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Dynamic Cooling Process Control Technology for Stabilized High Tensile Strength Wire Rod

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The mechanical property of wire rod is influenced by chemical composition and cooling conditions in the Stelmor cooling process. Although the composition range is controllable, the variation obviously affects the mechanical properties, especially for compositions near a specific limit. In the past, engineers had to artificially adjust the cooling speed to stabilize the mechanical properties. Chinese Steel (CSC) established a Composition Strength Index (CSI) to evaluate the correlation between composition and Tensile Strength (TS). Through evaluation, the dynamic cooling process has reduced the TS of the composition near the upper specification limits of wire rod as compelled by customer requirements. CSC merges the CSI models and cooling conditions into a Programmable Logic Controller (PLC) system, and has successfully developed a dynamic cooling process control technology.

Keywords: High tensile strength wire rod, Dynamic cooling control technology, Industry 4.0

1. INTRODUCTION

The high Tensile Strength (TS) wire rod has been widely used in the fields of high-strength construction, usually applied to wire ropes, precision springs, bead wires and PC wires. In order to keep stability whilst being drawn, the raw materials require stable TS and micro-structure, which are influenced by chemical composition and cooling conditions after hot rolling in the Stelmor conveyor. The effect of the carbon content and other alloy elements on micro-structural features and mechanical properties was investigated, it shows that TS is significantly influenced not only by inter-lamellar spacing but also by the carbon content in fully pearlitic steel(1). Alloying approaches to refine pearlite inter-lamellar spacing have included alloying with some elements, such as chromium, molybdenum, vanadium, and silicon(2-4). The variation of composition will shift the Continuous Cooling Transformation (CCT) curve, resulting in the change of pearlite transformation temperature.

The correlation between TS and micro-structure under different cooling conditions after hot rolling was fully studied. Research showed that a different mean lamellar spacing and TS were observed due to the transformation of austenite to pearlite during different cooling conditions(5). It was noted that in continuous cooling condition, as the cooling rate of steel is decreased, the pearlite transformation temperature is increased, therefore resulting in coarsened pearlite lamellar.

Although the chemical composition range is controllable, the variation obviously affects the mechanical property, especially for compositions near a specific limit. In the past, engineers had to artificially adjust cooling conditions to stabilize the TS. With the trends of industry 4.0, this research attempts to investigate the TS of high carbon wire rod in relation with chemical composition, establishing the Composition Strength Index (CSI), and combines it with PLC system to develop a dynamic cooling process control technology.

2. EXPERIMENTAL METHOD

2.1 Experimental material

The material used in this research was Stelmor cooled wire rod with NLP82B and SWRH62A, whose TS specification limit ranges from 116(kg/mm^2) to 129(kg/mm^2) and from 88(kg/mm^2) to 98(kg/mm^2) respectively.

2.2 Cooling process

Figure 1 shows the Stelmor conveyor at ROD 2 Mill. The total length of the conveyor is 102m, which can be divided into ten cooling zones. Each zone is equipped with cooling fans to provide forced air cooling for the coils, and each fan is connected via a plenum chamber at the bottom of the conveyor deck as shown in Fig.2[6]. The air flows through a series of nozzles on the deck and up through the coil to complete the air-cooling process.

2.3 Statistical analysis

To establish CSI, the TS data set was used to form a regression equation with the TS of aimed materials produced at CSC ROD2 Mill in recent years as independent variables and the correspondent composition as the dependent variables. Through statistical analysis, the contribution of each element to the TS can be determined, thus the correlation between TS and composition of high carbon wire rod can be established.

Fig.1. The Stelmor conveyor in the ROD2 Mill at CSC.

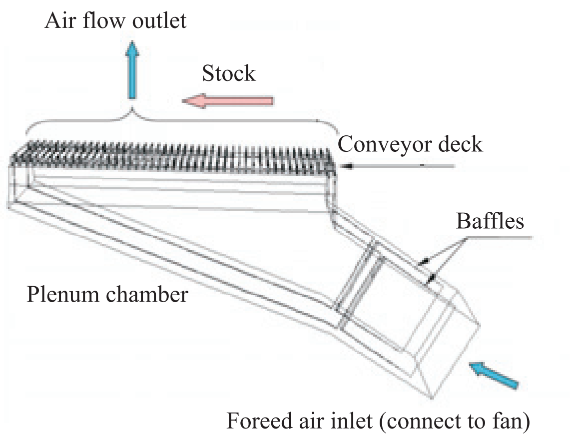

Fig.2. Assembly of a single plenum Stelmor air conveyor system.

2.4 Model evaluation

To evaluate the accuracy of the CSI, two sets of cooling conditions for the experiments were designed, one was the standard cooling condition, and the other was the slower cooling condition. Considering the variation of TS is extremely sensitive to cooling conditions, and the goal of this research is to stabilize the TS, we selected the opening degree of the fans as factors, and a infrared pyrometers was used to capture the surface temperature profile of wire rods in the Stelmor cooling process. Furthermore, we used a Scanning Electron Microscope (SEM) to observe the inter-lamellar spacing. The following cooling conditions for NLP82B and SWRH62A were applied as per Table 2.

3. RESULTS AND DISCUSSION

3.1 Statistical analysis

The statistical analysis was carried out by stepwise regression, and the coefficient and p value (<0.05) of the effect of the variables on TS are as shown in Table 2. The terms of full model having non-significant p value ($p>0.05$) have negligible contribution. The equations represent the quantitative effect of each element on the TS, and the positive and negative sign represent the effect on the TS. The results are in section 3.1.1.

Table 1 Chemical composition of material

Chemical composition of aimed material, wt-%					
Steel	C	Si	Mn	P	S
NLP82B	0.79~0.85	0.15~0.35	0.60~0.90	0.025max	0.025max
SWRH62A	0.59~0.66	0.15~0.35	0.30~0.60	0.030max	0.030max

Table 2 Cooling conditions of aimed materials

	Condition	Laying temperature (℃)	Opening degree of fans
NLP82B	standard	880	#1 to #10 100%
	slower		#1 100%, **#2 to #10 90%**
SWRH62A	standard	840	#1 to #4 90%, #5 to #10 70%
	slower		**#1 to #4 80%**, #5 to #10 70%

3.1.1 NLP82B

TS = 42 + 849[C] + 528[Mn] + 465[Mo] + 446[Cr] ....(1a)

Then the equation can be rearranged as

(TS-42) / 849 = [C] + (528 / 849)*[Mn] + (465 / 849[Mo] + (446 / 849)*[Cr] .... (1b)

CSI=C+0.62[Mn]+0.55[Mo]+0.53[Cr] ....(1c)

Equation (1c) indicates that the dominant element of TS is C, Mn, Mo, and Cr in sequence, all of them have a positive contribution to the TS, and the R^2 value of the fitted equation is 0.69 as shown in Fig.3.

3.1.2 SWRH62A

TS = 233 + 937[C] + 180[Mn] + 4936[Ti]+ 497[Ni] + 174[Cr]-108[Al]...............................(2a)

Then the CSI can be defined as

CSI=C+0.2[Mn]+5[Ti]+0.5[Ni]+0.2[Cr]-0.1[Al].....(2b)

Equation (2b) indicates that the dominant element for TS is Ti, C, Ni, Mn, Ni, Cr, and Al in sequence. All of the elements have a positive contribution to the TS, only Al having a negative contribution, and the R^2 value of the fitted equation is 0.79 as shown in Fig.4.

Furthermore, through distribution analysis of CSI, we regard the data which is out of ±1.5σ as the outliers. Therefore, the acceptable CSI range is set to 1.35~1.40 and 0.73~0.76 for NLP82B and SWRH62A, respectively.

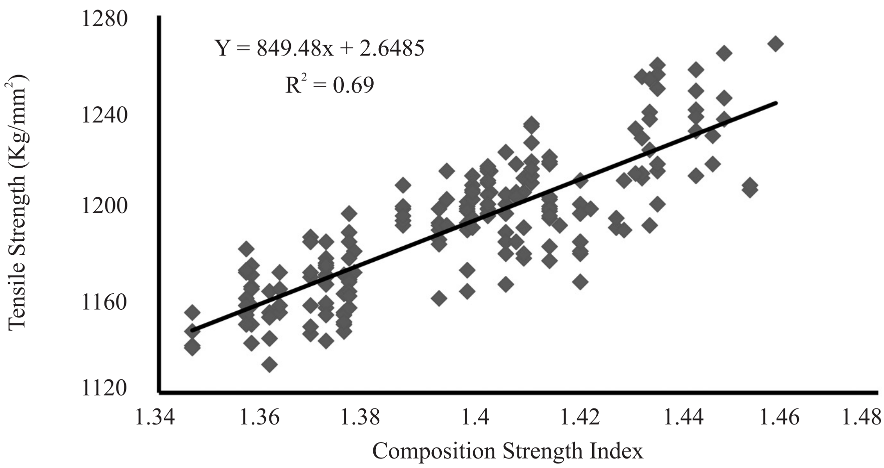

Fig.3. The correlation of NLP82B between CSI and TS.

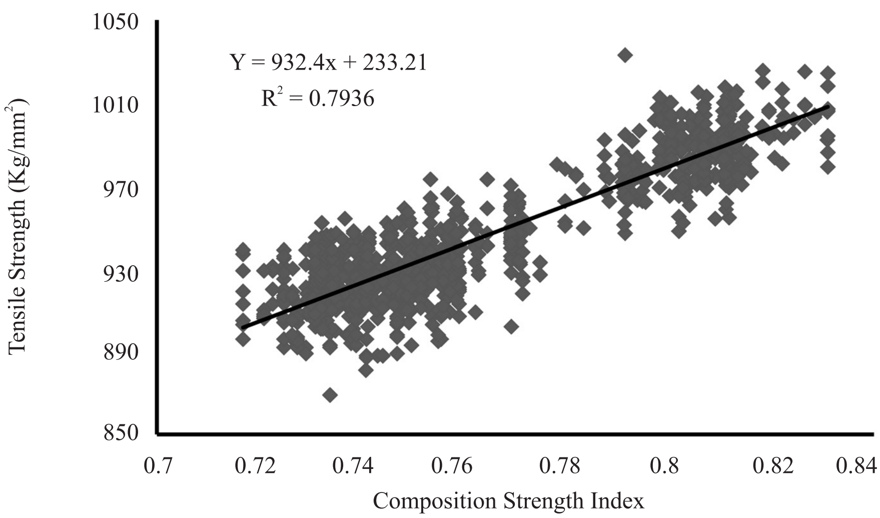

Fig.4. The correlation of SWRH62A between CSI and TS.

3.2 Evaluation result of CSI

To evaluate the accuracy of the CSI, we picked up two outliers whose values were 1.41 and 0.78 respectively for NLP82B and SWRH62A, whose TS were predicted to be out of specification, and cooling conditions were applied as described earlier.

3.2.1 TS test

The TS and cooling rate are presented in Table 4, it shows that in the standard cooling condition, the TS of the materials are out of the upper specification limit: 133kg/mm^2 and 100kg/mm^2 respectively, which were well predicted in the CSI model. While in the slower cooling condition, the results showed the TS can be reduced to the specification, which indicates that the high-risk materials undergoing pearlite transformation at higher temperature at a slower cooling rate can reduce the TS, as described before.

3.2.2 SEM inspection

A Scanning Electron Microscope (SEM) was utilized to investigate the pearlite structure of the sample. Figure 5, 6 and Table 4 show the inter-lamellar spacing of NLP82B and SWRH62A under different cooling conditions, exhibiting that a suitable inter-lamellar spacing is acquired while transformation of austenite to pearlite occurs at slower cooling conditions, which is in accordance with the theory as describing before.

3.3 Dynamic cooling control technology

After establishing CSI and evaluating through experimental tests, CSC has developed a specific cooling condition for material whose composition is near a specific limit. In order to develop dynamic cooling control technology, CSC merges the CSI models with the specific cooling condition into a PLC system. The procedure of wire rod manufacturing is as shown in Fig.7. The predicted TS of selected billets will be calculated through a CSI model, then the system will adjust the cooling conditions automatically to stabilize the mechanical property. Fig.8 is the box plot of TS, it shows that after applying the dynamic cooling control technology, outliers are eliminated and all data can be fitted to customer specification.

Table 3 Stepwise regression of the effect of the variables on TS

	Elements	Coefficient	p
NLP82B	C	849	<0.0001
	Mn	528	<0.0001
	Mo	465	0.0092
	Cr	446	0.012
SWRH62A	C	937	<0.0001
	Mn	180	<0.0001
	Ti	4936	<0.0001
	Ni	497	0.001
	Cr	174	0.002
	Al	-108	0.003

Regression coefficients, statistically significant (P<0.05)

Table 4 TS and inter-lamellar spacing under different cooling conditions

	Condition	Cooling rate (℃/s)	TS(kg/mm^2)		Inter-lamellar spacing(nm)
			Experiment	Customer Spec	
NLP82B	standard	6.5	125-133	116-129	74
	slower	5.1	122-128		110
SWRH62A	standard	6.1	97-100	88-98	75
	slower	5.2	94-97		105

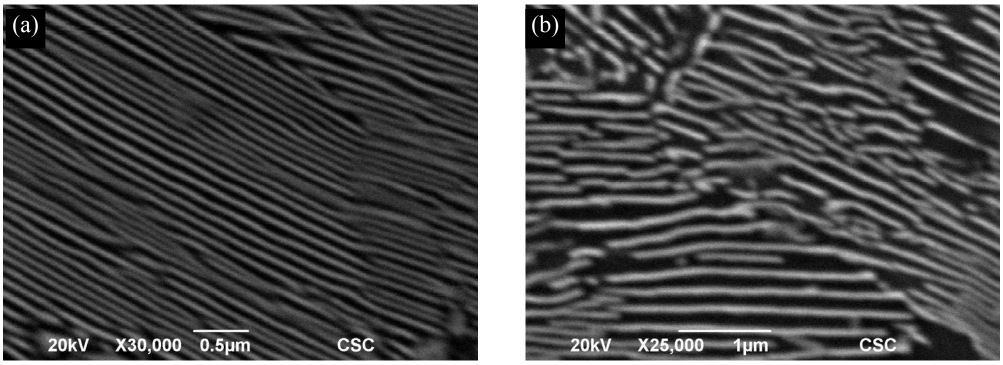

Fig.5. NLP82B inter-lamellar spacing of SEM samples (a) standard cooling, 74nm (b) slower cooling, 110nm.

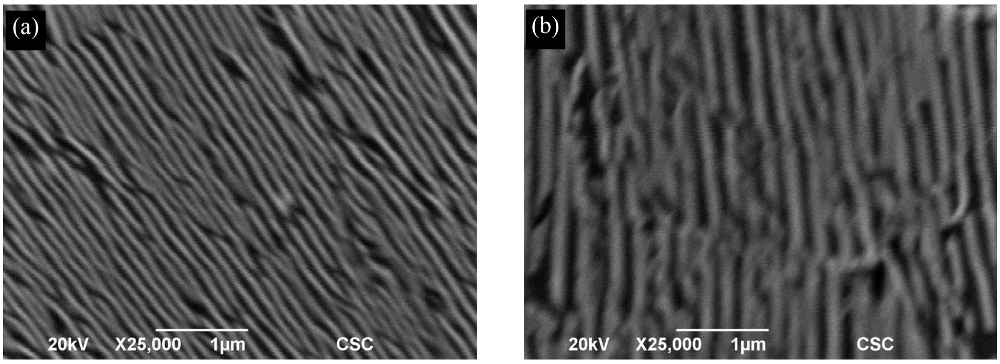

Fig.6. SWRH62A inter-lamellar spacing of SEM samples (a) standard cooling, 75nm (b) slower cooling, 105nm.

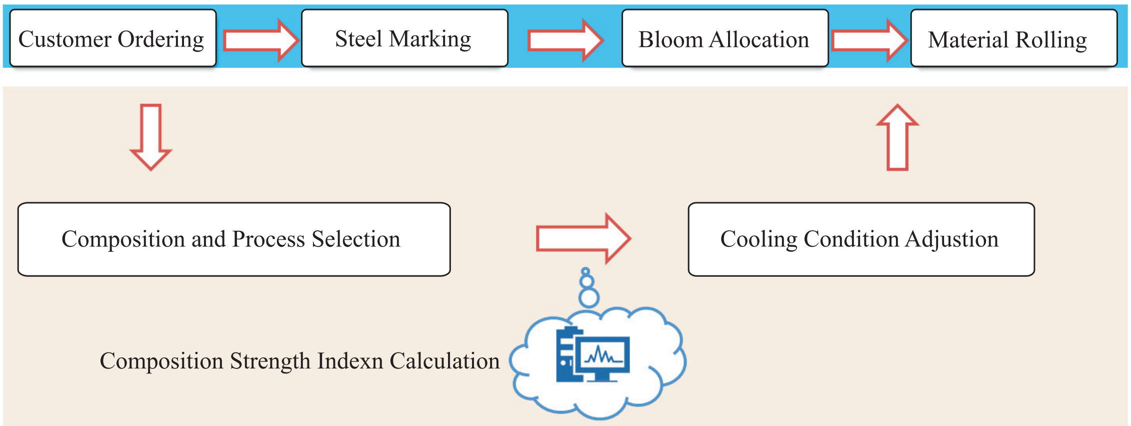

Fig.7. Schematic of wire rod production.

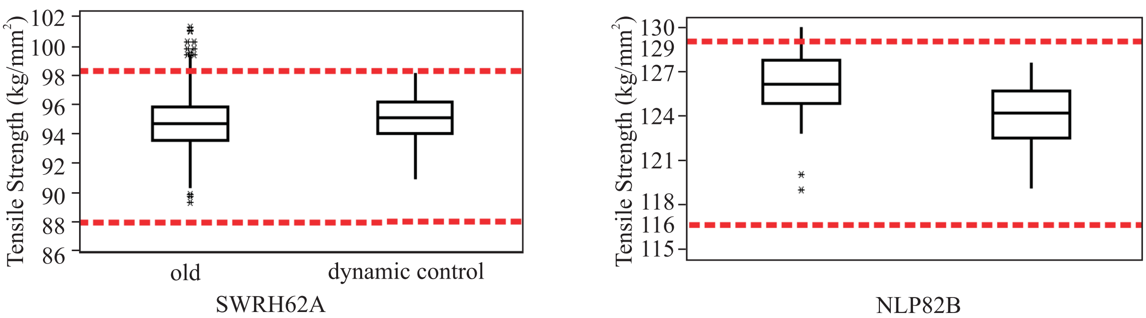

Fig.8. Box plot of TS after applying dynamic control technology.

4. CONCLUSIONS

The above statistics and experimental results were concluded as follows:

1. The CSI models for high TS wire rods such as NLP82B and SWRH62A are established through statistical analysis. The dominant element and quantitative effect of TS are C, Mn, Mo, Cr and Ti, C, Ni, Mn, Cr, Al in sequence for NLP82B and SWRH62A respectively.
2. The experiments show that not only the tensile strength of the wire rod can be stabilized, but also the suitable inter-lamellar spacing is acquired by the SEM inspection under a slower cooling condition.
3. A dynamic cooling process control technology has been established by merging the CSI model and cooling conditions into (PLC) system, therefore it's available to change the cooling conditions automatically to acquire suitable TS and micro-structure before rolling depended on CSI evaluation.

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