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DESIGN OF INCREMENTAL FUZZY SUPERVISORY CONTROLLERS FOR THE OPTIMIZATION OF THE INJECTION MOLDING PROCESS

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Abstract . In this paper a newly developed fuzzy supervisory control system for the injection molding process is presented. The system performs automatic tuning of the machine operating points and reduces the human effort for a complete optimization of the machine settings. The experimental results obtained from the application of the proposed fuzzy control architecture in a real industrial environment were encouraging

Keywords. Injection Molding Process, incremental fuzzy supervisory control, self-tuning systems, knowledge-based systems .

1. INTRODUCTION

The injection molding is one of the most widely used techniques in the plastics industry. The aim to produce plastic parts of high quality, on time and with the highest level of profitability indicates the necessity of optimal tuning of the injection molding machines [1].

There are many parameters that have to be tuned to derive products of high quality . Besides , the occurring faults and the continuous change of the ambient conditions , material and mould impose a constant re-examination of the process .

Recently the idea of applying knowledge-based systems for the tuning of the injection molding process has become quite appealing. Expert system and computational intelligence techniques that assist decision making and troubleshooting in plastics industry have been developed [2-4] .

Among these techniques , fuzzy logic is considered to be a suitable tool for such a kind of expert systems [4-6]. Starting from this observation a fuzzy incremental supervisory controller for the IMM was developed.

The paper is organized as follows : In Section 2 the injection molding process is analyzed . In Section 3 the fuzzy supervisory control for the IMM is introduced. In Section 4 a theoretical analysis of the proposed fuzzy control methodology is given focusing on the similarity between fuzzy increment control and incremental gradient descent . In Section 5 the experimental results derived from the application of the proposed fuzzy control in IMMs operating in real industrial environment are presented. Finally in Section 6 some concluding remarks are given.

2. INJECTION MOLDING PROCESS

The injection molding process occurs cyclically . The plastic resin, in the form of pellets or powder, is fed from the hopper and melted . In a reciprocating screw type injection molding machine , the screw rotates forward and fills the mold with melt . During the filling of the mold, the screw injects the melt with a specific pressure (*injection pressure*) and with a specific speed (*injection speed*) . The transformation of the plastic from the solid to the liquid state results in the shrinkage of the material in the mold. To compensate for the contraction due to cooling and solidification of the polymer, more melt is added and a second pressure is applied (*holding pressure* or *dwell pressure*) .

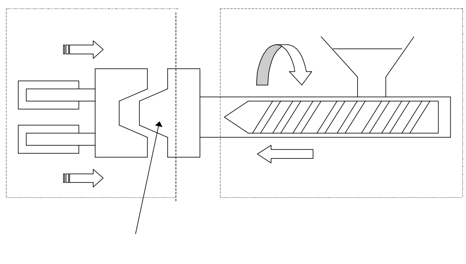

Fig. 1. The injection molding machine

The time during which this additional pressure is applied is called the *holding time* (or *dwell time*). During the dwell time the cooling and solidification of the melt in the mold starts. In parallel the new plastisizing phase may start too. This phase depends mainly on two parameters , the *plastisizing speed* and the pressure the screw applies on the melt while moving backwards (*back pressure*). The screw continues to rotate backwards until enough melt is generated for the next shot. The solidified part is then ejected and the mold closes for the next shot.

In the following diagram the phases of the injection molding cycle is demonstrated.

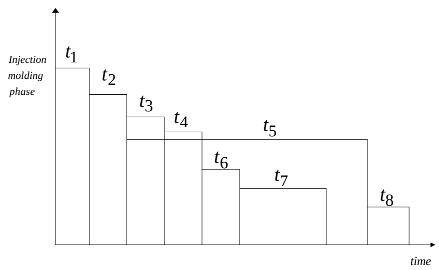

Fig. 2 Phases of the injection molding cycle

t_1 : closing of the mold

t_2 : the injection unit moves forward

t_3 : injection

t_4 : dwell pressing

t_5 : cooling

t_6 : the injection unit moves backward

t_7 : plastic ressin fed from the hopper

t_8 : opening of the mould

3. FUZZY SUPERVISORY CONTROL OF THE IMM

3.1. Supervisory control

A supervisory process control strategy works on the same level as the human operator. It takes over a part of , or all of the operator's job of controlling the process. Supervisory control of the IMM process has a configuration as shown in Fig. 3, where the operator selects between manual adjustments of the set-points and automatic set-point coordination based on fuzzy control rules .

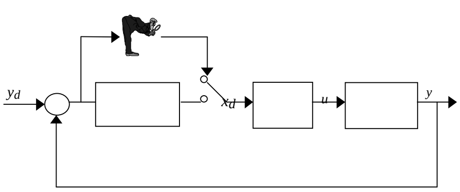

Fig. 3 Configuration of fuzzy control for the IMM process

The existing control loops are still active , and the high level control strategy makes adjustments of the controller set points in the same way as the operator used to do , before the automatic control strategy was installed. It is up to the operator to decide whether manual or automatic control is likely to produce the best possible operation of the IMM.

3.2. The fuzzy rule base for the IMM process

First , the state and the control variables of the IMM system have to be determined.

The state variables are assigned the fuzzy values {0,1,2,3,5} which correspond to the fuzzy sets {OK, Very Small, Small, Medium, Intensive, Severe} and declare the extent of the product's defect. The way in which the fuzzy values of the state variables are deduced is summarized in Table I :

Table I :
State Variables of the IMM process

1	Sink Mark
2	Flash
3	Excessive Shrinkage
4	Bad Finishing
5	Half Fill
6	Total Deformation
7	Wrapage
8	Larger Dimensions
9	Wide Burn
10	Under Gloss
11	Over Gloss
12	Under Weight
13	Over Weight

The crisp value v_i provided by the appropriate measurement station for the weight , the gloss or the dimensions of the product is fuzzyfied via the calculation of its membership degree to the following fuzzy sets :

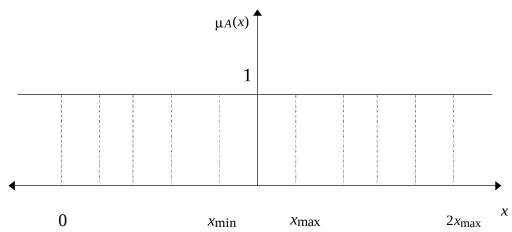

Fig. 4. Fuzzification of the defects extent

The control variables (machine settings) are chosen as follows :

Table II : Control Variables of the IMM process	
Name	**Range**
Cooling Time	10-20 sec
Mold Temperature	20 – 400 ^{o}C
Dwell Pressure	3-8 sec
Clamping force	100-5000 Nt
Dwell Pressure Time	0-80 bar
Nozzle Temperature	100-400 ^{o}C
Plastisizing Speed	0-100 % $v_{\max}$
Back Pressure	0-40 bar
Injection Pressure	0-160 bar
Injection Speed	0-100 % $v_{\max}$
Mold Opening Speed 1	0-20 % $v_{\max}$
Mold Opening Speed 2	0-100 % $v_{\max}$
Opening Stroke	300-400 cm
Barrel Temperature	0-400 ^{o}C

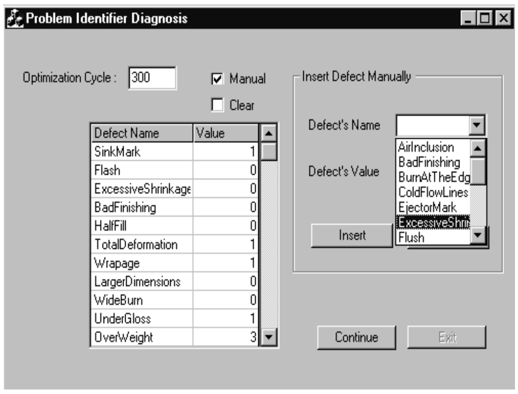

Fig. 5. Diagnosis of a product's defect

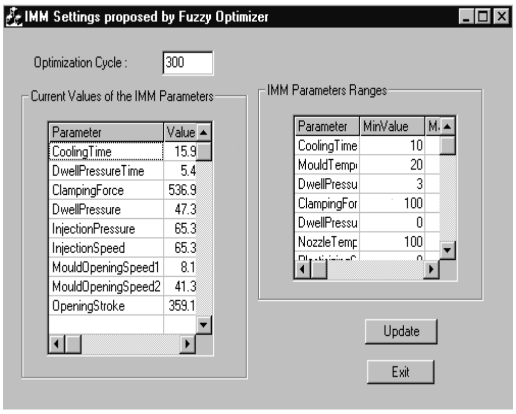

Fig. 6. Settings proposed by the Fuzzy Optimizer

The rules obtained via interviewing the expert operators of the IMM process and the operating manuals have the following form :

- IF $defect_i$ is OK THEN the increase (decrease) of the $control\ variable_j$ is ZERO
- IF $defect_i$ is Very Small THEN the increase (decrease) of the $control\ variable_j$ is Very Small
- IF $defect_i$ is Small THEN the increase (decrease) of the $control\ variable_j$ is Small
- IF $defect_i$ is Medium THEN the increase (decrease) of the $control\ variable_j$ is Medium
- IF $defect_i$ is Intensive THEN the increase (decrease) of the $control\ variable_j$ is Large
- IF $defect_i$ is Severe THEN the increase (decrease) of the $control\ variable_j$ is Very Large

The partition of the universe of discourse of a control variable change into fuzzy subsets is shown in Fig. 7

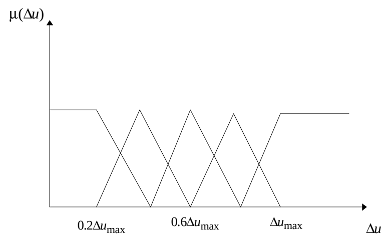

Fig. 7. Fuzzy Sets of a control variable change Δu

The control actions associated with each defect are summarized in Table III :

A typical control rule would be of the form :

IF Sink Mark exists THEN
i) increase Cooling Time
ii) increase Dwell Pressure Time
iii) increase Dwell Pressure

handle simultaneous appearance of many defects on a product an hierarchy of defects is defined. Priority is given to the removal of those defects which are considered to be more important.

However a more sound approach would be to use first evolutionary techniques (e.g. genetic algorithms [7]) , in order to reduce the coupling between the IMM settings and the product defects. Then the above fuzzy incremental controller can be applied .

Table III : Control actions Associated with each defect		
1	Sink Mark	Increase Cooling Time Increase Dwell Pressure Time Increase Dwell Pressure
2	Air Inclusion	Decrease Cooling Time
3	Flash	Increase Clamping Force Decrease Dwell Pressure Increase Injection Speed
4	Ejector Mark	Increase Cooling Time
5	Injection Point Mark	Decrease Nozzle Temperature
6	Excessive Shrinkage	Increase Cooling Time Decrease Plastisizing Speed Decrease Back Pressure
7	Bad Finishing	Increase Dwell Pressure Time Increase Injection Pressure
8.	Half Fill	Decrease Injection Pressure Increase Injection Speed
9	Total Deformation	Decrease Mould Opening Speed 1 Decrease Mould Opening Speed 2 Increase Opening Stroke
10	Wrapage	
11	Larger Dimensions	Increase Clamping Force
12	Burn at the Edge	Decrease Clamping Force Decrease Injection Pressure Decrease Barrel Temperature
13	Wide Burn	Decrease Mould Temperature Decrease Clamping Force Decrease Injection Pressure Decrease Barrel Temperature
14	Cold Flow Lines	Increase Mould Temperature
15	Over Weight	Increase Clamping Force
16	Under Weight	Decrease Clamping Force

4. SIMILARITY WITH INCREMENTAL GRADIENT DESCENT

One common variation on gradient descent intended to avoid local minimum trapping is called incremental gradient descent , or alternatively stochastic gradient descent [8] . Whereas the conventional gradient descent training rule computes parameters updates after summing over all the training examples, the idea behind stochastic gradient descent is to approximate the gradient descent search by updating weights incrementally , following the calculation of the error for each individual example.

In incremental gradient descent the parameters update is based on the relation

$w_i(k+1) = w_i(k) + \eta(t_d - o_d)x_i$ where t_d is the

target value and o_d is the current output of the $d-th$ training example .

In the injection molding problem each machine parameter is updated by an equivalent fuzzy rule

IF $defect_d$ is A_d THEN the increase (decrease) of $control\ paremeter_i$ must be B_i

the numerical formulation of which would be $w_i(k+1) = w_i(k) + \Delta w_i(k)$ where the increment $\Delta w_i(k)$ is proportional to the severity of the appearing defect. In the injection molding case the current value of the product's defect stands for o_d and the zero value of the product's defect stands for t_d . Therefore the simultaneous appearance of n defects is equivalent to the existence of n training examples . The sequential handling of the n defects according to their priority index resembles to the sequential convergence to each one of the n target values t_d by the incremental gradient descent algorithm.

5. EXPERIMENTAL RESULTS

The results of the optimization tests when the fuzzy optimizer was applied on Krauss-Maffei Injection Molding Machine are summarized in Figures 8-15. The plastic products were buckets used for the storage of alimentation and paints. The fuzzy supervisory controller was programmed in C++.

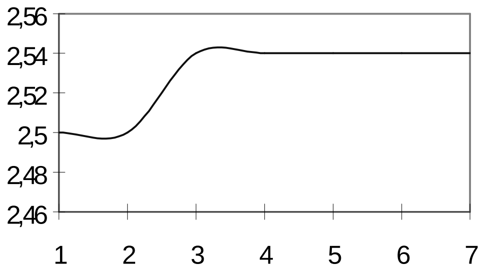

Fig. 8. Tuning of the Cooling Time parameter (sec)

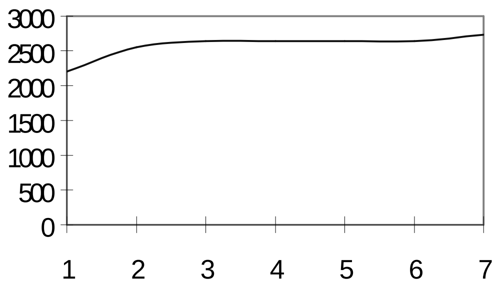

Fig. 9. Tuning of the Clamping Force parameter (Nt)

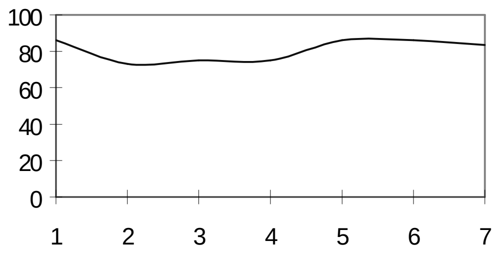

Fig. 10. Tuning of the Dwell Pressure parameter (Bar)

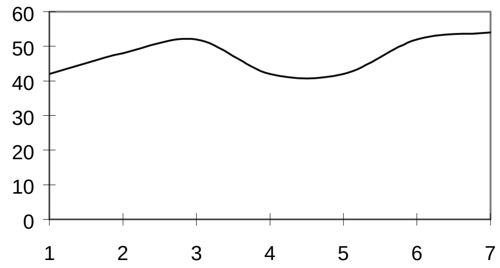

Fig. 11. Tuning of the Injection Speed parameter (% v_{max})

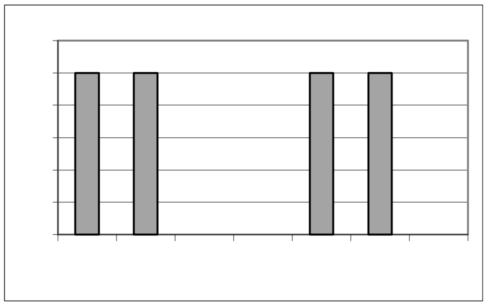

Fig. 12. Flash vs Optimization Cycles

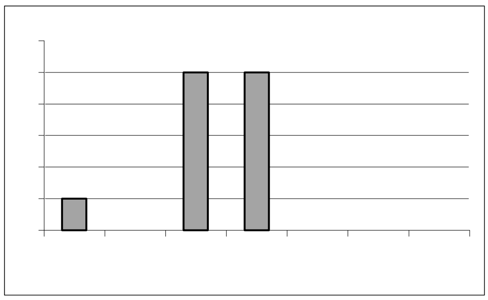

Fig. 13. Half Fill vs Optimization Cycles

The results obtained were quite encouraging . The proposed fuzzy supervisory controller converged fast to the IMM settings which result in products without defects. However the efficiency of the proposed fuzzy controller must be tested in various environments and operating conditions and for several types of machines and polymers .

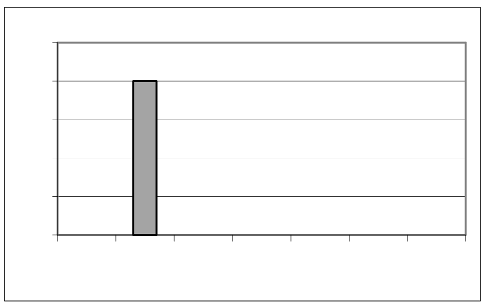

Fig. 14. Bad Finishing vs Optimization Cycles

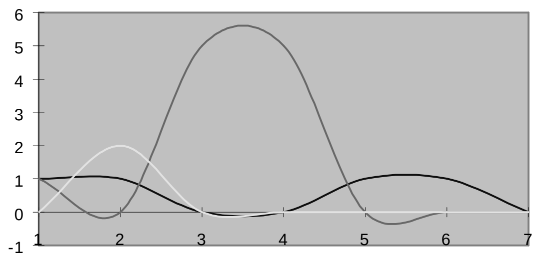

Fig. 15. Fluctuation of defects vs optimization :
Flash (black line), Half Fill (gray line)
Bad Finishing (white line) .

6. CONCLUSIONS

In this paper a fuzzy supervisory controller that permits the self-tuning of an injection molding machine was developed. Fuzzy logic based techniques can be considered as a suitable tool for the regulation of the IMM process for the following reasons : i) it is difficult to obtain an exact mathematical model for the process , ii) up to now the calibration of IMMs is performed efficiently by human experts.

The injection molding process can be viewed as a multiobjective optimization problem . Each machine parameter affects several qualitative attributes of the plastic product to a different degree. The tuning of the machine parameters was based on a priority policy. According to this concept if more than one defects appear simultaneously on the product then the change of the values of the machine settings is guided by the defect with the higher priority. The update of the machine settings is performed by an incremental fuzzy controller which uses rules of the form :

IF $defect_i$ is A_i THEN the increase (decrease) of $paremeter_j$ must be B_j

The magnitude of these incremental changes is proportional to the severity of the appearing defect. Using information provided by experts in the injection molding industry up to 16 defects were related with 14 different machine parameters. The similarity between the proposed incremental fuzzy controller and incremental gradient –descent techniques was noted . The efficacy of the proposed self-calibration mechanism was tested in a real industrial environment on a Krauss-Maffei injection molding machine . The first experimental results were encouraging. However to apply the proposed technique without dependence on the machine type or the polymer used, the existing rule base has to be enhanced and supplied with self-organizing capabilities.

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