Saeed N. Ghali, Mohamed K. El-Fawkhry

Simulation of cooling process effect on mechanical properties of 65Mn strip

Factorial design was used to investigate the contribution effect of cooling rate of stage between rolling and coiling and cooling rate after coiling on grain size, pearlite lamellar spacing, mechanical properties and hardness of hot rolled narrow 65Mn strip. The contribution of both cooling rates before and after coiling process, and the interaction combination effect of both rates were determined for each measured property. The regression models were built up to identify grain size, pearlite lamellar spacing, mechanical properties and hardness as a function in cooling rates before and after coiling process.

It was found that the contribution effect of cooling rate before coiling on grain size growth, enlargement of pearlite lamellar spacing, Ultimate Tensile Strength (UTS) and elongation is negative with different magnitude and it has positive effect on Yield Strength (YS) and hardness. Cooling rate after coiling has negative effect on grain size growth, enlargement of pealite lamellar spacing and elongation while it has positive contribution on UTS, YS, and hardness. The interaction combination effect of both two rates has very small positive contribution on YS and elongation, it has small positive effect on grain size growth, enlargement pearlite lamellar spacing, and it has large negative contribution on UTS and hardness. Factorial design technique is a successful technique to analysis the effecting parameters.

Introduction

There is a trend in simulation and modeling of steelmaking and ferroalloys, for example the prediction of magnesium content in production of ferrosilicon magnesium from dolomite, predicted nitrogen solubility in stainless steel, calculation of activation energy in nitriding ferromanganese are illustrated by authors [1-6]. The use of factorial design of experiments in metallurgical process is relatively limited. Factorial design is used in improving of process yield, reduction of development time and also can reveal the core – parameters that impact the final performance of material property [7-10]. Authors [11] used 2^4 factorial design to evaluate the magnitude effect of Ni, N, time and temperature on oxidation process.

65Mn steel is the main material of current domestic production of various kinds of saw blade, 65Mn steel is a high-quality carbon steel with characteristics of high carbon and low alloy steel. It has a good comprehensive mechanical properties after heat treatment [12-14]. The mechanical property of 65Mn hot rolled narrow strip are not only an important indicator of the saw blade quality but also the most important factor influencing the degree of hardening in the process of cold rolling [15]. In the cold rolling process, 65Mn hot rolled narrow strip steel has a high deformation resistance. Control cooling technology is an effective process to improve the microstructure and mechanical properties of the hot-rolled steel. In order to control the steel organization by using phase transformation strengthening effect. Improve the steel comprehensive and service life [16-18]. The steel of the phase change behavior and strength grade can be changed by changing the cooling rate and coiling temperature, different microstructure and mechanical properties can be got [19-21].

The use of factorial design of experiments in steel field is relatively limited, albeit the inherent advantages such as the improvement of process yield, reduction of development time and also can reveal the key – parameters that impact the final performance of material property [22-23]. This article aims at investigation the contribution effect of cooling rate of stage between rolling and coiling and cooling rate after coiling on the grain size, the pearlite lamellar spacing, the mechanical properties of hot rolled steel grade 65Mn.

Experiments

The factorial design was applied on the results of CHEN Lian-Sheng1 et al [24]. In these previous studies, the influence of cooling rate between rolling and coiling and cooling rate after coiling on grain size, pearlite lamellar spacing, mechanical properties of hot rolled steel grade Mn65. A 2^2 factorial design was used to estimate the contribution of cooling rates before and after coiling process on refining and/or different mechanical properties. Regression models were deduced to calculate the grain size, pearlite lamellar spacing, yield strength, ultimate tensile strength, elongation and hardness in terms of cooling rates (before and after coiling process). Interpretation between the predicted values and experimental values were investigated.

A factorial design 2^2 was built up based on cooling rate between rolling and coiling changes from 5.4 to 8.8°C/Sec. and the cooling rate after coiling change from 0.02 to 0.13°C/Sec. of hot rolled 65Mn steel, which its finishing rolling temperature is 940°C. Table 1 presents the influence of cooling rate between rolling and coiling with cooling rate after coiling on grain size, pearlite lamellar spacing, mechanical properties and hardness.

Let we donate the heat treatment at which high cooling rate between rolling and coiling and low cooling rate of coiling by "A", heat treatment at which low cooling rate between rolling and coiling and high cooling rate of coiling by "B", heat treatment at which low cooling rate between rolling and coiling and low cooling rate of coiling by "1", and heat treatment at which high cooling rate between rolling and coiling and high cooling rate of coiling by "AB". Complete analysis of cooling rates before and after coiling process was illustrated.

Thus, "a" represents the treatment combination of A at high level and B at low level, "b" represents A at low level and B at high level, "ab" represents both factors at the high level and (1) is used to denote both factors at low level.

The effect of cooling rate between rolling and coiling is A, its low level is 5.4°C/Sec., and its high level is 8.8°C/Sec., The effect of cooling rate after coiling is donated by B, its low level is 0.02°C/Sec., and its high level is 0.13°C/Sec.

The average effect of any factor can be defined as the change in response produced by the change in the level of that factor averaged over the levels of the other factor.

The effect of A at low level of B is [a-(1)]/n, where n number experimental repetition, and the effect of A at high level of B is [ab-b]/n. The main effect of A is the average quantities of its effect at low and high level of B as given in equation 1. By the same manner the average effect of B can be calculated as shown in equation 2

Steel No.		Cooling rate, ^{o}C/Sec.		Average grain size, µm	Pearlite Lamellar Spacing, nm	Mechanical Properies			Hardness, HRC
Serial	Symbol effect	Final rolling to roiling	After coiling			UTS, MPa	YS, MPa	El.%	
1	(1)	5.4	0.02	24.75	392	883	519	16.25	21.44
2	B	5.4	0.13	22.45	316	923	551	14.63	23.73
3	A	8.8	0.02	23.05	355	915	527	15.25	23.58
4	AB	8.8	0.13	21.2	293	930	563	13.75	24.06

Table 1: Cooling rates before and after coiling, Grain size, Pearlite lamellar spacing and mechanical properties

Results and Discussions

The factorial design in 2^2 was applied to investigate the contribution effect of cooling rate between rolling and coiling and cooling rate after coiling on grain size, pearlite lamellar spacing, ultimate tensile strength, yield strength, elongation, and hardness was investigated.

"A" refers to the effect of cooling rate after coiling, "B" refers to cooling rate between rolling and coiling, and "AB" refers to the effect of both cooling rate between rolling and coiling and cooling rate after coiling. The low and high level of A and B are denoted by "–" and "+" respectively. The four treatment combinations in the design are usually represented by lowercase letters. The high level of any factor in the treatment combination is denoted by the corresponding lowercase letter and that the low level of a factor in the treatment combination is denoted by the absence of the corresponding letter.

$$A = \frac{1}{2n}\{[ab - b] + [a - (1)]\} = \frac{1}{2n}[ab + a - b - (1)] \quad (1)$$

$$B = \frac{1}{2n}\{[ab - a] + [b - (1)]\} = \frac{1}{2n}[ab + b - a - (1)] \quad (2)$$

The interaction effect AB is defined as the average difference between the effect of A at the high level of B and the effect of A at the low level of B. thus,

$$AB = \frac{1}{2n}\{[ab - a] - [a - (1)]\} = \frac{1}{2n}[ab + (1) - a - b \quad (3)$$

Based on the 2^2 factorial design analysis the average effect of A, B, and their combination effect (AB) on grain size, pearlite lamellar spacing, ultimate tensile strength, yield strength, elongation, and hardness can be calculated as given in table 2.

Grain size			Pearlite lamellar spacing			Ultimate tensile strength		
Affecting Factor	Average effect	Magnitude effect	Affecting Factor	Average effect	Magnitude effect	Affecting Factor	Average effect	Magnitude effect
A	-1.475	124.3214	A	-29.75	38.90385	A	-12.25	4.446296
B	-2.075	246.0357	B	-68.75	207.761	B	1.75	0.090741
AB	0.225	2.892857	AB	6.75	2.002747	AB	-43.25	55.42407
Yield strength			**Elongation**			**Hardness**		
Affecting Factor	Average effect	Magnitude effect	Affecting Factor	Average effect	Magnitude effect	Affecting Factor	Average effect	Magnitude effect
A	10	4.878049	A	-0.9825	11.42712	A	1.265	217.7177
B	29.5	42.45122	B	-1.8425	40.18711	B	1.465	292.0034
AB	1.5	0.109756	AB	0.0175	0.003625	AB	-0.91	112.6667

Table 2: Contribution effect of A, B, and AB on grain size, pearlite lamellar spacing, ultimate tensile strength, yield strength, elongation, and hardness.

The calculation of factorial design shows that both the cooling rate between rolling and coiling and cooling rate after coiling have negative effect on the grain size. This means that both two cooling rate as increase as the grain size of the produced 65Mn decreases. But the cooling rate after coiling has highest negative effect on grain size. This means that as the coiling rate increase as the grain size of 65Mn steel decreases i.e. more refining grain size. The effect of cooling rate after coiling is about twice the effect of cooling rate between rolling and coiling on the grain size as illustrated in table 2. The interaction combination of two cooling rate is positive and small value of which can be neglected. The grain size can be determined as a function in both two cooling rates by using regression model as given in equation 4. Figure 1-A shows the variation between the calculated grain size from regression model and the experimental grain size.

$$Grain\ size = 27.93837 - 0.5066 * a - 27.139 * b + 1.0695 * a * b \quad (4)$$

Where grain size in µm, “a” is cooling rate between rolling and coiling, “b” is cooling rate after coiling.

The calculation of factorial design shows (as given in table 2) that both the cooling rate between rolling and coiling and cooling rate after coiling have negative effect on pearlite lamellar spacing. These mean both two cooling rates as increase as the pearlite lamellar spacing of the produced 65Mn decreases. But the cooling rate after coiling has highest negative effect on pearlite lamellar spacing. This means that as the coiling rate increase as the pearlite lamellar spacing of 65Mn steel decreases. The effect of cooling rate after coiling is more than five times effect of cooling rate between rolling and coiling on the pearlite lamellar spacing. The interaction combination of two cooling rate is positive and small which can be neglected. The pearlite lamellar spacing can be determined as a function in both two cooling rates by using regression model as given in equation 5. The variation between the predicted and measured pearlite lamellar spacing is presented in Fig. 1-B.

$$PLS = 469.5963 - 11.4572 * a - 881.283 * b + 36.09626 * a * b \quad (5)$$

Where is pearlite lamellar spacing in nm, “a” is cooling rate between rolling and coiling, “b” is cooling rate after coiling.

The cooling rate between rolling and coiling has negative effect on the strength i.e. as the cooling rate between rolling and coiling increases as the tensile strength decreases. While the cooling rate after coiling has little positive effect on tensile strength of 65Mn steel. It can be neglected. But, the interaction combination effect of both two cooling rates has the highest negative effect with the largest magnitude i.e. tensile strength sharply increases by decreasing the both two cooling rates. The interaction combination effect of two cooling rates (AB) is about 12 times of cooling rate between rolling and coiling on tensile strength as shown in table 2. The tensile strength can be predicted as a function in both two cooling rates by using regression model as given in equation 6. The variation between the calculated and measured ultimate tensile strength is illustrated in Fig. 1-C.

$$Tensile\ Strength = 798.1043 + 13.7433 * a + 1658.021 * b - 231.283 * a * b \quad (6)$$

Where tensile strength in MPa, “a” is cooling rate between rolling and coiling, “b” is cooling rate after coiling.

The calculation of factorial design shows that both the cooling rate between rolling and coiling and cooling rate after cooling has positive effect on yield strength i.e. when the cooling rates increase the yield tensile strength increases. While the interaction combination effect (AB) has little positive effect which can be neglected. The cooling rate after coiling contributes in increasing yield strength by about eight times of contribution of cooling rate between rolling and coiling as shown in table 2. Yield tensile strength can be predicted as a function in both two cooling rates by using regression model as given in equation 7. Fig. 1-D represent the variation between the predicted and measured yield strength.

$$\text{Yield Strength} = 503.2754 + 2.339572 * a + 211.2299 * b + 8.02139 * a * b \quad (7)$$

Where yield strength in MPa, "a" is cooling rate between rolling and coiling, "b" is cooling rate after coiling.

The contribution of both the cooling rate between rolling and coiling and cooling rate after cooling have negative effect on elongation i.e. when the cooling rates increase the elongation decreases. While the interaction combination effect (AB) has very little positive effect which can be neglected. The contribution of cooling rate between rolling and coiling is more than three times of the contribution of cooling rate after coiling on elongation as given in table 2. Elongation can be predicted as a function in both two cooling rates by using regression model as given in equation 8. The difference between the predicted and measured elongation is given in Fig. 1-E.

$$\text{Elongation } \% = 18.31152 - 0.29595 * a - 17.4144 * b + 0.093583 * a * b \quad (8)$$

where, "a" is cooling rate between rolling and coiling, "b" is cooling rate after coiling.

Both the cooling rate between rolling and coiling and cooling rate after cooling have

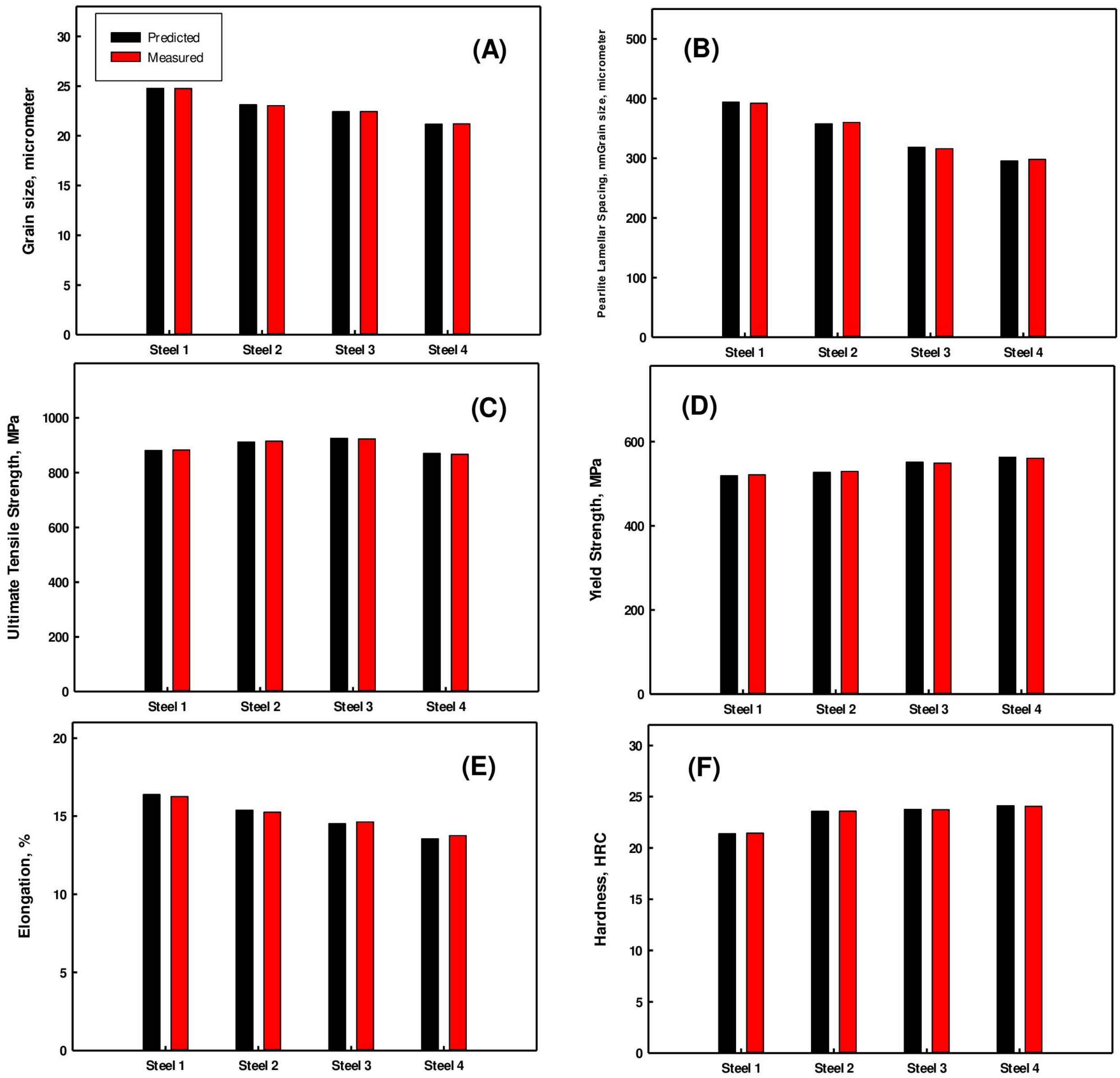

Fig. 1: The variation between measured and predicted in (A) Grain size, (B) Pearlite lamellar spacing, (C) Ultimate tensile strength, (D) Yield strength, (E) Elongation, and (F) Hardness for steel 65Mn

positive effect on hardness i.e. when the cooling rates increase the hardness increase. While the interaction combination effect (AB) has small negative effect on hardness. The contribution of cooling rate between rolling and coiling is larger than the contribution of cooling rate after coiling on increasing hardness by certain extent as shown in table 2. Hardness can be predicted as a function in both two cooling rates by using regression model as given in equation 9. Fig 1-F shows both the predicted and measured hardness of 65Mn steel.

$$\text{Hardness (HRC)} = 16.96821 + 0.737032 * a + 47.86898 * b - 4.86631 * a * b \quad (9)$$

Where, “a” is cooling rate between rolling and coiling, “b” is cooling rate after coiling.

Conclusions

The effects of cooling rate of rolling to coiling temperature and cooling rate after coiling of 65Mn Steel on grain size, pearlite lamellar spacing, tensile strength, yield strength, elongation, and hardness was investigated by using factorial design technique. Equations were deduced to predict grain size, pearlite lamellar spacing, tensile strength, yield strength, elongation, and hardness as function in cooling rate from rolling to coiling and cooling rate after coiling. The comparison between the predicted values and measured for grain size, pearlite lamellar spacing, tensile strength, yield strength, elongation, and hardness were investigated. The deviation in all cases is very small. It was found that the predicted values are very close to the measured values, which means factorial design is very useful technique in the field of steel and it is be recommended to be used in several processes in metallurgy.

References

1. Saeed Ghali, Mamdouh Eissa, Hoda El-Faramawy, “Validation of FeSiMg alloy production model for the experimental process”, Journal of Metallurgy, Vol. 2012, Article ID 176968, 6 pages, 2012. doi:10.1155/2012/176968
2. Saeed Nabil Saeed Ghali "A Model for FeSiMg Alloy Production by Reduction Technique", Journal of Minerals & Materials Characterization & Engineering, Vol. 10, No.9, pp.865-874, 2011
3. S. N. Ghali, M. M. Eissa & K. M. El-Fawakhry “Nitrogen Solubility in Stainless Steels” Advances in Theory of Ironmaking and Steelmaking Conf. 2009, Department of Materials Engineering, Indian Institute of Science, Bangalore - 560012, India, 9-11 December 2009
4. Saeed N. Ghali "Nitriding of Medium Carbon Ferromanganese Alloy in Gas Solid Reaction" Journal of Minerals & Materials Characterization & Engineering, Vol. 10, No.4, pp.315-322, 2011
5. Saeed N. Ghali, Mamdouh M. Eissa, Micheal L. Mishreky,” Activation energy of nitriding medium carbon ferromanganese alloy “, Journal of Iron and Steel Research, International, 2013, Vol.20(1), 58-61
6. S. N. Ghali, K. M. El-Fawakhry, M. M. Eissa and M. L. Mishreky , “ kinetic of nitriding process of ferromanganese alloy”, 12th International Ferroalloys Congress , INFOCON IIX, Helsinki, Finland, 6-9 June, 2010
7. Saeed Ghali, Elsayed A. Mousa, “Analysis of the reduction yield of synthetic iron oxide sinter reduced by H_2 at 900-1100°C using factorial design approach”, Steel Grips, 26 Aug. 2014, pp. 11 - 17, DOI:10.5161/STEEL/2014/sg14002
8. E.A. Mousa, S. Ghali , “Factorial design analysis of the reduction degree of simulated iron ore sinter reduced with CO gas at 1000-1100°C”, Ironmaking and Steelmaking, online paper, http://www.maneyonline.com/doi/full/10.1179/1743281214Y.0000000232
9. Saeed Ghali, "Mathematical Model of Prediction of Nitrogen Pickup in Nitriding Process of Low Carbon Ferromanganese," Journal of Metallurgy, vol. 2014, Article ID 793508, 5 pages, 2014. doi:10.1155/2014/793508
10. S. Ghali & E. A. Mousa "Mathematical Analysis of the Effect of Iron and Silica on the Reduction Performance of Manganese Ores," Journal of Metallurgy, vol. 2015, Article ID 679306, 10 pages, 2015. doi:10.1155/2015/679306
11. S. Ghali, M. Eissa, H. El-Faramawy, “Simulation of austenitic stainless steel oxidation containing nitrogen at temperature range 500°C – 800°C”, International Journal of Statistics and Mathematics, Vol. 1(3), pp. 024-032, August, 2014. © www.premierpublishers.org, ISSN: 2374-0499
12. Liu Z C, Zhang Y H, Ren huiping. Heat Treatment of Metals, 1991, 19(9): 8-11.
13. Zhang L Z. Metal Materials and Metallurgy Engineering, 2009, 5(4): 15-20.
14. Sun J B, Li G B, Li G Y, et al. Heat Treatment of Metals, 1999, 24(11): 17-19.
15. Guo J F. Metallurgical Equipment, 2005, 149(1): 43-48.
16. Liu J B.. Iron and Steel, 2002, (9): 43-46.
17. Qu J B, Wang S D , Liu X H, et al. Journal of Iron and Steel Research, 1998, (3): 32-34.
18. Zhang H M, Xu Y B, Liu Z Y, et al. Journal of Northeastern University(Natural Science), 2007. 28(3): 349-352.
19. Gao X T, Zhang M M, Zhao A M, Etc. Materials for mechanical engineering, 2011, 35(11): 24-27.
20. Hutchinson B. Microstructure Development during Cooling of Hot Rolled Steels [J]. Iron and Steel, 2001, 28(2): 145-151.
21. Lv H P. Master’s Thesis, Wuhan: Wuhan University of Science and Technology, 2005.
22. T.J. Mesquita, R.P. Nogueira, I.N. Bastos: Factorial design applied to corrosion of superduplex stainless steel, Latin America Applied Research, Vol. 41, 2011, pp. 311-315.
23. Pariona and Muller, 1998; Meng et al., 2007; Hajeeh, (2003)
24. CHEN Lian-Sheng1, QI Xiang-Yu1, TIAN Ya-Qiang1, WEI Ying-Li, SONG Jin-Ying, “ Effect of Cooling Process on Structure and Mechanical Property of Hot Rolled Narrow 65Mn Strip”, 3rd Global Conference on Materials Science & Engineering, Oct. 20 – 22, 2014, Shanghai

Authors

Saeed N. Ghali, Mohamed K. El-Fawkhry

Central Metallurgical Research & Development Institute (CMRDI), Cairo, Egypt

BOX: 87 Helwan, Cairo, Egypt

Corresponding Author: Saeed N. Ghali, e-mail: a3708052@yahoo.com