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Continuous Measuring of Heat Pattern in Sintering Bed and Its Application to Sintering Operation*

Syunji YASUMOTO ** Syu TANAKA **

In order to raise the productivity of sinter and to control its quality, it is important to grasp the characteristics of the combustion zone in the sintering bed. A heat pattern measuring apparatus recently developed permits a continuous measurement of about 25 heat pattern cycles. It consists of three parts, i.e., a metal-sheathed thermocouple, its protector and telemetery equipment. From a heat pattern obtained by this apparatus, two indexes, Q value and CT value, are calculated. The Q value is estimated by an integration temperature curve above 900°C, and CT value by the cooling rate from peak to 1 100°C. Results so far obtained through the use of the apparatus are summarized below.

(1) A correlation is found between the Q value and shatter strength.

(2) A simple correlation is found between FeO content in sinter and the CT value or peak temperature in the sintering bed.

1 Introduction

The quality of sinter is greatly affected by the characteristics of the combustion zone in the sintering process. As a method of estimating the characteristics of the combustion zone, the measuring of temperature changes in the sintering bed (hereafter called heat pattern) has been performed for some time.

Regarding the relation of the heat pattern with sinter quality and operating factors, many investigations have been conducted by using test sintering pots, and ample information has been obtained[1,2]. In order to apply this information to actual operation of the sintering machine, it is essential to measure the heat pattern in the actual operation.

Against the above background, an apparatus has been developed for measuring the heat pattern of an actual sintering machine.

In this report are described an outline of the measuring equipment installed at No. 4 sintering plant (pallet width 5 m and useful length 82 m) of Mizushima Works as well as the method of data processing of the heat pattern obtained and the results of application of the equipment to the actual sintering machine.

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** Mizushima Works

2 Heat Pattern Measuring Equipment

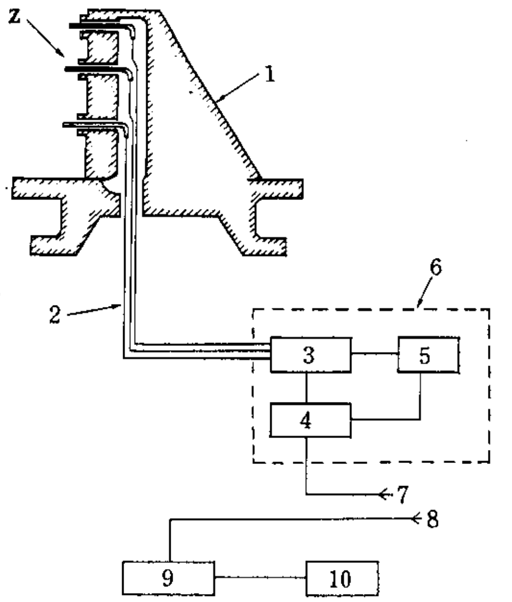
2.1 Outline

In developing the heat pattern measuring apparatus, a preliminary test was conducted in which the thermocouple was inserted from the side wall of the pallet of the sintering machine in order to investigate the effects on the measured heat pattern of the insertion length of the thermocouple, namely, the temperature measuring position in the pallet width direction.

From the results of this investigation, a thermocouple protector was devised which has a projection that forms a single unit with the grate bars, and in order to find some method of fixing the thermocouple to this protector, a preliminary test was carried out by using the test sintering pot to determine the basic conditions.

Fig. 1 shows the general view of the heat pattern measuring apparatus which has been fabricated on the basis of the above-mentioned investigation results.

In measuring the heat pattern, an exclusive pallet incorporating the apparatus as shown in **Fig. 1** was exchanged with an arbitrary pallet of the sintering machine before starting measurement, and once the measurement is started, heat patterns are measured continually.



1 —Protector
2 —Metal-sheathed thermocouple (PR : 13)
3 —Multiplexer
4 —Transmitter
5 —Battery
6 —Cooling box
7 —Transmission antenna
8 —Reception antenna
9 —Receiver
10—Recorder

Fig. 1 Schematic diagram of continuous measuring equipment of heat pattern in the sintering bed

2.2 Temperature Detector

The temperature measuring thermocouple is incorporated into a protector that is shaped like a projection 50 mm in thickness and 300 mm in height which is mounted on the grate bars at a position about 1/3 of the pallet width direction. The tip of the 4.8 mm dia. metal-sheathed thermocouple protrudes 15 mm into the mixed material zone at a position 35 mm away from the surface of the protector. This fitting length has been experimentally determined so that the wear of the thermocouple will be minimized and the presence of the protector will not adversely affect the measured temperature.

The measured-temperature signals of the thermocouple are led outside the pallet by the lead wire which consists of PR strand (0.5 mmϕ $\times$ 2 000 mm$l$) insulated with a glass-wool tube. Another lead wire from the bottom of the protector to the outside of the pallet is passed through a porcelain tube fixed securely between ribs of the pallet, to protect the lead wire from damages by dust.

The above-mentioned heat pattern measuring apparatus can continuously measure average 25 patterns (for about 1.5 days).

2.3 Telemetry Apparatus for Measured-temperature Signals

The measured-temperature signals from the thermocouples are wirelessed by the telemetry equipment installed outside the pallet.

Signals of temperatures taken at four points, consisting of bed temperatures at the upper, middle and bottom stages of the protector and the waste gas temperature at 150 mm below grate bars, are switched over at a cycle of about 23 sec. by the multiplexer and

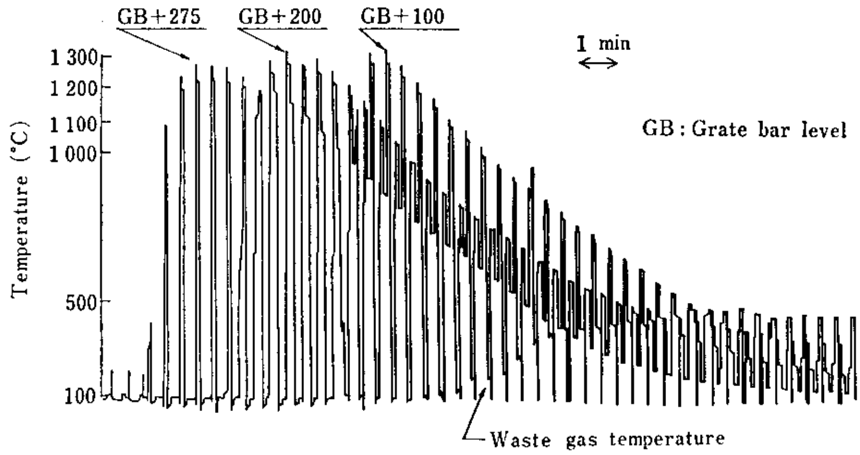


Fig. 2 An example of heat pattern obtained by continuous measuring equipment at Mizushima No. 4 DL sintering meachine

sent to the wireless transmitter. After applying cold-junction compensation, the wireless transmitter AM/FM-modifies thermoelectromotive-force signals of 0 to 16 mV and sends them at a frequency of about 100 MHz. A mercury battery is used as an electric power source for the multiplexer and wireless transmitter. The multiplexer, wireless transmitter and mercury battery are accommodated in a water-cooled box fixed securely to the pallet in order to protect them from mechanical and thermal damage.

Signals sent by the wireless transmitter are led to the receiver installed inside the operating room via the receiving antenna consisting of a coaxial cable stretched at the sintering machine side. The receiver converts the transmitted signal into analog signals of 0 to 1 VDC by FM/AM modulation. **Fig. 2** shows an example of recording by a pen recorder of signals from the thermocouple at four points consisting of three points of bed temperatures and one point of waste gas temperature.

3 Data Processing of Heat Pattern

3.1 Formulation of Heat Pattern

In order to process by computer the data obtained by the above-mentioned measuring apparatus, the heat pattern is formulated by using the following approximate functional equation **(1)** proposed by Korshikov et al.[3]:

$$T = T_0 + (T_M - T_0)\cdot\exp\left\{-m_i\cdot\left|\frac{t_M}{t} - 1\right|^{p_i}\right\} \cdots \textbf{(1)}$$

T: Temperature during heating or cooling state (°C)

T_M: Temperature at peak (°C)

t, t_M: Time elapsed after firing and time when bed temperature has reached a peak (min)

m_i, p_i: Coefficients which become values inherent to individual patterns

T_0: Temperature of raw material in wet state (°C)

In applying eq. **(1)**, coefficients are classified into two patterns of heating and cooling, and denoted by m_h, p_h, and m_C, p_C, respectively, because the heating state ($t < t_M$) and the cooling state ($t > t_M$) give greatly different heat patterns. These coefficients have been calculated by the least squares method, using the following eq. **(2)** which has been obtained by modifying eq. **(1)** into a linear equation of a logarithmic term and giving bed temperature T and time t corresponding to the temperature:

$$\ln\left(\ln\frac{T_M - T_0}{T - T_0}\right) = \ln m_i + p_i\cdot\ln\left|\frac{t_M}{t} - 1\right| \cdots\cdots \textbf{(2)}$$

Fig. 3 shows a comparison between the observed and calculated values. **Fig. 3** (a) shows an example of patterns which can be normally obtained. The difference between the observed and calculated values is 0.1 min. in the heating state and less than 30°C in the cooling state, thereby indicating good agreement between them. **Fig. 3** (b) shows an example of generating disturbance in the heating pattern. In this case, the calculated value becomes a smoothened pattern and the difference between the observed and calculated values in the high temperature region becomes larger, but both values show good agreement at the region where no disturbance occurs.

As shown above, the observed value of the heat pattern can be accurately approximated by using eq. **(1)**.

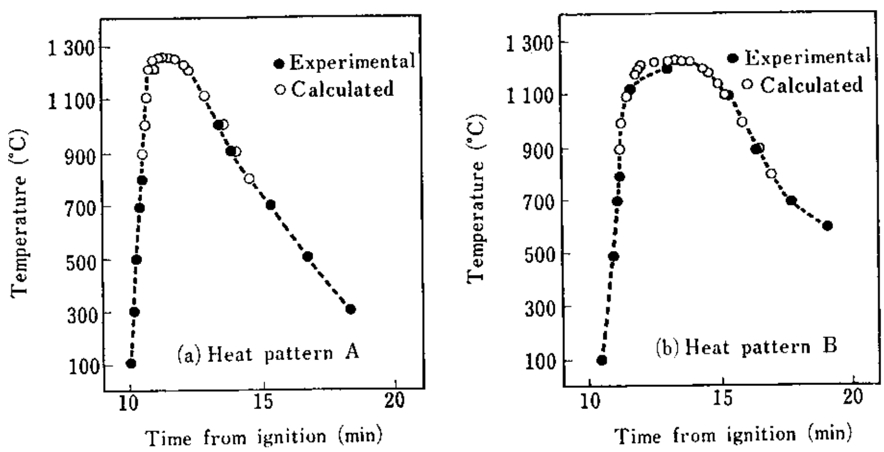


Fig. 3 Comparison of experimental and calculated heat pattern

3.2 Quantification of Heat Pattern

For the purpose of evaluating sinter quality, Mizushima Works frequently performs steady measurements of three items consisting of the shatter index (SI), reduction degradation index (RDI) and FeO content in sinter.

SI is an index showing the degree of molten material generation or inter-particle bonding due to solid phase diffusion, and its value is greatly affected by the supplied heat capacity. As the supplied heat becomes higher in temperature and longer in duration, SI tends to become higher. Since the average level of the coke fine ratio is about 3 wt % and the average level of the maximum bed temperature is about 1 300°C in normal operation, the molten quantity of raw material particles is very small, and even if molten material is generated, its range is localized. Therefore, the effect of the heat pattern index exerted on SI should be evaluated mainly by bonding due to solid phase diffusion. This bonding due to solid phase diffusion is considered to be governed by two factors, i.e., heated temperature and time, and an index of heat capacity (Q) expressed by the following eq. **(3)** has been defined as a heat pattern index, taking into consideration the history of temperature in the combustion process:

$$Q = \int_{t_1}^{t_2} (T - T_C)\cdot dt \quad (°C.\ min) \cdots\cdots\cdots (3)$$

T, T_C: Temperature (°C) obtained by eq. **(1)** and fixed reference temperature, respectively

t_1, t_2: Heating and cooling time (min), respectively, when $T = T_C$ is to be obtained

Next, RDI is affected by the quantity of reoxidized hematite which is generated by the sintering process and, therefore, has a negative correlation with FeO content in sinter. Further, it is known that FeO has a negative correlation with the easily reducible property (for instance, "reducibility" in JIS). From the above, it can be said that the control of FeO content in sinter is important in order to control RDI and the easily reducible property.

Now it is considered that FeO content in sinter is determined by the quantity of magnetite generated by the reducing reaction in the heating state and the quantity of magnetite that disappears through oxidizing reaction. On the basis of this concept, index of cooling rate (CT) is defined by the following eq. **(4)** as the heat pattern index that simultaneously evaluates quantities generated by two reactions of reduction and oxidation:

$$CT = -\frac{T_M - T_C}{t_M - t_2} \quad (°C/min) \cdots\cdots\cdots\cdots (4)$$

Namely, the above index evaluates maximum temperature (T_M) and time required for cooling ($t_2 - t_M$) as the quantity of reducing reaction and that of reoxidizing reaction, respectively.

From heat patterns obtained by No. 4 sintering machine at Mizushima Works, the above-mentioned index values were calculated, and the relation between SI and FeO content in sinter was investigated.

3.3 Relation between Heat Capacity Index and SI

With the aim of investigating in detail the critical temperature level of the heat capacity index that corresponds to SI, a heat capacity index was calculated which had been changed in steps of 100°C within the range of 800 to 1 200°C. It was so arranged that the measured value of SI would have time correspondence to sampling of the heat-pattern measuring portion; and for SI and the heat pattern index, average values for 4 hours were used.

Table 1 shows the simple correlation coefficient between SI and the heat capacity index in which the critical temperature was changed. The investigation period was 8 months extending from March to October, 1979.

The simple correlation coefficient between the heat capacity index and SI became largest when the critical temperature was set at 900°C. **Fig. 4** shows the scatter diagram of the heat capacity index and SI at this critical temperature.

3.4 Relation between CT Value and FeO Content in Sinter

An investigation was made on the relation between the CT value and FeO content in sinter which was in a negative correlation with RDI. Since FeO content in sinter greatly differed in level depending upon the type of material, analysis was made during blending the same material. The data sampling method for FeO content in sinter was the same as that used in investigating SI.

Table 2 shows the simple correlation coefficient between FeO content in sinter and the CT value when the critical temperature was changed. The critical temperature, at which the simple correlation coefficient between the CT value and FeO content in sinter was the largest, was 1 100°C. **Fig. 5** shows the scatter diagram of the CT value at this critical temperature and FeO content in sinter with respect to two types of materials. Although changes in the level of FeO content in sinter are observed depending upon the type of material, indexes of heat patterns showed similar trends.

Table 1 Simple correlation coefficients between Q values and shatter strength

	Mean value	Standard deviation	Correlation coefficient
	°C·min	°C·min	
Q_{800}	2 092.5	931.6	0.629
Q_{900}	1 498.7	746.7	0.665
$Q_{1\,000}$	959.9	525.3	0.640
$Q_{1\,100}$	539.5	373.3	0.517
$Q_{1\,200}$	202.9	168.3	0.542
SI	91.42(%)	1.31(%)	

Table 2 Simple correlation coefficients between CT values and FeO content (%) in sinter

	Mean value	Standard deviation	Correlation coefficient
	°C/min	°C/min	
CT_{800}	106.6	23.8	0.394
CT_{900}	100.8	20.8	0.618
$CT_{1\,000}$	91.7	20.0	0.740
$CT_{1\,100}$	79.2	16.7	0.831
$CT_{1\,200}$	55.2	16.8	0.733
FeO	4.67(%)	0.34(%)	

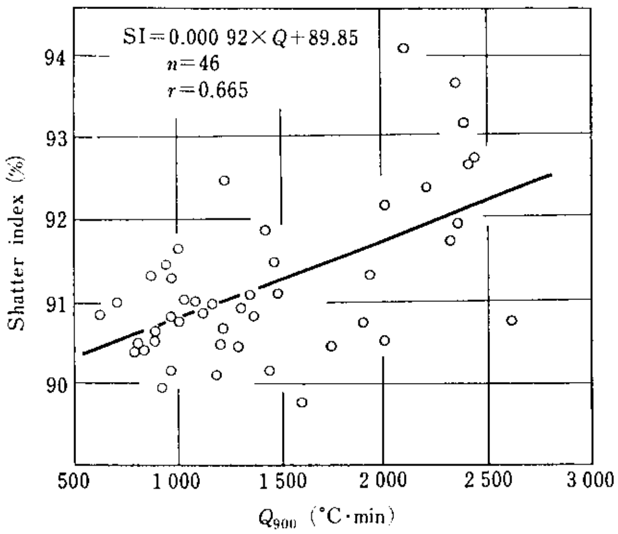


Fig. 4 Relation between shatter index and Q value at 900°C

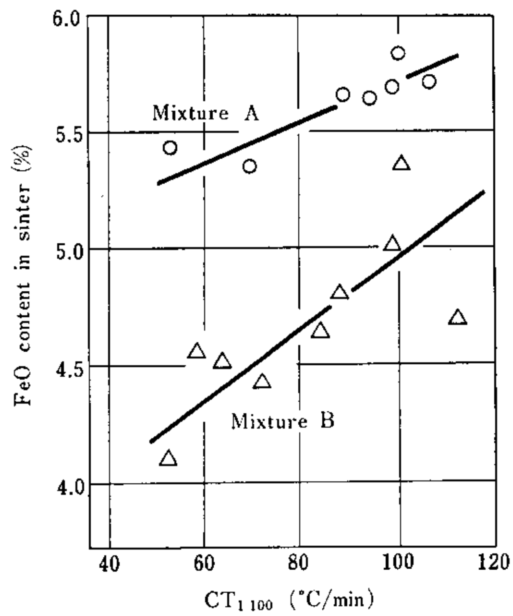


Fig. 5 Relation between FeO content in sinter and CT value at 1 100°C

3.5 Relation between Heat Pattern Indexes and Characteristics of Operating Conditions

While the control method of heat patterns was being studied, an investigation was made on the relation between the aforementioned two heat pattern indexes, which were corelated with SI and FeO content in sinter, and the characteristics of operating conditions. At this time, analysis was made by using investigation data which consisted of the aforementioned data plus those data which were subsequently obtained.

Table 3 shows a summary of simple correlation coefficients between heat pattern indexes and characteristics of operating conditions. In the characteristics of operating conditions which affected heat patterns,

Table 3 Simple correlation coefficients between heat pattern indexes and operating conditions in the sintering machine

	PS	V	C	R
Q_{900} (°C/min)	−0.607	−0.741	0.464	−0.343
$CT_{1\,100}$ (°C/min)	0.604	0.604	−	+
Pallet speed, PS(m/min)	1	0.766	−	0.389
Volume of suction, V(m^3/min)		1	−0.387	0.358
Coke fine ratio, C (%)			1	+
Return fine ratio, R (%)				1

the effects of the waste gas volume of suction or the pallet speed which were in a positive correlation with it were predominant, and these characteristics also had a negative correlation with the Q value and a positive correlation with the CT value. As for the effects of the coke fine ratio, its positive correlation with the Q value was observed, but its effect on the CT value was slight.

It was confirmed that the results of the above-mentioned investigation on the relation between heat pattern indexes and characteristics of operating conditions showed similar tendencies to those of examples reported on the basis of the sintering test[2] or by calculation in the simulation mode[4,5].

4 Application to Actual Sintering Operation

In order to examine in detail the control method of heat patterns, measurements of heat patterns were made under the actual operating conditions by changing pallet speed in three levels and the coke fine ratio in four levels within the period of blending the same material. The data sampling method at this time was the same as that mentioned earlier in paragraph 3.3.

Fig. 6 shows changes in sinter quality and heat patterns as a result of changing pallet speed. This figure indicates that changes in the level of the coke fine ratio resulted in changes in sinter quality and in the level of heat pattern indexes, but the effects of pallet speed on sinter quality and the level of the indexes tended to show no great changes. It is important to estimate changes in pallet speed as changes in the air volume of suction to the sinter bed, but at the present time the pallet speed is employed as the characteristics of operating conditions which enable setting of target values. As mentioned above, if pallet speed is raised, namely, if the air volume of suction is increased, SI will drop and FeO content in sinter will increase. Changes in heat pattern indexes at this time will appear as rises in temperature at the peak point and in CT value and a drop in Q value.

Fig. 7 shows changes that occur at the high temperature region (hereafter called "red heat zone") of more than 900°C. As can be clearly seen, the heat front speed becomes faster, as pallet speed increases, and the time during which the temperature is held at 900°C becomes shorter. As a result, changes in heat patterns due to an increase in pallet speed appear as a sharper figure with a slightly raised temperature at the peak point.

Fig. 8 shows changes in sinter quality and heat pattern due to changes in the coke fine ratio. An increase in coke fine ratio resulted in increases in SI and FeO content in sinter, and an increase in the heat pattern index resulted in increases in the temperature at the peak point and Q value and a decrease in CT value.

Fig. 9 shows changes in the red heat zone as an effect of the coke fine ratio. It is observed that different from the case of changes in pallet speed, an increase in the coke fine ratio caused practically no change in heat front speed, and holding time at 900°C or above became longer. This trend was particularly evident at the middle zone in the sintering bed. As a result, changes in the heat pattern due to an increase in the coke fine ratio caused a rise in temperature at the peak point and appeared as a flat shape.

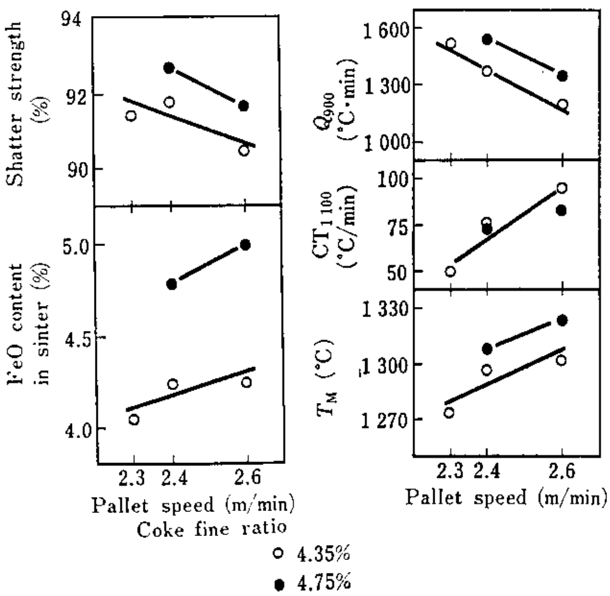


Fig. 6 Relation of qualities of sinter and heat pattern indexes vs. pallet speed

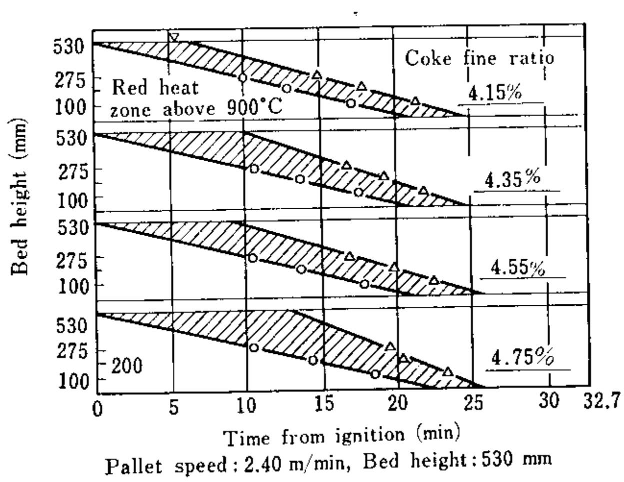


Fig. 7 Variation of red heat zone above 900°C in sinter bed with pallet speed

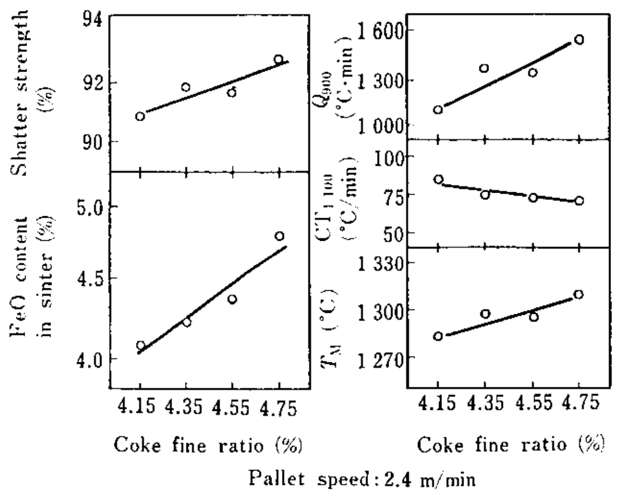


Fig. 8 Relation of qualities of sinter and heat pattern indexes vs. coke fine ratio in main ore

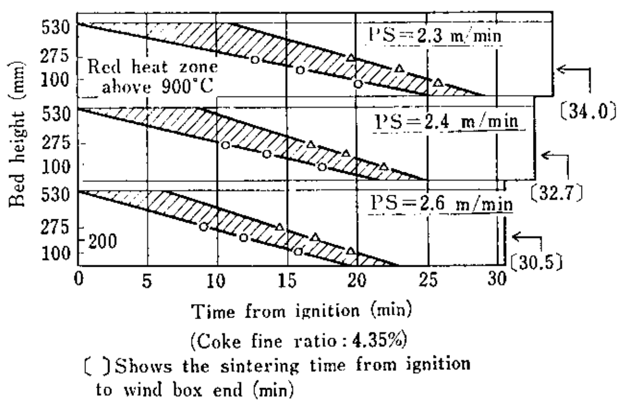


Fig. 9 Variation of red-heat zone above 900°C in sinter bed with coke fine ratio in main ore

Fig. 10 is a scatter diagram which shows the relation between Q value and SI obtained from the above-mentioned test results. Between these factors, a positive correlation is observed which resembles the results mentioned earlier in paragraph 3.3.

Fig. 11(a) is a scatter diagram showing the CT value and FeO content in sinter. In this case, no correlation was observed between the two factors, contrary to the test results shown in paragraph 3.4 earlier. **Fig. 11**(b) is a scatter diagram showing the relation between the average of temperatures at peak points and FeO content in sinter. In this case, a good positive correlation was observed between the two factors. Upon examining the relation between SI and temperature at the peak point, no correlation was observed between them.

Regarding the effect of the heat pattern on FeO content in sinter, it has been found, contrary to the concept mentioned eariler, that there are cases which cannot be evaluated by the CT value alone as mentioned above. Namely, these results seem to suggest that what can be evaluated by the CT value is only the amount of reoxidizing reaction in the cooling stage, and temperature at the peak point is evaluated as the amount of reducing reaction including thermal reaction at the heating stage.

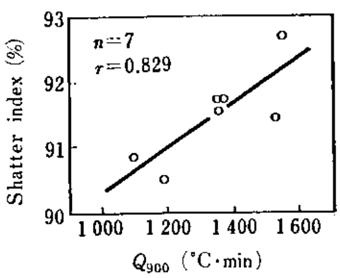


Fig. 10 Relation between shatter strength and Q value at 900°C

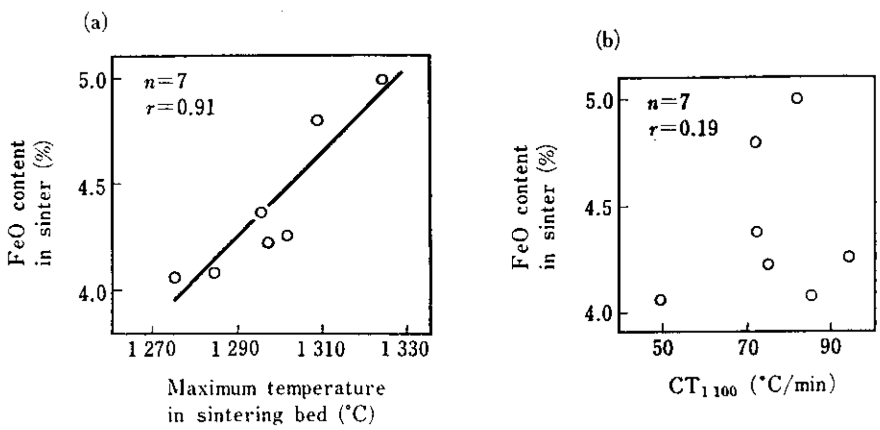


Fig. 11 Relation between FeO content in sinter and heat pattern indexes

5 Conclusion

A heat pattern measuring apparatus has been developed at No. 4 sintering machine of Mizushima Works with the aim of accurately estimating temperature variation (heat pattern) in the sintering process of an actual sintering machine and achieving more quantitative control over sinter quality.

The outline of the measuring apparatus developed is given below.

(1) The measuring part consists of a metal-sheathed thermocouple and its protector accommodated in a projection which forms a single unit with grate bars.

(2) Measured-temperature signals are wirelessed from a mobile pallet to a pen recorder installed in the operating room by telemetry equipment.

(3) The durability of this apparatus is limited by mechanical damage to the thermocouple, but the apparatus can continuously measure an average 25 heat patterns.

The results of the data analysis obtained through this apparatus are as follows:

(1) The heat pattern can be accurately approximated by using the exponential functional formula reported by Korshikov et al.

(2) The highest positive correlation is observed at a critical temperature of 900°C in the relation between SI and the Q value and at a critical temperature of 1 100°C in the relation between CT value and FeO content in sinter.

(3) Regarding the effect of the heat pattern index on FeO content in sinter, the results of actual sintering operation have proved a possibility of evaluating the generated amount of magnetite by using temperature at the peak point.

(4) The effects of pallet speed on the heat pattern appear in the heat front speed and the pattern shape including temperature at the peak point, and the effect on the former is more conspicuous.

(5) The effects of the coke fine ratio on the heat pattern appear more conspicuously in the pattern shape including temperature at the peak point, but the effect on heat front speed is minimal.

In future, the authors intend to modify the measuring apparatus so that it can perform continuous measurement for a longer period, improve the facilities for automating operation steps ranging from signal processing to data analysis, and achieve greater quantization of the relation of the heat pattern to sinter quality and characteristics of operating conditions.

References

1) K. Kitazawa, M. Haitani and S. Kotake: *The Hitachi Zosen Technical Review*, **36** (1975) 3, p. 169

2) K. Sanbongi, N. Nishida and A. Suzawa: *Tetsu-to-Hagané*, **46** (1960) 12, p. 1 527

3) G. V. Korshikov and V. A. Tsivilef: *Izv. VUZov. Cher. Met.* (1974) 10, p. 30

4) T. Hamada, T. Koitabashi and K. Okabe: *Tetsu-to-Hagané*, **58** (1972) 12, p. 1 567

5) M. Yoshinaga and T. Kubo: *Sumitomo Metals*, **29** (1977) 4, p. 383