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Condition Setting Method Utilizing Data Base System in CO_2 Laser Surface Hardening (Report III)†

— Evaluation and improvement of estimation models —

Katsunori INOUE*, Seimei MATSUMURA** and Yoshiaki ARATA*

Abstract

The effective method to investigate the causality model in the heat processing is discussed. The computer processing system in this method consists of the data base and several peripheral modules.

The hardness estimation of CO_2 Laser Surface Hardening is carried out as the concrete application of this system. The automatic evaluation of the hardness estimation models is discussed. These models are implemented by composing and utilizing small and simple program modules which are evaluated automatically and improved by steps. This process is very effectively executed in the whole system. The most suitable model that has been evaluated by the above method can be applied to the hardness estimation within the wide range of condition.

For the verification, the automatic condition setting is done. The estimated results of the set condition closely correspond to the experimental surface hardened results.

KEY WORDS: (Computer System) (Computation) (Data Base) (Heat Processing) (Process Condition) (CO_2) (Laser) (Hardening)

1. Introduction

The experimental methods have usually been carried out for estimating the relation between the conditions of heat processings and their results. Recently, the computer aided methods has been used for this purpose.[1)−2)] The calculation and the processing on the basis of the model which is formed by the rather simple expression of the relations between the heat processing conditions and their results are made in the most of these methods. However, the actual heat processings are affected by the very various factors and it is usually much difficult to make the useful model which can suit for the wide range conditions.

The authors introduced the idea of data base and created the computer processing system by which the examination and evaluation of various causality models could easily be done.[3)]

This system was applied to "CO_2 Laser Surface Hardening", the experimental method for laser surface hardening and the structure of data base were discussed and the data base processing system was constructed in the previous paper. In this paper, the analysis of the relation between the conditions of heat processing and their results and the creating of the suitable model were discussed in the application of CO_2 lase surface hardening. The created model is applied to the condition setting system. Applicability of this method is verified by the automatic condition setting experiment.

2. Computer Processing System

The process of hardness estimation which was usually done sequentially under the operater control hitherto is automated and statistically arranged. It becomes possible by this improvement to examine and evaluate a large number of hardness estimation models and to obtain the optimum model for the condition setting. A part of the service module of computer processing system which is shown in Fig. 8 of the previous paper is modified and expanded in this improvement. The new computer processing system is shown in **Fig. 1** in which other modules are the same in the previous system.

The expanded service module consists of the model evaluation module and the condition setting module as shown in Fig. 1 which becomes executable by linking with one of the processing modules. The model evalu-

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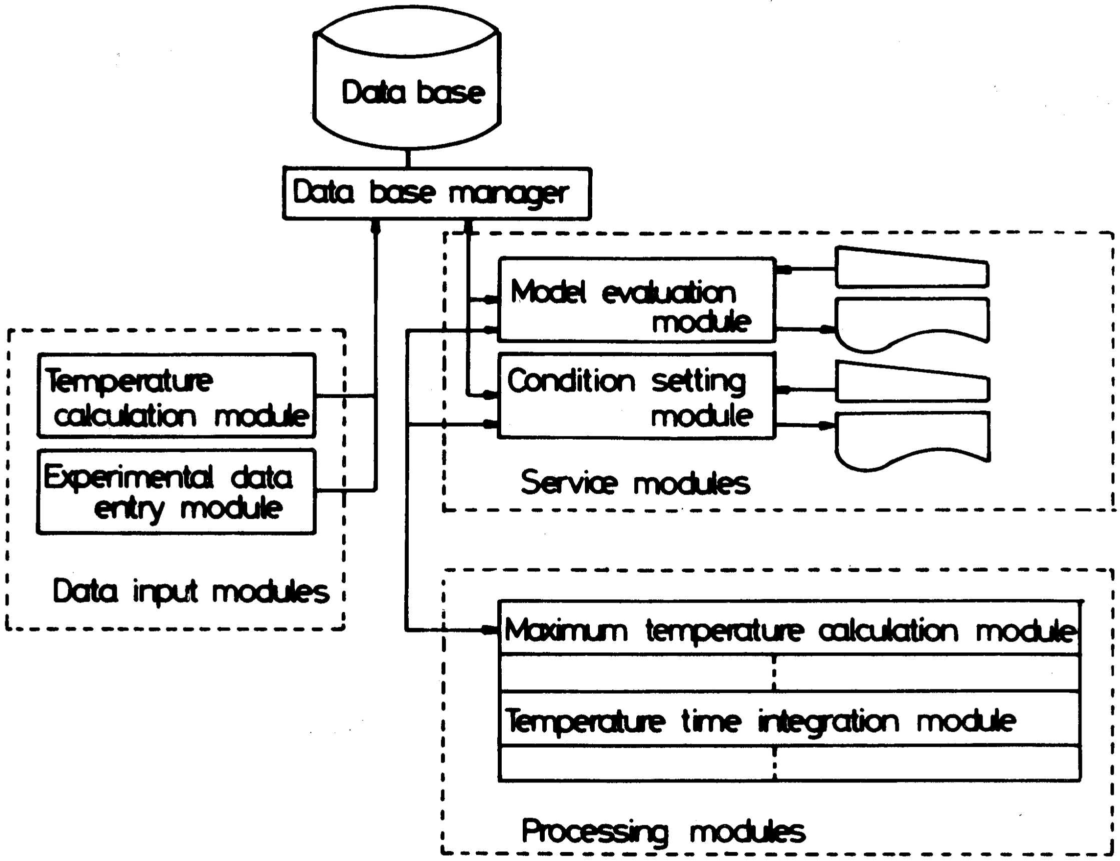

Fig. 1 Block diagram of computer processing system

ation module adjusts the parameters so as to minimize the error between the experimental data and the calculated data and outputs the value of the matched results and their errors that are useful for examining the varidity of the model.

The condition setting module searches the data base and finds out the heat input distribution that most suitably corresponds to the required heat processing result. In the next step, the condition setting module estimates the heat processing condition backwards by estimating the heat processing rerult from the model.

The actual CO_2 laser surface hardening application of these two modules are described into details at the chapters 4 and 5.

3. Experiment of Hardening

The experiment of CO_2 laser surface hardening was done by the same method as in the previous paper. The results were appended to the data base as the experimental data and used with the previously saved data. The material used in the experiment is also the same with that shown in Table 1 of the previous paper. The two kinds of low carbon steel, S20C and S40C, and the two kinds of high carbon steel, SK-5 and SK-3, are used respectively in the experiment. The heat input distribution, together with its indexing parameters M and α of Fig. 4 in the previous paper are also used.

4. Model Evaluation System and Evaluated Result

The concrete data processing procedure of the module evaluation system is explained about the example applied to the laser surface hardening, and the practical evaluation is mentioned in this chaper.

4.1 Model evaluation system

The flowchart of model evaluation system is shown in **Fig. 2**. This system consists of each module for evaluation and one subroutine (marked *) of the processing modules. The model is evaluated in this system as following.

When the conditions for evaluation is entered.

(1) The experimental data and the temperature distribution base data are retrieved from the data base which correspond to the specified condition.

(2) The temperature distribution corresponding to the required heat input distribution is calculated using

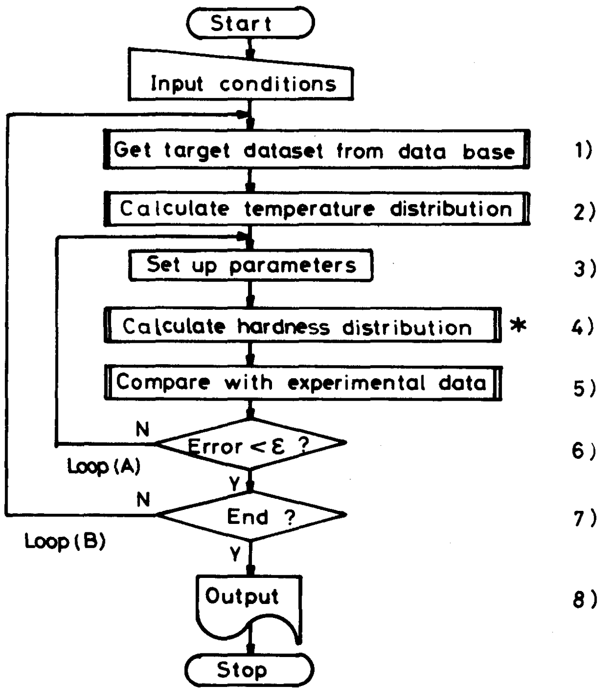

Fig. 2 Flowchart of model evaluation system

the retrieved temperature distribution base data.

(3) Matching parameters (mentioned later) are set up.

(4) The hardness distribution is estimated from the temperature distribution and matching parameters.

(5) The hardness distribution of the estimated result is compared with the distribution of the experimental result and the error between them is calculated.

(6) The parameters are modified to minimize the error by an iterative approximation.

(7) The evaluation is repeated to the all data retrieved from the data base within the specified condition range.

(8) The value of matching parameters which give minimum error in the step (6) are printed out. The graphs of the experimental data and the estimated data by these parameters are also drawn.

The function of the step (4) is the calculation of hardness distribution and performed by the one of the processing modules. This module is based on the assumed model and estimates the hardness distribution from the given input data which are the temperature distribution data and four matching parameters such as T_{RATE}, H_{MAX}, H_{MULT} and Ac_1 described as follows.

T_{RATE} is a coefficient of heating and proportionates to the heat input absorbed in the material.

H_{MAX} is maximum hardness on calculation and has a certain value to each material respectively.

H_{MULT} is a coefficient to relate the hardness distribution and the data calculated from the temperature distribution. It is called a coefficient of hardening.

Ac_1 is the Ac_1 transformation point on calculation.

These parameters are corrected repeatedly at the loop from the step (6) to the step (3) in Fig. 2 by an iterative approximation till their values that minimize the error between the experimental data and the estimated data are obtained. The processing module does not necessarily use all these four parameters, and it is easy to append new parameters if a certain other processing module needs them. The estimation of the hardness distribution was done at 384 points in the hardened cross section and compared with the experimental data at each point in the step (5).

The example of actually examined processing modules and the evaluated results of them are mentioned in the next section.

4.2 Estimation model by maximum temperature

The model which estimates hardness from the maximum temperature has large error with the experimental data as mentioned in the previous paper. The verification of the validity and the stability of this method is examined on this model. It is assumed that the increased hardness H of each point in the cross section of the material varies in direct proportion to the maximum temperature T_M of its point in this model which is expressed in Eq. (1).

$$H = \min(\mathrm{HMULT}, T_M, H_{MAX}) \tag{1}$$

, where H_{MULT} and H_{MAX} are matching parameters.

This model was evaluated by the model evaluation system using the subroutine that includes Eq. (1). One example of the model evaluation result is shown in **Fig. 3**. The distribution in the direction of oscillation is shown

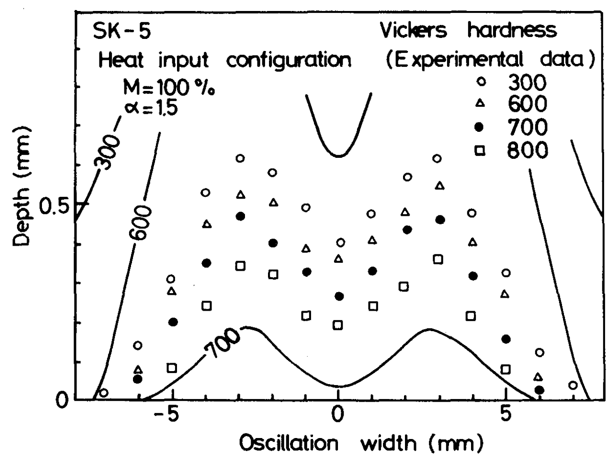

Fig. 3 Matching results by Eq. (1)

in the horizontal axis, and the distribution in the direction of depth is inversely shown in the vertical axis. The vertical axis is magnified ten times to the horizontal axis. The dotted points show the experimental values, and the solid lines show the calculated contour lines of hardness. The change of the calculated data is milder than that of the experimental data.

This model was evaluated on the ten to fifteen different pattern of heat input distribution in each material respectively. The values of the parameters (columns such as H_{MULT}) obtained by the matching process and the error (column of Error) between the experimental data and the estimated data are shown in **Table 1**. The left column (column of Av.) of each parameter is the average

Table 1 Matching results by maximum temperature calculation module

	H_{MULT}		Ac_1		H_{MAX}		T_{RATE}		Error	
	Av.	Var.	Av.	Var.	Av.	Var.	Av.	Var.	Av.	Var.
SK-3	150.8	873.7			848	58.4	450	64.5	78.5	98.6
SK-5	163.4	468.9			865	61.7	551	58.3	66.4	88.5
S40C	108.3	1281.0			707	73.5	416	63.8	83.7	89.9
S20C	123.0	929.4			396	80.1	328	71.7	60.3	106.8
Av. of variance		888.3				68.4		64.6		96.0

H_{MULT}: coefficient of hardening
Ac_1: Ac_1 transformation point on calculation
H_{MAX}: maximum hardness on calculation
T_{RATE}: coefficient of heating
Error: error between estimated and experimental hardness distribution

and the right column (column of Var.) is the variance under the evaluated conditions. Parameter Ac_1 is not used in this model. Both of error and variance are large, and it became clear not only from the manual consideration as mentioned in the previous paper but also from the statistical method that the hardness estimation by the maximum temperature is not suitable in the laser surface hardening.

4.3 Estimation model by integration of temperature with time

It is assumed that the increased hardness H varies in proportion to the integration of square of superheated temperature above Ac_1 transformation point with time. This model is expressed in Eq. (2) which is the same as described in 5.3 of the previous paper.

$$H = \min(u, H_{MAX}) \quad (2),$$

where

$$u = H_{MULT} \int f(T)\, dt \quad (3),$$

$$f(T) = \begin{cases} (T-Ac_1)^2 & T > Ac_1 \\ 0 & T \leq Ac_1 \end{cases} \quad (4),$$

H_{MAX}, H_{MULT} and Ac_1 are the matching parameters, T is the temperature and the function of position and time.

The subroutine for the evaluation of this model is temperature time integration module, and other processes are the same as mentioned in the previous section. The variances of each parameter and the average of error that are obtained by the evaluation under many heat input conditions as mentioned in the previous section are shown in the row of Eq. (2) in **Table 2**. The values in the row of Eq. (1) are of the previous section's model. The variances and the error are relatively improved compared with the values of Eq. (1). However, the estimated data are slightly different from the experimental data near by the points where the hardness reaches to the maximum hardness, and

Table 2 Variance of parameters and error in each model

Model equations	Variance H_{MULT}	Ac_1	H_{MAX}	T_{RATE}	Average Error
Eq. (1)	888.3		68.4	64.6	72.2
Eq. (2)	130.9	96.4	19.1	41.0	37.6
Eq. (5)	36.9	24.4	1.9	24.5	23.4
Eq. (6)	0.04	1.0	0.0	5.4	6.5

the variances and error increase due to this difference. Therefore, instead of Eq. (2) Eq. (5) is used for the approximation of the hardness near by the maximum hardness point.

$$H = H_{MAX}(1-e^{-u}) \qquad (5).$$

The necessary work for the evaluation of the model of Eq. (5) is only to append one new simple processing module to the previous one. The evaluated results of Eq. (5) are also shown in Table 2. Although the results of this model are improved compared with the results of the previous two models, yet some errors remain. Because the estimated value increases more rapidly than the experimental value in the low hardness region, while the experimental region increases more rapidly than the estimated in the high hardness region, the error occurs.

The model to modify the above mentioned defect is introduced. Equation (6) expresses this model.

$$H = H_{MAX}\sqrt{\frac{U^2}{U^2+1}} \qquad (6).$$

The evaluated results of Eq. (6) is also shown in Table 2. The variances and error are considerably smaller than the values of the previous models. The example of the evaluation result by this model is shown in **Fig. 4**. The estimated values closely correspond to the experimental data in a contrast to **Fig. 3** which is the result of Eq. (1). The hardness distribution can be estimated fairly well by this model. The variances and error are very small in the all over range of the experimented conditions. This model has a good appliability within the experimented conditions.

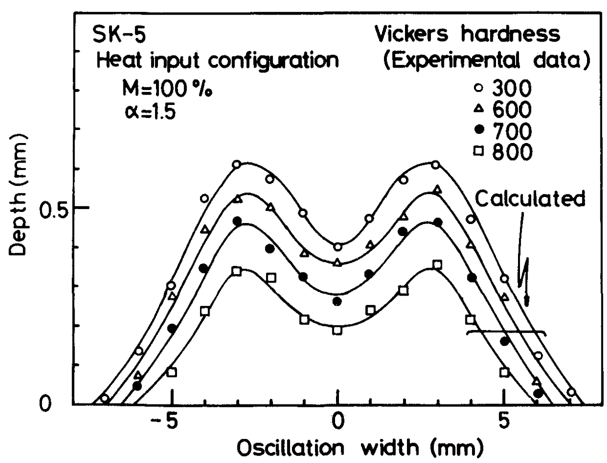

Fig. 4 Matching results by Eq. (6)

4.4 Evaluation of estimation models

The variance of parameters and the averages of error obtained as the results of the evaluation of each model are shown in Table 2 in order to compare each model. The variances of parameters are connected with the propriety of the model in this table. Automatic evaluation on the propriety and stability of the model is possible by calculation of the variances of parameters. It is especially effective by using this evaluation system to increase the propriety of the model by modifying it step by step.

5. Automatic Condition Setting of Surface Hardening

The method of automatic process condition setting by condition setting system is mentioned in this chapter. The condition setting system uses the model which is evaluated as optimum in the model evaluation system.

5.1 Condition setting system

The flowchart for the condition setting system is shown in **Fig. 5**. This system consists of the condition

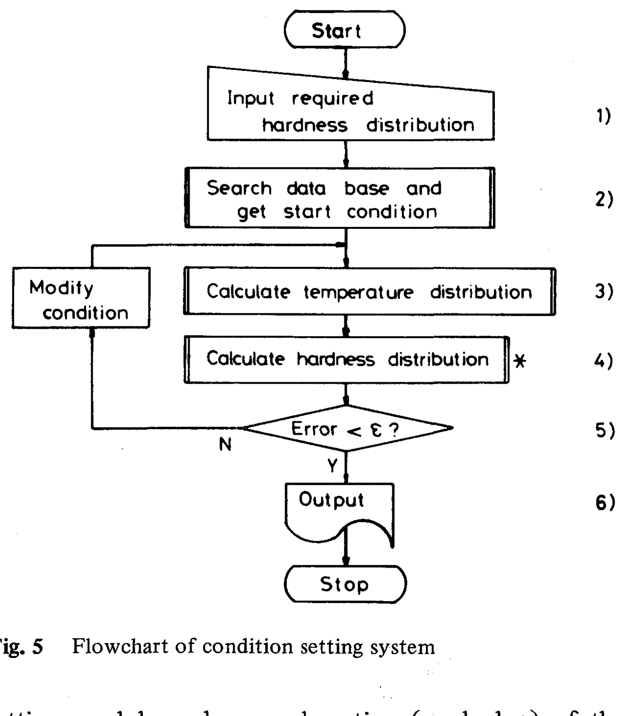

Fig. 5 Flowchart of condition setting system

setting module and one subroutine (marked *) of the processing modules.

The functions of each step are as follows.

(1) The required hardened shape on the cross section of the material is entered.

(2) The most similar data to the required hardened shape is retrieved from the experimental result data set in the data base. The heat input conditions of this data

are used as the initial data.

(3) The temperature distribution is calculated from the heat input conditions.

(4) The hardness distribution is calculated in the subroutine which is picked up from the many estimation model calculation subroutines including the processing modules.

(5) The heat input conditions are modified in order to minimize the error between the required hardened shape and the estimated result. The parameter M and α which give the heat input distribution pattern are used as the heat input condition parameters. The data are constricted by the iterative approximation.

(6) The heat input condition that minimizes the error and the estimation result of the hardness distribution are printed out.

Actual condition setting was performed by the condition setting system, and the hardness distribution was estimated. These results were verified by the experiment.

5.2 Condition setting and verification

The rectangular hardened shape was required to the condition setting system in the next step. The performance of the condition setting system was verified by the used to estimate the hardness distribution. The example of the condition setting process is explained as the following on Fig. 5 by applying this system to the hardening of high carbon steel, SK-5.

(1) The rectangular hardened form was required.

(2) M = 50%, α = 1.0 were obtained as the most similar condition by the retrieval of the data base. These data were used as the initial data.

(3), (4) The hardness distribution was estimated.

(5) M and α were modified by the iterative approximation. The steps from (3) to (5) were repeated to get the minimum error condition.

(6) The heat input distribution M = 40% and α = 1.05 and the estimated result of the hardness distribution were obtained.

The result of the surface hardening experiment under the condition is shown comparing with the estimated result in **Fig. 6**. The obtained hardened shape is similar with the rectangular, and the error between the estimated and the experimental result is very small.

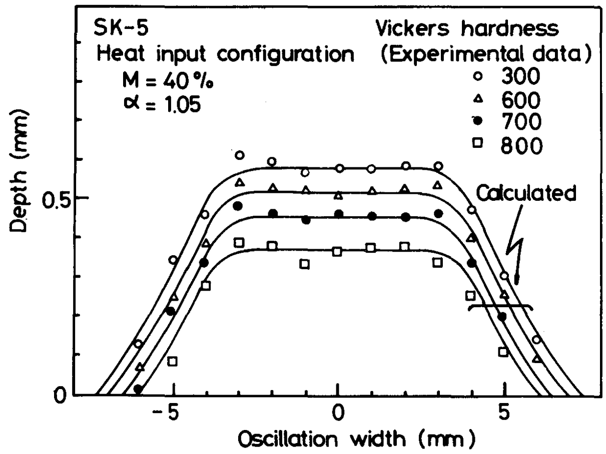

Fig. 6 Relation between estimated value and experimental results

6. Conclusion

The investigation method of the heat processing process is discussed. The causality of the heat processing process is effectively examined by this method on utilizing data base. Many causality models were evaluated and examined by the model evaluation system, and the following knowledges were obtained.

(1) The evaluation of a model is done automatically by the model evaluation system. The results of the evaluation are obtained by the numerical form of the variances of the parameters and the error between the estimated data and the experimental data. The better of the models can unquestionably be chosen from these results.

(2) The process to improve the model by these operation is especially effectively performed by using this system. The model which can be applied to the wide range conditions was obtained as the result of this process.

The automatic condition setting of the surface hardening was performed by applying this model to the condition setting system in the next step. The performance of the condition setting system was verified by the experiment, and the estimated result had very good correspondence with the experimental result.

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