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# A PID Controller with Anti-Windup Mechanism for Firminga Carbon Steel

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**ABSTRACT**
In this Paper, a classical PID controller with anti-windup technique is employed for controlling the microstructure development during hot working process. The strength of any material is dependent on the grain size of that material [4], [9]. The strength of the material is increased when its grain size is reduced. In this paper, 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 [8]. 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 controller by MATLAB simulink toolbox. From the response it is found that the PID controller with anti-windup provides better performance. 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, 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,

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

Where,

d = grain size
ε = strain
$\dot{\varepsilon}$ = strain rate
Q = Activation energy for dynamic recrystallization $= 267\mathrm{KJmol}^{-1}$
R = Gas constant = $8.314 \times 10^{-3}\mathrm{KJK}^{-1}\mathrm{mol}^{-1}$
T = 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. PID CONTROLLER WITH ANTI-WINDUP

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. Theintegral 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 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 [13]. To avoid this problem, a first order low pass filter is placed on the derivative term and its pole is tuned. 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 $2 \leq N \leq 100$ to meet the desired performance.

It has been recognized for many years that actuator saturations, which are present in most control systems, can cause undesirable effects such as excessive overshoots, long settling times [2], and in some cases instability. These phenomena were initially observed for systems controlled by conventional PID control but will be present in any dynamical controller with relatively slow or unstable states [5].

The problem arises when an actuator saturates and results in a mismatch between the controller output and the system input. A change in the controller output does not affect the system. The integrator in the PID controller, for example, is an unstable state, and saturations can cause the integrator to drift to undesirable values as the integrator will continue to integrate a tracking error and produce even larger control signals. In other words, the integrator windupcan lock the system in saturation. Control techniques designed to reduce the effects from integrator windup are known as anti-windup[6]. The integral windup may occur in connection with large setpoint changes or by large disturbances or by equipment malfunctions. Windup can also happen when selectors are used to the fact that several controllers are driving one actuator. In cascade control, windup may occur in the primary controller when the secondary controller is switched to manual mode, if it uses its local setpoint, or if its control signal saturates.

The impact of this integrator windup is to be minimized to obtain a faster rise time with less overshoot. Hence, anti-windup schemes are necessary to minimize performance degradation. For continuous time-controlled systems, there exists a large repertoire of so-called anti-windup techniques to compensate the potential performance degradation due to saturating actuators [7], [8], [10].

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 an 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.

By nesting PID controller using anti-windup mechanism with the carbon steel optimization system, full control and robust requirements are achieved. The controller parameters are all squared up using trial and error method. After several trial and error runs, the nominal values of the PID controller parameters are set as,

$K_p = 5$

$K_i = 2$

$K_d = 1.25$

$$T_d = \frac{K_d}{K_p} = 0.25$$

$$T_i = \frac{K_p}{K_i} = 2.5$$

Since $T_t \leq T_i$, let$T_t = 2.5$ and $N = 100$ to provide the desired response. The derivative filter time constant is calculated as,

$$\tau_f = \frac{T_d}{N} = \frac{0.25}{100} = 0.0025$$

The closed loop control system with a negative unity feedback is shown in Figure 1. Here, the PID controller with a derivative filter and the anti-windup mechanism is implemented for strengthening the carbon steel.

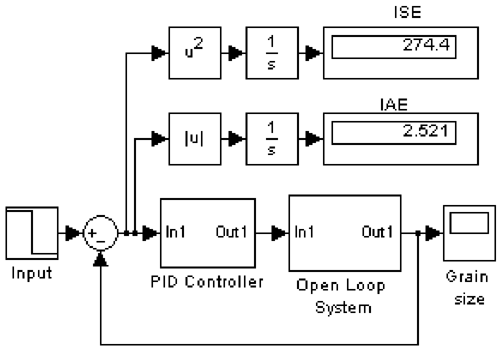


Figure.1Block Diagram to Optimize Grain Size by PID Controller with anti-windup

The PID controller with anti-windup implemented in optimization of grain size is shown in Figure 2.

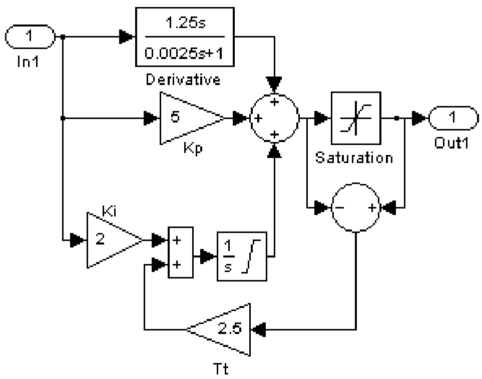


Figure.2PID Controller with anti-windup

## 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 3. 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 1.

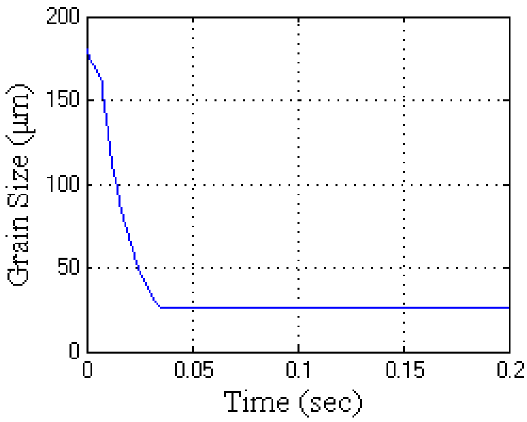

Figure.3Response for Grain Size of 26μm

TABLE 1 Performance analysis

| Set point | Settling Time (sec) | ISE | IAE |
|---|---|---|---|
| 26μm | 0.035 | 274.4 | 2.521 |
| 30μm | 0.037 | 282.8 | 2.542 |
| 35μm | 0.041 | 285.5 | 2.584 |

## VI. 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 grain size from 180μm to 26μm are selected as 1, 1 and 1100 respectively. The dynamic model is simulated by 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, PID controller with anti-windup seems to be better choice for optimization of process control parameters.

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