An Adaptive PID Controller for Reinforcement of Carbon Steel:Performance Analysis using MATLAB Simulink

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Abstract

The strength of any material is dependent on the grain size and percentage of volume fraction recrystallization. In this Paper, a new approach for controlling microstructure development during hot working process by percentage of volume fraction recrystallization is proposed. Here two different methods are employed. One of the approaches is based on the Optimal Control theory and involves the developing of state space models to describe the material behavior and the mechanics of the process. This approach is applied to obtain the desired percentage of volume fraction recrystallization of '1' from an initial value of '0'. The standard Arrehenious equation of 0.3% carbon steel is utilized to obtain an optimal deformation path such that the percentage of volume fraction recrystallization should be 1. The plant model is developed and an appropriate optimality criterion is selected to maintain strain, strain rate and temperature. The state-space model together with an optimality criterion is used to control the percentage of volume fraction recrystallization using Linear Quadratic Regulator method. In the other approach PID controller is employed for the plant model (microstructure development). The simulation is done on various values for percentage of volume fraction recrystallization using both the controllers by MATLAB simulink toolbox. When comparing the responses, the PID controller provides better performance compared with LQR. Resulting tabulated performance indices showed a considerable improvement in settling time besides reducing steady state error.

Keywords –Carbon steel, strain, strain rate, Temperature, PID Controller, LQR.

I. INTRODUCTION

The development of optimal design and control methods for manufacturing processes is needed for effectively reducing part cost, improving part delivery schedules, and producing specified part quality on a repeatable basis.

Existing designmethods are generally ad hoc and lack adequate capabilities for finding effective process parameters such as deformation rate, die and work piece temperature, and tooling system configuration. This situation presents major challenges to process engineers who are faced with smaller lot sizes, higher yield requirements, and superior quality standards. Therefore, it is important to develop new systematic methodologies for process design and control based upon scientific principles, which sufficiently consider the behavior of work piece material and the mechanics of the manufacturing process. A new strategy for systematically calculating near optimal control parameters for control of microstructure during hot deformation processes has been developed based on optimal control theory [1].This approach treats the deforming material as a dynamical system explained below.

II. STATIC AND DYNAMIC MODEL

The static model of 0.3% carbon steel for volume fraction recrystallization [3] is,

$$X = 1 - \exp\left[\ln 2\left(\frac{\varepsilon-\varepsilon_c}{\varepsilon_{0.5}}\right)^2\right] \qquad (1)$$

Where,

ε = Strain

ε_c = Critical strain $= 0.76\,X10^{-4}e^{8000/T}$

$\varepsilon_{0.5}$ = Plastic strain for 50% volume fraction recrystallization $= 1.144\,X10^{-3}D_0{}^{0.28}\dot{\varepsilon}^{0.05}e^{6420/T}$

D_0 = Average grain size prior to extrusion = 180µm

$\dot{\varepsilon}$ = Strain rate = $\partial\varepsilon / \partial t$

T = Billet temperature

The dynamic model of 0.3% carbon steel is obtained by using the Arrehenius equation for changes in temperature during hot extrusion [3] is given below.

$$\frac{\partial T}{\partial t} = \dot{T} = \frac{\eta}{\rho C_p}\sigma\dot{\varepsilon} \qquad (2)$$

Where,

η = Fraction of work which transforms into heat = 0.95

$$\sigma = \frac{sinh^{-1}[(\dot{\varepsilon}/A)^{\frac{1}{n}} e^{\left(\frac{Q}{nRT}\right)}]}{0.0115\, x\, 10^{-3}}$$

$$n = -0.97 + 3.787/\varepsilon^{0.368}$$

$$ln(A) = 13.92 + 9.023/\varepsilon^{0.502}$$

$$Q = 125 + 133.3/\varepsilon^{0.393}$$

$$\rho = Density = 7.8\ gm/cm^3$$

$$C_p = Specificheat = 496\ J/KgK$$

The dynamic equation for volume fraction recrystallization [3] can be obtained by differentiating the equation (1) with respect to strain and then multiplied by change in strain.

$$\frac{\partial X}{\partial t} = \frac{\partial X}{\partial \varepsilon} \cdot \frac{\partial \varepsilon}{\partial t}$$

$$= 2\, ln2\, \frac{(\varepsilon - \varepsilon_c)(1 - X)\dot{\varepsilon}}{{\varepsilon_{0.5}}^2} \qquad (3)$$

III. OPEN LOOP MODEL

It is proposed to obtain the desired percentage of volume fraction recrystallization of ‘1’ from an initial value of ‘0’. The Matlab/Simulink simulation model for open loop system is obtained from the equation (3). The steady state operating ranges for the control parameters temperature, strain, strain rate and the volume fraction recrystallization are considered as,

$$T = 1200K to\ 1300K$$
$$\varepsilon = 0.5\ to\ 1$$
$$\dot{\varepsilon} = 0\ to\ 1$$
$$X = 0\ to\ 1$$

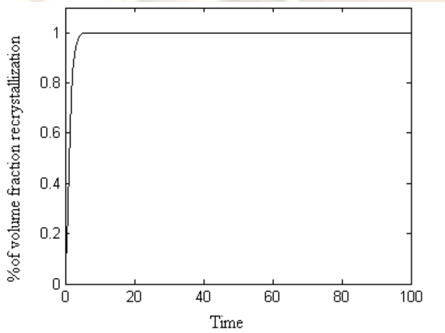

Figure.1.Open Loop Response for %of Volume Fraction Recrystallization

IV. PID CONTROLLER

PID controllers are used extensively in the industry as an all-in-all controller, mostly because it is an intuitive control algorithm. A theoretical PID controller [6] is,

$$u(t) = K_p[e(t) + \frac{1}{T_i}\int_0^t e(\tau)\, d\tau + T_d \frac{de(t)}{dt}]$$

Where,
u(t) = the input signal to the plant model
e(t) = the error signal is defined as e(t) = r(t) – y(t)
r(t) = the reference input signal.
y(t) = plant output

K_p, T_i and T_d are the proportional gain, integral time and derivative time respectively. The coefficients *Kp, Ti, Td* and *P, I, D* are related by:

$P = K_p$; $I = K_p/T_i$; $D = K_pT_d$

The controller has three parts:

The proportional term (*P*) gives a system control input proportional with the error. Using only *P* control gives a stationary error in all cases except when the system control input is zero and the system process value equals the desired value. The proportional term is providing an overall control action proportional to the error signal through the all-pass gain factor.

The integral term (*I*) gives an addition from the sum of the previous errors to the system control input. The summing of the error will continue until the system process value equals the desired value and these results in no stationary error when the reference is table. The integral term is reducing steady-state errors through low-frequency compensation by an integrator.

The derivative term (*D*) gives an addition from the rate of change in the error to the system control input. A rapid change in the error will give an addition to the system control input. This improves the response to a sudden change in the system state or reference value. The derivative term is improving transient response through high-frequency compensation by a differentiator. The following simulations are done in order to see the performance of the proposed PID controller. The controller parameters are all determined using trial and error method.

The combination of proportional controller stabilizes the gain but produces a steady state error but the integral controller reduces the steady state error and the derivative controller reduces the rate of change of error.

The Matlab/Simulink simulation model of the proposed PID controller is shown in Fig.2.After several trial and error runs, the controller parameters of the classical PID controller are set to Kp=100, Ki=3 and Kd=1 to provide the desired response.

V. LINEAR QUADRATC REGULATOR

Linear Quadratic Regulator (LQR) is theory of optimal control concerned with operating a dynamic system at minimum cost. It is a well-known design technique that provides practical feedback gains. It is a powerful technique to design

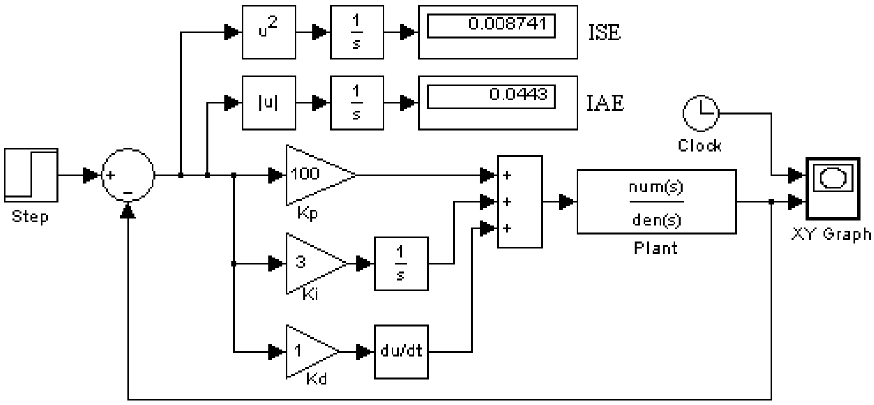

Figure.2 Block Diagram to Optimize %of Volume Fraction Recrystallization by PID Controller

controllers for complex systems that have stringent performance requirements.It is a powerful method for the control of linear systems in the state-space domain. The LQR technique generates controllers with guaranteed closed-loop stability robustness property even in the face of certain gain and phase variation at the plant input/output. In addition, the LQR-based controllers provide reliable closed-loop system performance despite the presence of stochastic plant disturbance.For most realistic applications, the LQR problem must be solved via a Computer-Aided-Design (CAD) package such as MATLAB. With the CAD packages solving the optimization problems, the challenge lies in how the weighting matrices are chosen.

The LQR design and analysis involves linearizing the nonlinear equations which describes the material behavior and developing the state space model [6], [7]. The state space model together with an optimality criterion is used to control the percentage of volume fraction recrystallization.

To obtain an approximate linearized model of the nonlinear micro structural equation, the Taylor's expansion is used. A linear model is developed around the steady state operating point.

To obtain the state space model for given dynamic model, MATLAB is used. The state diagram is used for this purpose. For state space representation, first the given nonlinear equations are represented in the state diagram with suitable blocks.

From this state diagramrepresentation of nonlinear equation, by invoking the MATLAB command [A B C D] = linmod ('filename'), the state space representation of the given system is determined. The state space model is,

$$A = \begin{bmatrix} -0.1642 & 1.3035 & 0.0042 \\ 0 & 0 & 0 \\ 0 & -53.7508 & -0.1260 \end{bmatrix}$$

$$B = \begin{bmatrix} 9.5 \\ 64.5 \\ 2200.7 \end{bmatrix}$$

$$C = [1 \quad 0 \quad 0]$$

$$D = [0]$$

The Matlab/Simulink simulation model of the proposed LQR is shown in Fig.3.

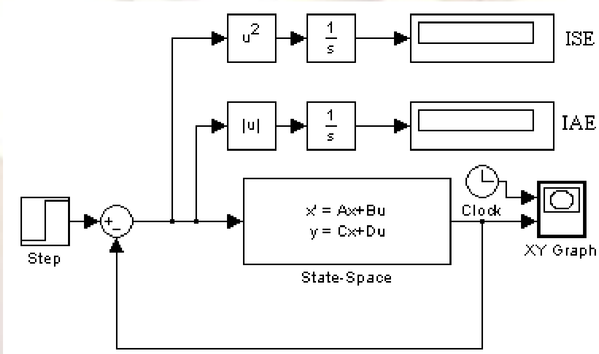

Figure.3 Block Diagram to Optimize %of Volume Fraction Recrystallization by LQR

VI. SIMULATION AND ERROR CALCULATION

The process control parameters strain, strain rate and temperature are optimized for a required %of Volume Fraction Recrystallizationand its corresponding trajectories are shown. The time taken is in seconds.

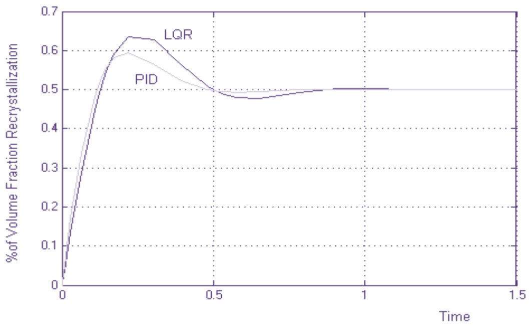

Figure.4 Response for %of Volume Fraction Recrystallization of 0.5

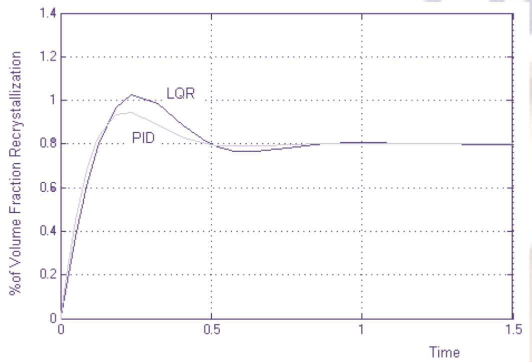

Figure.5 Response for %of Volume Fraction Recrystallization of 0.8

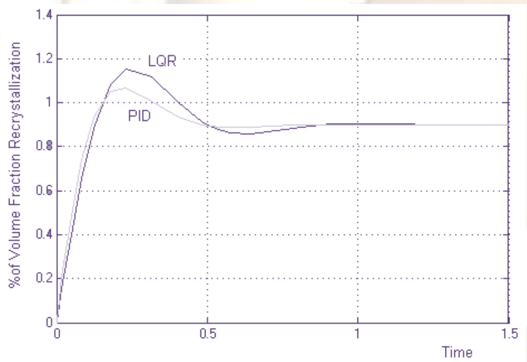

Figure.6 Response for %of Volume Fraction Recrystallization of 0.9

The following Integral Square Error (ISE) and Integral Absolute Error (IAE) values have been obtained using LQR and PID controller.

TABLE 1 Error Comparison

Set point	ISE		IAE	
	LQR	PID	LQR	PID
0.5	0.01269	0.00874	0.0678	0.0443
0.8	0.03247	0.02231	0.1085	0.07075
0.9	0.0411	0.02825	0.1221	0.07961

VII. CONCLUSION

The dynamic model for 0.3% carbon steel for microstructure control is developed. The steady state value for strain, strain rate and temperature to obtain percentage of volume fraction recrystallization from 0 to 1 are selected as 1, 1 and 1300 respectively. The dynamic model is simulated by PID controller and LQR separately. In both the case, a simulation time of 1.5 seconds is considered and the optimization is done. The integral square error and integral absolute error are also calculated. It is observed that the settling time is less and also the ISE and IAE are comparatively less in the case of PID.

The PID controller has only three parameters to adjust. It is commonly used to regulate the time domain behavior of dynamic system. Controlled system shows good results in terms of response time and precision when these parameters are adjusted well.

In LQR, linearization and choosing the weighting matrices was difficult. And it provides high IAE and ISE than PID.

From these results, PID seems to be better choice for optimization of process control parameters.

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R.Sumathireceived the U.G degree in Electrical and Electronics Engineering from Madras University, Tamilnadu, in 1998 and P.G degree in Process Control and Instrumentation from Annamalai University, Tamilnadu in 2004. She is a research student of Anna University, Tamilnadu under the guidance of Dr.M.Usha, Prof. & Dean (Research), Sona College of Technology, Salem, Tamilnadu. Currently, she is an Associate Professor at Pavai College of Technology, Namakkal, Tamilnadu.