An investigation on the fracture of $70Cr_2$ steel balls during a grinding process and water quenching

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Abstract

The balls of a mill have the highest application in different industries like cement, steel (as forged steel), and copper (as casting ductile iron), and their role is to grind and produce suitable grinded materials. These balls are required as a production agent of mineral substance in the processing industries of metallic and non-metallic minerals consisting of cement factories, iron ore mines, and copper mines. But then again, they are limitedly employed in some defense industries and heavy metal mines. In this research, the factors affecting the fracture of steel balls produced from a continuous-casted $70Cr_2$ ingot were investigated during a grinding process and water quenching. The studied samples consisted of two destructed balls and one sound ball. The destructed balls fractured during the production process and before locating in the exploitation state of affairs meaning after the quenching process and/or the tempering process. To investigate the reasons of destruction, eye inspection, emission spectroscopy tests (quantummetry), metallography, hardness test, and scanning electron microscopy (SEM) equipped with EDS analysis were conducted. By analyzing the results, the fracture reasons of balls were related to the presence of inappropriate structure at the center and on the surface of the ball, the high hardness of the sample initiated from unsuitable heat treatment, and the creation of a crack in the middle of the cooling process and at the moment of applying an impact to the balls from the location of forging defects, as well as underneath the surface in the location of grain boundaries, defects, and impurities.

Keywords: $70Cr_2$ ball, Heat treatment, Fracture, EDS, SEM, Hardness.

1. Introduction

Ball mills are used to mill some mineral stones and finally condensate them. The production conditions and the type of heat treatment conducted on the balls have been very influential regarding their properties [1]. One of the significant parameters in the appropriate performance of the balls is a suitable hardness and a high wear lifetime. Therefore, the production conditions of an ingot, the production process of a ball, and heat treatment are the most important production parameters that can have a pivotal role in the performance lifetime of balls [2, 3]. Based on the need and the high consumption of these balls in Iran in addition to the export viewpoint of this product, it seems that precise and extensive investigations should be conducted on appropriate production conditions and the properties required for balls. In this research, it was strived that the effective parameters in the fracture of balls during a grinding process and heat treatment were scrutinized with the help of the novel ball production method, and the properties of balls were evaluated. It is worthy to note that the difference between the novel and old production method of balls is attributable to the blanking process and heat treatment steps [4].

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2. Experimental procedure

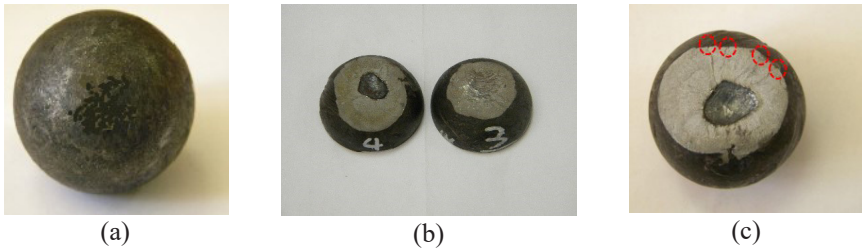
At first, during a rolling process, several 40 mm disks

made of $70Cr_2$ ingot which was produced by continuous casting and doing the purification process of the melt with Ca-Si, as well as blowing argon gas were prepared. The disks produced were located on the grinding device, and they go into the blanking part after passing some induction furnaces. The ingot temperature was about 950°C when it had exited from the last furnace. After the blanking process, the produced disk turned into a ball, and it then went into water after passing a 2 m distance to be quenched. Afterward, balls were extracted from water during the quenching operation and were fallen to barrels from a height of 50 cm. After filling the barrel, its door was closed, so balls were tempered by their own heat; this process is called self-tempering. During the falling of balls to the barrel, some of them were cracked and/or even fractured because of the collision occurring between them, but others were ready to be used in service without any certain problem. To study the reason concerning the destruction of balls, numerous investigations were started on two defective balls and one sound ball via dimensional measurement and eye inspections. The chemical composition was then determined by emission spectroscopy (quantummetry). In the following, the metallography samples prepared from the surface and center of the fractured and sound samples were provided, and the microstructural investigations of the samples were conducted by an optical microscope before and after the etching process with nital. In order to examine the mechanical properties of balls, a Microvickers hardness test was performed on the destructed and sound samples established upon Table 2. The hardness test was conducted in two directions and along the radius of the samples. Due to the lack of any standard concerning the properties of a ball, the surface and center hardness of the sample was compared to a sound one. Hence, the hardness number of the destructed sample was higher than the similar cases, but about a sound sample, the hardness number was approximately equivalent to the similar cases. Further investigations were conducted by SEM equipped with EDS analysis.

3. Results and Discussion

Figure 1 shows the samples experimented and the location of sampling in order to implement the tests. During the eye inspection of the destructed samples, it was observed that the surface fracture of the destructed sample was a combination of a shiny surface with wavy lines and a rough one. Besides, the stress concentration points (red circles in Fig. 1c) are observed in the fracture surface, indicating the nucleation of initial cracks in the outer surface of the ball. In the center of the fracture surface of one of the fractured surfaces, a part of the outer surface of the sample is detected, representing a rough surface and an incomplete and a non-integrated sphere of the ball. According to the fracture surface, it is detected that the surface of the ball is separated in the form of a skullcap in such a way as to occur the scaling phenomenon. The outer surface of the destructed ball has some stress concentration points, and the periphery effects initiated from the forging process are apparent. The fracture surface of the destructed ball was investigated by a stereomicroscope. On the word of Fig. 2, the center of the fracture surface has a wavy appearance, revealing the unstable growth of the crack, which is originated from the brittleness of the structure, under the influence of applying an impact force; the direction of these waves shows the direction of the crack growth. There are some cracks on the fracture surface, starting from the outer surface of the ball, and a number of them advanced to the central part of the ball and have no uniform shape. The results related to the chemical analysis from the core of the fractured and sound samples, as well as the standard chemical composition are presented in Table 1.

The chemical composition of the fractured and sound balls is in accordance with the standard. The high hardness of the destructed ball leads to brittleness and the reduction of the energy required for its fracture. The insensitive reduction of the hardness number from the surface to the center of the destructed ball by getting away from the surface compared to the sensitive reduction of the hardness in the sound sample is an indication of a high cooling rate during the thermal operation and the presence of needle martensite from the surface to the center of the destructed ball. It should be mentioned that the aforementioned hardness is before the tempering operation, while it decreases after the tempering operation. In the sound sample, it is observed that the hardness decreases from the surface to the center, and its value on the surface is about 150 HV lower than the destructed sample, indicating the cooling rate of the sound ball is very lower than that of the destructed ones.



(a) (b) (c)

Fig. 1. The cut cross-section of (a) the sound samples, (b) the fractured samples, and (c) red circles indicate the stress concentration points in the fractured ball.

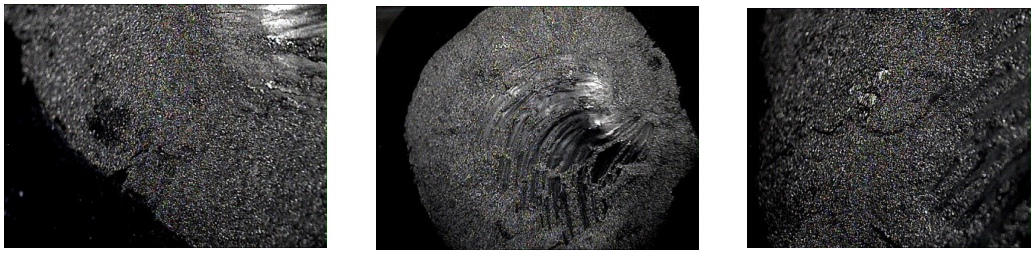


Fig. 2. fracture surfaces.

Table 1. The chemical compositions of the experimented and standard samples.

	% C	% Si	% Mn	% P	% S	% Cr
Standard	0.65 - 0.70	0.20 - 0.30	0.75 - 0.90	MAX 0.03	MAX 0.03	0.55 - 0.70
Standard sample	0.7	0.2	0.76	0.015	0.011	0.61
Fractured sample	0.67	0.27	0.87	0.028	0.018	0.63

Table 2. The results of the Microhardness test.

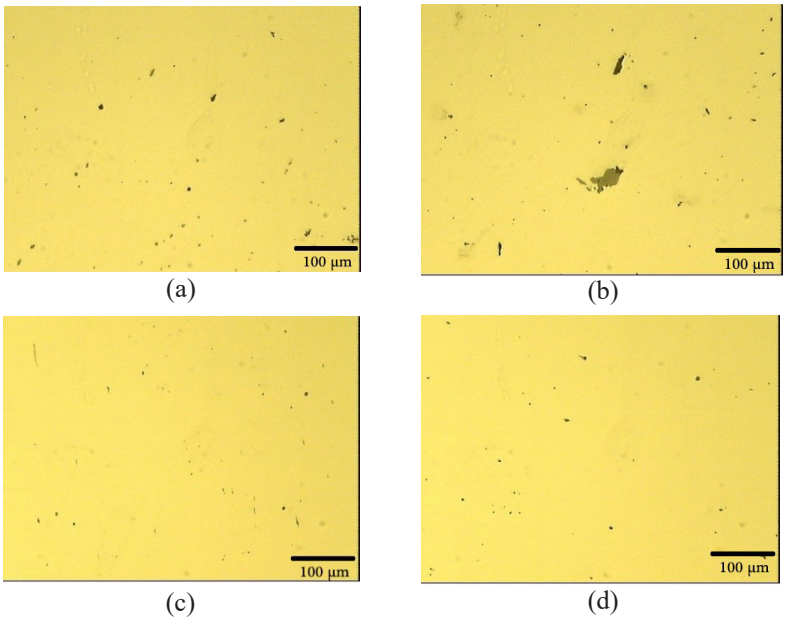
Sample	Hardness test location	Applying force	Hardness value (HV)			
Fractured	Ball center	30 kgf	810	804	817	810
	Half of Radius		823	817	817	819
	Ball surface		869	860	856	862
Sound	Ball center		372	375	381	376
	Half of Radius		434	420	425	426
	Ball surface		710	700	705	705

In the destructed sample, the temperature difference of the surface and core is very lower than that of the sound sample, so the martensitic transformation is started in all the volume of the ball in a very shorter time. This short time austenite-to-martensite transformation is accompanied by a volume increase and a thermal shock created on the surface of the ball together with a volume expansion, all of which result in a crack in the ball [5].

To investigate the microstructure of the balls, a metallography sample of the destructed and sound samples was prepared before chemical etching and was then examined by an optical microscope (see Fig. 3).

In the two destructed and sound balls, MnS and oxide impurity particles are detectable as gray and black colors in the matrix, respectively. The size of the impurities at the center of the destructed ball is larger than the area close to the surface, and the number of them at the center is lower than the aforementioned area. As can be seen, some sulfide impurities are nucleated from oxide impurities available in the matrix. Moreover, in metallography images, lots of cracks were detected, which typically reach the surface of the sample. The cracks detected are in the form of branching in such a way that some of them have many branches. The origin of these surface cracks is attributable to a high cooling rate in heat treatment and the formation of a brittle structure, i.e., the presence of needle tempered martensite on the surface of the ball. The nucleation of the location of some of these cracks is impurities (see Fig. 4).

It should be noted that there was no crack in the sound sample. The origin of the subsurface cracks in the destructed ball is the applying impacts to the balls during the production process. In the destructed ball, the microscopic structure was the same all over the sample and included tempered martensite and residual austenite together with dispersed sulfide impurities. In the sound ball, the structure was mainly bainite with a little tempered martensite at the half of the radius, as well as tempered martensite on the surface of the sample. Furthermore, the structure in the destructed ball was rougher compared to the sound ball (see Fig. 5).



(a) (b) (c) (d)

Fig. 3. The optical microscope images of the impurities: (a) the surface of the fractured sample, (b) the core of the destructed sample, (c) the surface of the sound sample, and (d) the core of the sound sample.

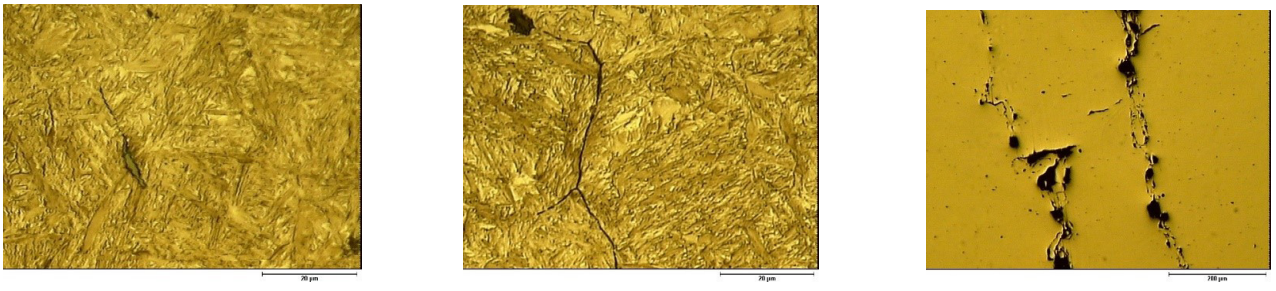
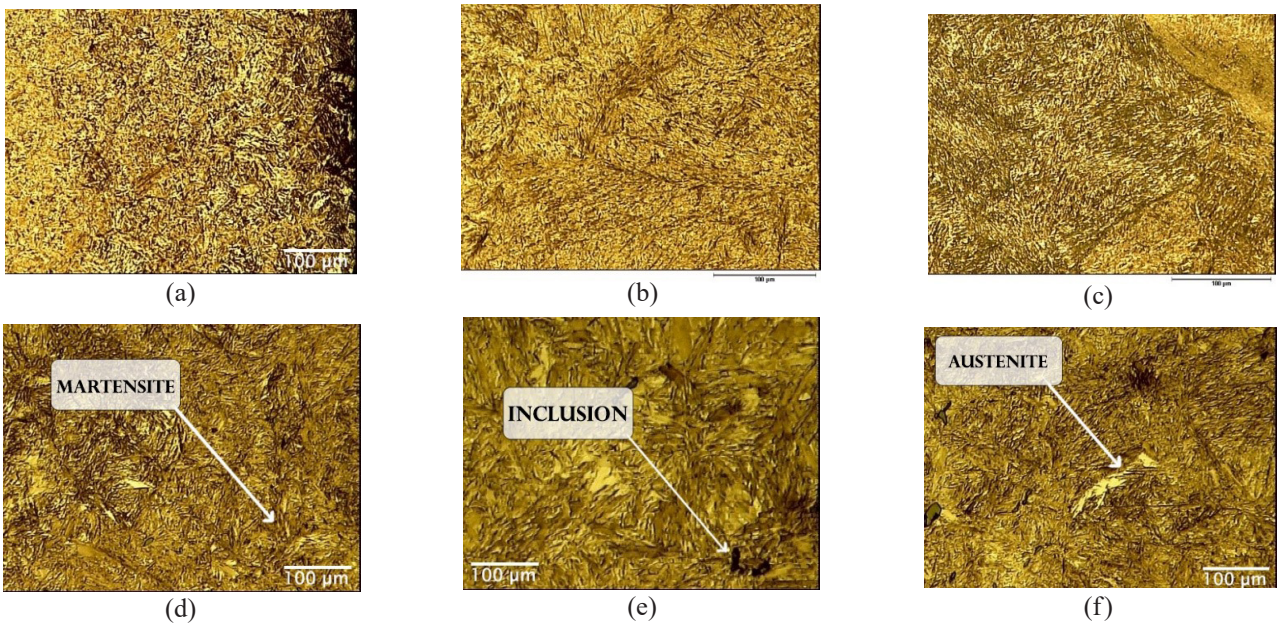


Fig. 4. The structure of the destructed samples and impurities as the starting origin of a crack.



(a) (b) (c) (d) (e) (f)

Fig. 5. The optical microscope images of (a) the surface structure, (b) the half of the radius, (c) the center of the sound ball, the structure of (d) the surface, (e) half of the radius, and (f) center of the destructed ball.

In the sound and destructed samples, a finer structure can be detected at the center of the sample compared to their surface. To complete the investigations, the fractography of fracture surface of the destructed balls was conducted with the help of a scanning electron microscope. The microscopic image obtained from the fracture areas is shown in Fig. 6. As can be seen, the surface at the starting and ending points is completely brittle and intergranular, and the microscopic and macroscopic cracks are observable in the grain boundaries. These observations are in accordance with the results of structural investigations and the presence of brittle martensitic structure of the ball. The presence of the intergranular fracture surface is an indication of the low fraction energy of the ball. Hence, it seems that the microscopic cracks are expanded easily with the first impacts. In the metallography images of the destructed sample, some cracks and stains were observed, indicating the brittle fracture surface with the help of SEM. It should be mentioned that the presence of the abovementioned cracks and stains shows the propagated cracks at the center of the ball. The impurities observed in the destructed and sound balls are sulfide (light gray color) and oxide (black color) compounds.

According to Fig. 7a and 7b, the oxide defects are observed at the center and underneath the surface of the destructed ball; the origin of the aforementioned defects is related to the deformation process of the sample (an incorrect deformation process and creating stress lead to the severity of the problems and the increase of possibility of fracture because a correct and precise deformation process eliminates the problems in keeping with the conducted studies). Similar to the fractured sample shown in Fig. 7c and 7 d, there are some oxide and sulfide impurities at the center and on the surface of the sound ball.

The defects affecting the fracture of the balls can be divided into three categories:

1) The casting process-initiated defects: Based on the investigations conducted, it is observed that although the impurities present in the sound sample are similar to the impurities available in the destructed sample, the nonuniform distribution of the impurities in the destructed balls can be influenced the early fracture of the sample.

2) The grinding (forging) process-initiated defects: In this step, oxide impurities reaching the surface and subsurface are created, and the crack grows by applying an impact to the ball, leading to an early fracture.

3) The heat treatment-initiated defects: The cracks created in the sample and the main reason for the fracture in the balls are as a result of the presence of a martensitic rough phase, residual austenite, and the high hardness of the sample due to the high cooling rate of the sample and the inappropriate heat treatment. In the heat treatment process, the cooling rate of the austenitic sample is one of the significant factors affecting the structure. During the quench operation, the austenitic temperature of the ball surface reaches a temperature lower than Ms, but its core might still be in the austenitic range [6]. By increasing the cooling rate, the surface and the core experience a lower temperature gradient, resulting in creating stress and nucleating cracks in the balls. Given the pieces of evidence, the destructed sample has a very high cooling rate so that a structure consisting of martensite and residual austenite can be detected even at the center of the ball. It is worthy to note that the surface hardness is arisen to reduce the wear of the balls during any service, so the structure of the center can be a combination of martensite and bainite. Therefore, it can decrease the cooling rate, which leads to the reduction of the stress in the sample during the austenite-to-martensite transformation, and consequently, the reduction of hardness and brittleness of the ball. The other point that should strikingly be mentioned is the continuity of the heat treatment in which the disk falls into water after turning into a ball, and the ball is then transferred to a barrel. In the middle of the process, the ball can be located in the temperature range of tempering brittleness.

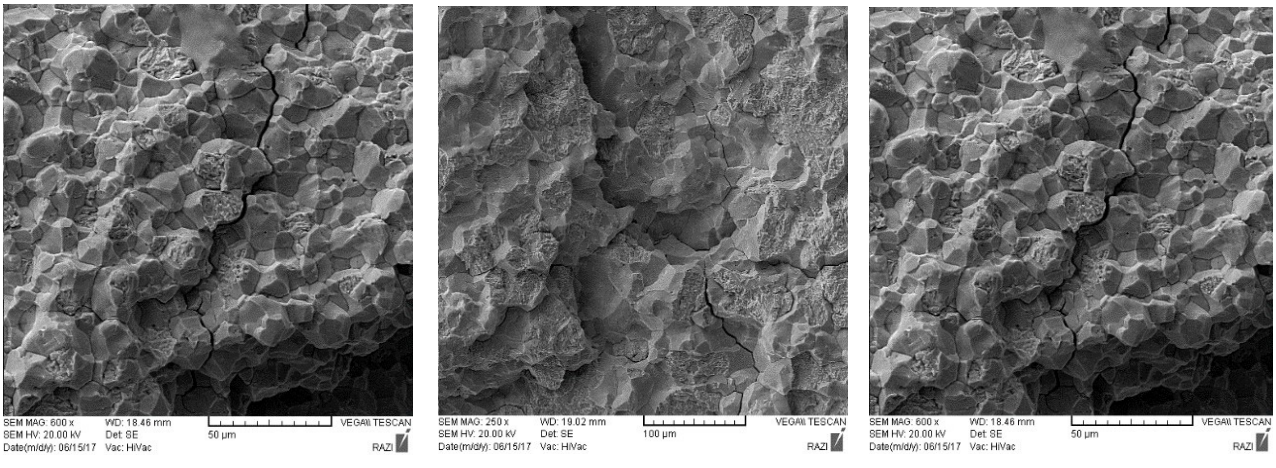
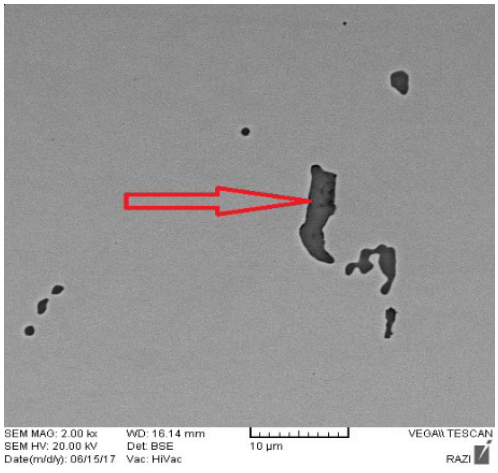


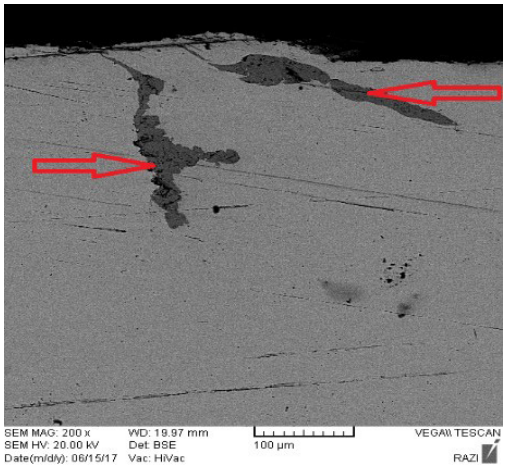
Fig. 6. The SEM images from the fracture cross-section of the destructed balls.



Spectra: C-MnS

Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Sulfur	K series	33.70	36.96	50.11
Manganese	K series	57.48	63.04	49.89

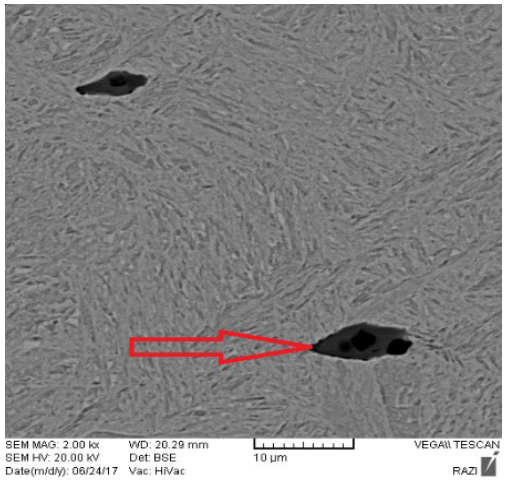
(a)



Spectra: C-B

Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Oxygen	K series	19.97	20.90	47.98
Iron	K series	75.58	79.10	52.02

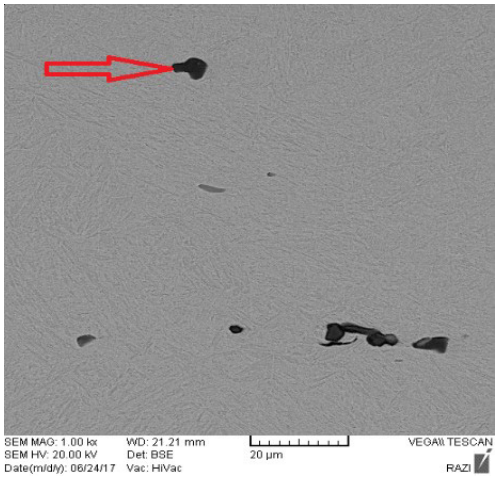
(b)



Spectra: D

Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Sulfur	K series	35.71	36.79	49.93
Manganese	K series	61.34	63.21	50.07

(c)



Spectra: C

Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Oxygen	K series	60.68	50.05	63.21
Iron	K series	1.26	1.04	0.38

(d)

Fig. 7. The SEM and EDS analysis images of oxide and sulfide impurities: (a) the center and (b) the surface of the fractured ball, and (c) the center and (d) the surface of the sound sample.

4. Conclusions

- The presence of oxide and sulfide impurities with nonuniform distribution, residual austenite, martensitic brittle structure in the ball, and hardness more than usual are of the factors affecting the fracture of the ball during the production process.
- Crack is created in the sample because of the stresses created during the austenite-to-martensite transformation and the high hardness of the sample before employing in any service.
- The inappropriate transportation process of the balls during implementing the heat treatment: The balls should not be under the influence of any impact before the tempering process because the cracking chance of the samples becomes higher owing to the presence of martensitic brittle and hard structure.
- On the basis of the results obtained from the current research in addition to the most important fracture factor which is the heat treatment, a number of disks were cooled up to the ambient temperature after turning into the ball. They were then located in a heat treatment furnace and were heated up to the austenitic temperature and were finally water-quenched after completely homogenizing. It was not observed any fracture in the balls produced by the aforementioned procedure.

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