Development of Pre-heating Spheroidization technology for Cr-added Low Alloy Steel

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The temperature range between A_{C1} and A_{C3} of low alloy steel is narrow, and consequently often leads to an unacceptable level of spheroidization. The distribution of cementite particles in steel coils could be improved by re-spheroidizing, but it would increase the cost and time. The pre-heating and slow ramping parameters were introduced, which helped stabilize the growth of Cr-contained carbides $(Fe, Cr)_3C$ at soaking temperature. When the coils were heated above A_{C1}, $(Fe, Cr)_3C$ still remained in the residual austenite matrix. During slow cooling, the cementite newly precipitated at the undissolved $(Fe, Cr)_3C$, which served as the nuclei, and formed an ideal globular cementite. By performing the new process, the re-spheroidizing ratio was reduced from 6.1 % to 0.8%, and it brought an estimated cost reduction of 2.72 million $NTD per year.

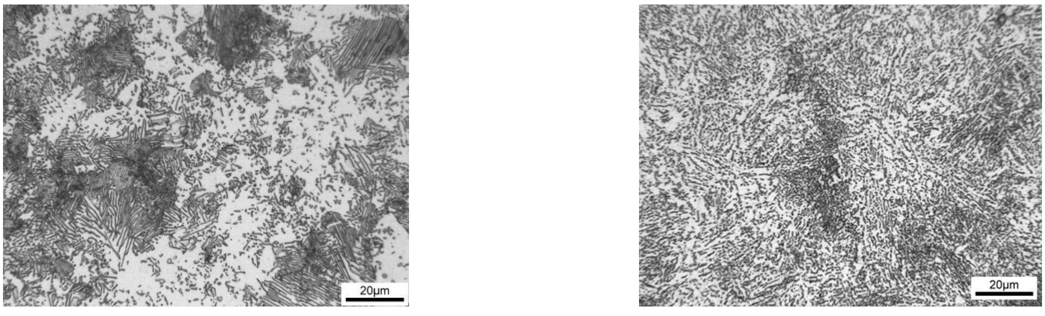
Keywords: Spheroidized annealing; Pre-heating; Cr-added low alloy steel; Re-spheroidizing ratio

1. INTRODUCTION

Spheroidization aims to improve the formability of steel and lower the deformation resistance during cold working, so it is widely used in the manufacturing of high-strength and high-toughness hand tools, fasteners, etc. Without adequate heat treatment, in which spheroidization is insufficient, the carbides are either unspheroidized or distributed unevenly, it may result in cold-heading crack. Although the disqualified steel coils can be retrieved by re-spheroidizing, it is costly both in terms of time and energy.

Wire coils usually use the intercritical process for spheroidized annealing, which heats the steel to a constant temperature between A_{C1} and A_{C3}, to promote the dissolution of carbides. When the subsequent slow-cooling or holding below A_{C1}, when driven by the reduction of interfacial energy of ferrite and cementite, the precipitated carbides tend to transform into a spheroidized morphology. Nevertheless, the temperature range between A_{C1} and A_{C3} of low alloy steel was narrow, which limited the process window, and thus a sufficiently spheroidized structure was considered hard to achieve.

At the soaking stage, if the temperature or the time was excessive, the austenite became homogenized, and followed by slow-cooling it would transform into lamellar pearlite as shown in Fig.1a. On the other hand, if the temperature or time was not enough, the carbon constituted from hot-rolled structure wouldn't be well dissolved, and the residual pearlite preserved in state at the



(a) (b)

Fig.1. Undesirable microstructure after spheroidization **(a)** lamellar pearlite **(b)** residual pearlite.

end of the heat treatment as shown in Fig.1b.

Figure 2 shows the relationship between the austenitizing rate and temperature of the eutectoid steel. When the temperature was higher than A_{C1}, the pearlite would gradually transform into austenite. Higher temperature resulted in faster transformation. At the beginning of the reaction, pearlite hadn't been completely dissolved. As time went by, the residual pearlite would mostly transform into austenite, which still contained some fragmented carbides inside. After further heating, the remaining carbides fully dissolved in the austenite, whereas the austenite formed a carbon concentration gradient. Finally, the carbon concentration gradient was gradually eliminated by prolonged annealing time, and homogeneous austenite would be obtained.

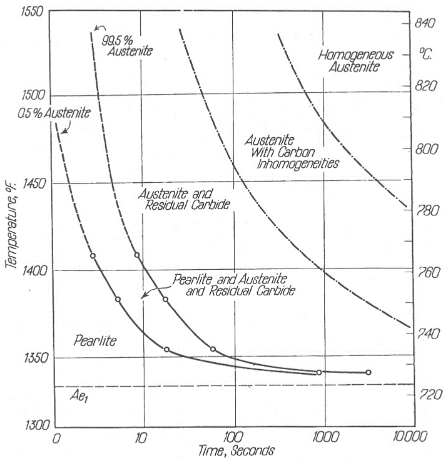


Fig.2. Austenitizing rate temperature curves for commercial simple-carbon eutectoid steel.[4]

If the spheroidization temperature and time were appropriate, austenite and residual carbides would be formed. The residual carbides during slow-cooling could develop the formation of granular carbides and enhance the level of spheroidization. In other words, if the stability of carbides were raised, the range of "austenite and residual carbides" could be expanded and result in the demanded spheroidized morphology.

According to the JMatPro® simulation results, when Cr content in low alloy steels increased, the cementite solution temperature increased simultaneously as shown in Fig.3. In other words, cementite enriched with higher Cr led to greater stability of the carbides (Fe, Cr)$_3$C.

Fig.4 illustrates the element fraction in cementite changed with temperature in the JmatPro® simulation. When Cr-added low alloy steels were heated closer to A_{C1} (740°C), the content of Cr in (Fe, Cr)$_3$C increased. In this manner, higher solid solution temperature was reached, and thus improved the stability of (Fe, Cr)$_3$C.

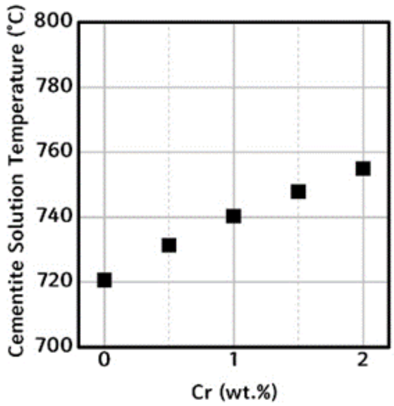


Fig.3. Cementite solution temperature varied with Cr content by using the JMatPro® simulation.[2]

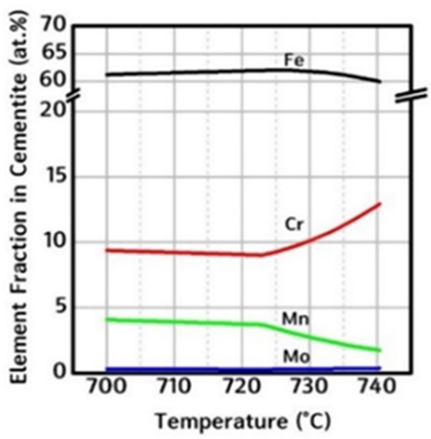


Fig.4. Element fraction in cementite changed with temperature by using the JMatPro® simulation.[2]

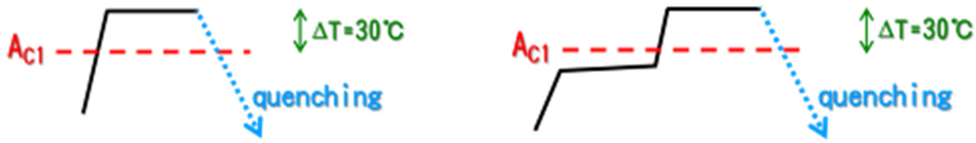
As a result, if the spheroidized annealing was preheated below A_{C1}, and followed by a slow ramping process to the soaking temperature, (Fe, Cr)$_3$C would tend to remain in the austenite matrix and served as nucleation sites of spheroidized carbides afterwards. Those sites induced carbon to precipitate during slow-cooling, and promoted to form an ideal globular cementite. By improving the stability of the nucleation site, it provided a wider processing window.

2. EXPERIMENTAL METHOD

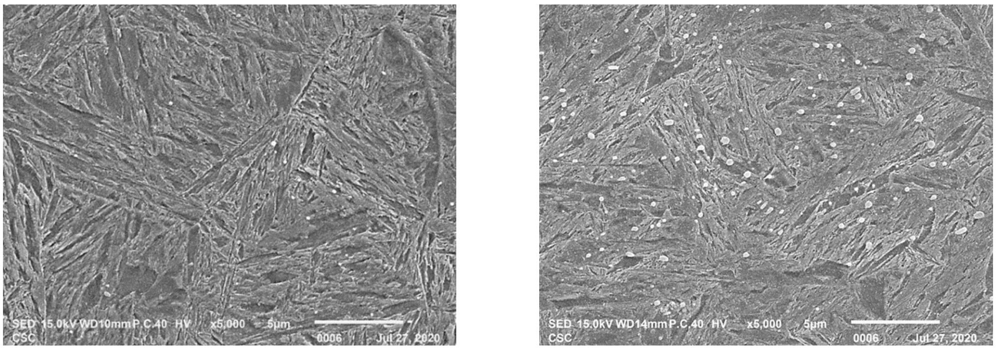
2.1 Verify the Simulation Results

To verify the pre-heating effect in the aforementioned research, two different heating paths were conducted as shown in Fig.5. As can be seen in Fig.5a, direct ramping to A_{C1} formed a homogeneous austenite. On the contrary, by performing a pre-heating parameter below A_{C1}, Fig.5b presents that there are many scattered white spots, which are carbides. This provided empirical evidence suggests that a pre-heating process could

Heating path

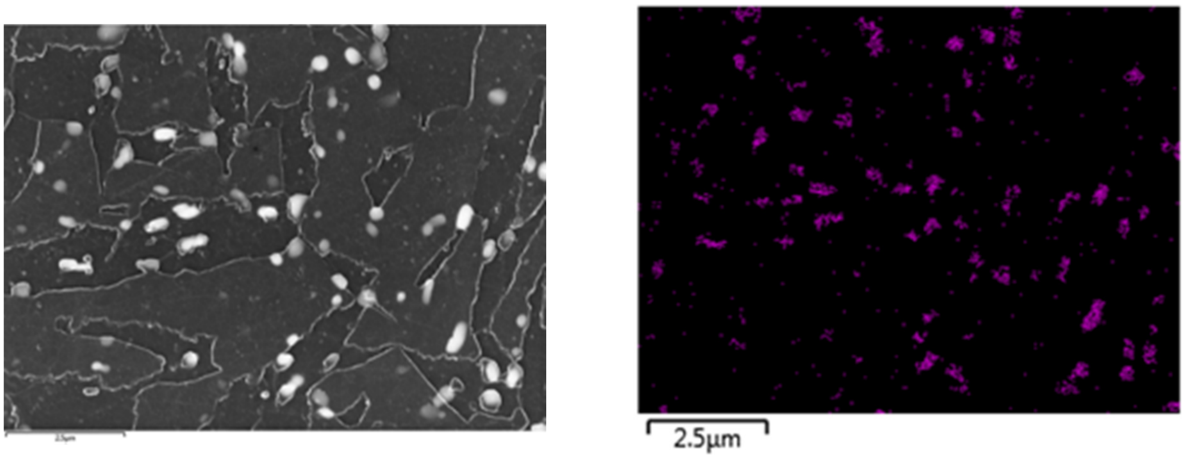


Micro-structure



(a) (b)

Fig.5. Microstructure after quenched by performing different heating paths.[2]



(a) (b)

Fig.6. The SEM images of Cr carbides (a) microstructure (b) EDS analysis.[2]

enhance the Cr content in $(Fe, Cr)_3C$, which could maintain the stability of carbides. Therefore, it kept the nucleation sites remaining at high temperature. Energy-dispersive X-ray spectroscopy was examined to analyze the composition of the carbides shown in Fig.6, it could be confirmed that Cr content in the carbides was significantly higher than the matrix.

2.2 Experimental Design

SCM435 with mass production was selected as the material for experiment. In order to obtain the optimum annealing pattern, a two-stage test was used to evaluate the spheroidization effect, as shown in Fig.7. As compared to the original spheroidized annealing pattern, Pattern A reduced the soaking temperature by 10°C . To expand the process window, Pattern B applied a pre-heating stage and slow ramping process.

3. RESULTS AND DISCUSSION

When the original annealing pattern was employed, the lamellar pearlite was observed dominantly in morphology. This could be due to the influence of overheating at soaking temperature. Thus, the soaking temperature of Pattern A was reduced by 10°C compared with the original annealing pattern. As can be seen in Table1, the spheroidization rate valued 4 in Pattern A. Agglomerated lamellae pearlite was formed, as shown in Fig.8a. The phenomenon implied that Pattern A is still with overheating temperature or excessive time.

Total process time of Pattern B was the same as Pattern A, but the pre-heating time was extended with the shrinkage of soaking time. By introducing pre-heating and slow ramping parameters, the process window was expanded, and therefore improved the stability of (Fe, Cr)$_3$C. It also helped prevent local over-heating in the furnace from rapid heating. As expected, it was observed that variations in the rates of spheroidization was eliminated as measured at different positions in the furnace. It implied that finer spheroidization rate and lower hardness were both obtained after imposing pre-heating and slow ramping parameters.

Since the improvement effect was assured, the novel technology was facilitated in five Cr-contained alloy steels, namely SCM435,SCM440, 6150, 8620, 8660. Table 2 presents the statistics of the spheroidized quality with original and new process. Except 8620, the spheroidization rate of all steel grades enhanced, and the standard deviation declined. Though average value of hardness increased slightly, the standard deviation reduced, especially for SCM435 and SCM440. The increase in the spheroidization rate, and the decrease in the standard deviation conduced to the reduction in re-spheroidizing ratio.

The pre-heating technology of spheroidization was initially applied to SCM440 in 2019, and then applied to other Cr-added low alloy steels in 2020. Fig.9 shows that re-spheroidizing ratio had decreased year by year, and the cumulative average re-spheroidizing ratio in 2021 had dropped from 6.1% to 0.8%. It was estimated to boost production by 1,100 tons per year, and reduced costs by 2.72 million $NTD per year.

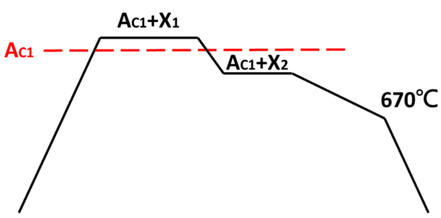
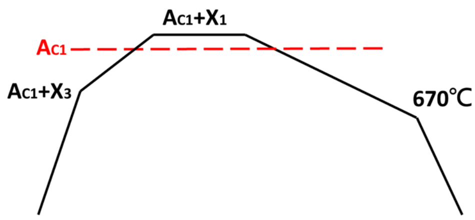
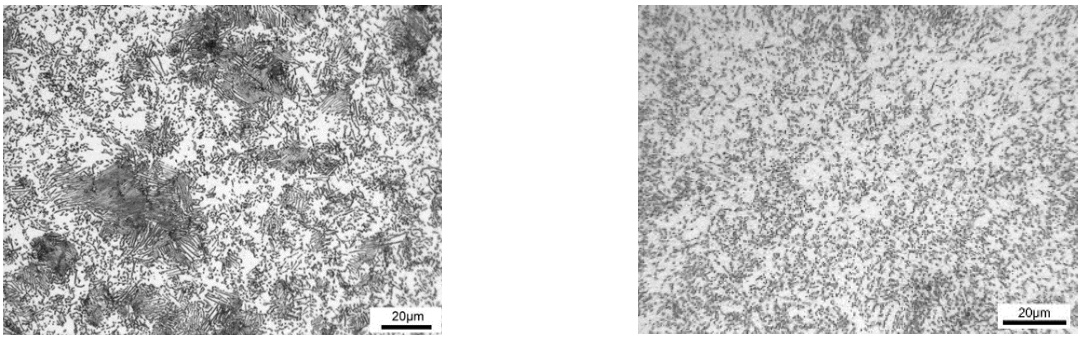
	A	B
Spheroidized annealing pattern		

Fig.7. Spheroidized annealing patterns.

Table 1 Experimental results of different spheroidized annealing pattern.

Pattern	A		B	
Quality index	spheroidization rate	hardness (HRB)	spheroidization rate	hardness (HRB)
Values	4	87.5	2	85.8



(a) (b)

Fig.8. The microstructure acquired from different spheroidized annealing pattern (a) Pattern A (b) Pattern B.

Table 2 Quality index with each grade steel.

Steel grade	Original process		New process	
	spheroidization rate	re-spheroidizing ratio	spheroidization rate	re-spheroidizing ratio
SCM435	2.0±0.9	5.6%	1.7±0.6	0.4%
SCM440	2.1±0.8	4.3%	1.8±0.5	1.8%
6150	1.6±0.7	2.3%	1.6±0.4	0.5%
8620	2.3±1.0	12.1%	2.4±0.9	8.7%
8660	1.9±0.8	2.4%	1.5±0.4	0.7%

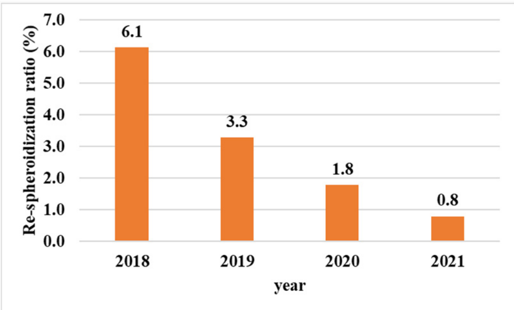


Fig.9. Re-spheroidizing ratio.

4. CONCLUSIONS

Simulation and empirical experiments provided crucial evidence for the effect of stability of residual carbides at soaking temperature. It indicated that imposing a pre-heating stage to Cr-contained steel could expand the process window. Through trial production, metallographic test, and facilitating the new process over a long period of time, it was confirmed that the pre-heating technology can effectively improve the quality of spheroidization for Cr-added low alloy steel.

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