

Investigation of Decarburization of Spring Steel During Hot Rolling

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Spring steels are high-quality materials widely used in the automotive, railway and manufacturing industries. To ensure high product quality, the wire rod must exhibit superior surface conditions. Decarburization is a critical parameter that significantly affects surface quality and reduces fatigue strength performance. In this study, the development of the decarburization structure in spring steel during hot rolling was investigated; the focus has been on when cooling covers were both in open and closed positions during the process of laying head.

Introduction

The iron and steel industry has been a cornerstone of the global economy since the Industrial Revolution. Today, it continues to lead the way in the development of many industries. Iron and steel products are widely used in various sectors such as automotive, construction, defense, machinery and energy. They are manufactured in both finished and semifinished forms and are exported to various markets around the world. Spring steel is one of them. Due to its high mechanical strength and excellent flexibility, spring steels are particularly preferred for suspension systems, elastic components and dynamic load-bearing parts in the automotive and mechanical engineering industries.¹

For spring steels to be reliable and long-lasting, they must have a very high surface quality and excellent mechanical properties. The spring material should have high fatigue strength, good elasticity and resistance to breakage. Besides the chemical composition, the manufacturing processes such as rolling and heat treatment play a critical role in achieving these properties. In this context, it is important to control the production processes of the semifinished products to ensure that the spring steels have the desired mechanical and surface properties.^{2,3}

Decarburization is a concept that occurs when carbon is lost from the surface of steels rolled at high temperatures and has a negative effect on mechanical properties. That usually happens when the steel is heated above the recrystallization temperature and is exposed to mainly oxygen and hydrogen, making carbon to react and diffuse out of the surface. Loss of carbon on the surface can reduce the hardness and strength of the material. It can also reduce fatigue strength and, in the long term, reduce service life.⁴

In the literature, most studies on the decarburization process have focused on the effect of heat treatment. There is very little research on the structure of decarburization during the rolling process.⁵ It is therefore necessary to characterize the decarburization structure of hot-rolled spring steels before heat treatment. Qin et al. reported that complete decarburization of 55SiCrA spring steel can be prevented by setting an appropriate final rolling temperature and slab temperature.⁶

In the same context, this study investigates the effects of the hot rolling process on the decarburization characteristics of 54SiCr6 spring steel. To this purpose, the depth of decarburization and the structural variation of the material surface under different rolling parameters were analyzed in

detail. The results of the study will provide a better understanding of the decarburization mechanism in the hot rolling process and is expected to contribute to optimization processes aiming to improve the surface quality of spring steels. For this purpose, $\text{Ø}13\text{-mm}$ diameter commercial hot-rolled wire with a chemical composition of 0.59 C, 0.80 Mn, 1.60 Si, 0.80 Cr, 0.025 P and 0.025 S was used as sample material. The evolution of surface decarburization during hot rolling has been studied by analyzing the changes in the decarburization layers in different zones. In this scope, many metallographic analysis and hardness measurements were conducted. The experiment was done on $\text{Ø}13\text{-mm}$ coil, which is rolled from $150 \times 150\text{-mm}$ billet. The sampling locations were at the $\text{Ø}90\text{-mm}$ 1st shear, $\text{Ø}50\text{-mm}$ 2nd shear, $\text{Ø}20\text{-mm}$ 4th shear and the final product itself.

Experimental Procedures

The normal production process of 54SiCr6 spring steel in Kardemir Karabük Iron and Steel Works high-speed wire rod plant is shown in Fig. 1. The steel selected for this study is wire rod coil of $\text{Ø}13\text{ mm}$, which is the final product that comes out after cooling in the finishing mill and cooling line. The industrial tests were carried out in two different ways; with the covers on closed and open positions. During the hot rolling process of the wire rod, the temperatures of the sampling locations were measured by hand pyrometer.

For microstructural examination, all samples were mounted, polished and etched with Nital of 4% by volume. The microstructures were observed using a Zeiss Axio Imager light microscope. Measurement of the decarburized depth was conducted using the metallographic method in accordance with the national standard of Turkey, TS EN 10089. The Vickers microhardness of the decarburized layer was measured using an Emcotest Duravision 70 Vickers hardness tester. The hardness

Figure 1

Schematic diagram of production process of spring steel at Kardemir high-speed wire rod plant.

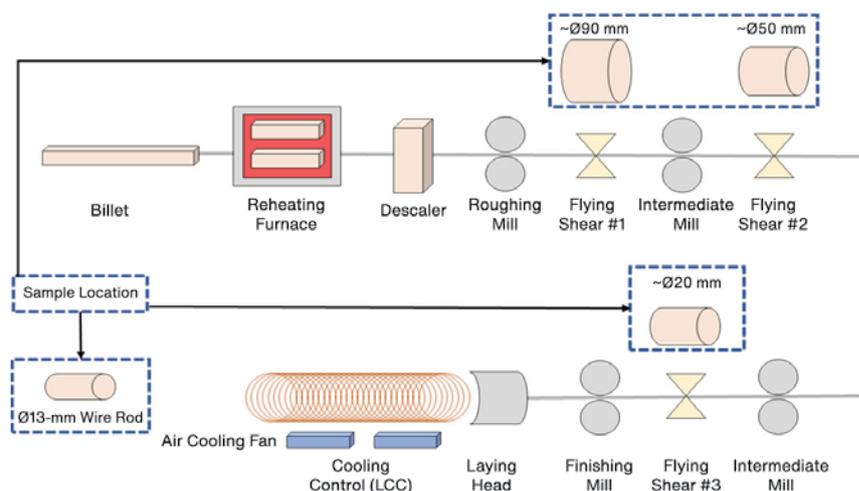
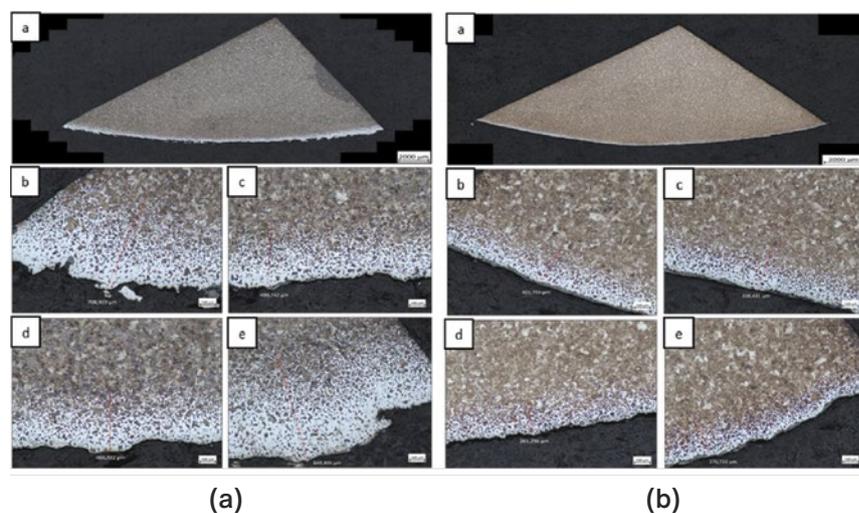


Figure 2

Optical examination of decarburized layer in samples from 1st flying shear (a) and 2nd flying shear (b).



examination of the wire rod was done with the HV5 method at angles of 0° and 90° from surface to surface. The hardness variation from the edge to the center was investigated in areas with both complete and partial decarburization. Additionally, JMatPro software was used in the analysis. The critical transformation temperature and cooling behavior of 54SiCr6 spring steel were calculated with JMatPro software. The critical transformation temperatures including A_{c3} , A_{r3} and equilibrium temperature of transition ferrite to austenite (A_3) were calculated using this software based on the chemical analysis of materials.

Results and Discussion

Evolution of Surface Decarburization

According to the EN ISO 3887 standard for the surface decarburization of steel, surface decarburization is categorized into two main types. These types are defined as complete decarburization and partial decarburization.⁷

With the covers closed, the images of the samples taken from the 1st flying shear and 2nd flying shear are shown in Fig. 2.

Samples from the 4th flying shear and final product are shown in Fig. 3.

With the covers open, images of the samples taken from the 1st flying shear and 2nd flying shear are shown in Fig. 4.

Samples from the 4th flying shear and final product are shown in Fig. 5.

All decarburization layer measurements are given in Table 1.

In the first production scenario, the cooling covers were kept closed, while in the second scenario, production was carried out with the covers open. Microstructural analysis of the samples shows that there are significant differences in decarburization between the two methods. Looking at the final product, a higher level of decarburization was observed in the production process with the covers closed. Fully decarburized areas indicate significant surface carbon loss.⁸ This factor can adversely affect mechanical properties such as fatigue strength and wear resistance. This extensive decarburization is thought to be caused by prolonged exposure of the material to high temperatures and the influence of the furnace atmosphere during production.⁹

A significant improvement in decarburizing depth was observed when producing with the covers open. Literally, the absence of completely decarburized areas indicates that carbon diffusion on the surface is more controlled

Figure 3

Optical examination of decarburized layer in samples from 4th flying shear (a) and final product (b).

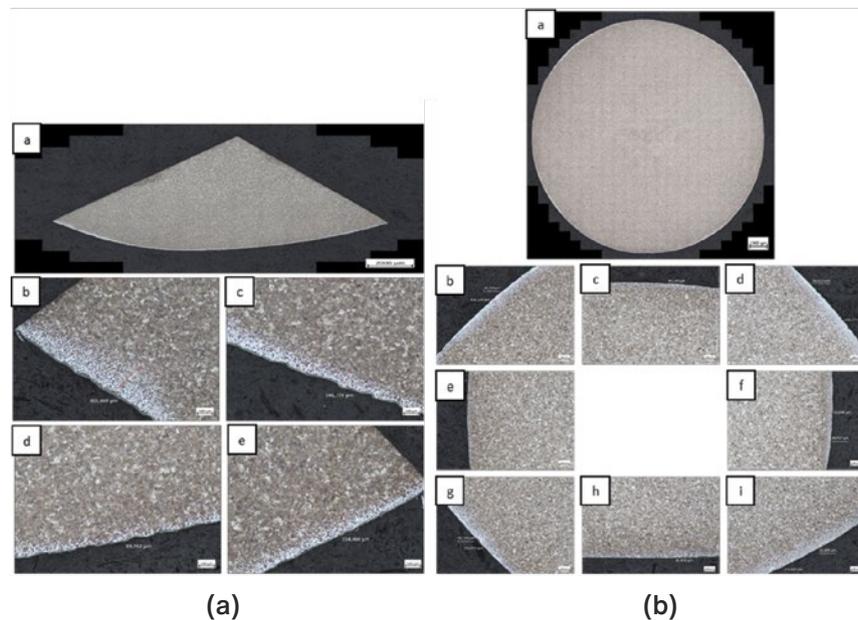
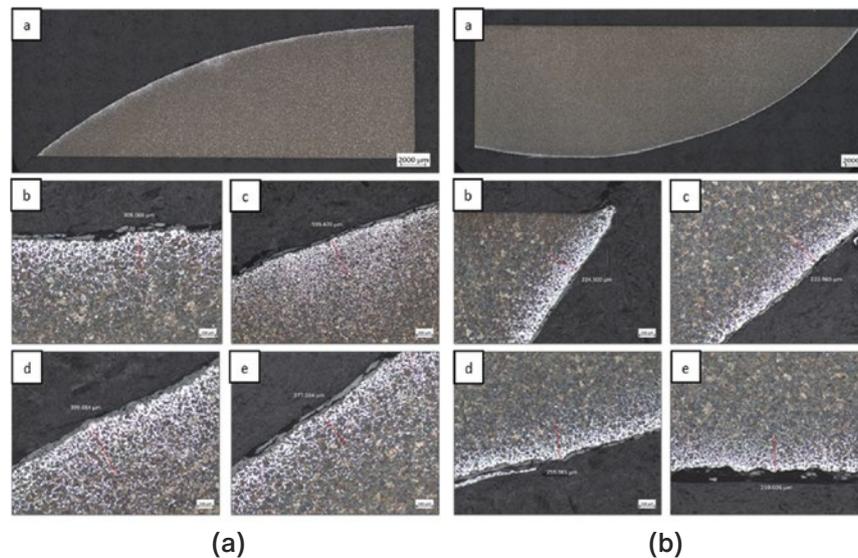


Figure 4

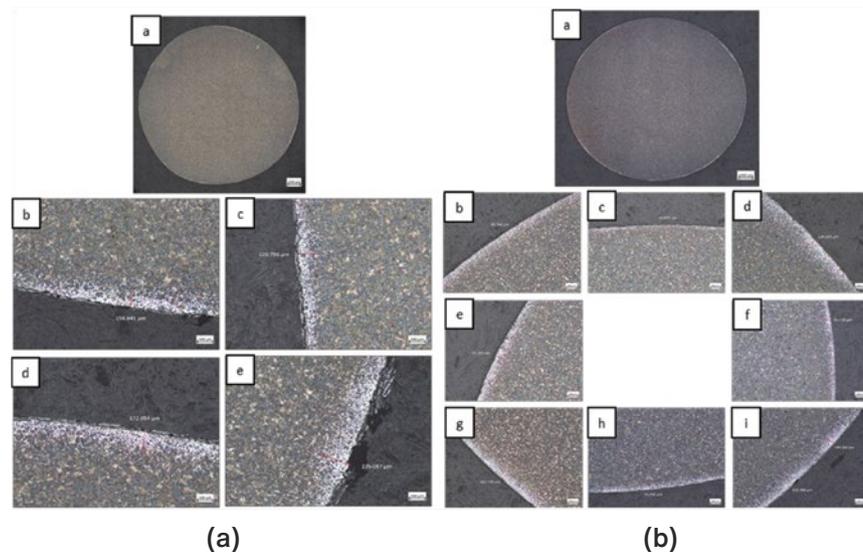
Optical examination of decarburized layer in samples from 1st flying shear (a) and 2nd flying shear (b).



with this method. On the other hand, samples from the 1st, 2nd and 4th shear zones showed improvements in decarburization, too. However, this improvement should not be linked directly to the result of the aforementioned cooling method only. It can be debated that, similar to other factors, such as the impact of changes in the

Figure 5

Optical examination of decarburized layer in samples from 4th flying shear (a) and final product (b).



reheating furnace atmosphere prior to the rolling process, the wait time of the billet in the furnace can also correlate with the depth of decarburization. In the same context, the gas composition in the furnace can limit

carbon loss by influencing oxidation and reduction reactions. Kai and Yinli conducted experimental studies under different atmospheric conditions and found that the oxidizing atmosphere has a significant effect on the decarburization structure.¹⁰ The complete decarburization layer is formed during reheating and rolling. Both production processes should be kept under control.

Hardness Examination

The hardness examination of the wire rod was measured with the HV5 method at angles of 0° and 90° from surface to surface. Hardness measurements HV5 load are given in Fig. 6.

The hardness examination and measured distances in the complete and partial decarburized regions from the surface

center, with the covers closed, are given in Fig. 7a. During the trials with the covers open, only partial

Table 1

Decarburization Layer Measurements (μm)

	Samples	1st M.	2nd M.	3rd M.	4th M.	5th M.	6th M.	7th M.	8th M.	Mean
Covers closed	1. F.S.	708.919	499.742	466.922	849.495	—	—	—	—	631.27
	2. F.S.	301.755	338.431	261.296	276.551	—	—	—	—	294.51
	4. F.S.	305.669	146.776	89.762	154.469	—	—	—	—	174.17
	F. P.	81.820	153.820	70.910	131.140	85.550	183.180	61.650	174.160	117.78
			58.720	—	36.330	—	36.610	20.760	19.080	34.30
Covers opened	1. F.S.	308.066	599.420	399.684	277.034	—	—	—	—	396.05
	2. F.S.	244.500	222.865	259.981	259.026	—	—	—	—	246.59
	4. F.S.	158.841	129.796	172.054	235.087	—	—	—	—	173.94
	F. P.	75.742	130.506	95.739	120.190	44.905	95.744	93.169	101.748	94.72

*Bold text show complete decarburization measurements; F.S.: Flying Shear; F.P.: Final Product; M.: Measurement

Figure 6

Covers closed (a) and covers opened (b) hardness test results at 0° and 90° from surface to surface.

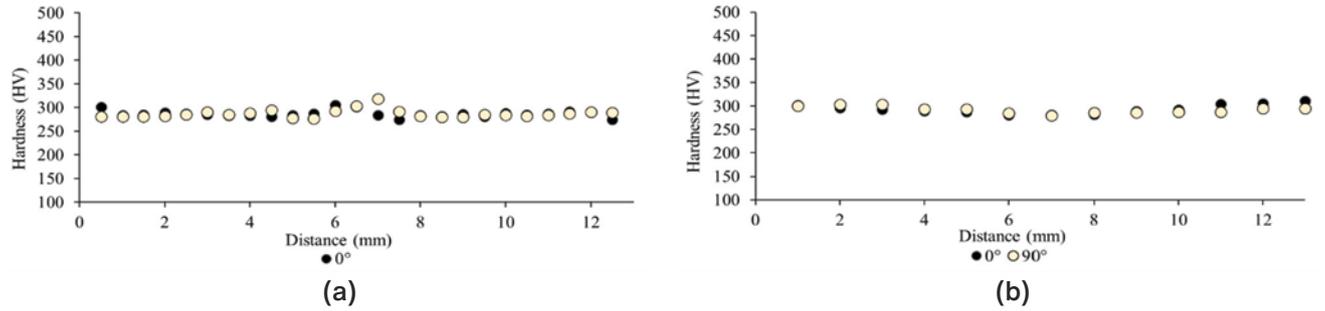
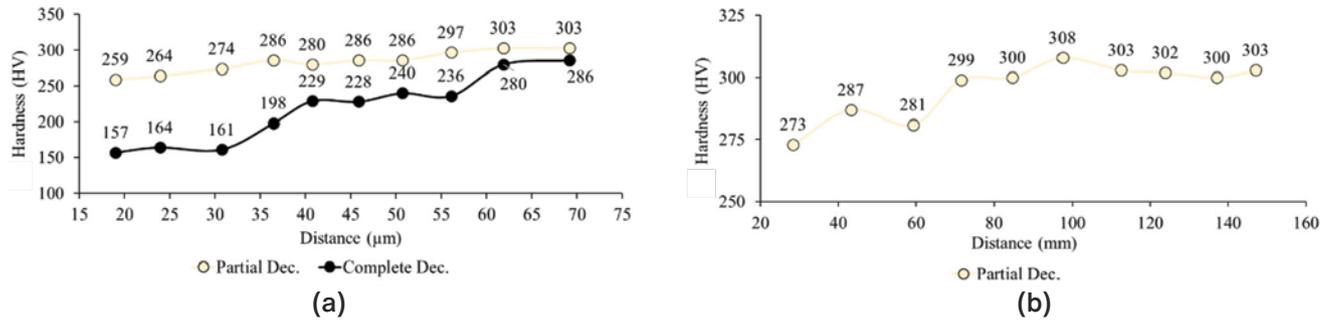


Figure 7

Covers closed, the hardness tests in complete and partial decarburization layer (a); and covers opened, the hardness tests in complete decarburization layer (b).



decarburization was observed, and the hardness examinations can be seen in Fig. 7b.

The hardness measurement results for the final product are given in Table 2. With the covers closed, there was an increase in hardness of 45% from surface to center in the fully decarburized zones and an increase of 9% in the same value within the partially decarburized zones.

In the situation where the covers were open, the hardness value has increased only by 7% from to surface to the center in the regions where partial decarburization was present.

The mechanical properties are negatively affected with the increase in depth of the decarburization layers. Due to surface decarburization, the fatigue limit shows a decline,

Table 2

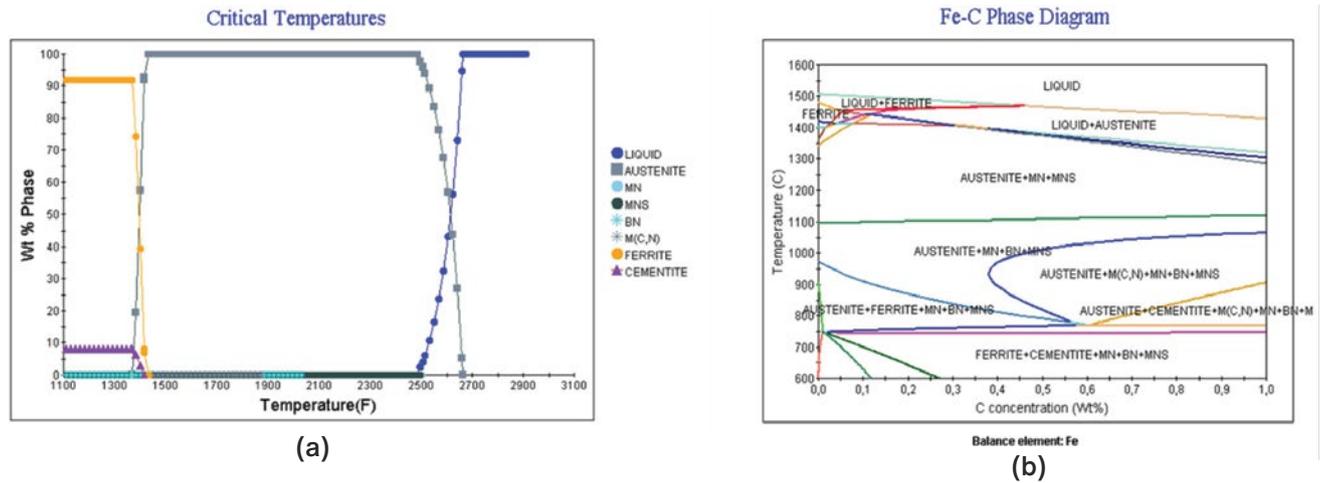
Decarburization Layer Measurements (HV)

	Decarburization types	1st M.	2nd M.	3rd M.	4th M.	5th M.
Covers closed	Partial	259	264	274	286	280
	Complete	157	164	161	198	229
Covers opened	Partial	273	287	281	299	300

M.: Measurement

Figure 8

Critical transformation temperatures (a); and Fe-C phase diagram of 54SiCr6 spring steel (b).



and the rate of this reduction is related to the depth of decarburization.¹¹ A comparison was conducted between the fatigue strength of undecarburized and decarburized materials, revealing significant differences.¹² Dalaei and Höljer investigated the effect of decarburizing on fatigue behavior. The specimens with 0.4–0.5 mm of decarburization show lower fatigue values while the specimen without decarburization shows high fatigue strength.¹³

Analysis of JMatPro Software

In the reheating furnace, due to the high Si content in 54SiCr6 spring steel, decarburization layer on the billet surface is formed easily.¹⁴ According to the iron-carbon phase diagram, the A3 temperature, which is the equilibrium phase transition temperature within the austenite to ferrite transition zone, was calculated by using JMatPro software and was found to be 830°C. The temperature at which the austenite transformation is completed (Ar3) was found to be 790°C. Below this temperature, the phase structure consists of ferrite and cementite. On the other hand, Ac3 is designated as the minimum temperature, above which the phase structure is entirely austenite in practical situation, and this was calculated as 880°C. The finish rolling temperature is also selected to be close to this value. The critical transformation temperatures and Fe-C phase diagram are shown in Fig. 8. Liu and Jiang calculated the temperature of Ac1 and Ac3 theoretically. They calculated the effect on the depth of decarburization. Theoretical and simulation results are relatively similar values in the calculations.¹⁵ In Trzaska's study, he calculated an empirical formula using a data set of about 500 chemical compositions. The formula found by Trzaska gave results closer to the simulation study.¹⁶ However, for the most accurate results, critical

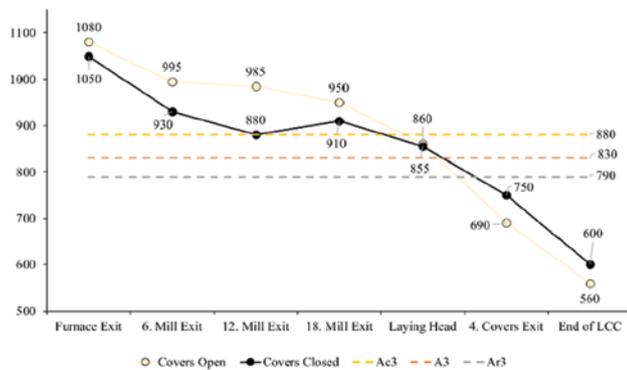
transformation temperatures should be calculated using equipment such as Gleeble.

Based on a study found in literature research, the decarburization structure was investigated during the hot rolling of the spring steel with 55SiCrA quality. This study aimed to identify different types of decarburization structures under various finishing rolling and laying head temperatures. During production, temperatures were monitored, and multiple samples were taken from various points and examined. Accordingly, it is also revealed that a complete decarburization layer can occur during the rolling process as well. This has occurred because, between the 2nd and 10th rolling stands, the surface temperature of the rolled pieces was lower than the Ar3 temperature, which gave rise to the formation of ferrite structure. It can be thought that rolling at this temperature may have provided sufficient time for the transformation of austenite to ferrite, resulting in the formation of complete decarburization on the surface.⁶

In the first trial at Kardemir, when the covers were in a closed position, complete decarburization was detected in the final product samples. As it is also seen in the black line in Fig. 9, the rolling temperatures do not fall below the Ac3 temperature. However, it can be thought that the complete decarburization has occurred in the cooling line during the laying head process because the wire rod material has spent adequate time within the temperature zone of 880°C (Ac3)–790°C (Ar3). This range is the austenite to ferrite transition zone. On the contrary, as seen with the yellow line at Fig. 9, in the second Kardemir trial, when cooling covers were open and therefore the cooling rate was faster, almost no complete decarburization was detected, but a reduction in partial decarburization overall was seen. Thus, it has been determined

Figure 9

Product temperatures for covers in closed and open positions.



that the Ac3 and Ar3 temperatures should be rapidly surpassed in the cooling line.

Another research study supports this topic. In this study, an experiment was performed on a 13-mm-diameter spring steel product, and it is seen that decarburization is reduced by cooling with air.¹⁷ Also one other patented production process refers to a cooling profile of 55SiCrA quality steel. By setting the laying head temperature to $850 \pm 10^\circ\text{C}$, when the first fan group was 50–100% open while the rest is closed, more stable strength and good plasticity was achieved. These could be linked to less decarburization since carburization leads to reduced surface hardness, stress and fatigue performance.¹⁸

However, too much fast cooling can pave the way to a bainite structure formation. This situation can be encountered if faster cooling than the optimum production conditions were to be applied. The formation of phases based on different cooling rates were calculated by using JMatPro software and displayed in Fig. 10.

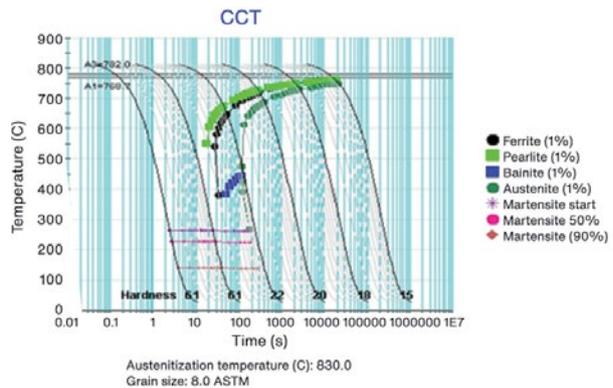
Based on the findings, the cooling process has been adjusted at Kardemir's wire rod mill during the production of 54SiCr6 spring steel. A few covers and fans have been opened in the cooling line to rapidly pass the Ac3 and Ar3 temperature range to obtain with a reduced and partially decarburized microstructure.

Conclusion

The following conclusions can be drawn from the investigations on the effects of hot rolling temperature and

Figure 10

Continuous cooling transformation for 54SiCr6 quality.



cooling rates on partial decarburization and the complete decarburization during the rolling of 54SiCr6 spring steel:

1. During hot rolling, the 54SiCr6 microstructure should be in the austenite phase and therefore should not drop below the Ac3 880°C temperature.
2. In the first trial, when the covers were closed, complete decarburization was detected in the final product. It was found that the complete decarburization occurs within the temperature range of Ac3 at 880°C and Ar3 at 790°C, when the austenite to ferrite phase transformation is happening. In the second trial, a successful rapid transition was achieved by opening the covers and fans. Therefore, it was determined that this range in the cooling line should be rapidly passed.
3. On measurements of hardness as a function of distance from the surface area inwards, a 45% increase in value was detected at fully decarburized areas and a 9% increase in partially decarburized areas. When the covers were in an open position, the fully decarburized areas were barely detected and hence surface-to-center hardness testing revealed only a 7% difference in hardness within the partially decarburized areas.

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