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The Influence of HH Type Steel Microstructure on the Distortion Behavior of Grate Bar Part in the Indurating Machine of Pelletizing Plant

M. Alizadeh [1*] , Y. Palizdar [2]

[1] *Department of Materials Engineering, Isfahan University of Technology, P.O. Box 84156-83111, Isfahan, Iran*
[2] *Nanotechnology and Advanced Materials Department, Materials and Energy Research Center, P.O. Box 31787-316, Karaj, Iran*

Abstract

Grate bar is an industrial part which is used in the indurating furnace of an iron ore pelletizing plant. Steel part of the grate bars are expected to have high resistance to atmospheric oxidation because of its contact with hot gases (up to 920 °C) during the normal operation of the process. In this study, different samples from several sections of used grate bars with apparent defects were selected. The microstructure of the selected samples from the affected areas was studied via optical and scanning electron microscopy with EDS analysis. The results showed that the internal oxidation would occur through the oxygen diffusion into the chromium carbide nets and caused the change of chromium carbide to chromium oxide. Furthermore, internal oxidation led to the separation of the grains from the steel matrix and resulted in the dusting phenomenon. In order to modify the steel microstructure, Ti element was added to the melt in different levels during the casting process and the results showed that the presence of Ti could modify the carbides structure and consequently improve the oxidation resistance of the steel. The grate bars with new composition were placed in the furnace and the monitoring of the consumption of the grate bar in Mobarakeh Steel Company pelletizing plant. In a six -month period revealed that the grate bar consumption decreased about 30%.

Keywords: Heat resistant steel; Chromium carbide precipitation; Grate bar; Microstructure.

1. Introduction

The steel part of the grate bars are made of HH (DIN 1.4837) type heat-resistant steel. Conventional shape and geometrical dimensions of this part are shown in Fig. 1. They are located in the pallet cars of the travelling grate in the indurating furnace of a pelletizing plant. Since these pallets pass through all the heat regions of the furnace, obviously they are expected to show high resistance to oxidation.

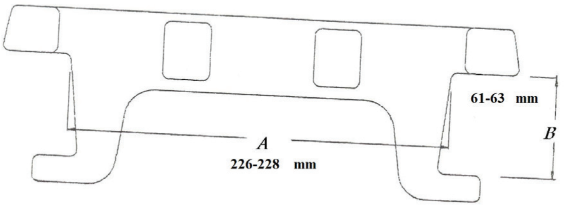

Fig. 1. Geometrical shape and dimensions of grate bar part.

It is well documented that the corrosion resistance at high temperatures needs an oxide barrier that protects the steel from the corrosive environment. If the protective oxide film persists, therefore the oxidation resistance can be obtained. In other words, every single factor which can cause cracking, evaporation and peeling of the aforementioned barrier, plays an important role in the oxidation of the alloys at high temperatures. Therefore, in order to achieve an effective oxidation resistance, alloys aim to form compact scales with small rates of diffusion of the reactantions [1)].

Subsequently, the oxidation of HH type heat resistant steel starts when the passive protective film (i.e. Cr_2O_3) is about to be distorted. The passive film on the steel surface damages because of the high temperature and thermal or/and mechanical stresses.

It has been shown that the scales formed from the oxidation reaction usually experience mechanical stress which is what causes fracture, microcracking, scale delamination and spallation. When the stress in the scale increases to the limit accommodated by elastic strain, the aforementioned scale will deform or fracture. The spallation of the scale eliminates its protective function, allowing the direct access of the environment to the metal beneath and leads to a rapid increase in oxidation [1, 2)].

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* *Corresponding author*
Email: alizadeh@cc.iut.ac.ir
Address: Department of Materials Engineering, Isfahan University of Technology, P.O. Box 84156-83111, Isfahan, Iran.
1. Associate professor
2. Assistant Professor

Furthermore, internal oxidation is one of the damaging mechanisms in the heat resistant steels. Mostly, the internal oxidation in alloys occurs via oxygen diffusion into the bulk. Diffusion occurs through different paths especially preferred paths such as grain boundaries. It is well known that the oxygen diffusion through the grain boundaries is relatively fast. When oxide particles form in grains and also at grain boundaries, the consumption of oxygen at the vicinity of those particles acts as a driving force for absorbing the oxygen. It is known that the formation of oxide components at the grain boundaries is easier than within the grains. Moreover, forming massive oxide phases at the grain boundary causes intense stresses around the boundaries which lead to the crack creation that can play as a new path of oxygen diffusion. In addition, in the internal oxidation, the oxygen reacts with chromium carbides at grain boundaries and produces chromium oxide as the following reaction [2)]:

$$2Cr_{23}C_6 + 40.5\ O_2 = 23\ Cr_2O_3 + 12CO$$

From thermodynamic point of view, the reaction takes place in the temperatures above 450 °C. Therefore, oxygen could diffuse to the grain boundaries and react with carbides and produce oxide components during the high temperature processes. The reactions can occur in two steps. In the first step, the chromium oxide reacts with the chromium carbides and produces pure chromium. Then the pure chromium again reacts with oxygen and produces the chromium oxide. However, the researchers have shown that it could even occur as alone-step reaction [3, 4)].

Mainly internal oxidation and oxide component formation lead to deterioration of the physical and mechanical properties of the bulk. In this condition, cracks and gaps will be formed when the grate bar parts working under stress. Dusting phenomenon is another mechanism of damage. It has been well established that the concentration of chromium is very low around the carbides which is due to the fact that the chromium diffuses to form carbide and therefore that region becomes chromium depleted. Consequently, the possibility of oxide scale formation increases and the most tendency for oxidation is observed in that area. Therefore, one method for increasing resistance against oxidation or prevention from dusting in ferrous alloys is to avoid chromium depletion in alloy's matrix especially around the carbides [2, 5)].

It is also worth mentioning that the discontinuity of carbide nets is an important parameter which control the rate of oxidation.It is owing the fact that the diffusion path of oxygen could be limited by increasing the dispersion of carbide nets. Although, carbon and nitrogen are the predominant compositional variables controlling the sensitization kinetics, other alloying elements also influence it by altering carbon and chromium activity. Strong carbide-forming elements such as Nb and Ti form carbides which are much more stable than $Cr_{23}C_6$, so they preferentially combine with the available carbon and thus lessen the opportunity for $Cr_{23}C_6$ to nucleate [6)]. Furthermore, it should be considered that the molten steel with low soluble oxygen can increase the impact toughness of the final material [7)].

The results reveal that TiN or Ti(C, N) precipitates in all as-received materials, originated from the fabrication process and were not dissolved by solubilisation treatment. The affinity of titanium for formation of these high-stability nitrides partially reduces its stabilizing role and results in consumption of titanium and relative enrichment of carbon, favoring the growth of Cr-rich carbides at the austenitic grain boundaries. In this way, Cr-rich precipitates were detected in high-carbon heat resistance steels. The equation Ti = 0.5*(% C+% N) could express the required titanium concentration to avoid intergranular corrosion [6, 8, 9)].

In this research the distortion mechanisms of grate bars were investigated by studying the microstructure of damaged grate bar parts. Then the modification of the carbide nets by adding the titanium to the chemical composition of steel has been examined as an improved method.

2. Research Method

The chemical composition of the primary examined steel according to standard of HH type steel is shown in Table 1.

In order to investigate the actual operational condition of the grate bar in the furnace, the operational condition of the furnace in each heat region has been recorded dynamically by thermocouple (K type, OMEGA Data Logger OM-CP-QUADTHERMOVAULT, USA) while the pallet was moving through the furnace. Fig. 2 shows the temperature changes of grate bars through the indurating furnace in the pelletizing plant of Mobarakeh Steel Co.

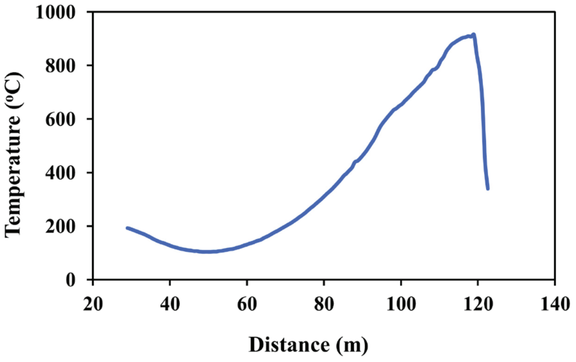


Fig. 2. Working temperature variation of Grate bar through the longitude of indurating furnace.

By visual inspection, the most damaged grate bars were selected and standard metallographic procedure was conducted in the damaged regions. Optical microscopy (OM, Zeiss, Axioplan2, Germany) and Scanning Electron Microscopy (SEM, Philips XI30, Netherlands) with the aid of Energy Dispersive Spec-

Table 1. Standard chemical composition of HH steel (DIN 1.4837)

Element	C	Si	Mn	Cr	Ni	Mo
wt. %	0.3-0.5	1.0-2.5	0.5-1.5	24-26	11-14	<0.5

Table 2. Chemical composition of HH steel melts with added Ti.

Element	%C	%Si	%Mn	%Cr	%Ni	%Mo	%Ti
Heat 1	0.46	1.34	0.92	24.70	11.66	0.19	0.12
Heat 2	0.52	1.39	0.96	24.68	11.43	0.20	0.2

troscopy (EDS, Seron AIS 2300, South Korea) technique were employed to characterize the microstructure and reveal the failure mechanism.

In order to improve the chemical composition and microstructure of HH type steel, modifications were conducted in the melting and casting process of the grate bars manufacturing. For trial production of the parts, molten steel was prepared in an induction furnace by 500 kg capacity. Then, it poured at 1540 °C in a preheated ladle and required titanium added. Chemical analysis of the new steel is shown in Table 2. Standard metallographic procedures were carried out on the new steel and the samples were investigated by optical microscopy. Then, in order to examine the research findings, the parts with the new compositions, have been placed in the furnace and the consumption rate of grate bars have been monitored in the pelletizing plant of Mobarakeh Steel Co. for a six-month period.

3. Results and Discussion

As cast microstructure of heat resistant steel usually consists of austenitic matrix (it can be austenite, austenite-ferrite, or complete ferrite based on the type of alloying elements and cooling rate), that chromium carbide precipitates appear as continues net or separate precipitate in the steel matrix (Fig. 3).

Fig. 4 shows the outward apparent of a distorted part. As seen, there are obvious defects such as cracks, gaps, bending and burning which can be observed on the surface.

To study the growth mechanism of the crack, the metallographic sample prepared in a way that investigating of crack section was feasible. SEM images of the progress of the crack tip are shown in Fig. 5. As can be seen, the crack moved throughout the path of the dark phases.

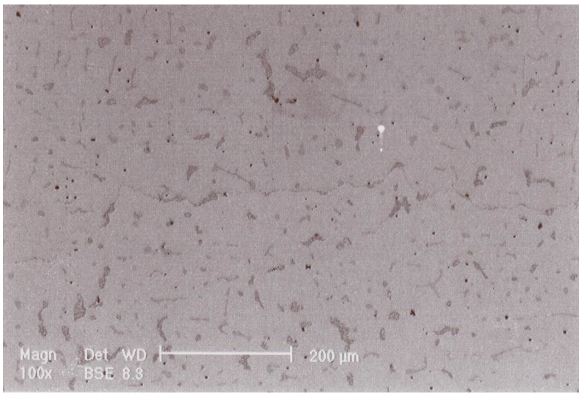


Fig. 3. SEM image of microstructure of HH steel (Austenite matrix with carbide precipitations).

Fig. 4. Appearance of an amortized grate bar part.

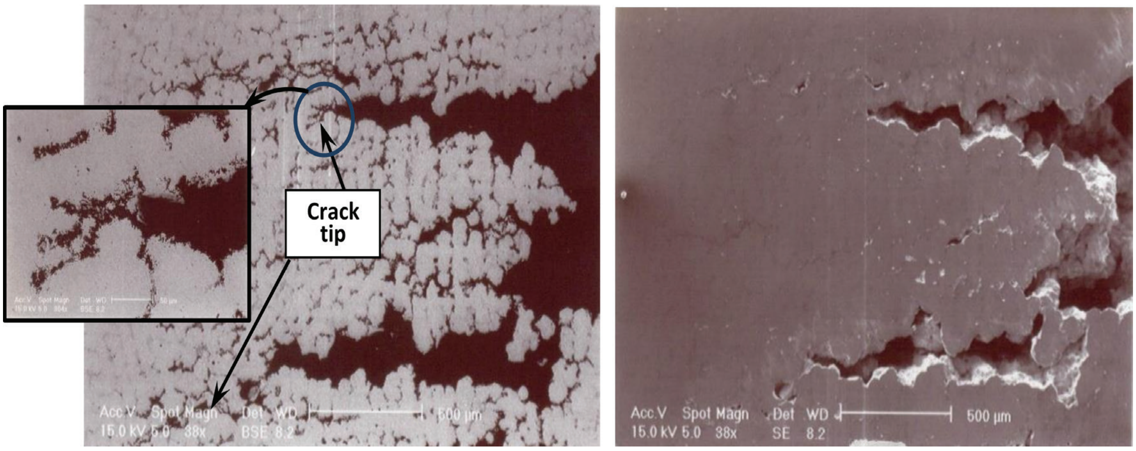


Fig. 5. SEM images in different states from crack tip in progress.

To study the growth mechanism of the crack, the metallographic sample prepared in a way that investigating of crack section was feasible. SEM images of the progress of the crack tip are shown in Fig. 5. As can be seen, the crack moved throughout the path of the dark phases.

Fig. 6 shows the microstructure of the vicinity of the crack tip. The EDS results of the dark phases is shown in Fig. 7. As illustrated, it contains chromium oxide components. Therefore, it could be deduced that oxygen diffused into the matrix and caused the change of chromium carbide to chromium oxide. Moreover, the oxygen diffusing is faster through this path (in comparison to the bulk) and the oxidation phenomenon will be faster because of the existence of the connected carbide net in the steel microstructure.

As seen in the Fig. 6, the grey chromium carbide phases have been converting to the dark chromium oxide phases during the oxidation reaction progress. Therefore, the oxidation through the connected carbide net proceeds and the internal oxidation occurs by diffusing oxygen into the matrix and the chemical composition of carbide net has changed to oxide.

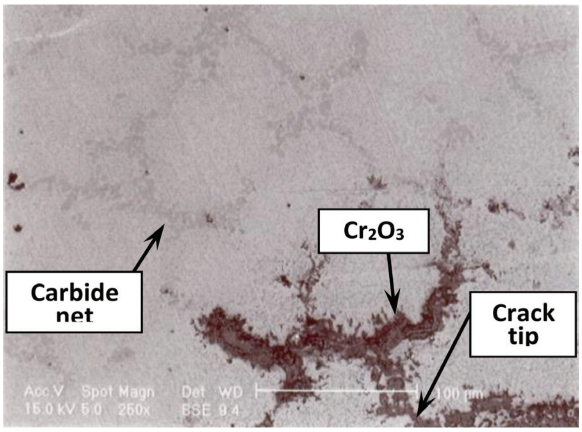
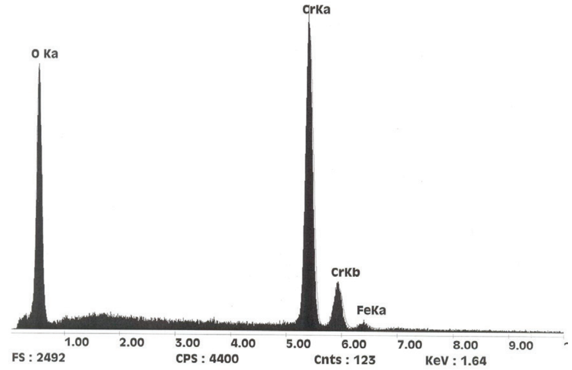


Fig. 6. SEM image from internal oxidation progress through chromium carbide nets.



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Standardless, Elements
      PEI Default Set : 1
Element   K Ratio    Weight %      Atomic %
------------------------------------------
 O K      0.3183        31.826       60.316
 CrK      0.6643        66.431       38.738
 FeK      0.0174         1.743        0.946
 Total                 100.000      100.000
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Fig. 7. EDS elemental analysis from dark color area in Fig. 6.

Although the oxygen diffusion is the main reason of the internal oxidation in the microstructure, the main requirement for the entering of the oxygen is destroying of the protection film. Mostly, the stress between the film and the metal interface destroys the protective layer. There are two main sources for these stresses. Firstly, the growth stress which is made when the passive film forms and secondly, the thermal stress which is generated because of the thermal expansion and contraction between the film and the metal. However, failed grate bars show current defects such as: crack, gap and bending which come up rarely. As a result, several synchronous situations are necessary for occurring internal oxidation which lead to crack initiation and growth. First, the part should be placed in high temperatures (more than 1080 °C) since, in high temperatures the protective film would be destroyed and as the next steps oxygen diffusion into the part could be possible. Furthermore, the inter-grain (Intergranular) oxidation would take place because of faster diffusion of oxygen through the grain boundaries by increasing the temperature. In this case, internal oxidation and oxide products lower the mechanical properties of the part and gradually the part become brittle and the cracks and gaps would be outward appearance [3, 4].

Thermal and mechanical stress in some parts (because of stocking between side parts and periodical heating and cooling of the part) are the other reasons for crack initiation and its growth.

Another source of damage is surface distortion because of the furnace gas movement on the surface (Fig. 4). The SEM image of a section of this part is shown in Fig. 8. As can be seen, the chromium oxide phase with dark color is observable on all over the surface which shows the internal oxidation at high temperatures. Also, it is seen that a grain is separated from the steel structure on the edge of part.

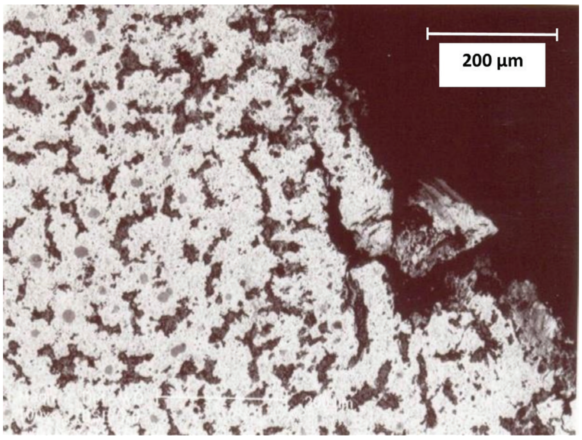

Fig. 8. SEM image of leaving a grain from the edge of part.

The investigations showed for some parts which are not under stress, fragmentation mechanism separates grains from the steel matrix [2, 5]. This phenomenon is known as “dusting” in Fe-Ni-Cr alloys.

The effect of titanium in the chemical composition of ferritic heat resistant steel on oxidation rate at 1300 °C has been shown in Fig. 9 [10]. Addition of titanium up to 0.5% can improve the oxidation resistance by modifying grains and chromium carbide nets in the microstructure. Although, excessive titanium was changed to $TiFe_2$ phase in the microstructure and decreased the oxidation resistance of steel [8, 11]. The intermetallic phases such as $TiFe_2$ cause changes in mechanical and corrosion properties of heat resistant steels. Intermetallic phases occur in particular temperatures range of 500 to 1000 °C. The chemical composition andaging temperature play an important role in intermetallic phase precipitations. Toughness is drastically reduced even with small volume fraction of intermetallic phases. Intermetallic phases are hard and brittle which cause embrittlement of the material. Corrosion resistance is lowered by the presence of intermetallic phases [7, 12].

As shown in Fig. 10, SEM image with EDS analysis reveals the presence of $TiFe_2$ inclusions that precipitated through the carbide net related to the Heat 2 samples.

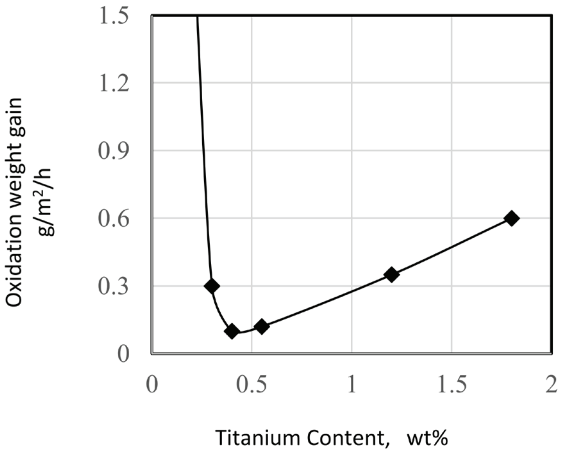

Fig. 9. Effect of Titanium in heat resistant steel on resistance to oxidation at 1300 °C [10].

The microstructures of both samples including Ti (Table 2) and samples not including Ti have been shown in Figs. 11, 12 and 13. Magnifications of all images are the same and the comparison of the images shows that the microstructure has been improved with the presence of Ti element in the chemical composition of HH steel. As seen in the microscopy images, carbide precipitation in the steel matrix has dispersed with adding the Ti element about 0.12 wt. % to the melt. Furthermore, the thickness of the carbide net precipitates and particles size of carbide precipitates have become thinner and finer respectively with adding 0.2 wt. % Ti into the melt (Fig. 14).

Above all, since the carbide formation tendency of the Ti is much higher than the Cr and owing to the fact that the available C is constant in both Ti added and without Ti steels, there would be a competition between Ti and Cr to form the carbide. This competition would result in lower volume fraction of Cr carbide in Ti added steels. In this case, the Cr would be in the bulk as solid solution and as a result, oxide passive layer would be formed uniformly on the steel surface due to the increase of the chromium concentration in the matrix. In other words, higher strength in the HH steels could be achieved by the presence of other carbide forming elements such as Ti. These carbides prevent the growth of chromium carbide in the matrix due to their thermal stability and the increase in the strength of steel.

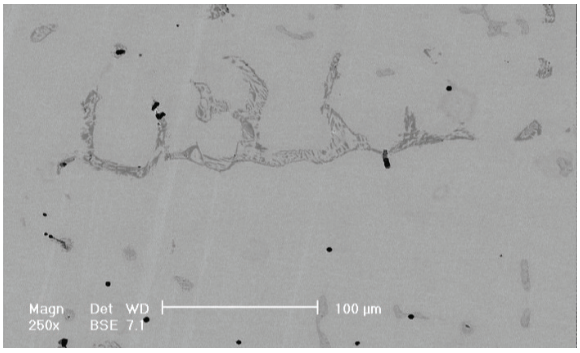

Fig. 11. SEM images of morphology and distribution of carbide precipitates in the sample without Ti.

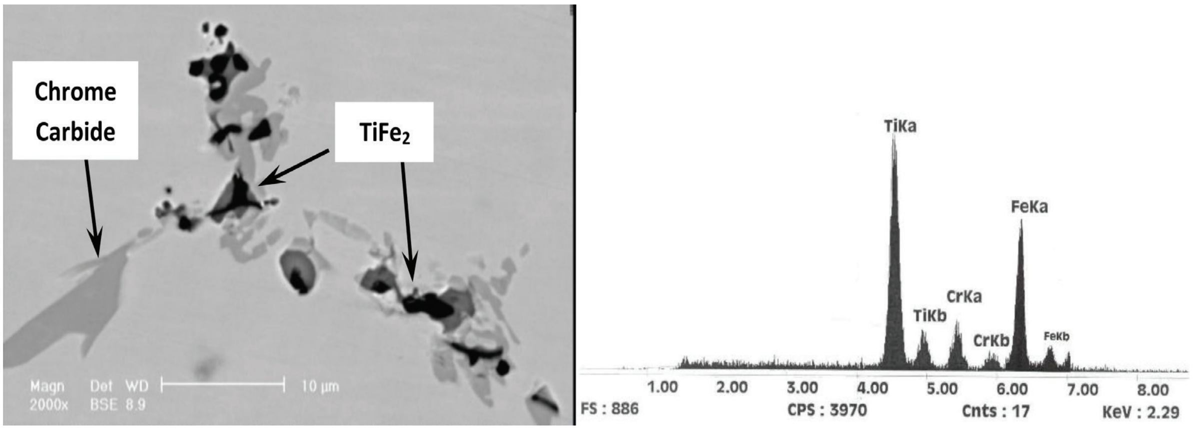

Fig. 10. SEM image of $TiFe_2$ particles that precipitated in the microstructure of sample with 0.2 wt. % of Ti.

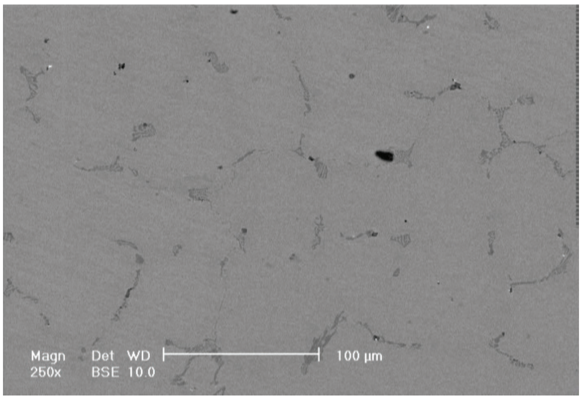

Fig. 12. SEM images of morphology and distribution of carbide precipitates in the sample with 0.12 wt. % of Ti.

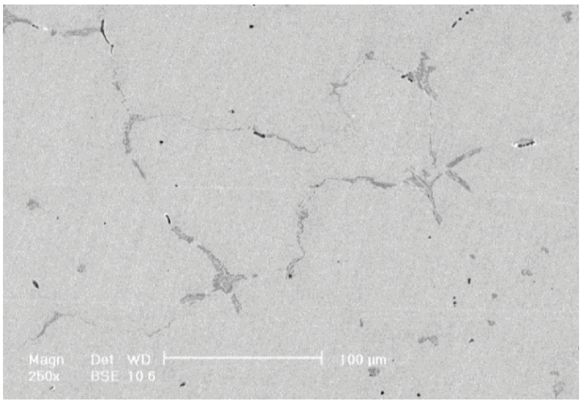

Fig. 13. SEM images of morphology and distribution of carbide precipitates in the sample with 0.2 wt. % of Ti.

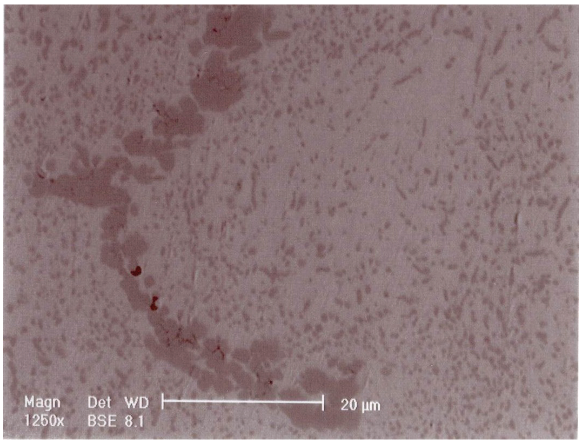

Fig. 14. Size distribution of precipitates as a particles and carbides net in the modified steel microstructure.

4. Conclusion

- Microstructural studies show that the governing distortion mechanism of parts is mostly internal oxidation with dusting phenomenon. It is also evident that the existence of the internal stress such as mechanical or thermal stress could lead to the initiation of cracks and appearance of gaps on the outward surface of parts.
- Damaging of the passive protective layer with the presence of the connected course carbides in the microstructure of steel leads to a higher parts distortion rate.
- Chromium carbide nets would be modified by adding 0.1 to 0.2 weight percent of Ti to the chemical composition of steel. Furthermore, the soluble chromium concentration in the matrix will increase. Therefore, the resistance of steel to the oxidation will be improved.

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