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Condition Setting Method Utilizing Data Base System in CO₂ Laser Surface Hardening (Report II)[†]

—On the Method of Hardness Estimation—

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Abstract

The new method for investigation of the causality among the parameters and the results in heat processing is proposed. The computer processing system in this method consists of the data base and several peripheral modules. By constructing and utilizing small and simple program modules, various parameters can easily be examined by this method. A series of the computer processing are performed by utilizing data base.

The hardness estimation of CO₂ laser surface hardening is carried out in this report as a concrete implementation of this system. Many parameters that are thought to affect the hardness of laser surface hardened material are effectively investigated by utilizing the temperature data base, which has been constructed on the basis of the heat conduction theory, and the experiment data base. The usefulness of this method is verified by comparing the theoretical result with the experimental data.

KEY WORD: (Computer System) (Computation) (Data Base) (Heat Processing) (Process Condition) (CO₂) (Laser) (Hardening) (Heat Conduction Theory)

1. Introduction

The experimental methods are usually carried out for obtaining the relation between the conditions of heat processings and their results. Recently, the computer aided methods have been used for this purpose.¹⁾⁻²⁾ The most of these methods are of a single program form, therefore, the relations among parameters are generally fixed in such methods.

However, it is well known that the actual heat processings are affected by the very various factors and the causality among the factors is so much complicated that they are never subjected to the simple fixed relation. The authors created the flexible system by avoiding the fixed relations among parameters in the computer processing system that consists of the data base at its center and many modules that are attached to the data base.³⁾

This system is applied to the condition setting of "CO₂ Laser Surface Hardening" in this study.

The following is discussed on the computer processing for hardness estimation and the experiment of CO₂ laser surface hardening which was made under various heat input distribution. Several types of steel were hardened by CO₂ laser beam that was oscillated to simulate many kinds of heat input distribution and the results of the hardening were measured with the micro vickers hardness tester on the cross section of the

material. The measured hardness distribution was compared with the computer estimation that was resulted from the calculation of temperature distribution in the processed material and the calculation of many parameters which include the cooling rate, the maximum temperature and the integration of temperature with time on the material.

2. Experimental Procedures of Surface Hardening

2.1 Laser heat processing system

The block diagram of the laser heat processing system is shown in Fig. 1. The laser oscillator, the DC power supply and the gas handling system are products of GTE Sylvania (Model 975, at present, products of Spectra-Physics) in U.S.A.. Maximum output power of this system is 5.5 kW. The laser

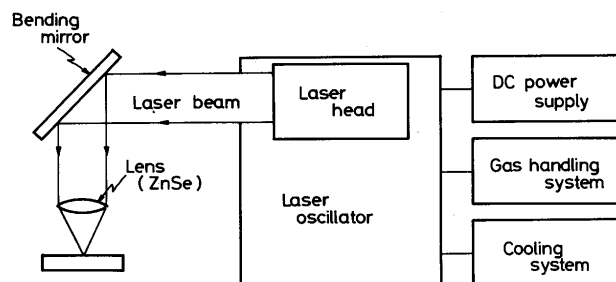


Fig. 1 Block diagram of laser heat processing system

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beam output from the laser head is bent by the bending mirror to the vertical direction, focused by the ZnSe lens and heats the objective material.

2.2 Oscillation and material handling system

The example of heat input distribution is shown in Fig. 2. Such heat input distribution in the X -axis was obtained by the oscillation of objective material in the manner described in the following and the thickness in the Y -axis was determined by the laser beam spot size. The schematic diagram of the mechanical oscillator and the laser beam is shown in Fig. 3. The heat input distribution $W(x')$ is given from the inverted value of v which is the oscillation speed at point x' in the X -axis. Therefore, the arbitrary heat input distribution can be obtained by controlling the oscillating speed.

The stepping motor of oscillator moves the test piece at the rate of 0.5 mm/step. Each interval time of step is independently controlled by the hardware logic circuit which was specially designed and constructed. This hardware logic is able to get each interval time data from the main memory of microcomputer system through the DMA (Direct Memory Access) channel and the oscillating speed at each moment is determined only by the set of data on the main memory of the microcomputer system, therefore, this oscillator is controlled only by the start and stop commands. Arbitrary speed distribution can be set in the main memory by the program.

The maximum oscillating rate of this mechanical oscillator is 20 Hz in the case of 10 mm oscillating width. The oscillating rate of 10 Hz was chosen in the experiment, since the stepping motor of this oscillator has 81 kg-cm holding torque, can move the test piece table by the force of 30 kg in 10 Hz and the various heat input distribution could be gotten at this frequency.

This oscillator is mounted on the table which is also controlled by the microcomputer and moves the whole oscillation mechanism at the arbitrary speed in the Y direction.

2.3 Heat input distribution

The oscillating speed is so fast that the oscillation effect is ignored and the heat input can be approximated by the spreading heat input distribution $W(x)$. Typical pattern of heat input distribution $W(x)$ adopted in the experiments is shown in Fig. 4. The total amount of heat input $\int W(x)dx$ and the gradient α of slanting part are kept constant through this study. The percentage

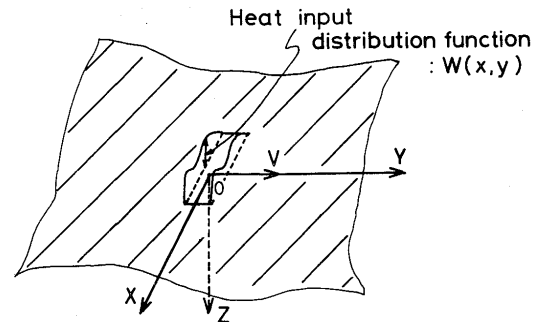


Fig. 2 Example of heat input distribution

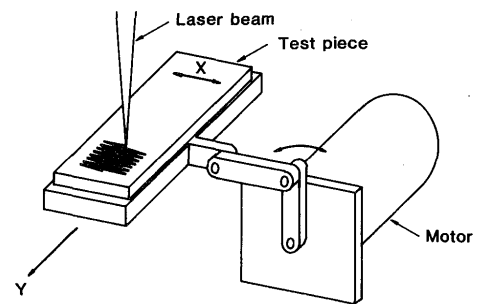


Fig. 3 Schematic diagram of mechanical oscillator

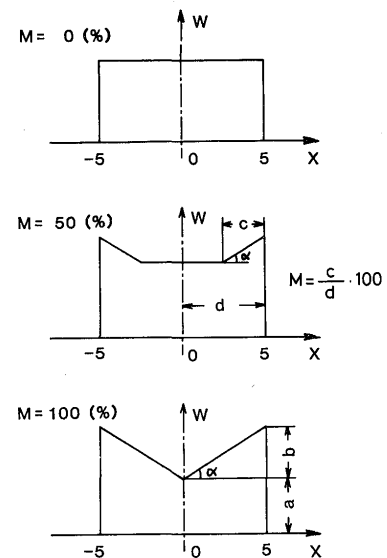


Fig. 4 Typical pattern of heat input distribution $W(x)$

M of the slanting part described in Fig. 4 is used as the heat input configuration parameter in these series. The value M is 100 in the all slanting heat input distribution, and 0 in the flat heat input distribution.

2.4 Material of test piece and measurement of hardness

Chemical compositions of material used in this experiment are shown in Table 1. The two kinds of

low carbon steel, S20C and S40C, and the two kinds of high carbon steel, SK-3 and SK-5, are used respectively in the experiment.

The hardness of each cross point at every 0.5 mm in the X direction and every 0.1 mm depth was measured with the micro vickers hardness tester on the cross section of the hardened material. These data were stored in the data base and used in the comparison with the estimated hardness.

3. Calculation of Temperature Distribution from Heat Input

The temperature distribution at the surface hardening part is calculated on the basis of the heat conduction theory. When the heat input $W(x', y')$ is given on the surface of semi-infinite solid, as shown in Fig. 2, equation (1) gives the temperature rise T at point (x, y, z) of the co-ordinate that travels in the direction of Y -axis together with the center of heat source.

$$T = \frac{1}{c\rho 4(\pi k)^{3/2}} \int_0^\infty t^{-3/2} dt \int_{-\infty}^\infty \int_{-\infty}^\infty W(x', y') \exp \left\{ -\frac{(x-x')^2 + (y+vt-y')^2 + z^2}{4kt} \right\} dx' dy', \quad (1)$$

where

- c : specific heat input
- ρ : density of base metal
- k : thermal diffusivity of test piece material
- t : time
- T : temperature
- v : travelling velocity in the direction of Y -axis.

The heat input distribution $W(x, y)$ in the Y -axis is approximated by the rectangular form whose thickness is determined by the laser beam spot size in the above mentioned heat input distribution. Therefore, $W(x, y)$ is given by Eq. (2) and the temperature distribution is given by Eq. (3).

$$W(x, y) = \begin{cases} 0 & y < s \\ W(x) & -s \leq y \leq s, \\ 0 & y > s \end{cases} \quad (2)$$

where

$2s$: thickness in the Y -axis.

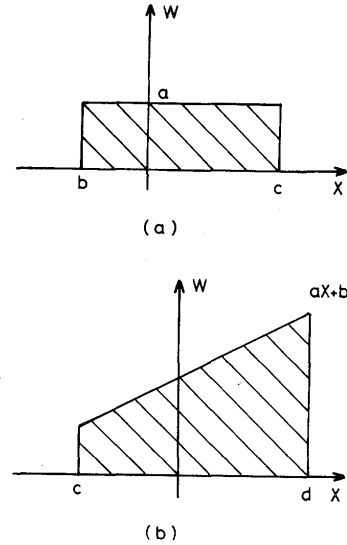


Fig. 5 Simple examples of $W(x)$

$$T = \frac{1}{c\rho 4(\pi k)^{3/2}} \int_0^\infty t^{-3/2} \exp\left(-\frac{z^2}{4kt}\right) \frac{\sqrt{4kt\pi}}{2} \left\{ \operatorname{erf}\left(\frac{y+vt+s}{\sqrt{4kt}}\right) - \operatorname{erf}\left(\frac{y+vt-s}{\sqrt{4kt}}\right) \right\} dt \int_{-\infty}^\infty W(x) \exp\left(-\frac{(x-x')^2}{4kt}\right) dx', \quad (3)$$

where

$$\operatorname{erf}(m) = \frac{2}{\sqrt{\pi}} \int_0^m \exp(-p^2) dp.$$

The temperature distribution is determined by $W(x)$ in Eq. (3). Simple examples of $W(x)$ are shown in Fig. 5, where (a) is the constant distribution model and (b) is the linearly changing model. When the heat input $W(x)$ is given by the form as shown in Fig. 5(a), the temperature distribution is given by Eq. (4).

$$T = \frac{1}{c\rho 4(\pi k)^{3/2}} \int_0^\infty t^{-3/2} \exp\left(-\frac{z^2}{4kt}\right) \frac{\sqrt{4kt\pi}}{2} \left\{ \operatorname{erf}\left(\frac{y+vt+s}{\sqrt{4kt}}\right) - \operatorname{erf}\left(\frac{y+vt-s}{\sqrt{4kt}}\right) \right\} \frac{a\sqrt{4kt\pi}}{4} \left\{ \operatorname{erf}\left(\frac{x-b}{\sqrt{4kt}}\right) - \operatorname{erf}\left(\frac{x-c}{\sqrt{4kt}}\right) \right\} dt. \quad (4)$$

Table 1 Chemical compositions of surface hardened material

Material	Chemical element (%)								
	C	Si	Mn	P	S	Cu	Ni	Cr	Al
S 20 C	0.19	0.26	0.46	0.018	0.020	—	0.01	0.02	0.040
S 40 C	0.41	0.28	0.73	0.021	0.016	—	0.01	0.01	0.032
SK-5	0.90	0.30	0.38	0.016	0.005	0.04	0.06	0.17	0.013
SK-8	1.05	0.45	0.93	0.015	0.004	—	—	0.35	—

When $W(x)$ is given as shown in Fig. 5(b), the distribution is given by Eq. (5).

$$T = \frac{1}{c\rho 4(\pi k)^{3/2}} \int_0^\infty t^{-3/2} \exp\left(-\frac{z^2}{4kt}\right) \frac{\sqrt{4kt\pi}}{2} \left\{ \operatorname{erf}\left(\frac{y+vt+s}{\sqrt{4kt}}\right) - \operatorname{erf}\left(\frac{y+vt-s}{\sqrt{4kt}}\right) \right\} \left[2akt \left\{ \exp\left(-\frac{(x-d)^2}{4kt}\right) - \exp\left(-\frac{(x-c)^2}{4kt}\right) \right\} - \frac{(ax+b)\sqrt{4kt\pi}}{2} \left\{ \operatorname{erf}\left(\frac{x-c}{\sqrt{4kt}}\right) - \operatorname{erf}\left(\frac{x-a}{\sqrt{4kt}}\right) \right\} \right] dt. \quad (5)$$

The temperature distribution in the case of more general heat input distribution is given by the combination of Eq. (4) and Eq. (5). Typical example of synthesised $W(x, y)$ is shown in Fig. 6.

4. Computer Processing System

The computer processing system was constructed on the HITAC E-800/7 minicomputer system. This computer hardware system has 1M byte main memory, dual 70M byte hard disk storages, floppy disk drive, magnetic tape drive, two CRT display terminals and line printer as shown in Fig. 7.

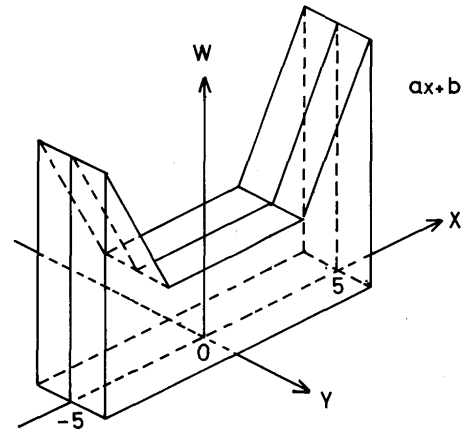


Fig. 6 Typical example of synthesised $W(x, y)$

The data base and the objective data set were constructed in the hard disk and all program modules were also stored in the hard disk. The CRT display terminals were used in the experimental data entry and all the interactive operations. The output data were mainly printed out using the line printer. The data base utility programs that are included in the operating system were used in the data base manager. The most of other programs are coded in Fortran language.

The block diagram of the computer processing

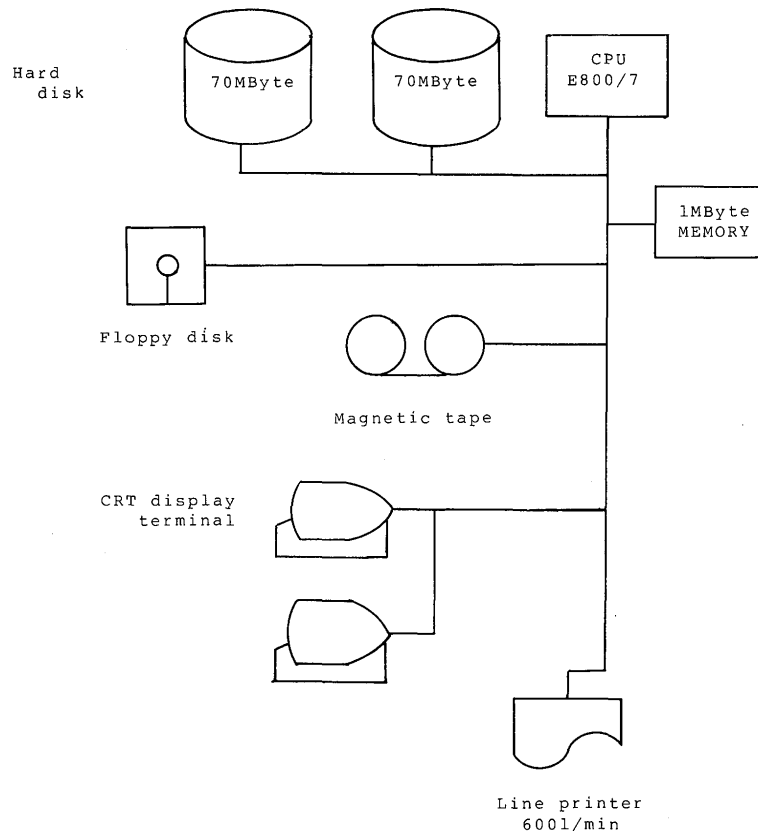


Fig. 7 Block diagram of computer hardware system

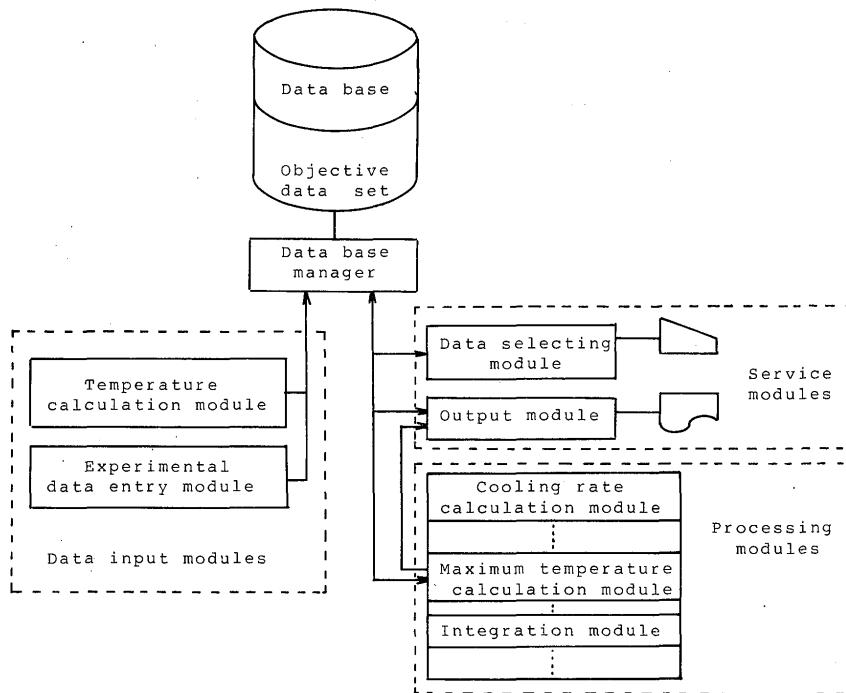


Fig. 8 Block diagram of computer processing system

system used in this study is shown in Fig. 8. The fundamental processing system which was mentioned in the previous report³⁾ was modified because the function of this system was restricted in the hardness estimation of laser surface hardening. "Store processing module" is composed of "Temperature calculation module" and "Experimental data entry module", "Semantic formatter" is combined with "Data base manager". "Query module" is simplified to "Data selecting module" and "Processing part" is formed as the collection of "Processing modules" in this hardness estimation system.

4.1 Data input module

"Temperature calculation module" and "Experimental data entry module" are attached to the data base as "Data input module".

"Temperature calculation module" can calculate the temperature distribution from the parameters by which the target heat input condition is given as manifold combination of Eqs. (4) and (5). The temperature distribution was calculated in "Temperature calculation module" for the 20 types of the heat input distribution which include the distribution of Fig. 4 and these data were combined with the condition data base and stored in the temperature data base as mentioned in the next section.

The experimental data of 30 test pieces were also combined with the condition data base and stored in

the experiment data base through "Experimental data entry module".

4.2 Data base

The data base consists of multi-indexed records and indexes. The record formats that are used in the data base are shown in Fig. 9, where are three kinds of type. They are "Condition data record", "Temperature data record" and "Experiment data record". The temperature and experiment data are selected by using the condition data base. The condition data base has six indexes which are "Distribution parameter code", "Parameter value", "Material", "Laser power", "Laser spot size" and "Oscillation frequency", and the condition data can be selected by the combination of these six indexed parameters. "Distribution parameter code" and "Parameter value" are " M " and M which was described in the example of Fig. 4. The heat input distribution is expressed by these two parameters. "Material" is the name of material used. "Laser power", "Laser spot size" and "Oscillation frequency" are also stored and indexed. "Experimental data number" or "Temperature data number" is the linkage number to the records of the temperature data base or of the experiment data base respectively. This is peculiar in the temperature data or the experimental data and the objective data can be selected only by using this number in each data base.

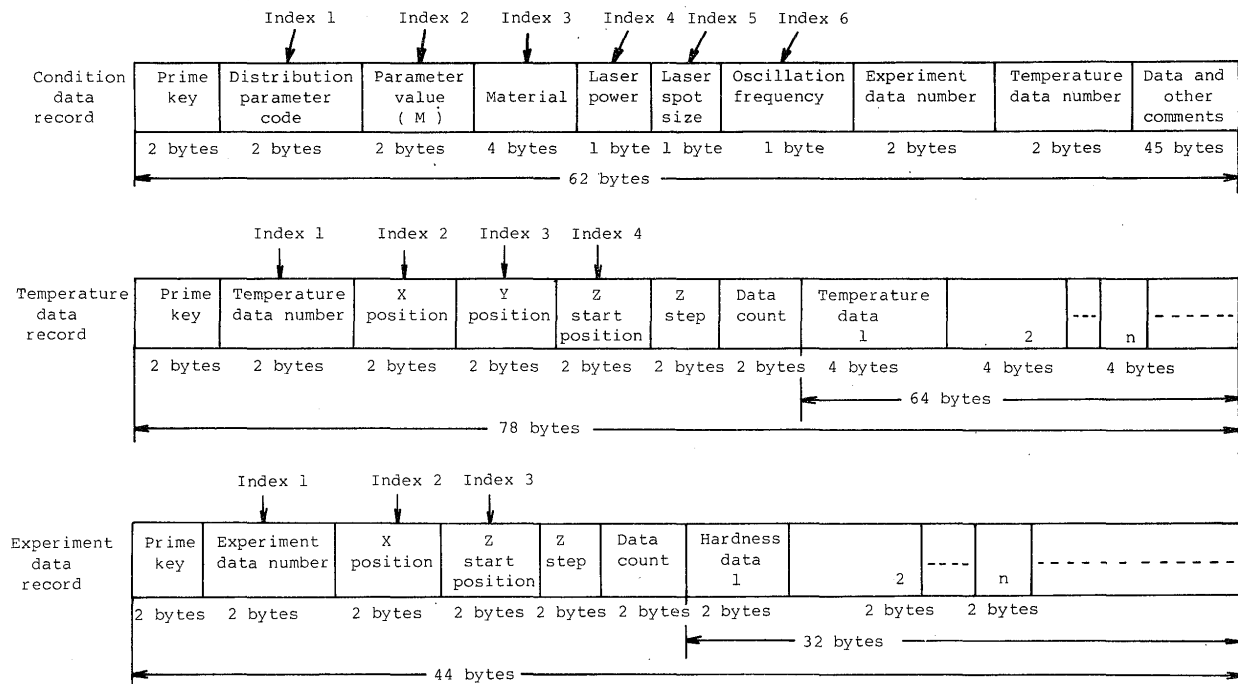


Fig. 9 Schematic diagram of record formats

The temperature distribution data, corresponding to a certain processing, consist of 200 to 1000 "Temperature data records". Each "Temperature data record" has one to sixteen temperature data in the same X and Y position and different Z positions. Each record of same condition has the same temperature data number, different X and Y positions and other data.

The experimental data of one condition consist of 25 to 30 "Experiment data records". Each "Experiment data record" has one to sixteen hardness data of same X position, the experimental data number, X position and other data. The amount of currently active records is about 10000.

4.3 Service modules

"Data selecting module" selects the objective condition data from the data base using the above mentioned indexed parameters and creates the data set for "Processing modules". "Output module" receives the data from "Processing modules". These data are compared with the experimental data in this module and printed out in the suitable form according as the various requirement of evaluation. The common processes that are necessary for the evaluation of many parameters are performed by these modules.

4.4 Processing modules

"Processing modules" consist of many modules. Each module is so compact that a new module can

easily be appended. Many "Processing modules" were programmed for the hardness estimation. The flowchart for the process of hardness estimation is shown in Fig. 10. At the first stage, the condition of surface hardening is selected and given to "Data selecting module". "Data selecting module" extracts the objective data set from the data base. One of "Processing modules" gets this data set that includes the temperature distribution data and conditions and calculates the objective parameter of this module in the next stage. The output data of this module are transmitted to the output module. These data are compared with the experimental data, which are included in the objective data set, and printed out through the output module in the last stage.

Thus, the function of each "Processing module" is restricted within calculation of only one parameter which is thought to affect the hardness of hardened material, and this function can be actualized by a small module. By constructing and utilizing a new small "Processing module", we can easily examine a new parameter by this system.

Three examples of the hardness estimation by introducing such modules are described and the discussions are made on the processed results in the following.

5. Hardness Estimation and Comparison with Result of Experiment

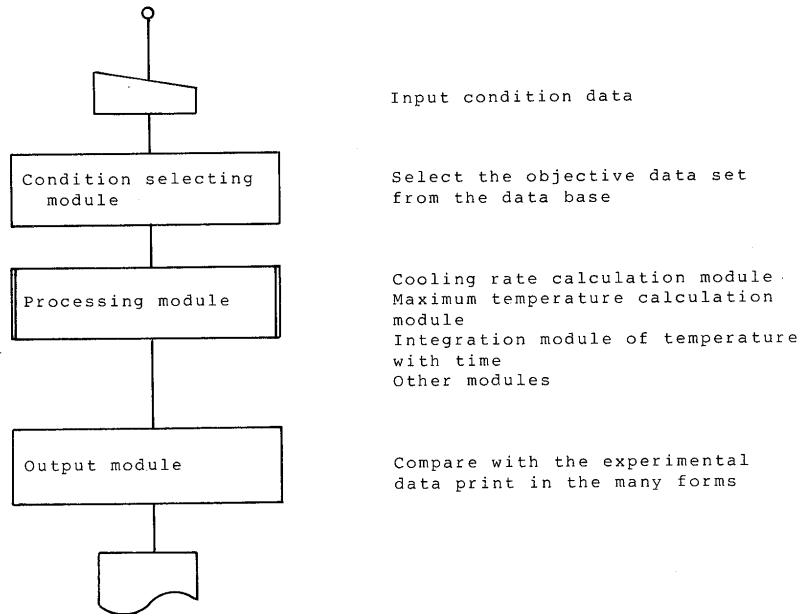


Fig. 10 Flowchart for the process of hardness estimation

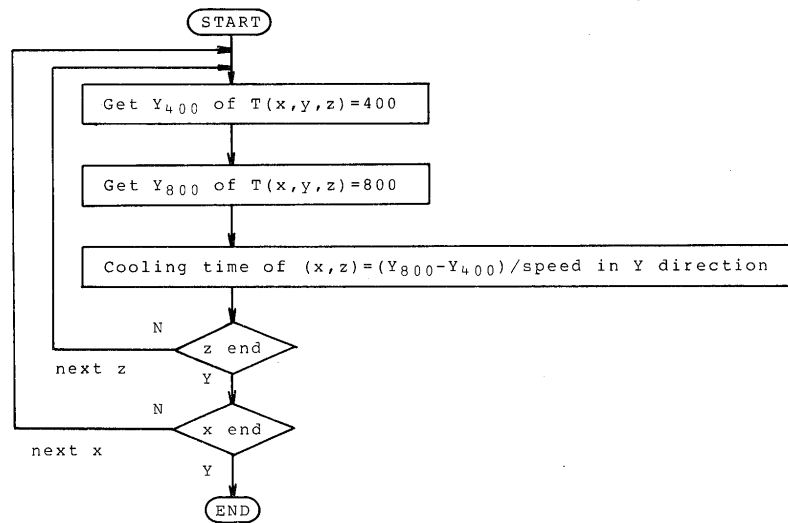


Fig. 11 Flowchart of "Cooling rate calculation module"

5.1 Hardness estimation by cooling rate

The cooling rate from 800°C to 400°C was calculated by "Cooling rate calculation module". The function of this module is calculation of the interval time of two points, whose temperature is 800°C and 400°C, from the temperature distribution data and the Y directional travelling speed which are included in the objective data set. The algorithm for calculation in this module is shown in Fig. 11. The example of the calculated result at "Cooling rate calculation module" is shown in Fig. 12. At the first stage of the process, the conditions of surface hardening were feeded to

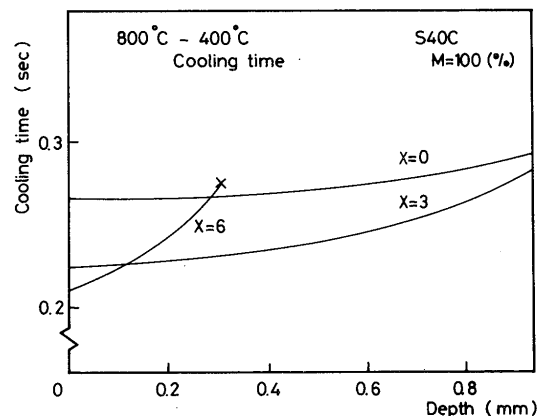


Fig. 12 Calculated result at "Cooling rate calculation module"

“Condition selecting module”. They were “M” as “Distribution parameter code”, 100 as “Parameter value”, S40C as “Material”, 2kW as “Laser power”, 3 mm as “Laser spot size” and 10 Hz as “Oscillation frequency” in the example of Fig. 12. The condition selecting module selected objective “Temperature data records” and “Experiment data records” by using the condition data base and generated the objective data set. “Cooling rate calculation module” got the temperature distribution data $T(x, y, z)$ from the objective data set in the next stage. The cooling time was calculated in every point of X - Z plane. The value of $T(x, y, z)$ was compared with 400°C in the cooling side and Y_{400} was gotten. The value of Y_{800} was gotten by the same method as Y_{400} . Then, the cooling time was gotten from Y_{400} , Y_{800} and speed in Y direction.

The cooling rate is enough high for the carbon steel to form martensite. The cooling rate is usually so high in the laser surface hardening that it may not affect on the hardness.

However, the cooling rate becomes low when the very large total heat input is given by the special and broad heat input distribution or the work piece is very thin. It is thought that the cooling rate has some effect on the hardness in such case.

5.2 Hardness estimation by maximum temperature

The maximum temperature distribution in X - Z plane was calculated by “Maximum temperature calculation module”. The algorithm of “Maximum temperature calculation module” is very simple. It only searches the maximum temperature data in each point of X - Z plane from the temperature distribution data $T(x, y, z)$ included in the objective data set.

The example of the calculational result at “Maximum temperature calculation module” is shown in Fig. 13. The plotted points in Fig. 13 are the experimental measured data on high carbon steel SK-3.

The hardened area is approximately estimated from the point, where the temperature cross the A_{c1} transformation point, on high carbon steel that is easily hardened to the saturated hardness. However, it is difficult to estimate the accurate boundary zone of hardened area on high carbon steel, and very difficult to estimate its shape. It is also difficult to estimate even the hardened area from the maximum temperature on low carbon steel because the hardness does not easily saturate.

5.3 Hardness estimation by the integration of temperature with time

The integration of temperature with time was

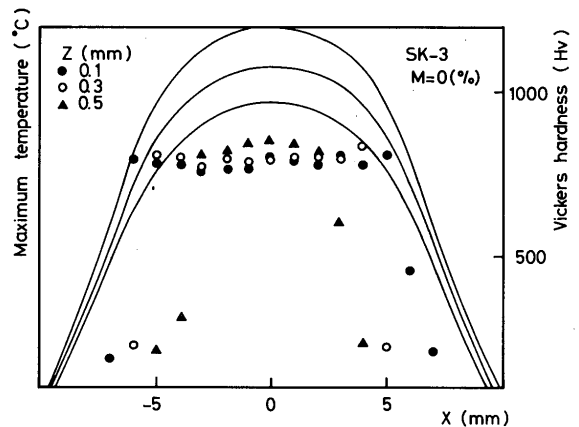


Fig. 13 Calculated result at “Maximum temperature calculation module” and experimental result

calculated by the integration $\int (T - A_{c1})^2 dt$ in the region where the temperature is higher than A_{c1} transformation point from the temperature distribution data included in the objective data set. The algorithm of this module is shown in Fig. 14. It is also simple. This module sums up $(T(x, y, z) - A_{c1})^2 dt$ in each Y step, when $T(x, y, z)$ is higher than A_{c1} . The sum of Y loop is the numerical integration value of $\int (T - A_{c1})^2 dt$ in point (x, z) . The integration is performed in every point of X - Z plane.

The example of the calculational result by the integration and the experimental data are shown in Figs. 15, 16, 17 and 18. The material of Figs. 15 and 16 is S20C and the heat input configuration is $M=0$ in Fig. 15, and $M=100$ in Fig. 16 respectively. Figure 17 is the result of S40C, $M=0$. Figure 18 is the result of SK-5, $M=100$. Calculated results are much higher than the experimental data in the saturated hardness part. These saturated hardnesses are well known value and it is easy to estimate as a broken line in Figs. 17 and 18.

Thus, the hardness distribution can be estimated by this calculation module in the considerably wide range of carbon contents of steel. The hardness of boundary area can be also estimated.

5.4 Hardness estimation by other parameters

The time when the temperature is higher than the transformation point, the rising rate of temperature and other parameters in the temperature history are thought to affect the hardness of hardened material. These parameters can be also calculated by constructing and utilizing small and simple processing modules.

6. Discussion

The above mentioned parameters can be calculated

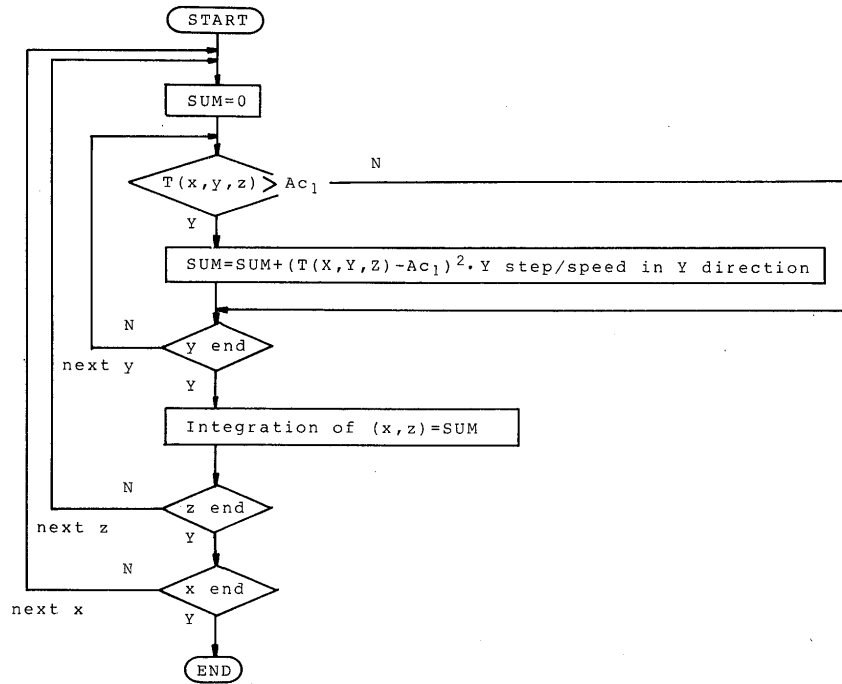


Fig. 14 Flowchart of "Integration module of temperature with time"

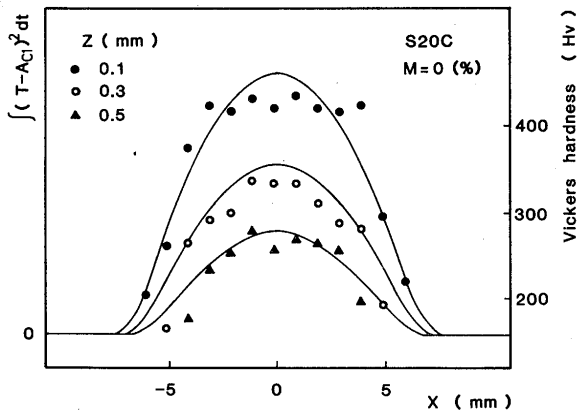


Fig. 15 Calculated result at "Integration module of temperature with time" and experimental result, S20C, M=0

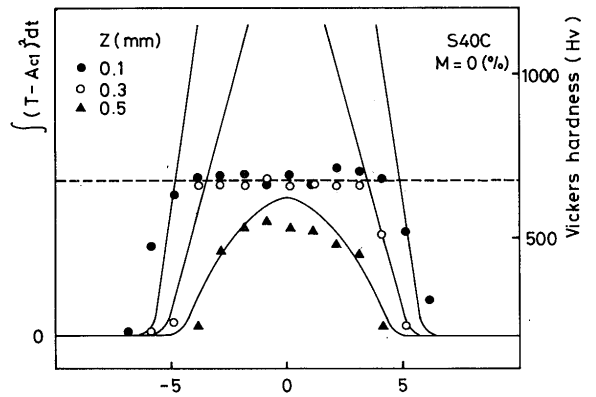


Fig. 17 Calculated result at "Integration module of temperature with time" and experimental result, S40C, M=0

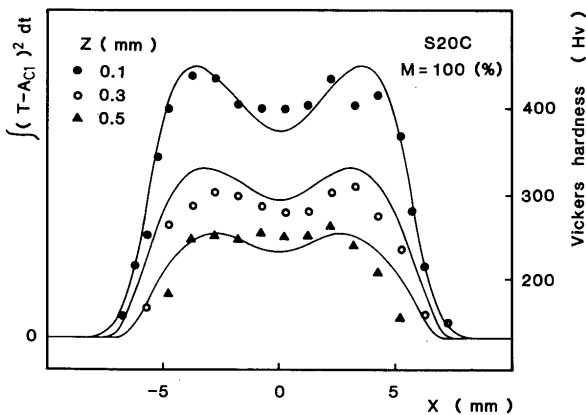


Fig. 16 Calculated result at "Integration module of temperature with time" and experimental result, S20C, M=100

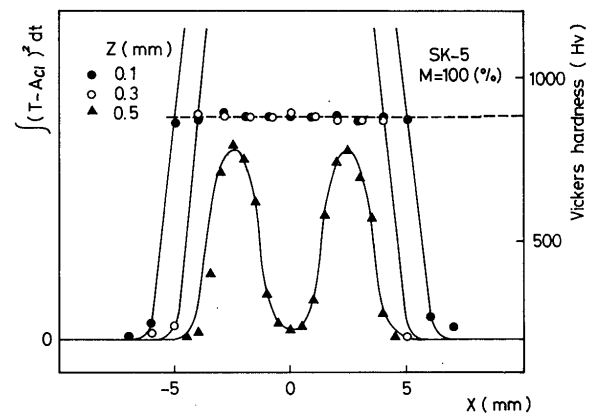


Fig. 18 Calculated result at "Integration module of temperature with time" and experimental result, SK-5, M=100

by the conventional method. However, the program of the conventional method is more complicated than "Processing module" in this system and needs very long calculation time. It is extremely difficult to calculate many parameters by using such method.

Against the conventional method, every "Processing module" in this system is very small and simple as mentioned above and the calculation time for them is short. The calculation of the parameter in the various heat processing conditions is possible in the very short time by using this system. Owing to those features of this system, it is easy to investigate the causality among the many parameters and the heat processing results.

7. Conclusion

It is easy to analyze the relations between many parameters by using the above mentioned method. This method was applied to the CO₂ laser surface hardening. Estimation of hardness distribution was made by this method under the various heat input conditions. The experiment of hardening was also performed under the same conditions and with several kinds of steel that have different carbon contents. The following knowledges were gotten by these estimations and experiments.

1) There are no significant relations between the cooling rate and the distribution of hardness in the high speed hardening such as the laser surface

hardening.

2) There is good correlation between the maximum temperature and the distribution of hardness especially in the high carbon steel.

3) The integration of temperature with time of the higher part than the transformation temperature has one to one correspondence to the distribution of hardness on the many kinds of steel and various heat input conditions.

4) By constructing and utilizing a small and simple processing module, we can easily examine a new parameter by the above mentioned computer processing method. This method is very useful and flexible in the investigation of the causality among the parameters and the heat processing results.

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