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Comparative Analysis of Factors Affecting Gas Carburization Optimization in Chromium and Chromium Molybdenum Alloy Steels

Chang-Yeol Oh[1], Bo-An Kang[*2], Choon Yoo[3], Sang-Jin Yoon[4]
[1,3]Ph.D., Department of Mechanical Engineering, Nambu University, Gwang-Ju, Korea.
[*2,4]Professor, Department of Mechanical Engineering, Nambu University, Gwang-Ju, Korea.
ocy203@naver.com[1], bakang@nambu.ac.kr[*2], fbichoon@naver.com[3], sjyoon@nambu.ac.kr[4]

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Abstract

Background/Objectives: We analyzed the optimal factors affecting the surface hardening properties of chromium alloy steel and chromium molybdenum alloy steel heat treated by propane gas carburization.

Methods/Statistical analysis: The heat treatment conditions were optimized using a simulation program. Simulation results were applied to control the atmosphere in the carburizing furnace. Control factors were temperature, time and carbon potential in the furnace. The effect on the surface properties of heat treated alloy steels was analyzed. Mechanical properties of the carburized layer were compared by measuring the Energy Dispersive X-Ray Spectroscopy, Scanning Electron Microscope, X-ray diffraction, Electron Probe Micro Analyzer and micro-Vickers hardness.

Findings: The carburizing temperature of 0.2 wt.% C chromium alloy steel for automobile parts was 930℃. The carburizing time was 10hr at carbon potential 0.90 wt.%. And the diffusion time was 3hr at the carbon potential 0.75 wt.%. The carburizing temperature of 0.2% C chromium molybdenum alloy steel was 930℃. The carburizing time was 2hr 10min. at the carbon potential 0.90 wt.%. The diffusion time was 1hr at carbon potential 0.75 wt.%. The surface hardness depth of alloy steels increased with decreasing carbon content. The surface structure of the alloy steels were a mixture of ferrite and pearlite, the martensitic structure decreased and the hardness decreased from the surface to the inside. In alloy steels, surface hardness seems to have a significant effect on the amount of martensitic structure. These results were consistent with EDS, XRD and EPMA analysis. Chromium alloy steel and chromium molybdenum alloy steel showed similar tendency in carburizing behavior.

Improvements/Applications: These results may be applicable to the study on the carburizing optimization of chromium and chromium molybdenum alloy steels used in automobile parts. In order to apply it to materials used in automobile driving parts, research related to durability will be conducted in the future.

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1. Introduction

Carburizing heat treatment is used because high strength is essential to satisfy the miniaturization and light weight of automobile parts and to secure sufficient durability and reliability. Steel made by

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adding molybdenum to chromium steel is called chromium molybdenum steel. Chromium-molybdenum steel is 0.2% molybdenum is added in addition to about 1% of chromium, the hardenability is improved and the tempering resistance is greater than chromium[1,2]. In general, water quenching can deform the shape, so it is better to quench it with oil as much as possible. Therefore, manganese must be added for this purpose. When molybdenum is added in addition to chromium, the hardening performance of steel is increased and temper brittleness is also reduced, so that high temperature workability is good and the processing surface is clean[3]. In addition, the strength and wear resistance are improved, and high temperature processing is easy, and it is used for various shafts, gears, and automobile parts. Gas carburizing heat treatment is the most widely used method of heat treating small auto parts in bulk. Carburizing heat treatment is a method of increasing the carbon content and hardening the surface by quenching the carbon after penetrating the surface. Carburized steel has abrasion resistance on the surface and internal structure is flexible to maintain toughness. Carburizing depth is influenced by raw materials, carburizing materials, carburizing atmosphere, carburizing temperature, carburizing time, holding time and carbon content.

1.1 Objectives

In this study, we want to find the optimal heat treatment conditions for chromium alloy steel used in constant velocity joint parts that transmit power to the wheels through axles in differential pinion gears. In addition, we will analyze the optimum heat treatment factors for chromium molybdenum alloy steels used in automatic transmission and crankshaft parts.

2. Experimental Methods

• Simulation of carburizing condition.

Heat treatment carried out to improve the mechanical properties of automotive parts should achieve the maximum economic effect at the lowest cost. In this study, we simulated the conditions affecting the carburizing temperature, carburizing time, diffusion time, carbon potential, carburizing depth, etc. suitable for carburizing in order to find a way to carburize large quantities economically. The reason for the simulation in this study is to find the optimal heat treatment conditions for the specimens used in automotive parts. In order to use it as a constant velocity joint part, the conditions which satisfy fill the hardening depth were simulated at the point of effective hardening depth 550Hv and carburizing amount 0.36% C. Crankshaft sprocket parts should have an effective carburizing depth in the range of 0.2∽0.45 mm, based on micro-Vickers hardness 550Hv. To find carburizing conditions meeting these criteria, carburization was simulated using the Carbon Profiler program (EUROTHERM). In addition, the pump drive hub should have an effective carburizing depth in the range of 0.8 to 1.2 mm based on micro-Vickers hardness 513Hv.

• Sample preparation.

The specimens were carburized after composition analysis using two chromium alloy steels and two chromium molybdenum alloys. The chemical compositions of the four specimens are shown in Table 1.

Table 1: Chemical composition of specimens

Elements (wt%)	Specimens			
	SCR-420H	SCR-415H	PDH-20	CSS-15
C	0.20	0.15	0.20	0.15
Si	0.25	0.24	0.26	0.25
Mn	0.83	0.84	0.82	0.83
P	0.014	0.013	0.015	0.014
S	0.007	0.008	0.007	0.006
Ni	0.06	0.06	0.09	0.08
Cr	1.14	1.13	1.12	1.13
Mo	-	-	0.19	0.20

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Chemical composition analysis of four specimens was performed using Brucker X-ray Fluorescence (WD-XRF Tiger). In XRF analysis, X-rays were irradiated to generate secondary X-rays to qualitatively and quantitatively analyze unknown elements in the sample. In order to observe the effect of alloying elements and carbon on the microstructure after the heat treatment, the specimens were cut and taken in the depth direction from the surface layer. Wire-cutting was performed in water to minimize the change of the hardness of the carburized layer and the structure change before and after carburization. The shape of the mounted specimen is shown in Figure 1. The specimens were separately mounted before and after the heat treatment. The test piece was fixed so that a vertical surface might be seen at the time of mounting, and the thermosetting acrylic resin powder was injected into the heat press. After aligning the specimen to the center of the piston as much as possible, the acrylic resin powder was added and the cover was fixed.

The fixed specimen was pressed at 150 kg/cm^2 by pressing the piston with the hydraulic handle. The temperature of the mold was maintained for 3 minutes at the conditions of 185℃ and cooled for 3 minutes. Mounting was performed to obtain a smooth surface for easy measurement, and rough polishing, fine polishing, and gloss polishing were performed.

Figure 1. Mounted specimens for instrumental analysis.

• **Propane gas carburization**.

Based on the simulation results, gas carburizing conditions were determined. For the SCR-420H specimen, the carbon potential was maintained at 0.9wt.% for 10hr/930 ℃ to allow carbon to penetrate the surface. 2.5 liters per minute propane (C_3H_8) gas was injected inside. RX-Gas was maintained at 350m^3/hr until the carbon diffusion. Constant carbon potential was maintained so that the carburized gas was evenly distributed on the test piece. And the carbon concentration was maintained at 0.75% by weight for 3 hours at 930℃ in order to carbon diffusion. The heat treatment cycle of two chromium alloy steels are shown in Figure. 2.

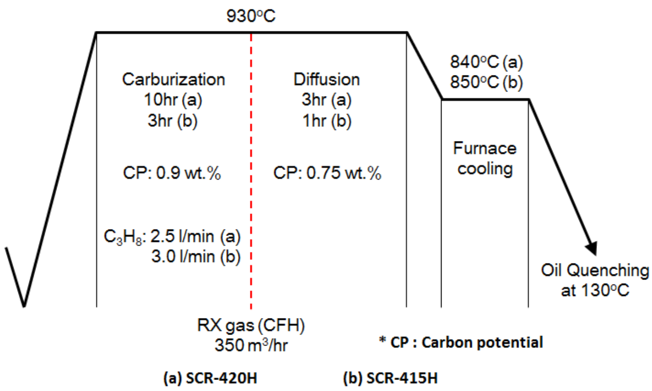

Figure 2. Gas carburizing cycle for two chromium alloy steels(SCR-420H, SCR-415H).

The heat treatment cycles of two chromium molybdenum alloy steels are shown in figure 3 and Figure 4.

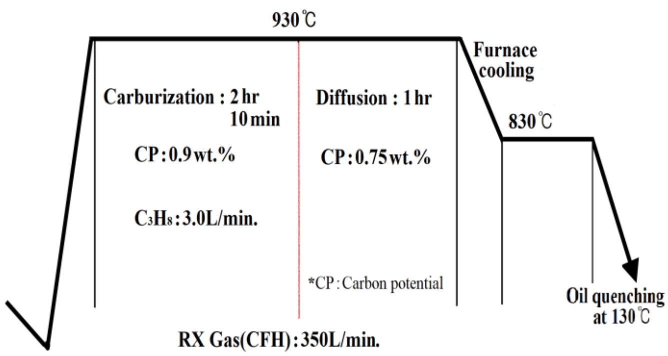

Figure 3. Gas carburizing cycle for chromium molybdenum alloy steel(PDH-20).

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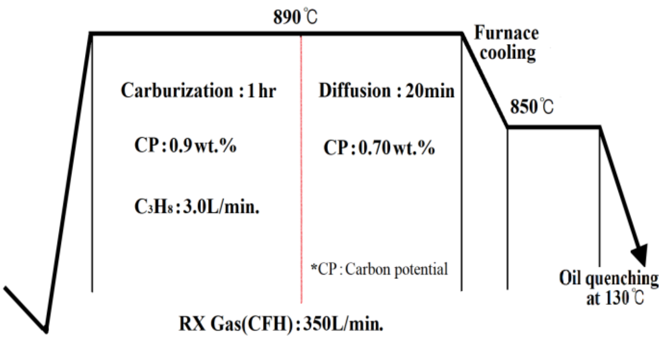


Figure 4. Gas carburizing cycle for chromium molybdenum alloy steel(CSS-15).

CSS-15 specimens maintained 1hr at a carburizing temperature of 890℃ and a carbon potential of 0.9wt.%. The diffusion temperature was run at 890℃ for 20min., and then the carbon potential was maintained at 0.7wt.%. Propane gas injection and RX-Gas were performed in the same manner as PDH-20.

• **Microstructure analysis**.

The change of microstructure in which carbon and other elements affect the hardness of four specimens was analyzed. Microstructure analysis was performed using scanning electron microscope, EDS, electron probe micro analyzer and x-ray diffractometer. The chromium alloy steel was etched for 8 seconds with a 5% Nital solution (nitric acid + ethyl alcohol). Chromium molybdenum alloy steel was etched before and after heat treatment, 5% nitric acid solution and 10% meta sodium bisulfite ($Na_2S_2O_5$) aqueous solution, and then the microstructure was observed. The main objectives of the study were to analyze the relationship between the formation of anomalous layers, the change of the structure on the hardness by carburizing depth, the formation of grain boundary oxides, and the change of carbon content and hardness. XRD analysis was performed in the range of 20 ~ 80 degrees under the conditions of CuKα radiation, 40kV, 300mA, 5deg. / min., and D8 Advance for high Power. The EMPA analysis measured the inside of the carburized surface, and graphically shows the component changes for Fe, Cr, Mn, Mo, and C. Microstructures were observed at 2,000, 5,000 and 10,000 magnification using a scanning electron microscope (TESCAN, MIRA / LMH) as shown in Figure 5.

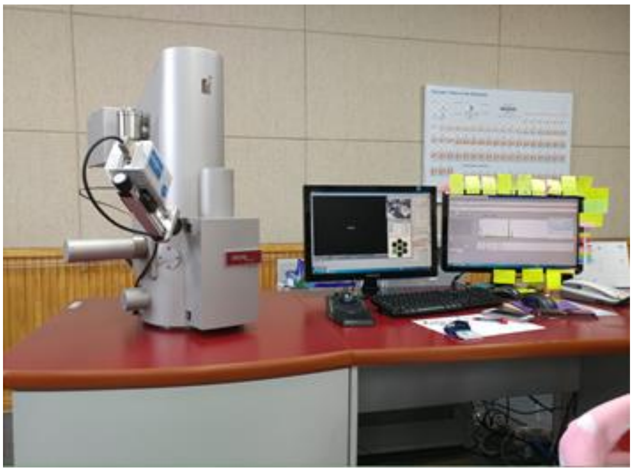


Figure 5. Scanning electron microscope(SEM).

Electron Probe Micro-Analyzer (EPMA, Bruker co.) combined with non-destructive data analysis was used to precisely analyze elemental components from the surface to the inside of the carburized specimens. EPMA is equipped with an energy dispersive X-ray spectrometer (EDS) and a wave length dispersive X-ray spectrometer (WDS) simultaneously.

• **Mechanical property analysis.**

The specimen surface hardness before and after carburization of the chromium alloy steel was analyzed using a Rockwell hardness tester. Hardening depth was analyzed with a VLPAK2000 Micro Vickers Hardness Tester. Since the measurement error may occur when the indentation interval is narrow, it was measured by the zigzag (W) method.

3. Results

3.1. Simulation results

T1, T2, and T3 simulation conditions for SCR-420H and SCR-415 specimens are shown in Table 2.

Table 2: Simulation condition for chromium alloy steels

Alloy steels	SCR-420H / SCR-415H		
Test No.	T1	T2	T3
Heat treatment temperature	900℃, 930℃, 960℃		
Carburizing time	10hr / 3hr		
Diffusion time	3hr / 1hr		
Carburizing C.P.	0.85	0.9	1.1
Diffusion C.P.	0.75		

The simulation conditions of the two chromium molybdenum alloy steels are shown in Table 3.

Table 3: Simulation condition for chromium molybdenum alloy steels

Chromium-molybdenum alloy steels	PDH-20	CSS-15
Heat treatment temperature	930℃	890℃
Carburizing time	2hr 10min.	1hr
Diffusion time	1hr	20min.
Carburizing C.P.	0.9wt.%	0.9wt.%
Diffusion C.P.	0.75wt.%	0.70wt.%
effective hardening depth (550Hv,0.36%C)	0.81mm	0.34mm

Economical heat treatment methods require mass production in a short time and high productivity. Reducing carburizing time will eventually increase economics. In general, to shorten the carburizing time, the carbon potential is increased and the carburizing temperature is increased. However, soot may build up in the furnace or damage the structure in the furnace[4]. Simulations were made in the range of 850~950℃ which is commonly used for gas carburization. Considering the economics, simulation results that are considered to be the best carburizing condition in chromium alloy steel are shown in Figure 6 and Figure 7. As a result of measuring the effective hardening depth 550Hv and the hardening depth at the point of carburizing 0.36% C necessary for the use of automobile parts, it was 1.193~1.447 mm at 900℃. It was 1.398~1.725 mm at 930℃ and 1.652~2.006 mm at 960℃. It seems that the temperature at which the hardening depth can be used for automobile parts can be obtained at 930℃. Simulation results of SCR-420H and SCR-415H showed that the carbon potential required for carburization was 0.9 wt.% And the carbon potential required for diffusion was 0.75 wt.%.

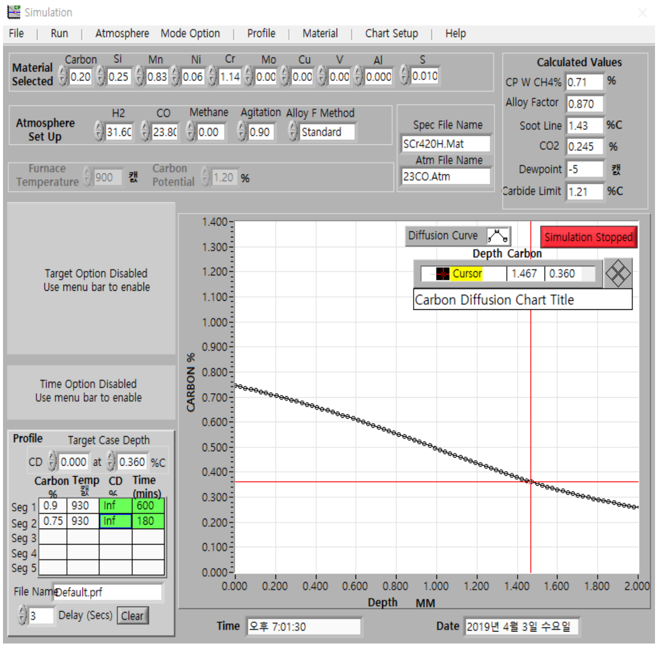


Figure 6. Simulation Result of the SCR-420H at hardening depth 1.467 mm(Temp. 930 ℃, C.CP 0.9, D.CP 0.75, C.T 10hr, D.T 3hr).

If the carburizing temperature is too high, maintenance costs such as soot and damage to the furnace may be high. Low carburizing temperatures may not reach the proper carburizing depth and carburizing depth, or may require long time carburizing. In such cases, it can be uneconomic. Simulation results suitable for carburizing chromium molybdenum alloy steels used in crankshaft sprockets and oil pump drive hubs are shown in Figure 8 and Figure 9. The carburizing temperature satisfying the effective hardening depth of 550Hv and the carburizing amount of 0.36% C showed that PDH-20 was 930℃ and CSS-15 was 890℃.

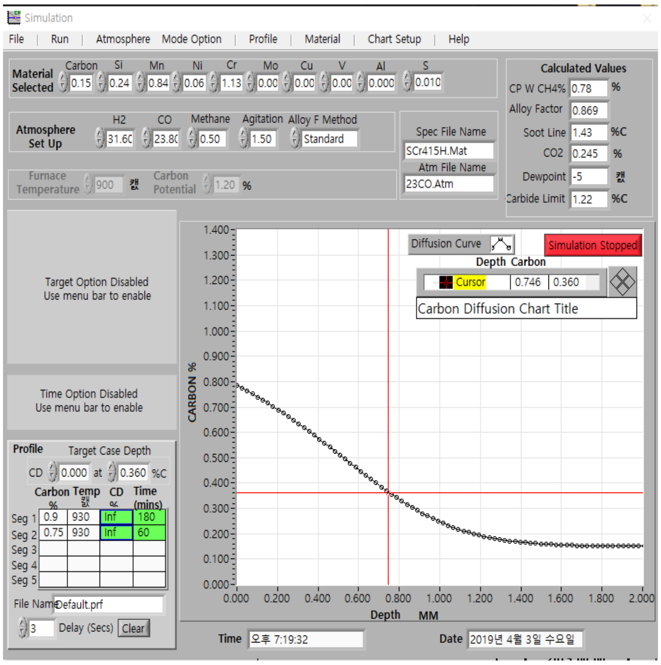


Figure 7. Simulation Result of the SCR-415H at hardening depth 0.746 mm(Temp. 930 ℃, C.CP 0.9, D.CP 0.75, C.T 3hr, D.T 1hr).

Figure 9 shows the simulation results for the CSS-15 specimen. The heat treatment conditions were set at a carburizing time of 1 hr and a diffusion time of 20 min, a carburizing carbon potential of 0.9 wt.%, And a carbon potential required for diffusion of 0.7 wt.%. Unlike oil pump drive hubs, crankshaft sprockets do not require high hardness and carburizing due to the low kinetic energy required for mechanical friction and power transmission. This is why carburization and diffusion time are short. If Agitation was set to 1.0 when controlling the internal atmosphere of the carburizing furnace, the curing depth was 0.279 mm that satisfied the carburizing amount 0.36% C at the effective hardening depth of 550 Hv. When adjusted to 2.5, the curing depth was 0.34 mm, 0.061 mm larger.

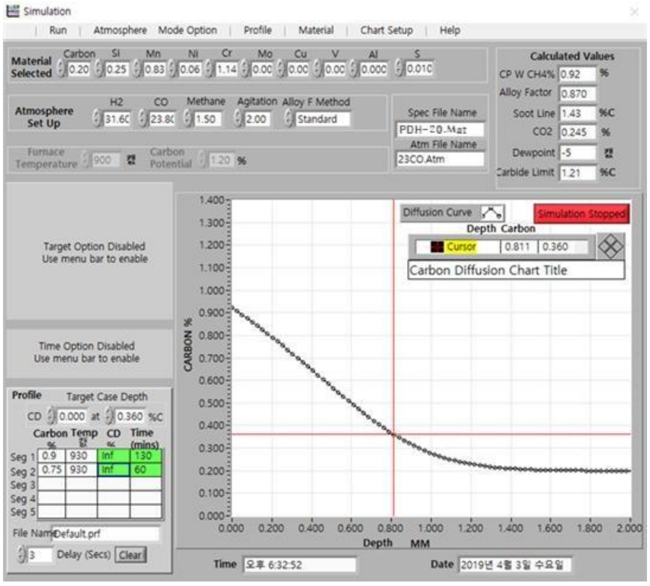


Figure 8. Simulation Result of the PDH-20 at hardening depth 0.81 mm(Temp. 930 ℃, C.CP 0.9, D.CP 0.75, C.T 2hr 10min., D.T 1hr).

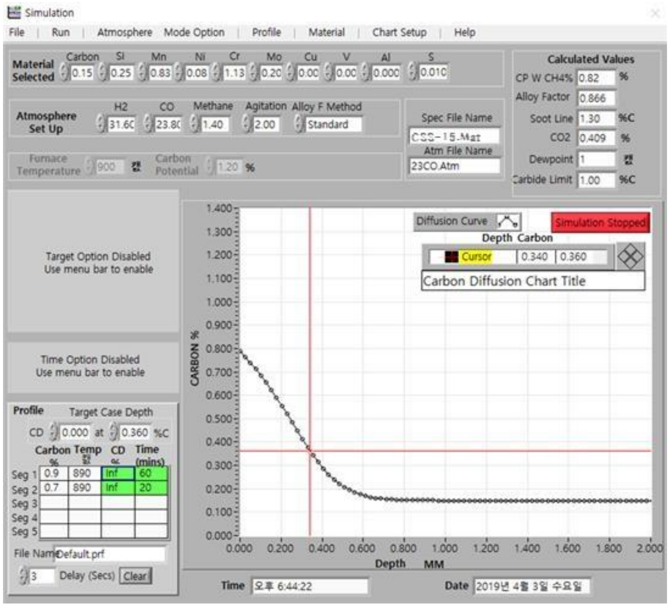


Figure 9. Simulation Result of the CSS-15 at hardening depth 0.340 mm(Temp. 890 ℃, C.CP 0.9, D.CP 0.70, C.T 1hr, D.T 20min.).

This is believed to be the result of high activity when methane is added to the carburizing furnace, and the carburizing action is activated. Therefore, we set CH_4 1.4 and agitation 2.5 as corrected values applying various environments and conditions in the carburizing furnace. The optimum heat treatment conditions for the CSS-15 specimen were a heat treatment temperature of 890℃. with a hardening depth of 0.34 mm at a carburizing amount of 0.36% C corresponding to an effective hardening depth of 550 Hv. Suitable carburized carbon potentials were 0.9 wt.%, Diffusion carbon potential 0.7 wt.%, Carburizing time 1 hr, diffusion time 20 min.

3.2. Microstructure analysis results

Figure 10 shows the carbon content analysis before and after carburization on SCR-420H specimens. The carbon content of the SCR-420H specimens shows a sharp increase after carburization. From 0.3 mm on the surface of the specimen, the carbon content was drastically lowered, and the carbon content gradually decreased with increasing carburizing depth.

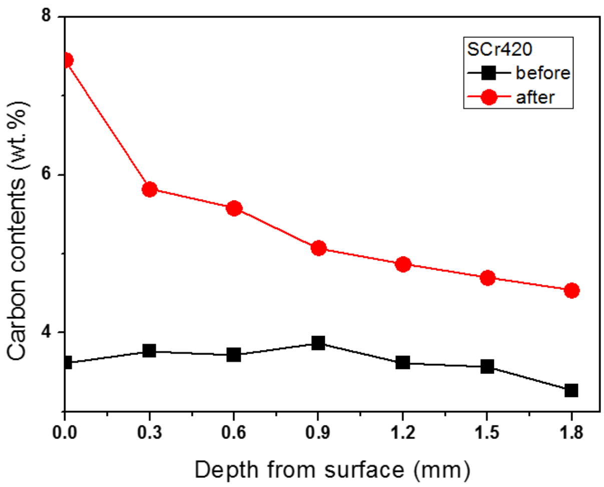
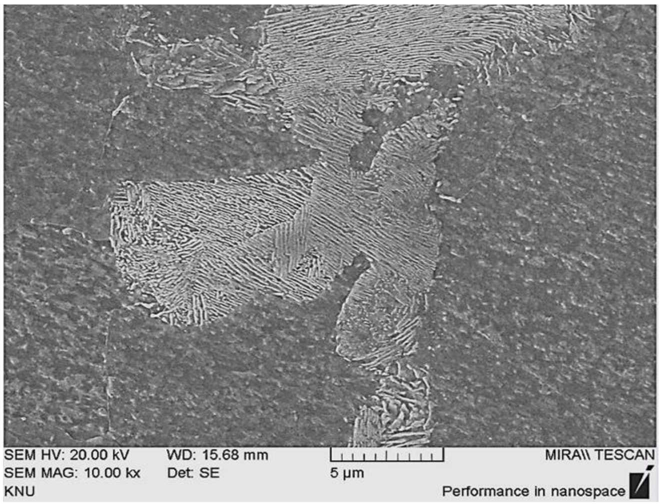
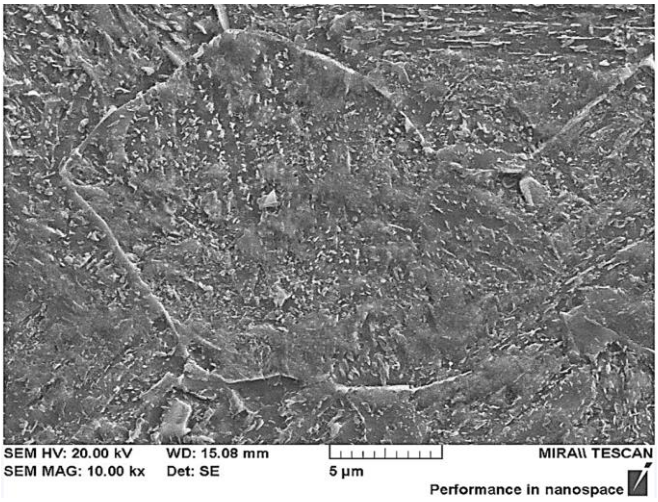


Figure 10. Carbon Content Change from Carburized Surface of SCR-420H Specimen.

Figure 11 shows SEM images of internal structure before and after carburization of the SCR-420H specimen. The microstructure photograph of the specimen before carburization shows a regular distribution of the ferrite (light) and pearlite (dark) structures in the form of stripes. Surface oxidation (black areas) that occurred during oil quenching after heat treatment at the top of the SCR-420H specimen was also observed. It was found that grain boundaries with irregular boundaries were formed inside the SCR-420H specimen. SCR-415H specimens showed similar results as the SCR-420 image.



(a) Internal SEM photograph before heat treatment (SCR420H 10000X)



(b) Internal SEM photograph after heat treatment (SCR420H, 10000X)

Figure 11. SEM images of internal structure before and after carburization(SCR-420H).

Figure 12 shows SEM images before and after carburization on PDH-20 specimens. Figures 13 shows the results of XRD analysis of carburized chromium alloy steel. XRD analysis showed that the structures of SCR-420H and SCR-415H were ferrite (α-Fe) and pearlite mixed structure before carburizing[5,6]. The (110) peak at 44.6°(2θ) indicates that the ferrite structure is dominant, and the (200) peak occurring at 64.9° (2θ) is identified

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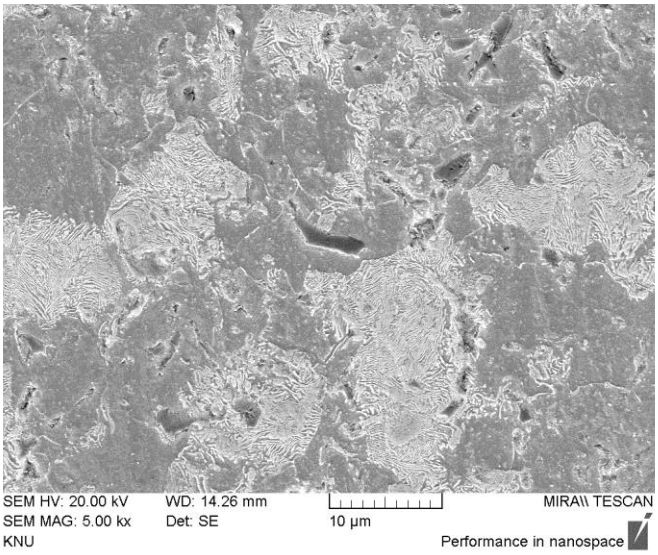
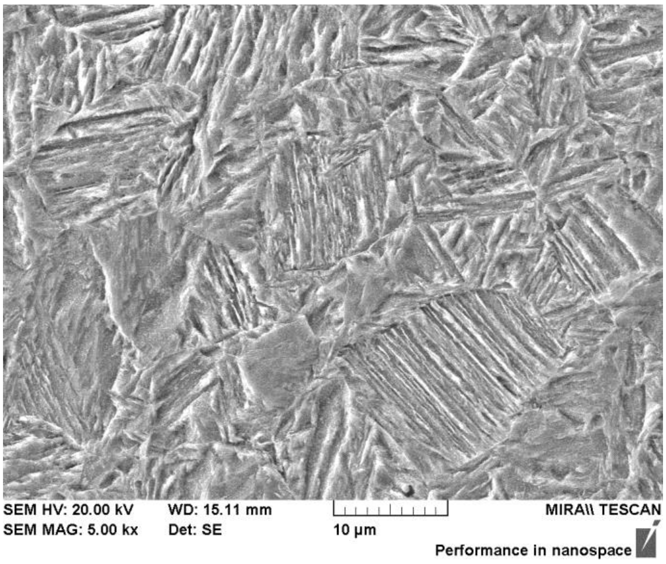
as the ferrite and pearlite structure. XRD results show that the ferrite is evenly distributed throughout the structure prior to carburization.



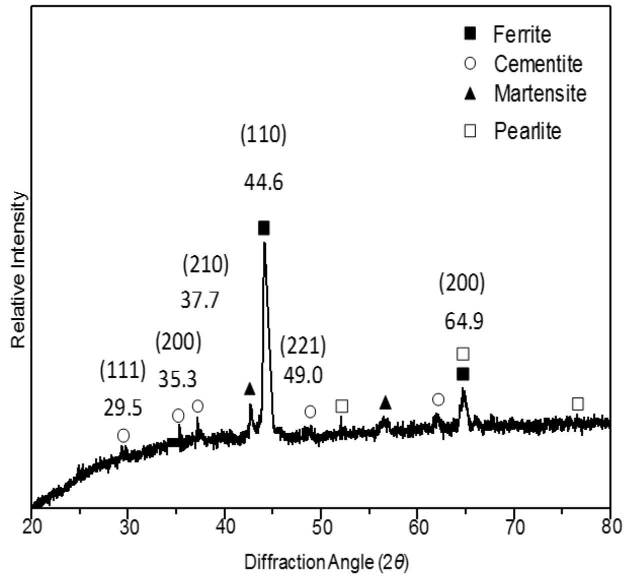
(a) before carburizing (magnifications 5,000)



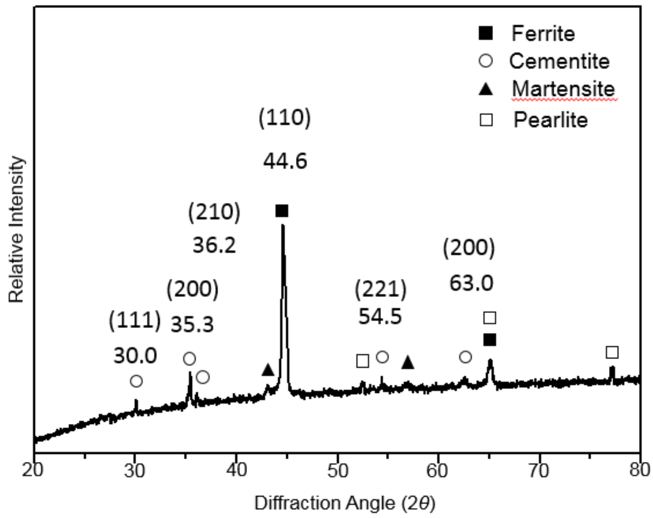
(b) after carburizing (magnifications 5,000)

Figure 12. SEM images of internal structure before and after carburizing(PDH-20).

After carburizing, the diffusion of carbon shows a mixture of martensite and cementite (Fe_3C) structures that contain carbon in a supersaturated state[7]. There are also ferrite and pearlite structures that could not be transformed into martensite. The reason for this is considered to be the influence of the element which suppresses and refines the change to the pearlite structure such as the alloying elements Mn and Si. On the surface, a needle-like martensite structure and a central layer of pearlite structure were observed[8].



(a) SCR-420H



(b) SCR-415H

Figure 13. XRD spectrum of chromium alloy steels after carburization.

This is because the amount of carbon is changed through carburization and diffusion during the heat treatment. Accordingly, it was confirmed that PDH-20 and CSS-15, which are automotive parts, were changed from ferrite and pearlite crystal

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structure to martensite crystal structure according to the standard of parts. Figure 14 shows the results of EPMA analysis of the carburized surface carbon content for chromium molybdenum alloy steels. In the EMPA analysis, the carbon content was the highest at the surface and the carbon content tended to decrease little by little. In the vicinity of the surface containing a large amount of carbon, Cr bonds with carbon and forms Cr carbide(Cr23C6, Cr3C2, etc.). This is because carbon reacts with Fe and Cr as it diffuses inward from the outside[9,10,11].

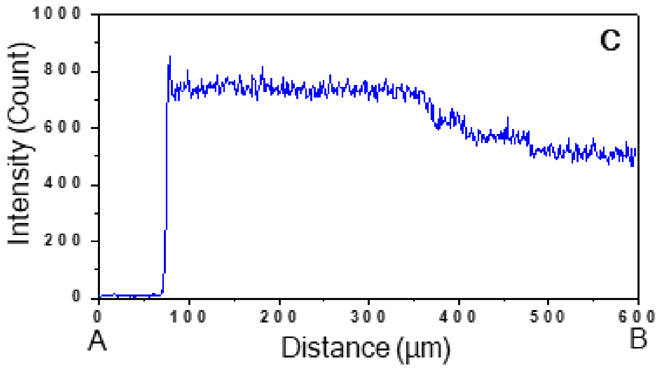

Figure 14. EPMA spectrum of chromium molybdenum alloy steels(PDH-20) after carburization.

3.2. Mechanical property analysis results

Figure 15 shows the results of measuring hardness distribution by carburizing depth after heat treatment on SCR-420H and SCR-415H specimens. The hardness change according to the carburizing depth of the specimen was measured using the micro-Vickers hardness tester. In the carburized layer, the load was measured at a load of 1000 g and a load time of 10 seconds. After measuring ten times for each depth, the average hardness was obtained and measured twice at different parts of the same materials.

Table 4 shows the result of comparing the hardness value required by the automobile drive unit with the heat treatment hardness value of chromium alloy steel. For SCR-420H specimens, the hardness value before carburization was 155~161Hv from the surface to the inside and the hardness value was constant throughout the range.

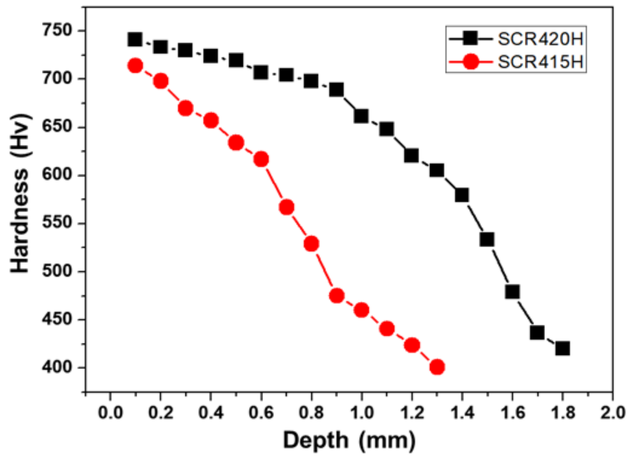

Figure 15. Hardness distribution of SCR-420H and SCR-415H.

However, after heat treatment, the hardness ranged from 741 Hv to 420 Hv. The hardness value on the specimen surface was increased up to 4.8 times, and the hardness value increased by 2.7 times at the carburizing depth of 1.8 mm[12]. SCR-415H specimens had Vickers hardness values of 175~184 Hv before heat treatment and 714~401 Hv after carburization. The hardness value of the gas-carburized chromium alloy steel increased 4.08 times at the surface and 2.29 times at the carburization depth 1.3 mm. As a result of heat treatment on SCR-420H and SCR-415H specimens, it was found that the difference in hardness value between the surface and inside was related to the carbon penetration and diffusion due to carburization[13]. These results are in agreement with the results of EDS and EPMA component analysis. As a result of analyzing the hardness of the PDH-20 specimen, it was found that the surface hardness increased rapidly after carburization than before carburization. From the 0.4 mm point on the specimen surface, the hardness decreased sharply and the carbon content

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Table 3: Standard and measurement results of the automotive driving parts

specimens	Standard			Measurement results		
	Carburizing depth (Hv513,mm)	Surface hardness (HRC)	Internal hardness (HRC)	Carburizing depth (Hv513,mm)	Surface hardness (HRC)	Internal hardness (HRC)
SCR-420H	1.3~1.7	58~63	25~45	1.54	61	35
SCR-415H	0.7~1.0	58~63	25~45	0.83	60	32

gradually decreased as the depth of carburization increased. The hardness value before and after carburization of the CSS-15 specimen is about 16 Hv lower than the hardness of the PDH-20 specimen. The reason why the hardness value after carburizing is small may be related to carburizing condition, diffusion condition and carburizing depth.

4. Conclusion

The purpose of this study is to analyze the factors affecting carburization to improve the durability of chromium alloy steel and chromium molybdenum steel used in automobile driving parts. In chromium alloy steel and chromium molybdenum alloy steel, the carbon content has a significant effect on carburization. It was found that the martensitic structure in the chromium alloy steel contributed to the surface hardness. The amount of carbon gradually decreased from the surface to the inside, and a sharply decreasing area was also identified. In terms of economics, in order to reduce the carburizing time and the diffusion time, it was effective to increase the carburizing temperature and increase the carbon potential by adding propane gas to RX-Gas. In future studies, there is a need for experiments on abrasion resistance, corrosion resistance and deformation.

5. Acknowledgment

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