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Effects of heat treatment on microstructure and ımpact resistance of high manganese steels

Isıl işlemin yüksek manganlı çeliklerin mikroyapısı ve darbe direnci üzerindeki etkileri

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Effects of Heat Treatment on Microstructure and Impact Resistance of High Manganese Steels

Highlights

- *Heat treatment effects on microstructure and behavior of high manganese steels were investigated.*
- *Microstructural investigations and spectrometric analyses were performed.*
- *Impact energy and hardness values were determined and evaluated.*
- *Significance of austenitization temperature on microstructure and mechanical properties was observed.*

Graphical Abstract

The effects of heat treatment on the microstructure were examined via optical microscopy investigations and spectrometric analyses in this study while impact resistance and hardness measurements were performed to investigate the change of mechanical properties of high manganese steels with the heat treatment conditions.

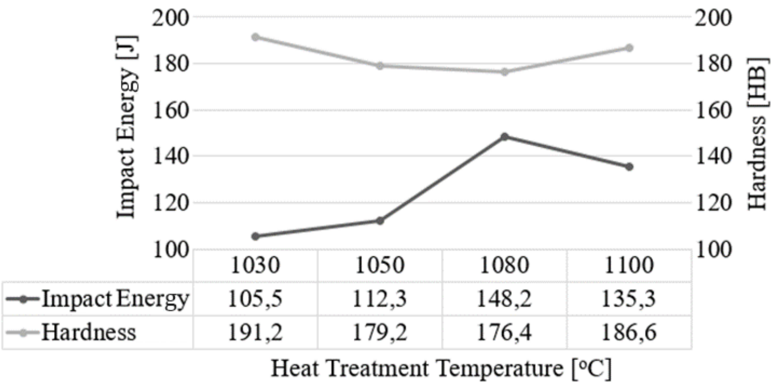

Figure. Average impact energy and hardness values depending on heat treatment conditions

Aim

The effects of heat treatment on the impact resistance of GX120MnCr18-2 high manganese steel were investigated.

Design & Methodology

Specimens were prepared according to GX120MnCr18-2 standard and spectrometric analyses were performed. Charpy V-notch impact tests and Brinell hardness measurements were realized on the heat-treated specimens.

Originality

Heat treatment conditions were determined in the optimal range for the mentioned high manganese steel specimen and microstructural changes related to austenitization temperature were investigated.

Findings

It was seen that the heat treatment conditions have significant effects on the microstructure and mechanical behavior of the cast specimen.

Conclusion

It is extremely important to determine the optimal heat treatment parameters of the cast high manganese steel products working in high-impact loading and wear situations since mechanical properties are significantly affected by the heat treatment conditions.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Effects of Heat Treatment on Microstructure and Impact Resistance of High Manganese Steels

Araştırma Makalesi / Research Article

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ABSTRACT

High manganese steels are widely used as wear- and impact-resistant materials in many areas, especially in the mining, construction, cement, and metallurgy sectors, where it is extremely important to be able to work safely in high-stress conditions as well as resistance to abrasion under heavy loading conditions thanks to their unique work-hardening performance. At this point, the carbon and manganese ratio of the material has a considerable influence on the microstructure of the cast part after the heat treatment. Therefore, heat treatment conditions have to be determined appropriately depending on the chemical composition of the material. In this study, heat treatment processes were applied to high manganese steel specimens having GX120MnCr18-2 DIN standard at various austenitizing temperatures between 1030~1100 ^{o}C. The specimens were examined under an optical microscope and SEM/EDS analyses were performed. Impact resistance and hardness values of the above-mentioned specimens were measured via the tests performed with TS EN ISO 148-1 and TS EN 130 6508-1 standards, respectively. From these investigations, it was determined that the carbide solubility increased as the austenitizing temperature increased while the impact resistance first increased and then decreased.

Keywords: High manganese steel (HMS), heat treatment, microstructural analysis, impact resistance.

Isıl İşlemin Yüksek Manganlı Çeliklerin Mikroyapısı ve Darbe Direnci Üzerindeki Etkileri

ÖZ

Yüksek manganlı çelikler, yüksek gerilme koşullarında güvenli bir şekilde çalışabilmenin son derece önemli olduğu madencilik, inşaat, çimento ve metalürji sektörleri başta olmak üzere birçok alanda aşınmaya ve darbeye dayanıklı malzemeler olarak yaygın şekilde kullanılmaktadır. Bu noktada, malzemenin karbon ve manganez oranı, ısıl işlem sonrasında döküm parçanın mikroyapısı üzerinde önemli bir etkiye sahiptir. Bu nedenle ısıl işlem koşullarının malzemenin kimyasal bileşimine göre uygun şekilde belirlenmesi gerekmektedir. Bu çalışmada GX120MnCr18-2 DIN standardına sahip yüksek manganlı çelik numunelere 1030~1100 ^{o}C arasındaki çeşitli östenitleme sıcaklıklarında ısıl işlemler uygulanmıştır. Numuneler optik mikroskopta incelenerek SEM/EDS analizleri gerçekleştirilmiştir. Yukarıda bahsi geçen numunelerin darbe dayanımı ve sertlik değerleri sırasıyla TS EN ISO 148-1 ve TS EN 130 6508-1 standartlarına göre yapılan testler ile ölçülmüştür. Bu incelemelerden östenitleme sıcaklığı arttıkça karbür çözünürlüğünün arttığı, darbe dayanımının ise önce arttığı daha sonra azaldığı görülmüştür.

Anahtar Kelimeler: Yüksek manganlı çelik (YMÇ), ısıl işlem, mikroyapısal analiz, darbe dayanımı.

1. INTRODUCTION

High manganese steels (HMS) exhibit a unique combination of good strength and ductility with high impact resistance. The combination of these properties has resulted in a growing interest in high manganese steels over the past years Thanks to their high formability and energy absorption capability, ferritic and martensitic transformation-induced plasticity (TRIP) and austenitic twinning-induced plasticity (TWIP) HMS having low or medium carbon (C) content are used especially in the automotive industry. The above-mentioned good mechanical properties of TWIP and TRIP steels are due to the high dislocation densities, and additional deformation mechanisms other than the slip mechanism [1]. Investigation of the wear, deformation, and strain-hardening behavior of high manganese (Mn) steels is of great importance under extreme loading conditions [2]. There have been numerous studies to improve the mechanical properties in recent years on HMS due to the increasing interest in these materials [1,3-27].

High manganese steels (HMS) having high 1.1~1.3% C content are indispensable due to their superior deformation hardening properties, especially in aggressive working conditions where high impact and wear resistance are required. Carbon is an element that contributes to the hardness value in steels [28], and the amount of carbon in HMS is evaluated together with the

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amount of manganese in determining the mechanical properties. Superior deformation hardening capacity which depends on the Mn content of HMS provides usage of these materials as a good alternative in wear applications thanks to a considerable amount of increase in hardness under compelling working conditions [4,5]. In this respect, HMS are preferred in high-speed rotating crushing machines in the mining, cement, and metallurgy industries as well as the construction, automotive, and railway industries. In this direction, Hadfield steels having 1.1~1.3% C and 12~14% Mn content have been widely used in industry in the last few decades. There are a number of studies in the literature on the mechanical behaviors and microstructural properties of Hadfield steels [6-15]. It is known that the working life of HMS increases via the increase in the hardness of the part with the occurrence of surface deformation due to the high-impact effect of aggressive working conditions. When the worn-out HMS specimens taken from field samples are examined it is seen that the hardness values of the parts are increased up to 550 HB levels depending on the surface deformation effect. In this context, the Mn content of these steels has increased up to 20% levels nowadays by keeping C content at 1.1~1.3% to obtain maximum available working life under the existing aggressive working conditions. Carbide-making micro-alloying elements such as chromium (Cr) and molybdenum (Mo) have been also added with the increasing Mn ratio to further increase the wear resistance and service life of HMS. TRIP/TWIP mechanisms are also effective in the mechanical properties of high C HMS at a certain level [1]. At the same time, casting temperature has a considerable influence on the microstructure and mechanical behavior of HMS. The manufacturing method of materials having the same chemical composition changes their mechanical and metallographic properties [29]. Extra high casting temperatures lead to grain growth and alloy segregation which end up with a decrease in strength and ductility. This unfavorable effect increases with increasing cross-sectional area of the cast part and carbon ratio. Former studies showed that casting temperatures higher than 1450 ^{o}C significantly increase alloy segregation. In other words, changing heat treatment conditions leads to different metallographic properties [30]. The austenite stabilizing characteristics of manganese provide a final microstructure in which carbides totally dissolve and the whole structure is composed of austenite after a heat treatment applied at 950~1100 ^{o}C to HMS. Nevertheless, the amount of carbide dissolved in the grain boundaries, as well as the amount of carbide in the austenite phase undissolved after the heat treatment adversely affects ultimate mechanical properties. Brittleness increases as a result of the decreasing impact resistance. In this respect, increasing heat treatment temperature is extremely important to improve the impact properties of the cast product via increasing carbide solubility in the austenite structure depending on the increase of carbon and carbide-making micro-alloying admixtures in the structure.

In this recent study, the effects of heat treatment conditions on microstructure, hardness, and impact resistance of GX120MnCr18-2 HMS having 1.15% C and 16.5% Mn was investigated. In this examination, four different austenitizing temperatures varying in a wide range from 1030 to 1080 ^{o}C which are appropriate for actual manufacturing conditions were selected. Optical microscopy examinations and SEM/EDS analyses were performed to investigate the microstructural properties of the cast specimens. Afterward, impact resistance and hardness values of the specimens were measured via the experiments performed with TS EN ISO 148-1 and TS EN 130 6508-1 standards, respectively. It was aimed to shed light on both the literature and manufacturing practice by clearly associating how the phases and compounds formed in the structure change the mechanical properties depending on the austenitizing temperature via comprehensive microstructural investigations and mechanical tests.

2. EXPERIMENT AND ANALYSIS PROCEDURE

In the current study, the impact resistance and hardness of HMS alloy in the GX120Mn18-2 standard were investigated by means of various heat treatment conditions. Above mentioned material is widely used in mine crushing machines due to its high impact and wear resistance as well as superior deformation hardening capacity. For the experimental study, specimens having 40 mm x 40 mm x 220 mm dimensions were manufactured by casting method. Microstructural changes due to various heat treatment temperatures were examined on these specimens. Standard impact specimens were prepared to investigate the impact resistances and hardness measurements were performed. The obtained results were compared to determine the appropriate heat treatment conditions. Additionally, microstructural evaluations were made to expound the mechanisms that determine the mechanical properties of HMS. The experiment and analysis procedure of the study was schematically represented in Figure 1.

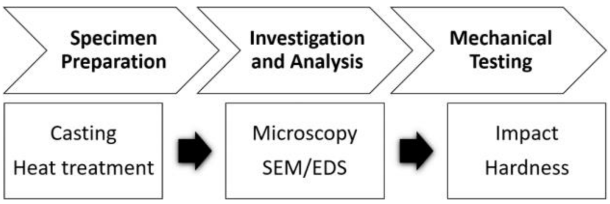


Figure 1. Schematic representation of the experiment and analysis procedure

Chemical examination results of the specimens cast in the same charge obtained from ARL 3460 Spectrometry equipment were given in Table 1.

Table 1. Chemical composition of GX120MnCr18-2

C	Si	Mn	P	S	Cr	Mo	Fe
1.15	0.48	16.50	0.04	0.01	1.56	0.01	Res.

Heat treatment processes were applied to the specimens in an electrical oven having a digital temperature control. Heat treatment conditions were presented in Table 2. In the heat treatment process, appropriate selection of the heat treatment temperature as well as the heating and holding times is extremely important for the final mechanical properties of the part [31]. While determining the heating times, it was considered not to cause any discontinuity in the samples due to thermal expansion while reaching the austenization temperature, and to ensure a balanced and homogeneous heating, and the heating times in practical applications were taken into account as well as the section thickness. Similarly, thickness, chemical composition, temperature distribution in the useful area of the furnace, the general principle of '1 hour holding per inch', and the holding times during the heat treatment of similar cast parts were taken into account while determining the holding durations. A water tank having 28.5 m^3 volume at 8 ºC was used for the quenching process with moving water.

Table 2. Heat treatment conditions

Heat Treatment Temperature [ºC]	Heating Duration [h]	Holding Duration [h]	Quenching Conditions
1030	7	4	Moving water
1050	7	4	Moving water
1080	8	4	Moving water
1100	8	4	Moving water

Heat-treated specimens under the above-mentioned conditions were cauterized with 3% Nital solution including 3% nitric acid (HNO3) and 97% ethyl alcohol after metallographic preparation. Microstructural investigations were made with the Nikon L150 Eclipse microscope. Hardness measurements were performed with EMCO universal hardness testing equipment according to TS EN ISO 6508-1 and impact tests were executed with WPM ZWICK impact testing equipment according to TS EN ISO 148-1 standard.

3. RESULTS AND DISCUSSION

Influence of heat treatment on microstructure was examined via optical microscopy investigations and spectrometric analyses in this study while impact resistance and hardness measurements were performed to investigate the change of mechanical properties of HMS with the heat treatment conditions. In the following sections, the results obtained from the analyzes and tests were given in detail.

3.1. Microstructural Investigations and Spectrometric Analyses

The microstructure of the HMS specimens depending on four different heat treatment conditions given in Table 2 were examined in detail via optical micrographs taken at 10X, 20X, 50X, and 100X magnifications (Figures 2-5).

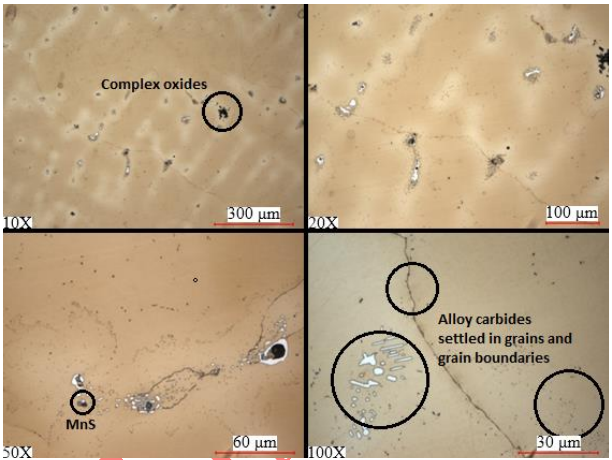


Figure 2. Micrographs of the cast part that was heat-treated at 1030 ºC with 10X, 20X, 50X, and 100X magnifications

As seen in Figure 2, manganese sulfide (MnS) compounds and carbide formations in grains and grain boundaries of the cast part that was heat-treated at 1030 ºC are seen under various magnifications. Moreover, the formation of complex oxides is also seen in the micrographs.

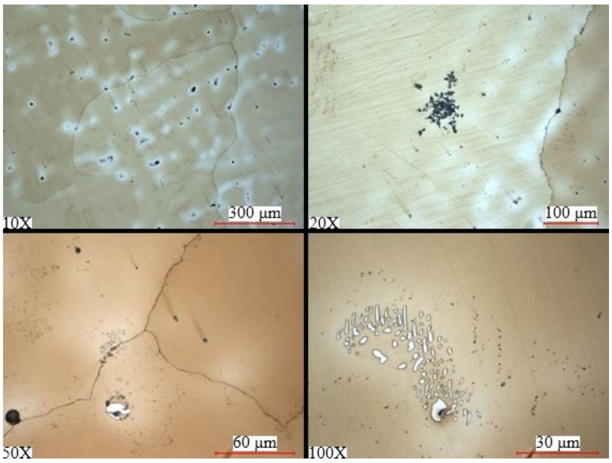


Figure 3. Micrographs of the cast part that was heat-treated at 1050 ºC with 10X, 20X, 50X, and 100X magnifications

It is clear from Figure 3 that MnS inclusions and non-metallic complex oxides have occurred in the microstructure of the cast part that was heat-treated at 1050 ºC. Besides, the formation of settled alloy carbides is seen in grains and grain boundaries.

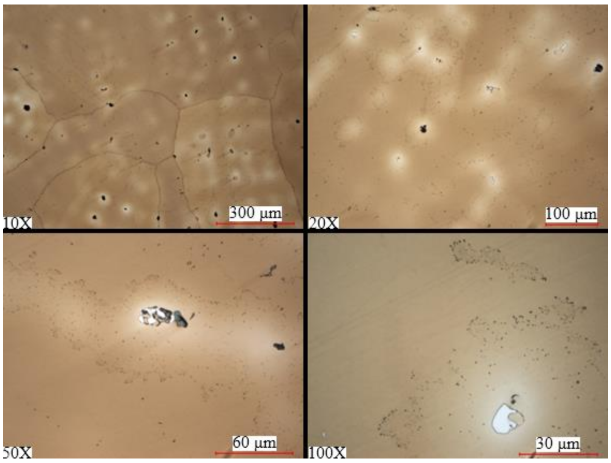


Figure 4. Micrographs of the cast part that was heat-treated at 1080 °C with 10X, 20X, 50X, and 100X magnifications

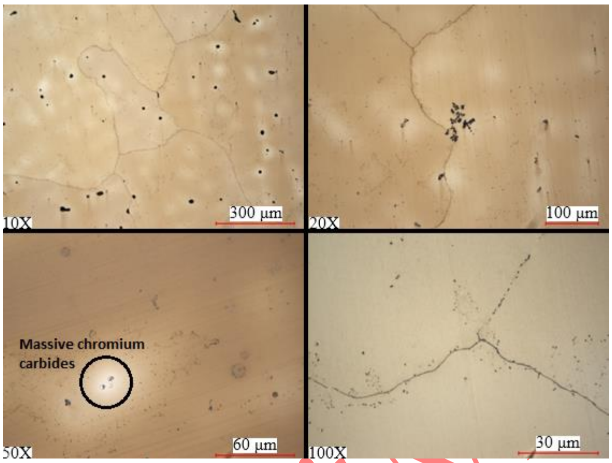


Figure 5. Micrographs of the cast part that was heat-treated at 1100 °C with 10X, 20X, 50X, and 100X magnifications

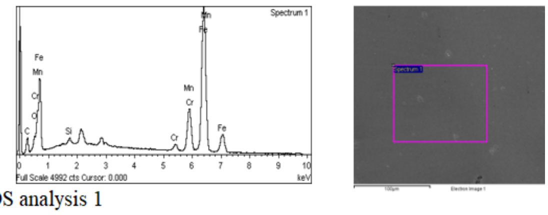
It is clearly seen in Figure 4 that the cast part that was heat-treated at 1080 °C also contains non-metallic oxide inclusions and MnS compounds in the microstructure. It is also clear from the micrographs that there is a decrease in massive chromium carbides, but there are still carbide impurities in the boundaries of the grains.

In the microstructure of the cast part that was heat-treated at 1100 °C, MnS formations, and complex oxide inclusions are seen in Figure 5. The existence of massive chromium carbides is less than the cast part that was heat-treated at 1080 °C. Moreover, it is seen that the amount of the settled carbides in the grain boundaries is decreased in comparison with the specimen heat treated at 1080 °C.

The chemical and phase structures of the HMS specimens depending on four different heat treatment conditions given in Table 2 were examined in detail via semi-quantitative SEM/EDS analyses (Figures 6-9).

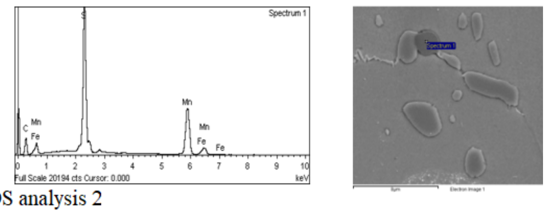
Semi-quantitative SEM/EDS analyses of the cast part that was heat-treated at 1030 °C were given in Figure 6. Analysis 1 was taken from the matrix phase and it gives the composition of the Fe-Mn solid melt austenite phase. Analysis 2 was taken from the non-metallic MnS residue in which the carbides can be seen. Analysis 3 was performed on primary eutectic carbides precipitated in the matrix phase and the grain boundary. The carbides that precipitated in the matrix phase are M7C3 type (Fe, Cr) carbides which are extensively utilized for wear-critical applications. In the grain boundary analysis, the

Element	Weight [%]	Atomic [%]
C K	5.61	20.76
O K	1.72	4.78
Si K	0.45	0.71
Cr K	1.63	1.40
Mn K	17.39	14.08
Fe K	73.20	58.28
Totals	100.00	



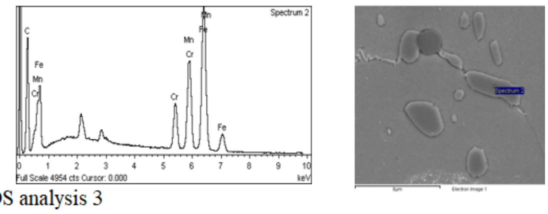
(a) SEM/EDS analysis 1

Element	Weight [%]	Atomic [%]
C K	25.68	55.51
S K	27.80	22.51
Mn K	44.22	20.90
Fe K	2.31	1.07
Totals	100.00	



(b) SEM/EDS analysis 2

Element	Weight [%]	Atomic [%]
C K	22.14	56.62
Cr K	8.48	5.01
Mn K	23.25	13.00
Fe K	46.13	25.37
Totals	100.00	



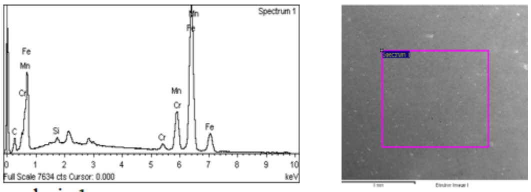
(c) SEM/EDS analysis 3

Figure 6. SEM/EDS analyses of the cast part that was heat-treated at 1030 °C

chtome ratio is low since the signal was received from the matrix phase.

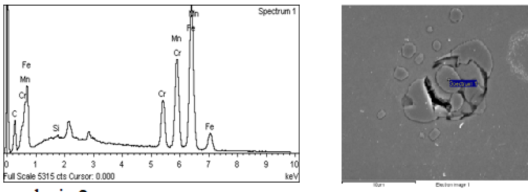
SEM/EDS analyses obtained from the cast part that was heat-treated at 1080 °C were given in Figure 8. Analysis

Element	Weight [%]	Atomic [%]
C K	5.25	20.36
Si K	0.44	0.74
Cr K	1.55	1.39
Mn K	16.60	14.06
Fe K	76.15	63.46
Totals	100.00	



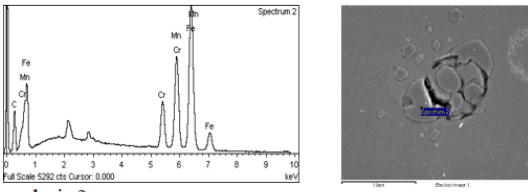
(a) SEM/EDS analysis 1

Element	Weight [%]	Atomic [%]
C K	7.87	28.12
Si K	0.13	0.20
Cr K	10.79	8.91
Mn K	26.95	21.06
Fe K	54.26	41.71
Totals	100.00	



(b) SEM/EDS analysis 2

Element	Weight [%]	Atomic [%]
C K	10.28	34.47
Cr K	9.92	7.68
Mn K	26.74	19.60
Fe K	53.06	38.26
Totals	100.00	



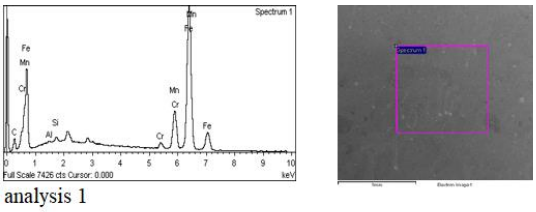
(c) SEM/EDS analysis 3

Figure 7. SEM/EDS analyses of the cast part that was heat-treated at 1050 °C

SEM/EDS analyses made with the cast part that was heat-treated at 1050 °C were given in Figure 7. Analysis 1 was taken from the matrix phase and the austenite matrix is in the form of Fe-Mn solid melt likewise the specimen that was heat treated at 1030 °C. Analyses 2 and 3 show the M7C3 (Fe, Cr) carbides precipitated in the matrix phase.

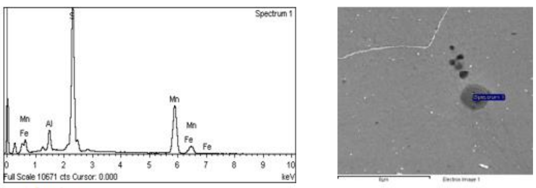
1 is the analysis of the Fe-Mn solid melt austenite phase. Analysis 2 was taken from MnS residues in the matrix. Analysis 3 is of the precipitated carbide in the form of a film at the grain boundaries. However, the analysis result is similar to the analysis of the matrix phase since the precipitated carbide layer is extremely thin.

Element	Weight [%]	Atomic [%]
C K	4.84	18.97
Al K	0.24	0.42
Si K	0.45	0.76
Cr K	1.59	1.43
Mn K	16.42	14.05
Fe K	76.46	64.37
Totals	100.00	



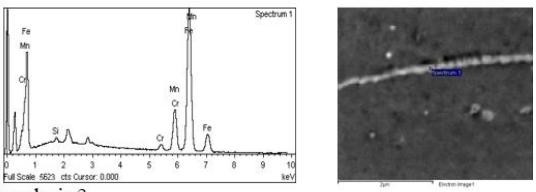
(a) SEM/EDS analysis 1

Element	Weight [%]	Atomic [%]
Al K	4.40	6.90
S K	35.81	47.18
Mn K	56.01	43.07
Fe K	3.78	2.86
Totals	100.00	



(b) SEM/EDS analysis 2

Element	Weight [%]	Atomic [%]
Si K	0.51	1.00
Cr K	1.79	1.90
Mn K	18.63	18.76
Fe K	79.07	78.33
Totals	100.00	



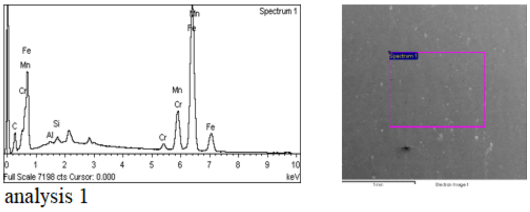
(c) SEM/EDS analysis 3

Figure 8. SEM/EDS analyses of the cast part that was heat-treated at 1080 °C

SEM/EDS analyses taken from the cast part that was heat-treated at 1100 °C were given in Figure 9. Analysis 1 was taken from the matrix phase which is the austenite phase containing the Fe-Mn element. Analysis 2 shows the non-metallic complex pollution. The carbides precipitated at the grain boundaries are seen in Analysis 3. The results of Analysis 3 are similar to the matrix analysis since the precipitated carbide layer is very thin.

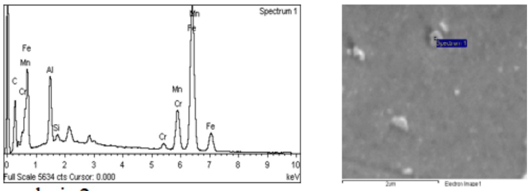
It is clear from Figure 10 that the impact energy first increases and then decreases with the increasing austenitization temperature. It is also seen from the figure that the hardness value first decreases and then increases with the increasing austenitization temperature contrary to the impact energy. As clear from the figure, best impact strength was obtained at 1080 °C where hardness has the minimum value. However, even the maximum hardness value of 191.2 HB obtained at 1080 °C is considerably low for tough working conditions,

Element	Weight [%]	Atomic [%]
C K	7.09	25.98
Al K	0.20	0.33
Si K	0.45	0.70
Cr K	1.51	1.28
Mn K	16.11	12.90
Fe K	74.64	58.81
Totals	100.00	



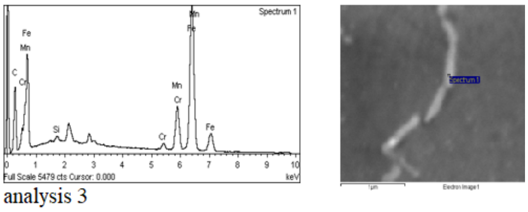
(a) SEM/EDS analysis 1

Element	Weight [%]	Atomic [%]
C K	15.39	44.04
Al K	5.15	6.55
Si K	0.49	0.60
Cr K	1.35	0.89
Mn K	14.31	8.95
Fe K	63.31	38.96
Totals	100.00	



(b) SEM/EDS analysis 2

Element	Weight [%]	Atomic [%]
C K	18.86	51.73
Si K	0.31	0.36
Cr K	1.41	0.89
Mn K	15.08	9.04
Fe K	64.36	37.97
Totals	100.00	



(c) SEM/EDS analysis 3

Figure 9. SEM/EDS analyses of the cast part that was heat-treated at 1100 °C

3.2. Impact Energy and Hardness Values

The average impact energies of the specimens were determined by performing Charpy V-notch impact tests on the specimens heat treated at four different heat treatment conditions varying from 1030 °C to 1100 °C. In addition, the hardness values of the HMS specimens after the above-mentioned heat treatment processes were measured. The results obtained from the experimental studies were represented graphically in Figure 10.

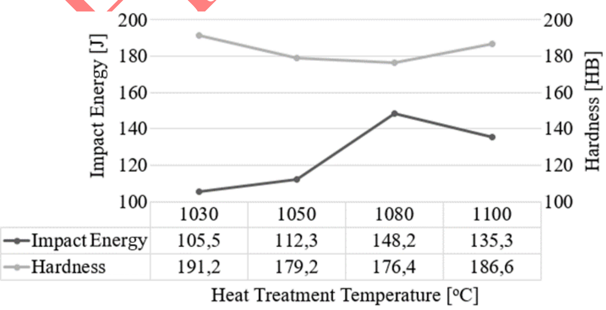


Figure 10. Average impact energy and hardness values depending on heat treatment conditions

especially in which wear resistance is required. At this point, it should be remembered that the hardness values of HMS could increase up to 550 HB at approximately 1~3 mm depths from the surface under compelling conditions.

4. CONCLUSION

In this study, the following results were obtained by examining the metallographic changes, hardness measurements, and impact resistance values of GX120MnCr18-2 HMS which are commonly used in the mining, construction, cement, and metallurgy industries after the heat treatment process at different austenitic temperatures.

• It is extremely important to determine the optimal heat treatment parameters of the cast HMS products working in high-impact loading and wear situations since mechanical properties are significantly affected by the heat treatment conditions.

• It is seen that low austenitic temperature decreases carbide solubility in high manganese steels.

• It is also apparent that the carbide solubility of the matrix phase in the microstructure increases as the heat treatment temperature increases (Figure 2-5).

• In the austenitization process at low temperatures, it is seen that the carbide structures insoluble in the matrix phase settle at the grain boundaries and float as contamination in the structure.

• By the evaluation of the average impact energy and hardness values, it is seen that the toughness value increases significantly with the increasing austenitization temperature, and the best result was obtained at 1080 ^{o}C with an impact energy of 148,2 J.

• With the examination of the microstructures of the specimens, it can be said that this result is due to the significant reduction of undissolved carbide clusters in the grain boundaries and structure. In other words, the increase in the amount of dissolved carbide in the austenite structure increases the toughness value significantly.

• The hardness first decreased when the austenitization temperature was increased. Then it was observed that hardness increased again. This is thought to be due to the increase in the amount of dissolved carbide in the austenite structure with the increasing austenitization temperature.

• In future studies, the wear resistance of the HMS can be investigated since these materials which have considerable work-hardening capability are widely used as wear- and impact-resistant materials.

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DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Hakan YILDIRIM: Prepared the specimens, performed the experiments and analyses, contributed to the analysis of the results.

Muhammed Emin ERDİN: Contributed to the analysis of the results and writing of the manuscript.

Ali ÖZGEDİK: Contributed to the analysis of the results and writing of the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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