An in-situ TiC-reinforced Hadfield manganese austenitic steel matrix composite has been synthesized by conventional melting and casting route. The microstructure has been characterized using an optical microscope, a scanning electron microscope coupled with an energy dispersive spectrometer and X-ray diffraction. Hardness and abrasion resistance have also been measured. The microstructure of the as-cast composite consists of austenite, \( \alpha \)-ferrite and (Fe, Mn)\(_3\)C together with TiC particles. The microstructure of the solution-annealed (1 273 K for 36 ks) composite contains TiC particles in the \( \gamma \) matrix. It has been observed that the abrasive wear resistance of the solution-annealed composite is significantly better than that of the solution-annealed austenitic manganese steel.

**KEY WORDS:** Hadfield manganese austenitic steel; in-situ steel matrix composite; titanium carbide; solution annealing treatment; abrasive wear resistance.

### 1. Introduction

The composite materials with steel or iron alloy as the matrix and ceramic particle as the reinforcement offer the possibility for producing relatively inexpensive wear-resistant materials. Recently, there has been a great deal of interest in the development of particle reinforced steel or iron matrix composites as structural materials for industrial applications. Particle-reinforced steel matrix composites have higher strength and wear resistance than those of its matrix material, because the particle phases can strongly resist abrasive wear. Austenitic manganese steel has excellent strength and toughness together with good wear resistance. The incorporation of hard ceramic particles into austenitic steel matrices can further enhance its wear resistance.

The most commonly used ceramic particles for reinforcement of various types of steel matrices include various oxides (e.g., Al\(_2\)O\(_3\) and ZrO\(_2\)), nitrides (e.g., TiN and Si\(_3\)N\(_4\)), and carbides (e.g., TiC, Cr\(_2\)C\(_2\), VC, and B\(_4\)C). Among them, TiC has proven its suitability in steel or iron alloys due to its high hardness, low density, high melting temperature and high corrosion resistance. It is the very hard second phase particles that imbue steel or iron-based composite with the increased hardness needed to improve its abrasion resistance. For example, additions of titanium carbide (TiC), niobium carbide (NbC) or vanadium carbide (VC), three of the refractory metal carbides, with Vickers hardness of 2 000–3 200 HV, 2 400–2 850 HV and 2 460–3 150 HV, respectively, can be expected to improve the abrasion resistance of many different alloy systems.

Steel or iron matrix composites have usually been produced through powder metallurgy route. However, the process has intrinsic limitations for product size, production costs and material qualities. Therefore, efforts have been directed to make these composites by solidification processing which offers an opportunity to generate the TiC particles in situ in the molten alloy. In situ techniques involve a chemical reaction resulting in the formation of a very fine and thermodynamically stable ceramic phase within a metal matrix. As a result, the reinforcement surfaces are likely to be free from gas absorption, oxidation or other detrimental surface reaction contamination, and the interface between the matrix and reinforcement therefore tends to be strong.

The present work has concentrated on the microstructure and abrasive wear resistance of in-situ TiC-reinforced Hadfield manganese austenitic steel matrix composite synthesized by conventional melting and casting route.

### 2. Experimental Procedure

The synthesis of the Hadfield manganese austenitic steel matrix composite was carried out in a high-frequency induction furnace in air, where the melt was covered with a ceramic block to protect from the oxidation. The charge calculation for the synthesis of composite was done by simple stoichiometric method aiming 10 vol% TiC in Hadfield austenitic manganese steel. At first the blend of steel scrap (0.049% C, 0.43% Mn, 0.028% Si, 0.023% P, 0.013% S, 0.003% Al, 0.035% Cr and balance Fe, all in wt%) and cast iron (4.5% C, 0.043% Mn, 1.05% Si, 0.175% P, 0.043% S and balance Fe, all in wt%) was heated to 1 848 K and maintained at that temperature for 900 s and...
then the temperature was raised to 1883 K. The calculated amount of Fe–Ti (70% purity) and electrolytic manganese (95% purity) were added to the melt at this temperature. The Fe–Ti was added to iron alloy melt by plunging due to lower density of Fe–Ti with respect to iron alloy melt. The melt was stirred continuously at 1893 K temperature for 600 s and subsequently cast in a metallic mould. The chemical compositions of the Hadfield manganese austenitic steel and TiC-reinforced composite are presented in Table 1.

Metallographic samples of dimension 12 mm × 12 mm × 10 mm were cut from the middle portion of the casting. The specimens were polished according to the standard metallographic technique and finally etched with 2% nitric. The samples were examined using an optical microscope (OM) and a scanning electron microscope (SEM) equipped with an energy-dispersive X-ray spectrometer (EDS). The various phases revealed by metallography were analyzed by the X-ray diffraction (XRD) analyses using the Co Kα, radiation.

The macrohardness was measured using a Vickers hardness tester at an applied load of 30 kgf and loading time of 20 s at room temperature. The samples were first surface finished and then ten measurements were performed randomly in each sample. The average of ten measurements has been represented as the hardness of the specimen.

Abrasive wear tests were carried out on 12 mm × 12 mm × 10 mm samples against 220 grit SiC paper affixed to a rotating flat disc of 250 mm diameter. The rotating speed and the track diameter were fixed as 300 r.p.m. and 80 mm, respectively. The sliding velocity was fixed at 1.25 m/s. The experiments were carried out at the load of 24.5 N. As the TiC (2900–3200 HV)20) particles in the composite are harder than SiC (2850 HV)20) abrasives, SiC particles get blunted after sliding for only 30 s. To ensure fresh supply of abrasive particles, worn SiC abrasive paper was replaced with a new one after 30 s. Wear rate of the specimens has been computed by the weight loss technique. The wear data has been plotted as cumulative volume loss.

| Table 1. The chemical compositions (wt%) of the Hadfield manganese austenitic steel and TiC-reinforced composite. |
|---------------------------------|---|---|---|---|---|---|---|
| Materials                        | C  | Mn | Si | Al | Cr | S  | P  | Ti |
| Hadfield manganese austenitic steel | 1.23 | 11.53 | 0.42 | 0.36 | 0.33 | 0.008 | 0.019 | - |
| TiC-reinforced composite         | 3.80 | 11.40 | 0.37 | 0.59 | 0.33 | 0.032 | 0.04 | 10.34 |

The wear rate of the specimens was calculated by using Eq. (1):

\[
W \text{(mm}^3/\text{m}) = \frac{\text{mass loss (g)/density (g/mm}^3)}{\text{sliding distance (m)}} = \frac{\text{mass loss (g)/density (g/mm}^3)}{\frac{\pi DN T}{60 000} \text{(m)}}
\]

where, \(D\) is the diameter of the wear track in mm, \(N\) is the disc speed in r.p.m. and \(T\) is the test duration in seconds.

3. Results and Discussion

3.1. Microstructure

Figure 1(a) shows the as-cast SEM micrograph of Hadfield manganese austenitic steel. The microstructure shows that (Fe, Mn)C carbide is mostly present along the austenite grain boundary. The optical micrograph (Fig. 1(b)) of solution-annealed unreinforced matrix alloy shows that most of the (Fe, Mn)C carbides, present along the austenite grain boundaries, is dissolved. The description of the microstructure in detail has been reported in our previous paper.21)

Figure 2(a) shows the optical micrograph of the as-cast TiC-reinforced composite. In this figure, ‘A’ represents the interdendritic area which is rich in manganese (14%) and ‘B’ represents the dendritic area which is depleted in manganese (8%). The SEM micrograph (Fig. 2(b)) of the as-cast composite clearly shows the two phase microstructure, i.e., ferrite (α) and (Fe, Mn)C in the dendritic region along with the interdendritic regions of austenite (γ) and TiC particles. X-ray dot maps (Fig. 3) from the selected area containing the particles show the presence of Ti in the particles.

The XRD pattern, shown in Fig. 4, indicates that besides γ peaks, there are also prominent peaks of TiC, α and (Fe, Mn)C. The XRD and EDS analysis confirm the presence of TiC particles in the composite. Due to the positive segregation of manganese during solidification, the interdendritic regions of γ become rich in manganese. As a result, the γ in the interdendritic region is stable at room temperature. However, the γ dendrites which are depleted in manganese decomposes to α and (Fe, Mn)C during cooling after solidification.

In order to remove manganese segregation, the composite was subjected to the solution-annealing at 1273 K for 10.8 ks followed by water quenching. The SEM micrograph of the solution-annealed microstructure shows that the ret...
versed austenite, whose crystallographic orientation is different from that of the interdendritic $\gamma$, is formed through $\alpha+(\text{Fe, Mn})_3\text{C}\rightarrow\gamma$ in the dendritic region. The amount of manganese in the interdendritic (A) and the dendritic (B) regions are still 14 and 8%, respectively. It has been observed that the interdendritic structure of $\gamma$ in the specimen persisted even after the solution annealing treatment (Fig. 5). The XRD of the solution-annealed composite, as shown in Fig. 6, confirms that the microstructure consists of $\gamma$ and TiC particles. The persistence of interdendrites of $\gamma$ in the microstructure is due to the concentration gradient of manganese from interdendritic to dendritic region. A homogenizing treatment for longer time is required to remove the compositional variation.

Therefore, the as-cast composite was homogenized at 1273 K by holding the specimen for 36 ks followed by water quenching. Figure 7 shows the homogenized microstructure after the solution annealing treatment. The manganese content has been evaluated in the homogenized matrix region, which is found to be 12%. The XRD (Fig. 8) of this composite shows that the homogenized microstruc-
ture consists of austenite and TiC. It has been observed from Figs. 5 and 7 that the amount (10 vol%) of TiC particles in the solution-annealed composites remains almost the same as that of the as-cast material. It reveals that the TiC particles are stable at 1273 K. There are many discrepancies in the literature over the exact temperature above which TiC is not stable, with values ranging between 1085 and 1173 K.

3.2. Hardness

Figure 9 shows the hardness values of TiC-reinforced composite and unreinforced matrix alloy in the as-cast and solution-annealed condition. The higher hardness of the composite materials compared to the Hadfield manganese austenitic steel can be attributed to the presence of hard TiC particles. In addition, it is quite likely that an increased density of dislocation is generated during cooling because of the difference in coefficient of thermal expansions between the matrix and reinforcement resulting increased hardness of the composite both in as-cast and solution-annealed conditions. The coefficient of thermal expansions of the Hadfield manganese austenitic steel and TiC are (1.7–2.5×10^{-5}/°C) and (5.5×10^{-6}/°C), respectively.

The higher hardness of the as-cast specimens compared to that of the solution-annealed specimens may be due to the presence of (Fe,Mn),C carbide in the as-cast specimens. It has been observed that the hardness values of the composite materials, solution-annealed at 1273 K for 10.8 and 36 ks, are almost the same. This is because that in both cases, the microstructures consist of the same amount of TiC in γ matrix.

3.3. Abrasive Wear Resistance

Figure 10(a) shows cumulative volume loss versus sliding distance for the composite materials solution-annealed at 1273 K for 10.8 and 36 ks and the equivalent unreinforced Hadfield manganese austenitic steel solution-annealed at 1273 K for 10.8 ks. It is evident from Fig. 10(a) that material loss is more in case of the solution-annealed Hadfield manganese austenitic steel compared to the solution-annealed composite materials. The increase in abrasive wear resistance of the composites is attributed to the load bearing capacity of the hard TiC particles and the retention of the particles on the sliding surface of the composites. By this way the TiC particles reduce the contact area between the matrix of the composite and abrasive SiC particle during sliding that is directly responsible for the improved wear performance of the TiC-reinforced composites.

It has been observed that the cumulative volume loss of the composite solution-annealed at 1273 K for 10.8 ks is more compared to that of the composite solution-annealed at 1273 K for 36 ks. The comparative wear loss of the two solution-annealed composite can be explained on the basis of their hardness and toughness. Wear loss depends on both hardness and toughness. It has been reported in the litera-
ture that the wear loss is inversely proportional to the hardness. The hardness of both the composites, solution-annealed for 10.8 and 36 ks are same. Therefore, it seems toughness plays an important role in determining the wear loss. The toughness of \( \gamma \)-matrix which is homogenized is expected to be more than the toughness of matrix having reversed austenite and interdendrites of \( \gamma \), whose crystallographic orientation is different from each other. Therefore, the cumulative volume loss of the composite solution-annealed for 10.8 ks is more compared to that of the composite solution-annealed for 36 ks.

Figure 10(b) shows that the wear rate of the solution-annealed composite materials is less compared to the solution-annealed Hadfield manganese austenitic steel. In the case of the unreinforced solution-annealed alloy, the wear rate is more at the initial stage and then decreases slightly and finally levels off with the increase in sliding distance while in the case of the solution-annealed composite materials, the wear rate is more at the initial stage and then almost levels off at the longer sliding distance. In the case of the unreinforced solution-annealed matrix alloy, initially the SiC abrasive can deform and remove the material from soft austenitic matrix. However, at large sliding distance a strong work-hardening layer with high hardness develops on the worn surface resulting an improvement in the abrasive wear resistance. In the case of the solution-annealed composite materials, in addition to the above mentioned factor hard TiC particles, exposed to the surface at large sliding distance bears the load resulting a lower wear rate compared to the unreinforced material.

During the wear process, the ploughed surface of the specimens react and form a thin layer of iron oxide, which gets ruptured by the action of hard SiC particles and joins the wear debris. EDX of the wear debris, as shown in Fig. 11, confirm that the wear debris consists of iron oxide along with SiC abrasive. It has been reported in the literature that three different types of oxides may form with respect to the produced contact temperatures. Below 473 K the major constituent is Fe\(_2\)O\(_3\), for temperatures between 473 and 843 K it is Fe\(_3\)O\(_4\), and above 843 K it is FeO. In the present investigation, the sliding speed and applied normal load are 1.25 m/s and 24.5 N, respectively. Therefore, it is expected that at such low sliding speed and load, the temperature in the wear track will not be higher than 473 K resulting formation of Fe\(_2\)O\(_3\).

4. Conclusions

The microstructure of the as-cast TiC-reinforced composite consists of interdendritic regions of \( \gamma \) and matrix of \( \alpha \) and (Fe, Mn)\(_2\)C together with TiC particles. Solution annealing treatment at 1 273 K for 36 ks is sufficient to remove manganese segregation resulting more or less uniform distribution of TiC particles in \( \gamma \) matrix. The TiC particles do not undergo dissolution during the solution annealing heat treatment. The abrasive wear resistance of the solution-annealed composite materials is higher than that of the unreinforced solution-annealed material. The abrasive wear resistance of the composite solution-annealed at 1 273 K for 36 ks is better than that of the composite solution-annealed at 1 273 K for 10.8 ks.

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