Analysis of hadfield scrap shredder hammer fracture and replacing it with carbide-free nano-bainitic steel

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ABSTRACT

Shredders are widely used in metal scrap recycling. The Shredder device includes hammers joined to a massive rotor. Hammers are responsible for grinding, therefore, play a key role in the shredder. Most of the casted hammers are made from austenitic manganese steel. Austenitic manganese steels usually have good mechanical properties at impact and wear use but in field use as shredder hammer, they are faced to the different type of failures. Finding reasons for these failures could help increasing shredding efficiency and reducing cost. In this study, several factors, such as the lack of work hardening of the as quench hammer, low yield strength and tensile strength, carbide growth at the user’s temperature and stopping the work hardening at temperatures between 200 and 300 °C have been defined as reasons of failure. Regarding these points, castable Nano bainitic steel suggested as an alternative to the austenitic manganese steels. In file test results proved that nano bainitic steel hammers has better performance than austenitic manganese steel hammers.

1. Introduction

Today Shredder is widely used as a modern device in field metal scrap recycling. The Shredder device includes a massive rotor, with a numbers of crushing hammers mounted on it [1]. Hammers are responsible for grinding [2]. Therefore hammers play a key role in the function of this device [3]. Due to the needs for high toughness and good abrasive resistance against the impacts, the material for cast hammers is often chosen from austenitic manganese steels (Hadfield or mangalloy) [4–8]. Fig. 1 shows the overall and schematic view of the shredding chamber along with the rotor and the hammer with regular hammers dimensions.

Steel scrap such as automobile body, cooker gas, refrigerator and washing machine and ... have a wide range of different materials. So, in order to better separate of these scarps, these materials need to be converted into smaller pieces. With the help of hammerers, Shredder machine crushes the scraps into smaller and homogeneous pieces, and then their sorting operations are performed using their magnetic properties [3]. Hammers are therefore severely subjected to wear and mechanical impacts. Unfortunately, the performance of the austenitic manganese steels were not always ideal [3,4] and in some cases are facing with fractures, quick wear, or fatigue that are less likely to be present in normal operation [5]. The hammer fracture will result in a stop in procedure to open and replace it. Pause at any stage can cause financial losses. Hence finding the factors causing hammer fracture and...
resolving them is important. The aforementioned cases have led researchers to seek optimization or replacement for the austenitic manganese steels [6].

In recent years, new carbide-free nano-bainitic steels (CFB) have been introduced into the market [7]. The microstructure of CFB steels including bainitic ferrite and retained austenite has been stabled. The fracture toughness of CFB steels are in the range of 100–160 MPA m^{1/2} and their tensile strength are above 1.5 GPa [8]. In terms of wear properties, they also have a better performance or similar to those of austenitic manganese steels. Since the austenitic manganese shredder hammers in working conditions will be subjected to early failure and degradation consequently, CFB steels seems to be a good alternative for austenitic manganese steel in shredder hammers. In the present study, firstly, factors affecting the fracture of austenitic manganese steels are investigated and then, due to the aforementioned defects, it has been tried to resolve them by replacing hammers with CFB steel hammer.

2. Materials description and experimental methods

Shredder hammers are usually produced of Manganese Austenitic Steel (according to DIN 1.3401 standard) in various weights by casting methods. Austenitic Manganese steel microstructure consists of austenite and grain carbides after casting. The existence of carbides in the structure is harmful and reduces the mechanical properties and ultimately the fracture of the hammer. To remove carbides, solution annealing is used at 1100 °C for 4.5 h (according to the thickness of the hammer) and, are quenched in water in
order to prevent the re-precipitation of carbides. The hammers will be installed on the Shredder machine. The studied shredder device was Metso® worked at 6000 horsepower with 16 hammers for grinding the scraps. In the process of grinding of scraps, Shredder hammers and shredding chamber are subjected to periodic inspections. In this study, 16 of them subjected to abnormal wear or fractured were investigated in order to destruction and failure analyze of the austenitic manganese hammers. Optical microscopy was used for fractography and scanning electron microscopy (SEM) with chemical analysis of X-ray diffraction spectroscopy (EDS) were used to examine the fracture surfaces chemical composition. The process of producing hammers by casting and stress distribution was simulated and examined by SUT cast and SolidWorks 2018, respectively. To better identify the production problems and weaknesses of the hammers. The chemical analysis of these hammerers by optical emission spectrometry has been presented in Table 1.

In the following, carbide-free bainitic steel of DIN WN 1.6511 + 2Si was used to replace the austenitic manganese steel. Specimens of both analyzes related to austenitic manganese steel and carbide-free bainitic steels by the chemical composition listed in Table 1 were cast in accordance with ASTM A 350 standard. Austenitic manganese steel samples were solution annealed at the temperature of 1100°C and then quenched into water, and carbide-free bainitic samples were prepared using Austempering operation at 300 °C. Tensile, impact and hardness tests on both series of samples were performed according to ASTM E8, E23, and E10 standards, respectively. The Brinell test indenter was 10 mm diameter and test force of 3000 kgf.

The abrasion test was performed according to the standard ASTM G99 with the method of pin on the disk. The applied Normal Pressure was 152 N/mm [9], and the rotation speed of the disk was 0.1 m/s.

In the field test, 32 hammers were made from DIN WN 1.6511 + 2Si carbide-free bainitic steel and in four periods of time and in each period, 8 of these types of steels were randomly installed with austenitic manganese steel hammers in different places of the shredder to check them in real conditions. In each of these intervals, the wear rate and surface cracks were considered several times, and the results were compared with each other.

3. Results and discussion

Fig. 2 shows a view of the damaged areas of an austenitic manganese steel shredder hammer. As observed, the failure of hammer usually occurs in two areas around the hammer hole (Zone A) and the outer surface of the hammer (Zone B) [10]. The failure in Zone A is often fractured and the failure at Zone B is wearing.

The same chemical analysis of damaged hammers and normally worked and non-deviation from the standard range of DIN WN 1.3401 revealed there is no association of failure with the chemical composition.

3.1. Fracture of Zone A

Fracture in Zone A is the worst possible occurrence in the operation of the shredder, which results in the hammer being released from the rotor and damage to the shredding chamber and even stops the machine. Considering enclosed shredding chamber at the scarp grinding operations, a large part of the energy is transformed to heat [11]. Measuring the temperature of the shredder output

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Table 1
Chemical composition of Austenitic manganese steel hammer and CFB steel hammers.

<table>
<thead>
<tr>
<th>Hammer type</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Max. S</th>
<th>Max. P</th>
<th>Others</th>
</tr>
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<tbody>
<tr>
<td>Austenitic manganese steel</td>
<td>1.25</td>
<td>0.60</td>
<td>18.00</td>
<td>&lt; 0.75</td>
<td>&lt; 0.75</td>
<td>-</td>
<td>0.02</td>
<td>0.05</td>
<td>Al = 0.04</td>
</tr>
<tr>
<td>CFB steel</td>
<td>0.4</td>
<td>2</td>
<td>0.6</td>
<td>1</td>
<td>1</td>
<td>0.4</td>
<td>0.02</td>
<td>0.05</td>
<td>Al = 0.04</td>
</tr>
</tbody>
</table>
```

Fig. 2. Fracture and wear zones of hammer. A zone common fracture zone and b zone common wear zone.
parts shows that the temperature of the shredding chamber can reach 400 °C by increasing the operating time. With the warming of the chamber, the carbides begin to precipitate in the hammer, which causes embrittlement of hammer [12]. The metallography image of the microstructure Zone A of the broken sample shows the presence of carbides along the grain boundary (Fig. 3). Carbides cannot tolerate the shear strain due to the crispness and brittleness and act like cracks and cause a sharp decrease in the impact resistance of the austenitic manganese steel [13]. Spherical and discontinuous carbides do not have a widespread effect on the mechanical properties of the parts, but if the carbides form on the grain boundary continuously, can be considered as an important factor for the part fracture.

Carbide-formation in austenitic manganese steels seems to be related to the production process. Austenitic manganese steels are produced by casting. The microstructure of the as-cast part includes austenite grains and carbides (Fig. 4). In order to remove the carbides that formed during the solidification, parts are heated to a temperature of 1100 °C for sufficient time to dissolve all of the carbides in the matrix, then quench them in water to avoid the possibility of re-forming carbide during cooling down [12]. Fig. 5a shows the microstructure of a heat-operated sample, which has a homogeneous structure. If homogenization be done incompletely (insufficient time or temperature or both), the carbides will not dissolve completely or if a cooling down after homogenization be done slowly at a temperature range of 800 °C to 400 °C, will lead to carbides formation again. These carbides grow at the working stage of the shredder hammer (Fig. 5b). Due to the fact that the grain boundary is high diffusivity paths [14], the carbon diffusion in the grain boundary is greater and causes the carbides grew along the grain boundary continuously (Fig. 3).

Fig. 6 and Table 2 respectively show, the microstructure of the SEM and the EDS chemical analysis of austenitic manganese steel of shredder hammer Zone A after heat treatment. In this case, the time interval between hammer out the heat treatment furnace to its quenching in quench pool was slow and lasted more than two minutes. In these conditions, the presence of carbide nucleus and grown carbides are observable. The results of the hammer cooling simulation from its exit from the heat treatment furnace until the quenching pool (Fig. 7) also indicate that the cooling rate in the different hammer areas is not the same. In the points around the hole, hammer and the lateral surfaces are cooled faster due to the higher surface-to-volume ratio, reaches the carbide nucleation critical temperature in shorter time, thus the probability of nucleation and growth of carbides in these areas is higher.

In addition to the formation of carbides, other factors that cause the fracture of shredder hammer in the Zone A, is local extrusion that caused by local stresses around the shredder hammer hole. This extruded area, shown in Fig. 8, and its schematic design is also
shown with a rectangle, one face is protruded from the hammer surface, which causes the hammer to trap between the shaft and the wall. This phenomenon eliminates hammer pendulum movement and causes the early fracture. Fig. 9 shows another aspect of this defect and the stretch of shredder hammer.

Zhou et al., by using the simulation of the scrap crushing process inside the shredding chamber, concluded that at some crushing stages, the stress applying the points around the shredder hammer hole reached to over 600Mpa [10]. This amount of stress is more than the hammer’s yield strength and it can cause plastic deformation. As shown in Fig. 10 a and b, the stress between the shredder hammer and the scrap input is divided into two components of vertical compressive stress (red) and parallel shear stress (blue) compared to the shredding chamber wall. The vertical component is usually important in the presence of smaller scrap because in this case, the scrap is trapped between the wall of the chamber and the hammer and pushes the hammer to the shaft and causes the yielding the hammer and plastic deform. Due to the fact that the volume of the material is constant in the plastic deformation [15], the material flow results in hammer extrude around the shaft. This deformation causes the hammer traps and eliminate pendulum movement.

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**Table 2**

<table>
<thead>
<tr>
<th>Element</th>
<th>Atomic%</th>
<th>Units</th>
</tr>
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<tbody>
<tr>
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<td>20.99</td>
<td>wt.%</td>
</tr>
<tr>
<td>Si</td>
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<td>wt.%</td>
</tr>
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<td>S</td>
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</tr>
<tr>
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<td>Fe</td>
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<tr>
<td>Ni</td>
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<td>wt.%</td>
</tr>
<tr>
<td>Total</td>
<td>100.00</td>
<td>wt.%</td>
</tr>
</tbody>
</table>

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Fig. 5. Metallography of micro structure of as quench austenitic manganese steel. (A) Fully solved carbides. (B) Carbide solution did not happen completely.

Fig. 6. SEM and EDS of carbides nucleus’s in matrix of austenitic manganese steel.
motion. The trapped hammer is subject to severe erosion or fracture due to the impact of scrap materials. As shown in Fig. 11, the results of the simulation of stress distribution through finite element show the concentration of stress in these areas in red. The shear stress component (blue) usually occurs when the hammer collides large pieces. Simulation of stress distribution by the finite element method in this case also shows that in some regions, the stress generated is higher than the yield strength of the shredder hammer wall of hole (Fig. 12). Due to hammer impacts to the scrap, the in a cyclical way, which results in high cycle fatigue and fracture of the piece. Fatigue in the austenitic manganese steel at stress rang of 400–700 MPa will happens 400,000–100,000 cycles and the resulting semi-cleavage fracture surfaces have also been reported by other researchers [10,4].
The details of the finite element analysis performed by SolidWorks software are presented in Table 3.

3.2. Failure of Zone B

According to working conditions of hammers in the shredder device, the failure of the outer surfaces of the hammer (Zone B) is
inevitable and is generally of wear type and face crack. Since the input scrap of the shredder device has a wide range of mechanical properties and dimensions, depending on the type of feed of the shredder device, different wear conditions will occur in the shredding chamber:

1. The austenitic manganese steel in as quench condition have no desire mechanical properties and abrasion resistance [16], if the feeding scrap has a low strength and small dimensions (slightly larger than the hammer distance with the body) (Fig. 10b), the hammers will only be exposed to severe wear. Previous studies have also shown that if for a long time the majority of the input scrap charge to the shredder machine lasts, the pieces with a moderate size and low strength, such as bins of oil storage containers or the body of metal kitchen cabinets, have a severe wear on the hammer [17,10].

2. If the size and weight of feeding scrap be relatively large for shredder device, in such a situation, due to continuous impacts, the austenitic manganese steel hammer becomes work hardened and its abrasion resistance increases and the austenitic manganese hammer will function properly [16,17]. On the other hand, according to the findings of Dastur and Leslie, work hardening occurs in high manganese steel under certain amounts of stress [18]. Hence, in austenitic manganese steels hammers, points are often found whose depth of the hardness is low, and this work hardening layer may disappear in conditions, and the wear will occur at a very high rate after the removal of this layer. Also, if these hammers doesn’t become work hardened before increasing the temperature of the chamber that caused by crushing, the risk of inappropriate operation and extreme wear is very high. On the other hand, the results obtained by Dastur and Leslie studies show that the hardness of the austenitic manganese steel works sharply decreases between 200 °C and 300 °C, which will also be effective in increasing the wear rate [18].

Therefore, in order to prevent wear and/or fracture of austenitic manganese steel hammers, it is necessary that each charging time includes a different range of fine to coarse pieces with different strengths. But this solution has many difficulties in practice and in some cases it is impossible. So other methods such as changing the shredder design or selecting martials for hammers which are less sensitive to operation should be examined.
3.3. Problem solution

There may be two solutions for the problem of fracture and wear of a shredder austenite manganese hammer. One is to change the design of the hammer shape in such a way that the probability of jamming scrap parts between the hammer and the body of the shredder device and wear is minimized, which, according to Zhou et al. in a study, greatly contributed to the performance of these hammers [10]. Other is that choosing shredder hammer material is of the alloys which are more resistant to fracture and wear, which is the purpose of this research.

The microstructure of CFB steels includes bainitic ferrite and retained austenite. So because of their microstructure prevents crack growth in steel and provides good resistance to wear and fatigue. They also have high yield strength due to their nano-structure [19]. Table 4 compares the mechanical properties of 1.6511 steel (in addition to 2 wt% of silicon) with the austenite steel used in the shredder hammer.

As can be seen, the yield strength and the hardness of the nanostructured bainitic steel is higher than the Austenitic Manganese Steel. On the other hand, due to the higher resilience coefficient (the area below the stress and strain diagram in the elastic region), carbide-free nano-bainitic steel will be better than the austenitic manganese steels.

Wei et al. showed that the presence of carbide-free bainite microstructure in duplex steels (martensitic/austenite) reduced the crack growth rate and increased crack growth resistance [20]. The crack tip stress transforms the austenite transformed to martensite, which delayed the growth of micro-cracks [21]. On the other hand, increasing the volume of the phase resulting from the martensitic transformation leads to crack closure [22]. In addition, the presence of a retained austenite (due to the penetration of the carbon rejected from the ferrite to the matrix) can also lead to the blinding of the crack tip, hence the fatigue cracks in these steels grow with difficulty and their fatigue lifetime usually is more than other steels. Fig. 13 shows the position of the crack tip which is completely rounded and its growth is limited. In such a situation, the fracture strength will increase.

In order to investigate and compare the wear resistance of the carbide-free nano-bainitic steel with an austenite manganese steel, the pin on disc wear test was used, the results of which have been shown in Fig. 14. As observed, due to the fact that the wear rate of the austenite manganese steels depends on the work hardening, with increasing wear time due to the creation of work hardening, the
Table 3
Solidworks FE simulation details for hammers in both small and big parts input.

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<tr>
<td>Mesh type</td>
<td>Solid Mesh</td>
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Mesher Used: Curvature-based mesh
Total Nodes: 110044
Total Elements: 73766
Maximum Aspect Ratio: 8.8148

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<tr>
<th>Fixture name</th>
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<td>Fixed Geometry</td>
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<tr>
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<td>Angular Velocity: -20 rad/s</td>
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<td></td>
<td></td>
<td>Angular Acceleration: 0 rad/s²</td>
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</table>
wear rate decreased but the hardness of the nano-bainitic steels is less changed than the wear time, hence the more uniform wear behavior is observed. It is worth noting that the wear of carbide-free nano-bainitic steel is always less than austenite manganese steels weather before or after work hardening.

Another advantage of nano-structure nano-bainitic steels compared to austenitic manganese steels is their thermal stability in the operating temperature range of the shredder hammer. The microstructure of this steel will remain stable up to the temperature of 760 °C. Fig. 15 shows the results of the Jmat Pro software for the enthalpy of this steel and, as can be seen, there is phase stability in the working temperature range of the shredder hammer and there is no change.

In the field test, 32 hammers were prepared from DIN WN 1.6511 + 2Si CFB steel. In 4 working periods, 8 of these types of steel hammers were randomly installed beside the austenitic manganese hammers in different places on the shredder. The results showed that none of the shredder hammers of CFB steel has fractured, in addition, that the hammer operating time increased from 5000 h to

Table 3 (continued)

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Table 4
Mechanical properties of Austenitic manganese steel and CFB steel used in this study.

<table>
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<tr>
<th>Steel</th>
<th>Hardness (Brinell)</th>
<th>Young modulus (GPa)</th>
<th>Impact energy (joule)</th>
<th>Elongation (%)</th>
<th>Tensile stress (MPa)</th>
<th>Yield stress (MPa)</th>
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<tr>
<td>Austenitic manganese steel</td>
<td>200</td>
<td>150</td>
<td>110</td>
<td>45%</td>
<td>1000</td>
<td>400</td>
</tr>
<tr>
<td>CFB Steel (1.6511 + 2Si)</td>
<td>360</td>
<td>210</td>
<td>50</td>
<td>7%</td>
<td>1880</td>
<td>1580</td>
</tr>
</tbody>
</table>
Fracture and wear have limited the use of austenitic manganese steels in shredder hammer. The reasons for the fracture and wear of these hammers are related to several factors, such as the lack of hardness and wear resistant of the as quench austenitic manganese steel, low yield and tensile strength, carbide growth at the operating temperature and lack of work hardening at temperatures between 200 and 300 °C. CFB steel 1.6511, with a higher strength, suitable wear and fatigue cracking resistance as well as stability in the process temperature range, is a suitable alternative for austenite manganese steels. In practice, the use of CFB steel in the shredder device increased the lifetime of the hammer to 2000 h.

4. Conclusions

Fracture and wear have limited the use of austenitic manganese steels in shredder hammer. The reasons for the fracture and wear of these hammers are related to several factors, such as the lack of hardness and wear resistant of the as quench austenitic manganese steel, low yield and tensile strength, carbide growth at the operating temperature and lack of work hardening at temperatures between 200 and 300 °C. CFB steel 1.6511, with a higher strength, suitable wear and fatigue cracking resistance as well as stability in the process temperature range, is a suitable alternative for austenite manganese steels. In practice, the use of CFB steel in the shredder device increased the lifetime of the hammer to 2000 h.
Fig. 15. Thermal stability of CFB steels calculated by Jmat Pro.

Fig. 16. CFB steel hammer after 700 h working without failure. Both side used completely.

Declaration of Competing Interest
The authors declare no conflict of interest.
Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.engfailanal.2019.104230.

References