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A Robust PID Controller For Microstructure Development During Hot Working Process

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***Abstract:** An intelligent control system for microstructure development during hot working process is designed and analyzed in this paper. The strength of any material is dependent on the grain size of that material. The strength of the material is augmented when its grain size is reduced. Here, the standard Arrehenious equation of 0.3% carbon steel is utilized to obtain an optimal deformation path such that the grain size of the product should be 26μm. The 0.3% carbon steel improves in the machinability by heat treatment. It must also be noted that this steel is especially adaptable for machining or forging and where surface hardness is desirable. The plant model is developed with grain size. The effect of process control parameters such as strain, strain rate, and temperature on important microstructural features can be systematically formulated and then solved as an optimal control problem. These approaches are applied to obtain the desired grain size of 26μm from an initial grain size of 180μm. The simulation is done on various grain sizes using the designed controller by MATLAB/simulink toolbox. From the response it is found that the Set-point weighted PID controller with anti-windup provides better performances. Resulting tabulated performance indices showed a considerable improvement in settling time besides reducing steady state error.*

***Keywords:** Carbon steel, strain, strain rate, temperature, set-point weighted, PID Controller, anti-windup.*

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 design methods 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 [3] is,

$$d = 22600\ \dot{\varepsilon}^{-0.27} e^{-0.27(Q/RT)} \quad (1)$$

Where,

$\mathrm{d} = \text{grain size}$

$\varepsilon = \text{strain}$

$\dot{\varepsilon} = \text{strain rate}$

$\mathrm{Q} = \text{Activation energy for dynamic recrystallization} = 267\mathrm{KJmol}^{-1}$

$\mathrm{R} = \text{Gas constant} = 8.314 \times 10^{-3}\mathrm{KJK}^{-1}\mathrm{mol}^{-1}$

$\mathrm{T} = \text{Billet temprature}$

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

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

Where,

H = Fraction of work which transforms into heat = 0.95

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

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

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

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

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

$C_p = Specific \ heat = 496 \ J/KgK$

The dynamic equation for grain size can be obtained by differentiating the equation (1) with respect to temperature and then multiplied by change in temperature T, which follows that,

$$\frac{\partial d}{\partial t} = \frac{(-0.27) dQ\eta \left[\sinh^{-1}\left(\left(\frac{\dot{\varepsilon}}{A}\right)^{\frac{1}{n}} e^{\left(\frac{Q}{nRT}\right)}\right)\right] \dot{\varepsilon}}{RT^2 \rho C_p \ x \ 0.0115 \ x \ 10^{-3}} \qquad (3)$$

III. OPEN LOOP MODEL

It is proposed to optimize the grain size of 26µm from the initial grain size of 180µm. 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 grain size are considered as,

$T = 1200K \ to \ 1300K$

$\varepsilon = 0.5 \ to \ 1$

$\dot{\varepsilon} = 0 \ to \ 1$

$d = 180\mu m \ to \ 26\mu m$

IV. DESIGN OF PID CONTROLLER

The PID controller is incontrovertibly the most common way of solving practical control problems. This is because the implementation of PID controller is fairly easy to understand, build and tune [5]. Here an intelligent controller is required to control the grain size of carbon steel which is a non-linear and time varying system during hot process. But, the PID controller being linear is not suited for strongly nonlinear systems. The linear PID controller will provide inconsistent performances for different condition due to some non-linearities [8] [10]. Also PID controller requires a precise mathematical model of any system. So, the classical PID controller cannot achieve the desired control results for a nonlinear system and it will produce more overshoot and steady state error. Hence, a controller that has been tuned only once cannot achieve the control objective over the entire operation. The controller should meet the design specifications based on the available knowledge and it should meet limitations on computational power and resources available for design. Therefore, there is a need for several different design procedures with varying objectives and complexity. Also tuning the coefficients of the PID controller periodically is necessary in order to change control objective parameters in such a way that the control objective is achieved.

The common problems occurred in PID control are the noise produced by any real sensor which gives the measurement of the output shaft position and the integral windup due to the presence of actuator limitations and nonlinear effect of the material [6]. Another problem is the proportional and derivative kick in the controller result in large overshoot and larger settling time. These complications can be solved with adaptive control which, depending on the adaptation algorithm, presupposes constant or periodic corrections in the PID controller coefficients.

The derivative term can improve the stability of the closed loop system but the drawback of derivative action is that an ideal derivative controller has very high gain for high frequency signals. The derivative action has to be filtered in order to make the controller proper and to filter the measurement noise; in addition, the derivative action is often applied directly to the process variable instead of to the control error in order to avoid the so-called derivative kick when a step signal is applied to the set-point. The derivative filter has to be taken into consideration in the overall design of the controller [7]. So, a first order low pass filter is placed on the derivative term and its pole is tuned [8]. Since it attenuates high frequency noise, the chattering due to the noise does not occur. The low pass filter to be incorporated into the derivative term is,

$$G_{md}(s) = \frac{T_d s}{\frac{T_d}{N} s + 1} \qquad (4)$$

Where, T_d and N denote derivative time constant and filter coefficients respectively. In the commercial PID controllers, the value of N should be in the range $2 \leq N \leq 20$ [10] to meet the desired performance.

The effect of integrator windup is to be minimized to obtain a faster rise time with less overshoot by incorporating an anti-windup scheme into the controller. The actuator saturation occurs due to the input voltage applied to the PWM amplifier which is in the range of +10 to -10 volts. This actuator saturation effect is emphasized by limiting the control signal to +5 to -5 volts. This is achieved by placing a saturation block at the output of the PID controller. It has an extra feedback path around the integrator. The signal e(t) is the difference between the nominal controller output v(t) and the saturated controller output u(t). The signal e(t) is fed to the input of the integrator through gain $1/T_t$. The extra feedback loop reduces the input to the integrator in proportion to the saturation error [11]. The time constant T_t determines the speed with which the integral term is reset. It is chosen as $T_t \leq T_i$, where T_i is integral time of the controller [12]. The signal e(t) is zero when there is no saturation. Under this condition it will not have any effect on the integrator. When the actuator saturates, the signal e(t) is different from zero and it will try to drive the integrator output to a value such that the signal v(t) is close to the saturation limit.

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In order to reduce the proportional and derivative kick effects and to improve the time response characteristics, it is essential to consider a two degree of freedom PID structure [13]. To attain a two degree of freedom controller, the setpoint value for the proportional action can be weighted so as to reduce the overshoot in the setpoint step response. In this case a suitable choice of the value of the setpoint weight can yield a significant increment of the control performance. The conventional PID controller is reformed into a setpoint weighted PID controller by introducing the parameters α and β which shape the error in the proportional and derivative terms respectively. Based on the setpoint weighting parameter α and β, it is possible to obtain a variety of modified PID controller structure. Here, the SPW-PID controller is equivalent to an error feedback PID controller with a PD controller in the inner loop.

Figure 1 depicts the microstructure development control system by SPW- PID controller with anti-windup technique. It has the closed loop control system with a negative unity feedback. Here, the SPW-PID controller with a derivative filter and the anti-windup mechanism is implemented for strengthening the carbon steel.

It has 2DOF structure and the parameters to be tuned are K_p, K_i, K_d, N, T_t, α and β. The SPW-PID with anti-windup controller with derivative filter is mathematically expressed as,

$$v(t) = K_p e_p(t) + \int_0^t [K_i e_i(\tau) + \frac{e}{T_t}] d\tau + K_d \frac{de_d(t)}{dt} \frac{s}{\frac{T_d}{N}s + 1} \qquad (5)$$

Where,

$$e_p(t) = \alpha\, r(t) - y(t)$$

$$e_i(\tau) = r(\tau) - y(\tau)$$

$$e_d(t) = \beta\, r(t) - y(t)$$

$$e(t) = u(t) - v(t)$$

Where, K_p, K_i and K_d denote proportional gain, integral gain and derivative gain respectively. The term α is setpoint weighting parameter for P controller and β is for D controller. In this controller, proportional and derivative actions only act on a fraction α and β. The nominal controller output is ‘v’ and the saturated controller output is ‘u’. The integral action has to act on the error to make sure that the error goes to zero in steady state. The controller parameters are all squared up using trial and error method. There is no systematic method given for the selection of the setpoint parameters [4]. When $\alpha \in (0,1)$ and $\beta \in (0,1)$, the PID controller functions as a PID-PD controller [9]. It improves the performance where a high robust regulatory control system is required. After several trial and error runs, to maintain the guaranteed accuracy, the nominal values of the proposed PID controller parameters are chosen as specified in Table I.

Description	Parameters	Value
Proportional gain	K_p	5
Integral gain	K_i	2
Derivative gain	K_d	1.25
Integral time	$T_i = \frac{K_p}{K_i}$	2.5
Derivative time	$T_d = \frac{K_d}{K_p}$	0.25
Time constant	T_t	2
Filter co-efficient	N	2
Setpoint weighting parameter for P controller	α	0.14
Setpoint weighting parameter for D controller	β	0.24

Table 1: Controller Parameters

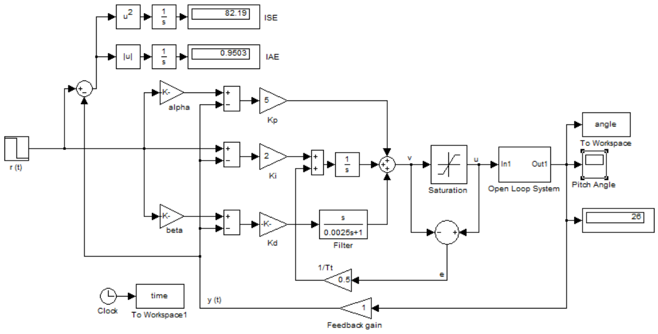

Figure 1: Microstructure Development by SPW-PID Controller with anti-windup

V. SIMULATION AND ERROR CALCULATION

On the above analyzing, the simulations are carried out for the grain size optimization in Matlab-simulink using the solver ODE45 to examine the performance of the proposed control system

The process control parameters strain, strain rate and temperature are optimized for a required grain size of 26µm from an initial grain size of 180µm and its corresponding trajectories are shown in Figure 2. The time taken is in seconds.

The performances such as settling time, integral square error (ISE) and integral absolute error (IAE) values are obtained in PID controller with anti-windup technique which is tabulated in Table II.

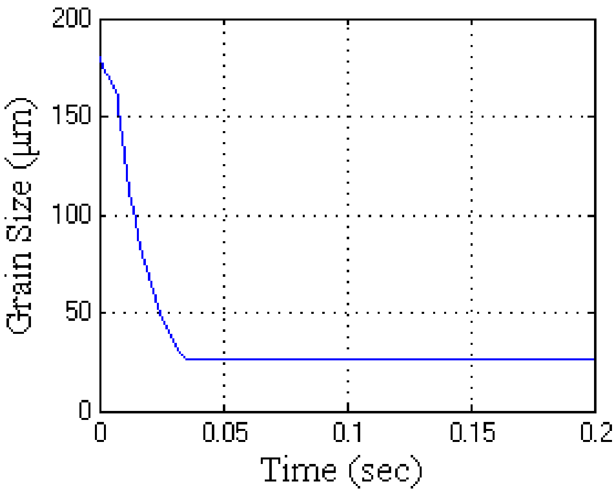

Figure 2: Response for Grain Size of 26µm

Set point	Settling Time (sec)	ISE	IAE
26µm	0.0205	82.19	0.9503
30µm	0.0172	74.87	0.88
35µm	0.0154	66.48	0.7994

Table 2: Performance analysis

VI. CONCLUSION

The dynamic model for 0.3% carbon steel for microstructure development during hot working process is developed. The steady state value for strain, strain rate and temperature to obtain grain size from 180µm to 26µm are selected as 1, 1 and 1200 respectively. The dynamic model is simulated by SPW-PID controller with anti-windup to optimize grain size from 180µm to 26µm. Simulation time of 10 seconds is considered and the optimization is done. The settling time, 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 less. From these results, SPW-PID controller with anti-windup seems to be better choice for optimization of process control parameters.

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