A GA-based PID Control of the Plate Width in Hot Plate Mills

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ABSTRACT

In hot plate mills the slabs from incoming reheat furnace are reduced to the desired width and thickness, being rolled out with considerable accuracy. The process of changing the plate width is controlled by a pair of edge rolls, which is called edger. The objectives of this edging process are to meet tight width tolerances of plates and to reduce the yield loss caused by trimming when irregular width is formed at the plate edge. There are several factors that result in complexity and uncertainty in width control. These include inaccurate edger set-up model, degradation of various mill equipment, variation of operation conditions, environments and variation of the dimension of incoming cast slabs. In this paper, a genetic algorithm(GA)-based PID control is proposed to ensure the control of the desired width at the exit of the mill. The approach adopted here is essentially optimization of the PID controller gains in order to minimize the error between the desired and actual slab width. Since the design parameters associated with genetic algorithm affect convergence performance, the effects of these parameters are investigated in detail. In addition, the control performance is also evaluated for various process parameters such as initial width of the incoming slab and temperature of the slab. Based on the results obtained from a series of simulations, the proposed control method is found to yield satisfactory performance for various process conditions.

Keywords : hot rolling process, automatic width control, PID gain tuning, genetic algorithm(GA).

1. INTRODUCTION

The process of rolling the slab in hot plate mills consists of two principal stages called edging and gap rolling, as shown in Fig. 1. The former takes charge of rolling the slab in the direction of the width, the latter takes charge of rolling the slab in the direction of the thickness. In spite of the different role of each rolling process, these two sub processes are directly coupled in the sense that the slab dimension modified by the edger motion affects the subsequent motion of the horizontal roll which in turn produces the slab dimension needed to be modified by the edger during multi-pass reversible rolling. Therefore, precise control of the slab width is ultimately required in order to provide the gap roll with accurate slab width dimension so as to produce slabs of desired thickness and width at the exit of the roll. Another important objective of this edging is to reduce the yield loss caused by trimming when irregular width is formed at the plate edge[1].

The irregular width spread occurs as a result of plastic deformation[2-4]. This phenomenon is very much complex and influenced by thickness reduction process. This leads the rolling control problem to be very complicated and made it intricate to achieve the desirable specification in the plate dimension.

There are several causes that result in rather unsatisfactory width control performance[5]. The inaccurate edger set-up model, degradation of various mill equipment, variation of operation conditions and environments may be responsible for that. One important factor responsible for the cause is the inherent characteristics of the edging process that are expressed by uncertainty, high nonlinearity and the dynamics of the hydraulic servo systems. In addition to this complexity, temperature variation during rolling and the variation of the dimension of incoming cast slabs come into the process in a form of

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disturbance. This situation makes the design of process controller difficult.

One form of controller widely used in industrial process control is PID controller, which is installed easily and is robust in a finite operating range. In spite of these advantages, there are many difficult problems, one of which is determination of PID gain in adequate operating range. Many researchers' efforts give birth to some solutions such as Ziegler-Nichols PID tuning method and linear approximation method[6]. But these have many limitations for a real industrial plant. For example, Ziegler-Nichols tuning method can not be used to the system including integral factor like hydraulic servo systems. In the case of linear approximation method, it is difficult that the exact mathematical model of the process is formulated and the determination of adequate PID gains from the mathematical model is more difficult. Thus, most industrial process control engineers use trial and error methods, which are laborious and time consuming. But It is more reliable than others.

In order to surmount these difficulties, we attempt a GA approach in an effort to determine PID gain of edging process controller in hot plate mills. Genetic Algorithms (GAs), which are search and optimization algorithms initially inspired from the processes of natural selection and evolutionary genetics, are useful when the closed-form optimization technique cannot be applied[7].

In this work, the response in a nominal operating range for the specific time is regarded as a basis, and the fitness function is defined by inverse of ISTAE (Integral of Square Time multiplied by Absolute Error) between the actual response and the desired response. A population is constructed by gray strings which represent each PID gain. Since the performance of the proposed gain tuning method is affected by GA parameters, the effects of the parameters are carefully investigated. The effectiveness of the proposed controller is shown for various process conditions.

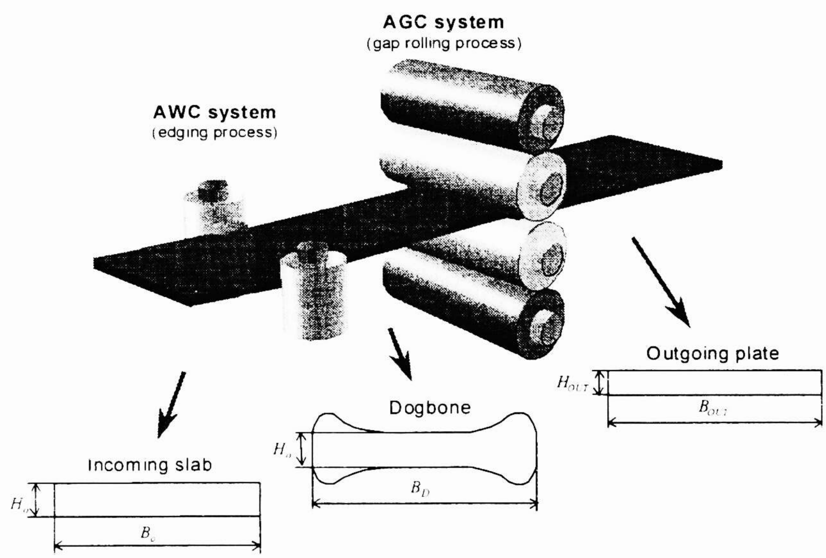


Figure 1. A schematic of the automatic width control system

2. Automatic Width Control System

2.1. The Overall control system

In hot plate rolling process, the reduction of a plate in thickness is accompanied with an increase in the width of the plate. This interacting phenomenon results from the plastic deformation of plate during edging and gap control process. This process is very complex and difficult to analyze with a mathematical model. We will consider only the width control process without consideration of the interaction with the thickness control process.

There are some empirical formulae for this process. These formulae have a common feature, which is that these are based on the geometrical parameters. One of those is the model reported by Shibahara, et al[4,8,9], which was verified by the results of the experiments. This model may be shown through a simple functional form as follows:

$$B_{OUT} = B_D + f(B_o, B_D, H_o, H_{OUT}, R_E, R_G) \quad (1)$$

Where,

$f(\cdot)$ = the width spread after gap rolling

B_{out} = the plate width after gap rolling

B_D = the plate width after the edging rolling

H_o, H_{out} = the plate thickness before edging rolling, after gap rolling

R_E, R_G = the radius of edger and gap roll.

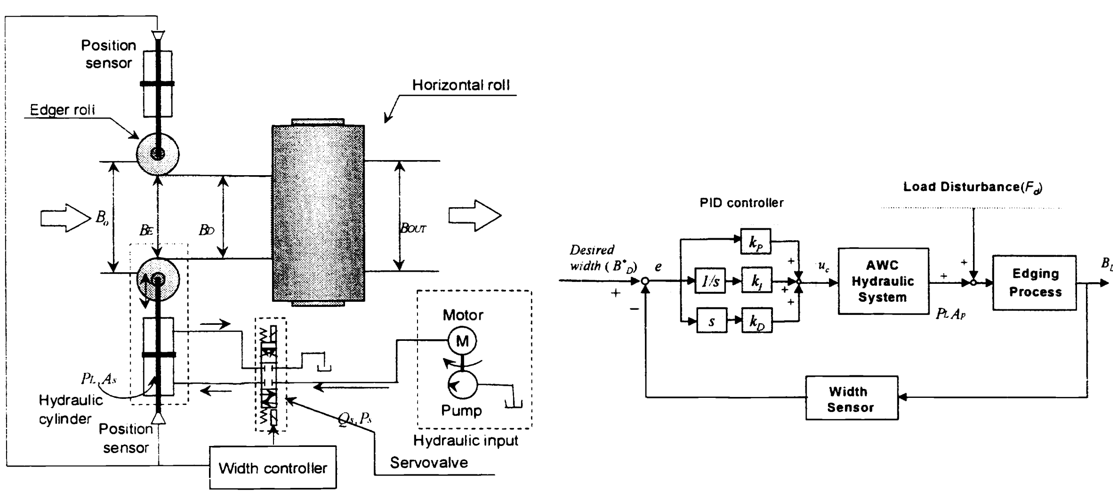
In the above, all parameters except the plate width after edging process (B_D) are constants during one pass rolling process [10-11], only if automatic gap control (AGC) system produces the constant desired thickness (H_{out}) exactly. This means that the desired final slab width can be obtained by making the plate width adequate after edging process (B_D).

2.2. The control system of the edging process

The control system of an edging mill is partitioned into three sub systems as shown in Fig.2 (a), (b). It consists of a hydraulic positioning system, a rolling stand consisting of two rolls and a steel plate to be rolled and a width sensor which measures instantaneous width of the slab.

The control action begins as the plate is entering the mill. According to the command signal a servo value of the hydraulic servo system is operated in such a way that the piston generates the required rolling force. This force, in turn, produces a width dimension of the plate to be controlled. A sensor then measures the instantaneous width of the plate and this signal is feedback to the controller for comparison with the reference signal. Utilizing the error between the actual and reference signals, the controller generates appropriate command signal for the next time step to actuate the servo value. This action is repeated until the actual width value reaches steady state. In this control system, the hydraulic system has to be robust to handle the high edging force of slabing to meet the demand of edging and also should respond quickly to command signal coming out from the servo controller.

It is noted here that the control system shown in the figure differs slightly from those installed in the actual production lines in view of sensor location. Here, we consider the edging process independently from the thickness control process in order to confine ourselves to the design problem of width control only. There are several factors to be considered for accurate measurement of the width; location of width sensor, width sensing technology and accuracy of length tracking. One thing to be most carefully treated here is the sensor location, since it critically affects the control performance. It should be located as close to edgers as possible to minimize the effect of time-delay of the feedback signal and length tracking error. If this can not be achieved, then desirable control performance many not be guaranteed.



(a) The configuration of the automatic width control system (b) A block diagram of automatic width control system

Figure 2. The structure of the automtic width control system

2.2.1. The edging process model

Edging accomplished by rolling introduces plastic deformation of the hot slab, resulting in width reduction. There are two major phenomena associated with the process that follow the reduction; elongation of the rolled slab and increase on thickness. The thickness increases greater near the edger, which causes the material to bulge at edge in a shape of dogbone as shown in Fig.1. It also causes head and end of tail extrusion that can result in under-width tapes at the ends. The amount of thickness rolling also affects the width of the plate through lateral plastic flow of material, which increases width. For the development of the width control system, we will consider only edging process model without consideration of the horizontal roll[12,13].

The process model given in Eq. 1 predicts the variation of the plate width after gap rolling which involves characterizing the relationship between the given dimension of the plate and the roll force. Let F denote the rolling force required to develop the plastic deformation of the plate. According to Okado[8], the F is calculated by

$$F = \sigma \cdot H_o \cdot L \cdot Q \tag{2}$$

where σ is the stress of the plate, H_o is the initial thickness of the plate entering the edger, L the contact length of the roll width of the plate during rolling, and Q is the shape factor to be adjusted when the contact area is represented by H_o multiplied by L. In the above, the σ is given by

$$\sigma = 0.40\exp\left(\frac{4000}{T}\right)\cdot \varepsilon^{0.41}\cdot \dot{\varepsilon}^{\left(\frac{0.126T}{1000}+0.075C-0.050\right)} \tag{3}$$

And the L is expressed by

$$L = \sqrt{R_E(B_o - B_D)} \tag{4}$$

where R_E is the radius of the edger roll, B_o is the initial width of the plate, and B_D is the width of the dogbone, which was mentioned by the plate width after the edging rolling in chapter 2. The shape factor Q can be expressed in terms of the mean plate width B_m, the contact length L and the initial thickness H_o as follows:

$$Q = 1.59 - 666\frac{H_o}{B_o} + 0.11\frac{B_m}{L} + 1.08\frac{H_o}{B_o}\cdot\frac{B_m}{L} \tag{5}$$

where the B_m is given by

$$B_m = B_o - \frac{2}{3}(B_o - B_D)\,. \tag{6}$$

The above equations reveal that the actual width of the dogbone (B_D) is determined by the rolling force applied to the material and that their relationship is highly nonlinear. In conclusion, the dogbone width (B_D) is primarily affected by the rolling force, the temperature of the rolled plate, the roll radius and the initial dimension of the incoming plate.

2.2.2. The hydraulic servo system

The rolling force expressed in Eq. 2 needed to produce the required width must be generated by a hydraulic servo actuator. As shown in Fig. 2 the servo system consists of a servo value that adjusts the flow rate of oil entering a cylinder and a hydraulic cylinder that provides appropriate rolling force through a piston motion. The piston motion is largely governed by the servo valve motion, which controls the instantaneous pressure built within each side of the chamber. The dynamics of the hydraulic servo system is highly nonlinear and time-varying due to oil flow phenomena and uncertain due to leakage of oil and variation of working oil temperature[9].

Due to this oil flow motion the dynamics of the piston that produces the rolling force against the plate is governed by

$$M\ddot{x} + c\dot{x} + F = p_L A_p \tag{7}$$

where M is the effective mass of combining the roll and the piston, c is the viscous damping coefficient, and F is the rolling force. Since the piston position x, that is the roll position is equal to the plate width, B_D, the above equation determines the instantaneous width of the plate according to the rolling force *F*. The p_L is the load pressure of the cylinder and A_p is the piston area. In the above equation, the p_L is controlled by the servoing motion of the valve.

It is noted that the rolling force and resulting plate deformation in Eq. (2) is derived based upon empirical approach. Therefore, the relationship may not be accurate in the sense that the model may be often affected by some other conditions and parameter variation that are not considered in the assumptions made for derivation of the model. Also, the roll motion governed by the hydraulic actuator given in Eq.(7) is subject to be highly nonlinear, uncertain and time varying due to its inherent characteristics.

3. A Genetic Approach to PID Gain Tuning

3.1. The GA-based PID gain tuning in the automatic width control system

The GA can be mainly classified into three parts. One is the structure of strings, which includes coding and decoding method, another is the fitness function that is defined to obtain our specific control performance in the edging process and the other is the genetic operator such as reproduction, crossover, and mutation. In this section, we describe the details in employing the GA to obtain optimal PID gains.

3.1.1. Structure and coding method of strings

The control input of PID controller(u) is defined by

$$u = k_P \cdot e + k_D \cdot \dot{e} + k_I \cdot \int e \cdot dt \tag{8}$$

where k_P is proportional gain, k_D is differential gain, k_I is integral gain and e is the error between the desired response and the actual response.

In order to represent parameters in GA, binary vectors are used. There are two coding methods, which are binary coding and gray coding. Generally, the former is preferred to the latter because of its simplicity. But it has inherent discrepancy that each bit in the binary coding method has a different weight in a real searching space, which may result in slow convergence or converging on local minimum. Thus, gray coding method is used in this paper.

Each parameter has a finite bit string. All parameters are coded one long string, named population, for the late calculation. Such strings can be lengthened to provide more resolution or shortened to provide less resolution for the representation of the parameters. In this study, the number of bits in a string is total of 30 and each gain has 10 bits. The figure 4. (a) shows this coding of the parameters.

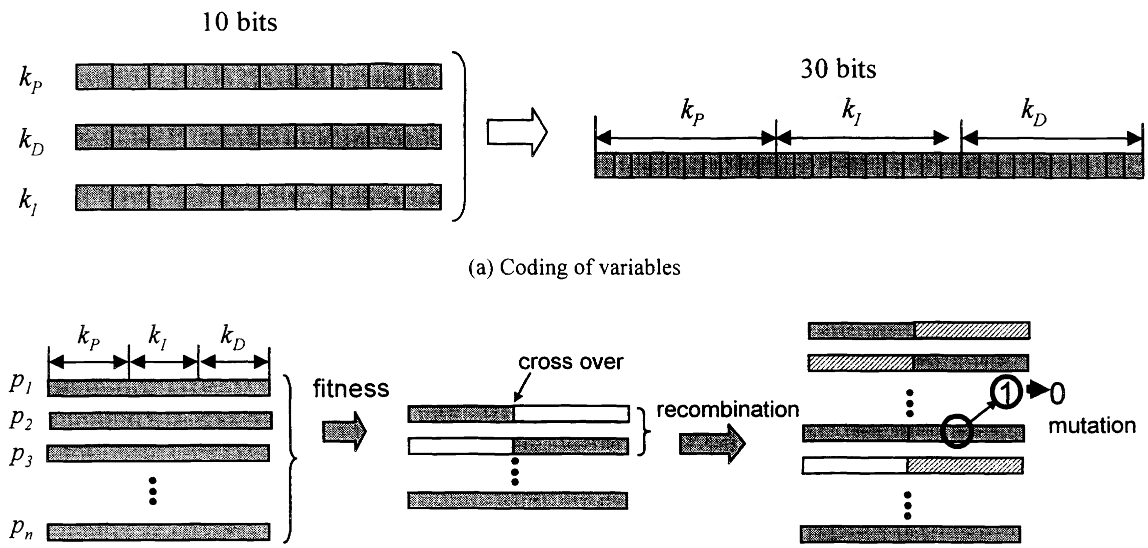
3.1.2. Fitness function

The controller of the edging process performs a position control as described previously. In designing of the controller, the characteristics of the control scheme and the requirements of the system must be considered. In this system, the controller is designed on the basis on the transient response. To evaluate the PID controller, its fitness function is defined by

$$fitness = \frac{1}{ISTAE} \tag{9}$$

$$ISTAE = \int_0^T t^2 \cdot |e| \, dt \tag{10}$$

where ISTAE is the integral of square time multiplied by absolute error and T is a finite time chosen arbitrarily so that the integral approaches a steady-state value. In this case, we select 1 sec as T. In ISTAE, the initial error is less affected than IAE (integral of absolute error) in evaluating the performance of the controller and steady state error is more weighted.



(b) Operators of genetic algorithm

Figure 3. The operation orders of genetic algorithm

3.1.3. Reproduction

After evaluating every string in a population, new offsprings are generated. In this procedure, next generation is reproduced in proportion to its fitness. There is no guarantee that the most dominant string of last generation is generated. In this study, the most dominant string of one generation is reproduced only once and its reproduction is independent of others, which prohibits early convergence caused by super dominant string.

3.1.4. Crossover and mutation

Crossover provides a mechanism for strings to mix and match their desirable qualities through a random process. Crossover proceeds in three steps. First, two strings in a newly reproduced population are selected randomly using crossover rate (p_c). Second, position of crossover point is generated randomly. Third, gray code following the crossover point is exchanged. Although crossover uses random choice, it should not be thought of as a random search. When combined with reproduction, it is an effective means of exchanging information and combining portions of high-quality solutions.

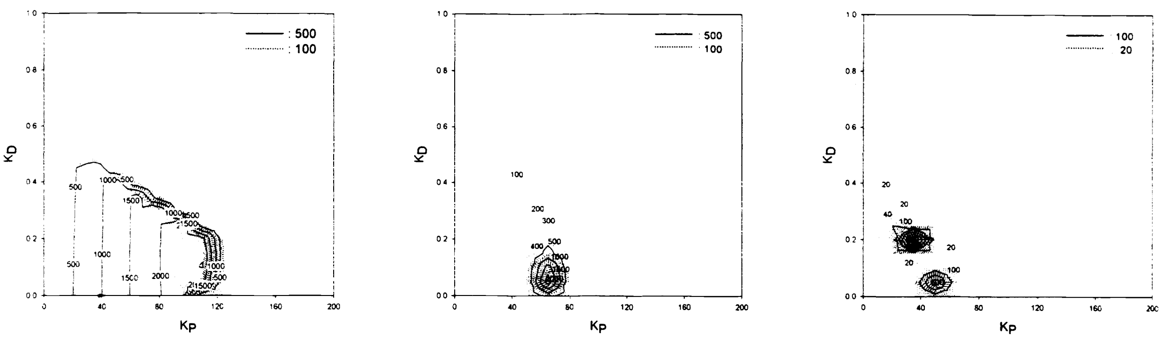
After crossover is performed, mutation is applied to every string in population according to mutation rate(p_m), which is very small value. As generation goes by, mutation can take an effect of local fine tuning.

3.2 The selection of main parameters in GA

3.2.1. Determination of the searching area of the parameters

To obtain the proper resolution of the parameters, the range of the searching space has to be provided. The wide range of the searching space makes the low resolution of the parameters. To select the proper searching area, we pre-calculated the fitness value at some range. Figure 4 shows the result of the pre-calculation of the fitness value. The previously defined fitness value is calculated when the k_p and k_d are changed at fixed k_I values. From the figure 4, the change of I gain (k_I) is affected to the performance of the system very sensitive and the optimal value of I gain (k_I) is expected very small. From this result, the searching domain of parameter is selected as below:

P gain (K_P): $0 \sim 200$ I gain (K_I) : $0 \sim 0.5$ D gain (K_D) : $0 \sim 0.5$



(a) fitness value at k_I=0.0 (b) fitness value at k_I=0.01 (c) fitness value at k_I = 0.1

Figure 4. Change of fitness due to change of the PID gains

3.2.2. Selection of the GA parameters

GA has several important parameters on which effect the performance of GA. There are crossover rate (p_c), mutation rate (p_m) and the population number (p_n) and those parameters must be selected carefully. The bigger population number promises improved results because it enables the parameters are searched in more large space. But the large population number directly affects the computational burden. The GA continues the iterative searching of parameters until it finds the optimal parameters.

4. Simulations

To evaluate the performance of the proposed controller a series of the simulations are carried out. In this simulation, the eq.s through 7 and 9 are used to calculate the fitness values for various k_p, k_d and k_i gains. Simulation conditions are listed in Table 1. The initial slab width, initial edger position and desired slab width are 2050mm, 2020mm and 2017mm, respectively and the temperature of the incoming slab is 1000 °C. And the simulation parameters of the hydraulic system are selected from the plants in Pohang steel company.

Table 1. The parameters of AWC system for simulations

Parameters	Values	Parameters	Values
Initial slab width	2050 [mm]	Initial edger position	2020 [mm]
Desired slab width	2017 [mm]	Temperature of slab	1000 [°C]
Mass of edger roll	15000 [kg]	Radius of edger	50 [cm]
Supply pressure	70 [bar]	The coefficient of leakage	0.3495
Oil Bulk	6800 [N/cm^2]	Max. supply flow	460 [l/min]
Cylinder area	1428 [cm^2]	Area gradient	4.57
Total volume	8511 [cm^3]	Oil density	850 [kg/m^3]

The population number is set to 50 and the crossover rate (p_c) is assigned to 0.2, 0.7 and the mutation rate (p_m) is 0.7 and 0.01 respectively. We can get four cases with the values of parameters given above. Case 1 has 0.2 for the crossover rate and 0.01 for the mutation rate, case 2 has 0.2, 0.05, case 3 has 0.7, 0.01 and case 4 has 0.7, 0.05, respectively.

Figure 5. shows the change of the fitness value at each generation. All cases show the similar results except case 1(p_c is 0.2 and p_m is 0.01). In case 1, it shows a slow convergence caused by small crossover rate (p_c) and mutation rate (p_m). The

larger crossover rate (p_c) shows faster convergence and the change of the mutation rate (p_m) effects less than that of crossover rate (p_c). Table 2 shows the fitness value and optimal PID gains. Case 3 and case 4 show almost same fitness value, 2653 and 2655 which is obtained when P gain (k_P), D gain (k_D) and I gain (k_I) are 90.8, 0.000212, 0.138 and 90.2, 0.00024, 0.25, respectively. And we select the PID gains of case 4 as a optimal gain.

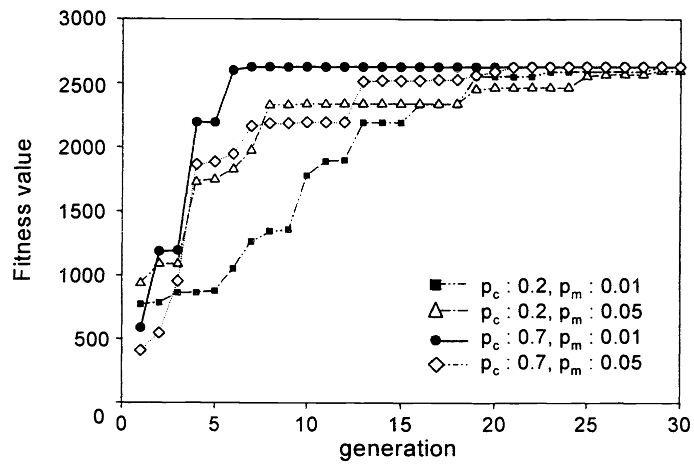


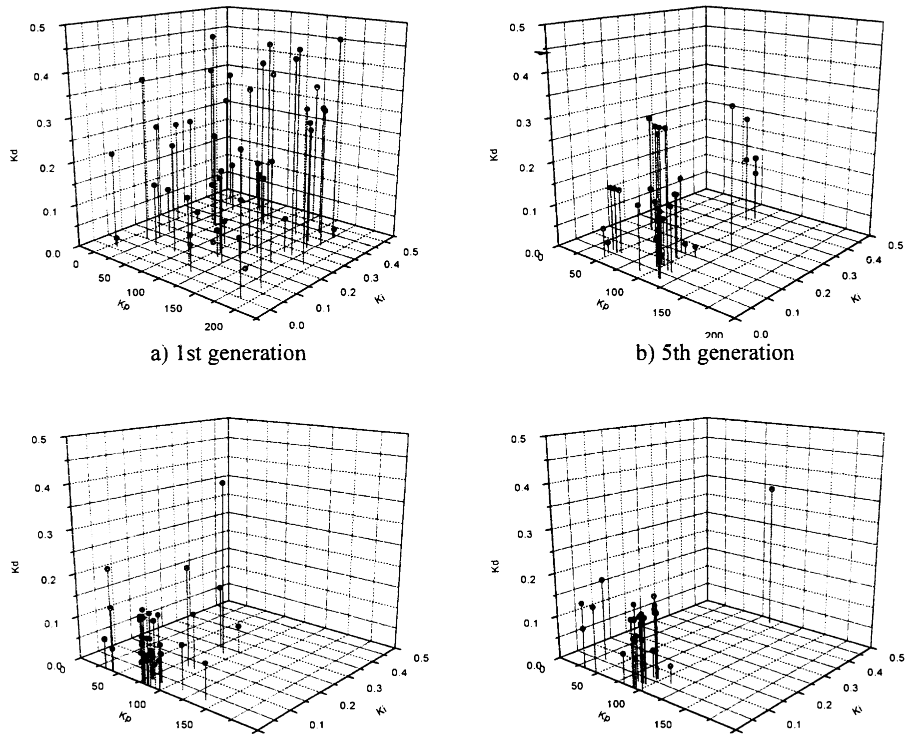
Figure 5. The change of the fitness value with variation of crossover rate (p_c) and mutation rate (p_m)

Table 2. The results of simulation

	Case 1		Case 2		Case 3		Case 4	
p_c	0.2		0.2		0.7		0.7	
p_m	0.01		0.05		0.01		0.05	
Fitness Value	2512		2595		2653		2655	
PID Gains	K_P	90.8	K_P	91.1	K_P	90.8	K_P	90.2
	K_I	0.00023	K_I	0.000293	K_I	0.000212	K_I	0.00024
	K_D	0.138	K_D	0.142	K_D	0.138	K_D	0.25

The I gain (k_I) and the D gain (k_D) searched by GA are very small than the P gain (k_P). Compared with the result of the pre-calculation, the GA searched optimal parameters are located in peak area in figure 4. Figure 6 shows the distribution of the populations in each generation. The populations are scattered widely in 1st generation. As the generation is descended, the distribution of the population is gathered in neighbor of the optimal point and the other points search the new optimal point by crossover and mutation. In figure 6 (d), one point is apart from group of the points which is generated by the mutation.

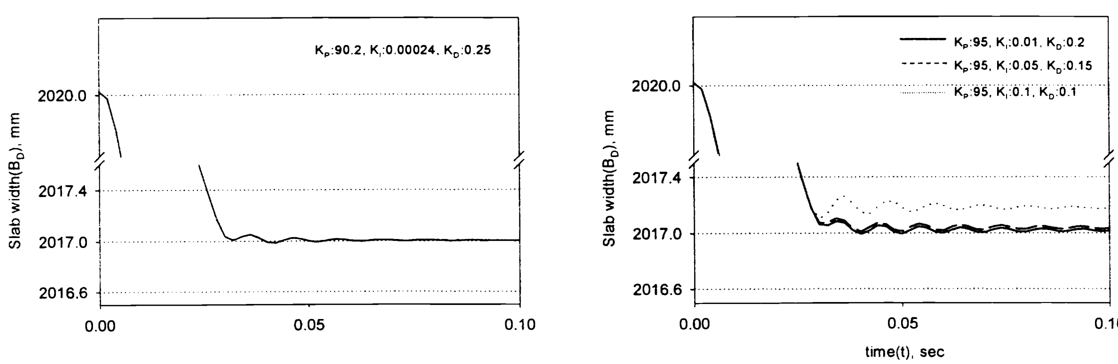
The time response of the AWC system with GA optimal PID gains is shown in figure 7 (a) and those of other PID gains selected by trial and error method are shown in figure 7 (b). The optimal PID gains by trial and error are 95, 0.005 and 0.2, respectively. The simulation results show the small change of the I gain(k_I), which makes the large variations of overshoot and settling time. The response with GA optimal PID gain using GA shows a low overshoot and the short settling time than that of trial and error method. The steady state error of the GA optimal PID gain is 0 mm and that of the trial and error is 0.0094 mm.



a) 1st generation b) 5th generation

a) 15th generation b) 30th generation

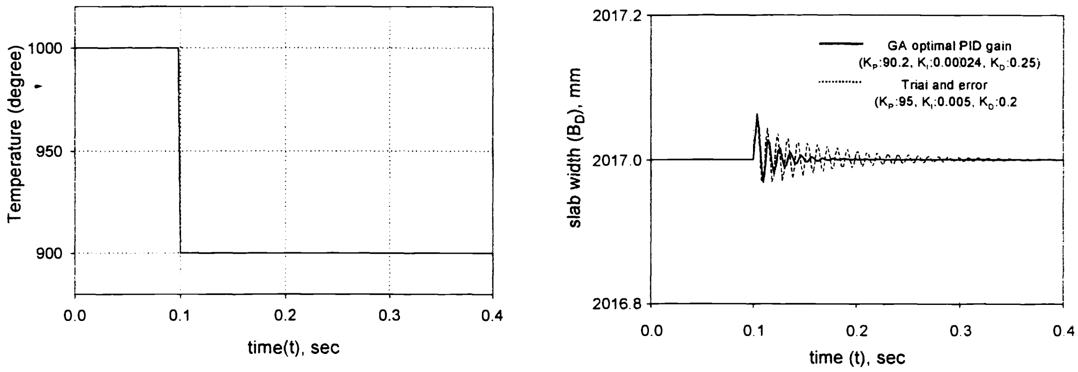
Figure 6. Distribution of chromosomes according number of generation ($p_c = 0.7$, $p_m = 0.01$)



(a) GA optimal PID gain (b) Trial and error method

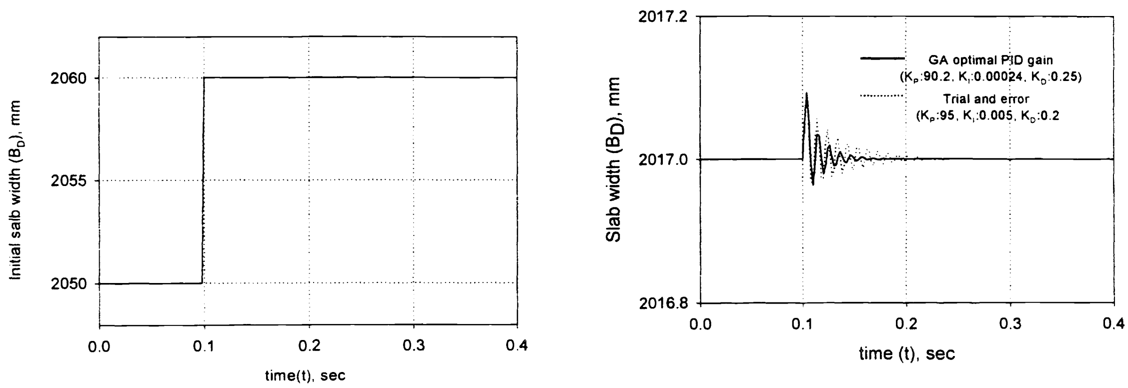
Figure 7. Time response of AWC system applied with PID gains determined by GA

To verify the performance of disturbance rejection, the temperature and the initial slab width are changed 1000°C to 900°C and 2050mm to 2060mm, respectively, during the operation. Lower temperature makes the deformation of the slab more difficult. So, more hydraulic force is needed to reduce the same amount of the slab width. Figure 8. (a) shows the change of the plate temperature and figure 8. (b) shows the outputs of the plate in two case. Applying the GA optimal PID gain, the settling time is short and less overshoot is occurred than the case of applying of the PID gains by the trial and error method. Figure 9. shows the simulation result when the initial slab width is changed. Figure 9 (a) shows the change of the initial slab width and figure 9 (b) shows the results of the PID control. When disturbance is occured, the system responses show a vibration phenomena. The frequency of the vibration with disturbance is almost same with that of the control response in figure 7 (a), (b) and magnitudes are almost same also. The GA optimal PID gain shows fast settling time and less magnitude of vibration.



(a) The change of plate temperature (b) The output width of the plate

Figure 8. The transient response due to temperature variation



(a) The change of initial plate width (b) The output width of the plate

Figure 9. The transient response due to initial slab width change

5. Conclusions

A GA approach for PID gain turning in hot plate mill has been proposed. The edging process is characterized by nonlinear, time-varying and uncertain properties, so it is very difficult to find an optimal PID gain analytically. For obtaining the optimal PID gain, the GA is used to find optimal value by maximizing the fitness function, which is defined by the inverse of the ISTAE (integral of the square time multiplied by absolute error) and GA parameters such as crossover rate, mutation rate and the number of population are selected carefully. The simulation results are demonstrated the efficiency and effectiveness of the GA. The GA based fine tuning shows many advantages such as global optimization, less steady state error and disturbance rejection. We are convinced by simulation that the PID gain chosen by the above criteria, has not only a good performance in nominal operating range but also in environment with a disturbance.

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