the final properties of the product, particularly during fabrication process is the melted chemical composition of the cast, followed by the proper heat treatment in order to produce suitable microstructure so as to prevent structural defects (voids, cracks, inclusions) and the formation of brittle phases (carbides). Therefore, various parameters such as alloying elements, casting conditions, rate of solidification, micro alloying elements and heat treatment cycles can determine optimum microstructure [15].

Typical mechanical properties for the high manganese steel include: yield strength, ultimate tensile strength, hardness as quenched; hardness at fracture and charpy V-notch impact. The unique feature of this tough, high strength steel is the rapid work hardening, from yield strength of 379 MPa to an ultimate tensile strength of 965 MPa. In gouging abrasion tests, the Hadfield steel performs better than wrought alloy steels, cast alloy steels, stainless steels, tool steels or high-chromium steel and white cast irons [15]. In closing, the combination of these properties makes the high manganese steel to have superior properties as compared to other alloying steels when working under gouging abrasion.

THE INFLUENCE OF CHEMICAL COMPOSITION ON HADFIELD STEEL

Chemical composition is one of the most important factors that can affect the mechanical properties of high manganese steel castings. Carbon and manganese content plays an important role in the production of high manganese steel. Manganese steel foundry can have several modified grades on its production route, and these grades are usually produced to meet the requirements of application, section size, casting size, cost and weld ability considerations [15]. Pribulova added that many variations of the original austenitic manganese steel have been proposed, often in unexploited patents, but only a few have been adopted as significant improvements [12]. These usually involve variations of carbon and manganese, with or without additional alloys such as chromium, nickel, molybdenum, vanadium, titanium and bismuth.

The mechanical properties of austenitic manganese steel vary with both carbon and manganese content as it was shown in table 1. As carbon is increased it becomes increasingly difficult to retain all of the carbon in solid solution, which may account for reductions in tensile strength and ductility [15]. One important fact raised by Chakrabartti, 2012 is that the Carbon and Manganese content in manganese steels are not only interrelated, but they are also related to casting thickness [4].The figure below shows the effect of carbon content on the properties of Hadfield steel relating to section thickness.

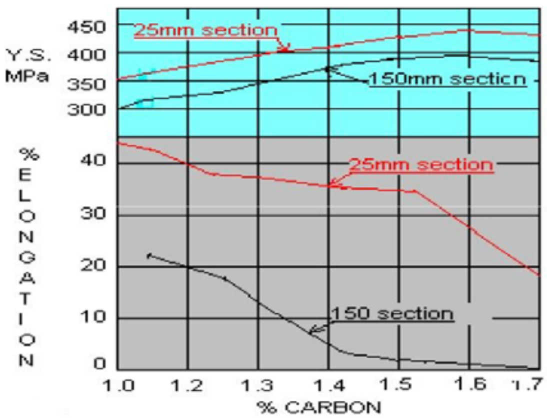

Figure 2: Effect of carbon content on yield strength and elongation of Hadfield steel [4]

Chakrabartti, 2012 also showed systematically that the abrasion resistance of high manganese steel casting will increase with an increase in carbon content [4]. Carbon content above 1.4% is seldom being used due to the difficulty of obtaining an austenitic structure free of grain boundary carbides which are detrimental to strength and ductility of the said steel.

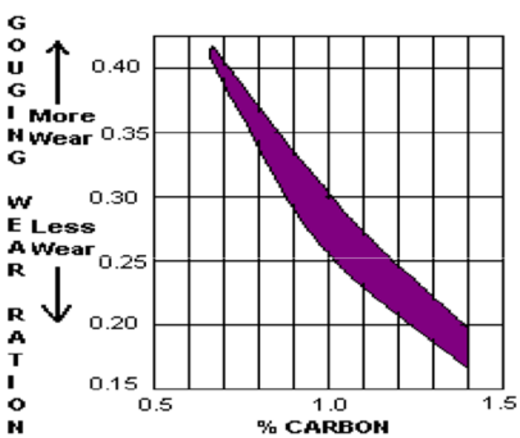

Figure 3: Effect of carbon content on wear resistance of manganese steel [4]

The low carbon content (0.7% C minimum) may be used to minimize carbide precipitation in heavy castings or in weldments, and similar low carbon contents are specified for welding filler metal. On the other hand, it is known that Manganese is an austenite stabilizer thus excess of manganese to steel will make the austenitic phase become stable at room temperature. Austenite has a FCC structure; therefore excess of manganese (20 – 26) % by weight can decrease the Yield strength as it was reported in table 1.1.

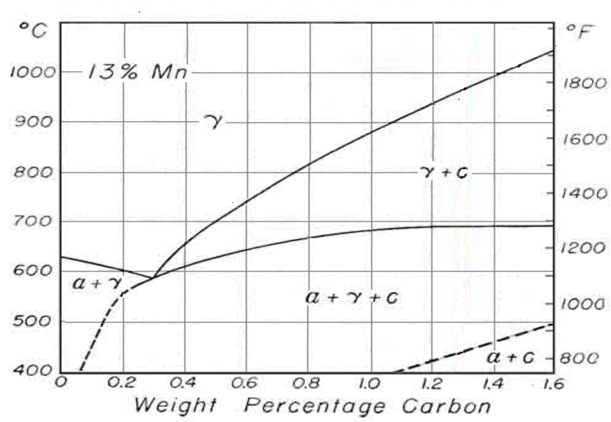

Figure 4: Phase diagram of steel containing 13% manganese [12]

Chromium has a tendency to increase hardness penetration. This element has interesting effects on steel as well as improving the corrosion resistance to Manganese steel. Chromium acts as a carbide former thus excess of Cr to Manganese steel will results in carbide precipitated at grain boundary in the as cast condition. Pribulova results showed that, to decrease the volume fraction of carbide and to obtain good values of impact, the chromium content must be limited to 0.1%. This carbide can be removed by solution treatment between 1050°C – 1100°C. If carbides exist in the as-quenched structure, it is desirable for them to be present as relatively innocuous particles or nodules within the austenite grains rather than as continuous envelopes at grain boundaries [15]. If these carbides are present as innocuous particles within the matrix, yield strength will increase while impact energy decrease.

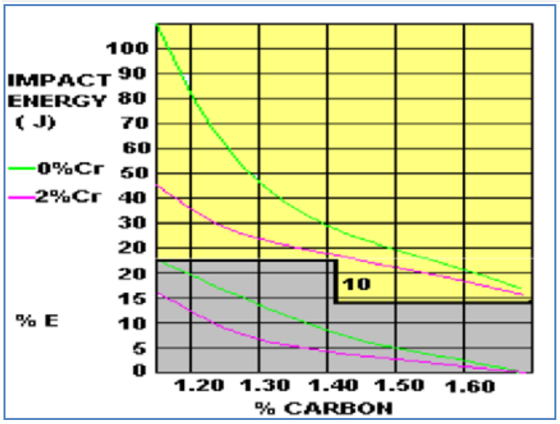

Figure 5: Effect of chromium content in 13% manganese [4]

Silicon is used as a deoxidising (killing) agent in the melting of steel, but for manganese steel, the addition of silicon changes the Fe_3C morphology and has an effect on the hardness of Mn steel [1].

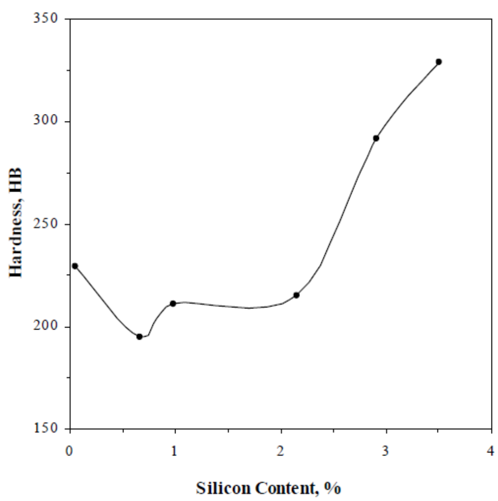

Figure 6: Effect of silicon content on Hadfield steel *[1]*

The increase in hardness can be explained on the basis that with increasing silicon content beyond 1.99%, the volume fraction of Fe_3C will increase thus giving rise to the hardness of Hadfield steel.

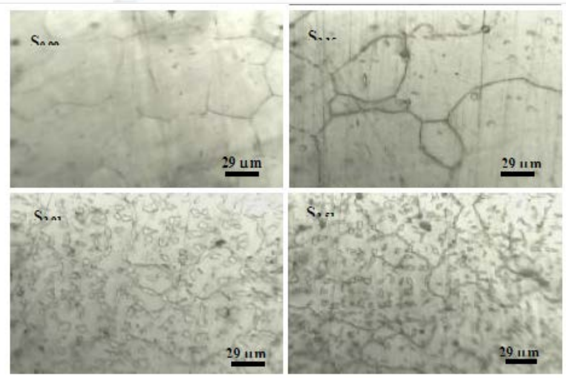

Figure 7: Effect of silicon content on carbide morphology [1]

Phosphorous is a greater concern in manganese steel and it tends to segregate at grain boundaries, liquefies during solution annealing and forms an embrittling phosphide eutectic film [10]. Phosphorus content for test bars of 25mm, show little change in tensile properties. Above 0.06% phosphorus, the high temperature plasticity of manganese steel is severely reduced due to phosphide eutectic. Above 0.1%, the tensile strength and elongation of manganese steel decrease [4].

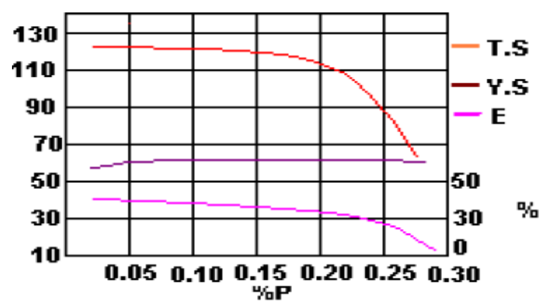

Figure 8: Effect of phosphorus content on Hadfield steel [4]

THE MANUFACTURING PROCESS OF HADFIELD STEEL

Steel scrap is one of the most important in-put in the foundry industry. Most of the foundries use steel scrap for the production of their castings. For manganese steel castings, clean scrap or manganese returns can be used. Clean scarp is free of dirt, nonferrous metals, or foreign material of any kind and excessive rust and corrosion. Steel scrap must not containing over 0.05% phosphorus or sulphur and not over 0.5% silicon and it should be free from alloys elements [9]. Manganese steel scrap will consist of non-magnetic manganese steel alloy materials having 11-14% manganese content.

Figure 9 : Clean Scrap [21]

Figure 10: Manganese returns [22]

The practice in most manganese steel melting furnace is to raise the melting and pouring temperatures to 1500°C and above so as to enhance fluidity of the molten metal and easy removal of slag, but Balogan has found that this practice is counterproductive. The reasoning behind this counter productiveness is that high temperature promotes micro and macro carbide segregation of alloy elements and formation of embrittling transformation products. The presence of segregation of carbide at the grain boundaries acts as barrier to dislocation movement; this could be responsible for uneven, inconsistent wear rate and pattern of the steel [2]. One important fact about this segregation of carbides is that, once they have formed during high pouring temperature they cannot be removed by heat treatment

Table 2: Different pouring temperature of manganese steel [2]

Heat	**H1**	**H2**	**H3**
Temp C	**1550**	**1450**	**1380**

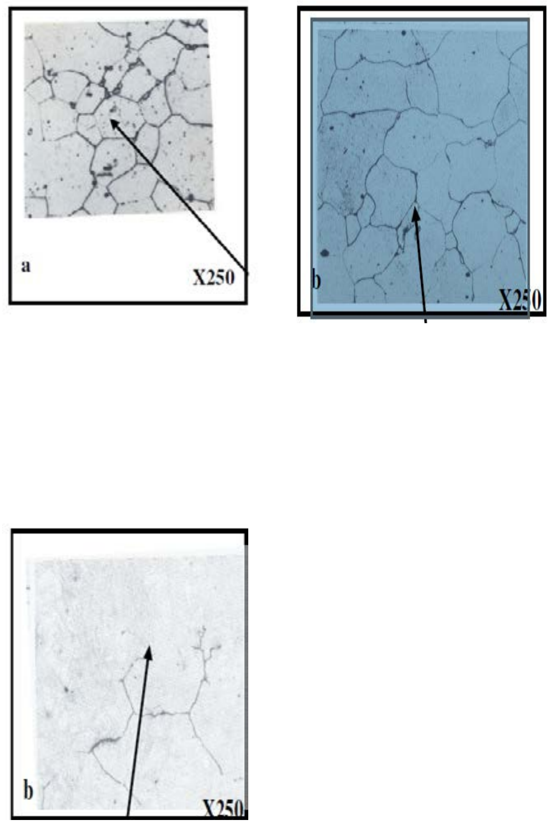

Figure 11: Microstructure of Hadfield manganese steel poured at three different temperatures of 1550, 1450, and 1380 respectively [2]

High melting temperature can also promote grain growth of the austenitic grain and as it is known that once grain growth occurs there is no possible method to reverse those grains to be small again, thus the mechanical properties will be affected. Therefore high temperature practice is not recommended due to the difficulty of avoiding embrittling transformation products as well as avoiding grain growth that lead to a decrease in tensile properties.

HEAT TREATMENT OF MANGANESE STEEL CASTING

Austenitic Manganese steel in the as-cast condition contains austenite as the matrix, pearlite and a bit of carbide precipitated on the grain boundaries. Manganese steel in the as-cast condition is very hard and brittle due to the presence of carbides; it cannot be used because upon impact it will fail in a brittle manner. Therefore a proper heat treatment procedure is required. The figure below shows the as-cast structure of high manganese casting [17].

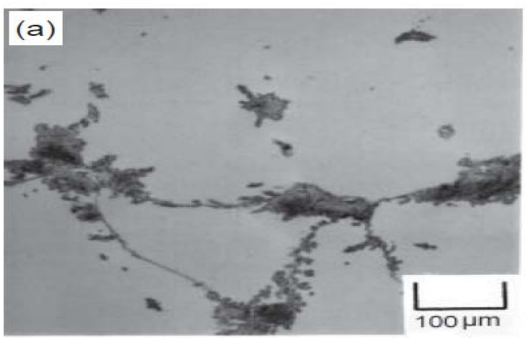

Figure 12: As cast Microstructure of Manganese steel taken at 100X [17]

Heat treatment strengthens austenitic manganese steel so that it can be used safely and reliably in a wide variety of engineering applications. Solution annealing and quenching is the standard treatment that produces normal tensile properties and the desired toughness. This involves austenitizing followed quickly by water quenching [10]. The austinizing temperature is held between 1050°C – 1100°C then quenched in agitated water so as to remove the vapour stage. The figure below show a typical heat treatment cycle:

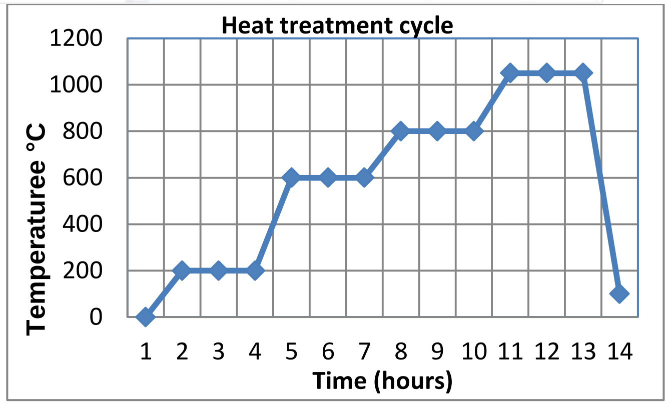

Figure 13: Typical heat treatment cycle

Factors that affect the heat treatment of austenitic manganese steel include chemical composition, section size, austinizing temperature and quenching rate. As section size increases, chances of forming grain boundary carbides are high; this is the result of slow cooling rate at the centre of the thick casting. So in short, the will always be carbides on the centre of thick castings. Figure14 shows the graph of fraction of carbide formed vs distance from the surface.

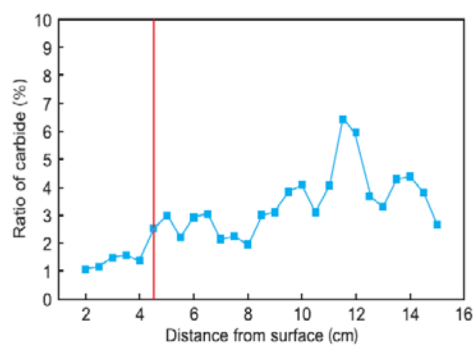

Figure 14 : Carbide ratio vs distance from surface [17]

MECHANICAL PROPERTIES OF HADFIELD STEEL

It is interesting to note the combination of high values of elongation and impact resistance, ensuring that castings will not suffer the brittle failure in heavy-duty performance. Considering the mechanical properties, it is difficult to imagine that a casting made from Hadfield steel could suffer failure in service. However, cases like this do happen, especially in heavy-section [3]. Table 3 below shows typical mechanical properties of Hadfield steel.

Table 3: Mechanical properties of 10-13% Manganese steel [24]

YS MPa	UTS MPa	Elongation %	Modulus	Hardness Brinel	Impact J/cm^{-2}
414	995	40%	186x10^{3}	200	112

Manganese steel in its as quenched condition has a hardness value of 200BHN and can increase the surface hardness up to 600BHN due to its work-hardening abilities. As the section size of manganese steel increases, tensile strength and ductility decrease substantially in specimens cut from heat-treated castings. This occurs because, except under specially controlled conditions, heavy sections do not solidify in the mold fast enough to prevent coarse grain size, a condition that is not altered by heat treatment [10]. Mechanical properties vary with section size, Tensile strength, tensile elongation, reduction in area and impact strength.

Hadfield steel is normally used where a combination of hardness, toughness and wear is required; therefore the study of wear and abrasion is essential when looking at the mechanical properties of this grade of steel. Tribology is the science and engineering of interacting surfaces in relative motion. It includes the study and application of the principles of friction, lubrication and wears [17]. The interactions of a solid surface's exposed face with interfacing materials and environment may result in loss of material from the surface. The process leading to loss of material is known as "wear". Major types of wear include:

- Erosion or Low-Stress scratching abrasion.
- High-Stress grinding abrasion.
- Gouging abrasion

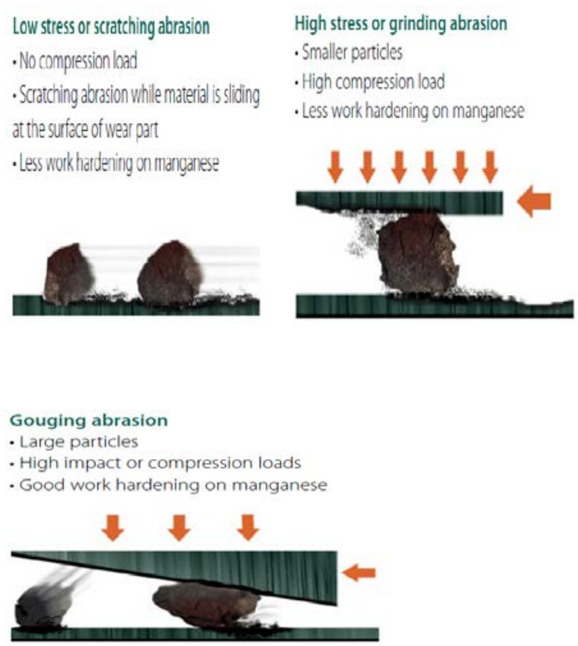

Figure 15: Different abrasion and its effect on the work hardening of Hadfield steel [14]

Hadfield steel as said is one of the wear resistance materials that show good combination of impact and hardness (Gouging abrasion). Hardness is directly proportional with wear resistant, thus the harder the material, wear life is uncompromised.

WORK HARDENING OF HADFIELD STEEL

Work hardening, also known as strain hardening or cold working, is the strengthening of a metal by plastic deformation [19]. This strengthening occurs because of dislocation movements and dislocation generation within the crystal structure of the material. The usual method of plastic deformation in metals is by the sliding of blocks of the crystal over another along definite crystallographic planes, called slip planes. The atoms move an integral number of atomic distances along the slip plane and a step is produced which is known as slip line [5].

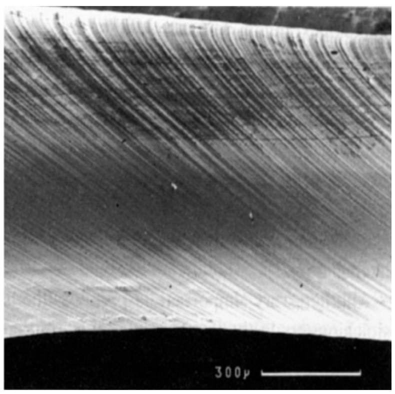

Figure 16: Microstructure showing slip lines [22]

Strain hardening results due to dislocation pile up on slip plains at barriers in the crystal. It is understood now that strain-hardening or work-hardening is caused by dislocations interacting with each other and with barriers which impede their motion through the crystal lattice. It can be said that the rate of work hardening can be increased if the barriers which impede movement of dislocations can be increased [6].

It has been mentioned that the unique feature of this tough, high-strength manganese steel is the rapid work hardening, from yield strength of 379 MPa to an ultimate tensile strength of 965 MPa on the surface. It is commonly taught that the rapid work hardening in Hadfield steel arises from strain-induced transformation of austenite to martensitic [6].

Some authors have attributed the work hardening to the formation of mechanical twins, while Nigel and Peters stated that Lambakakhar and Paska observed no correlation between frequency of twins and hardness Instead, they concluded that the hardness of Hadfield steel is more likely a function of the general dislocation structure than of the specific microstructure [6]. Drobnjak and Parr suggested that stacking fault-dislocation interactions were responsible for increasing the strain hardening rate of Hadfield steel. Several authors have proposed that the rapid work hardening is due to the interaction of dislocations wit with carbon atoms in solid solution in austenite.

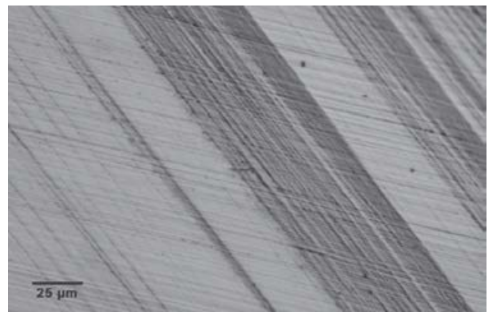

Figure 1715: Microstructure showing Twins [22]

It is now well established that the best way to improve the performance of austenitic manganese steels substantially in wear applications involving erosion and impact, is to question its strain hardening capacity and the dislocation mechanism of high manganese steel casting.

CONCLUSION

An overview of high manganese steel casting was conducted; the emphasis was based on the effect of chemical composition on Hadfield steel where it was shown how chemical composition can affect the final mechanical properties of the steel. The manufacturing process of high manganese steel casting was analysed and this includes the important of foundry steel scrap, the effect of high melting temperature, the heat treatment cycle for manganese steel and the final mechanical properties of the said steel. Work hardening or strain hardening was shown to be the mechanism responsible for the rapid surface hardening and it was shown that this mechanism occurs due to dislocation interaction, slips, twins and stalking fault that occur at high impact or compressive loads.

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