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Technical Briefs

Forecasting Control of Waterborne Basecoat Viscosity

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Waterborne basecoat is gaining popularity in the automotive industry. However, the viscosity of some waterborne basecoats may be unstable while circulating in the paint supply-and-storage system. This instability has caused significant problems in the paintability of the basecoats and the quality of the final finish. An original application of forecasting control is implemented to control the viscosity of certain waterborne basecoat. Both manual and automatic implementations of forecasting control result in significant improvement of process capability.

1 Introduction

Waterborne basecoat is a relatively new material in automotive paint shops [1]. It has become popular mainly because it is less toxic and environmentally preferable to paint containing oil solvents. In addition, it provides better color styling. However, waterborne basecoat encountered several difficulties during its early application because of lack of experience. One difficulty is that the rheological properties of some waterborne basecoats are not very stable in the paint mix room. In other words, their apparent viscosities are time-dependent.

Time-dependent viscosity affects the paintability by introducing disturbance to the shape of atomized paint leaving the spray guns and affecting the ability of the paint to stay on vertical panels without running and sagging, therefore affecting the final finish of coatings. This paper presents an immediate solution to the control of waterborne basecoat viscosity using time series based forecasting control [2,3,4].

This paper is organized as follows. Section 2 briefly introduces the concept of forecasting control. Section 3 applies forecasting control manually on the production floor. Section 4 describes an automatic implementation. Section 5 draws the conclusions.

2 Forecasting Control

Forecasting control makes use of the dynamics in the data and the developed time series models. In this study, a multi-input single-output ARX-model as shown in Eq.(1) is employed. Model order is determined using either the F-test or the Akaike Information Criterion (AIC) [5].

$$x_t = \phi_1 x_{t-1} + \phi_2 x_{t-2} + \ldots + \phi_n x_{t-n} + \varphi_0 \mathbf{u}_t + \varphi_1 \mathbf{u}_{t-1} + \ldots + \varphi_n \mathbf{u}_{t-n} + a_t \quad (1)$$

where x_t is the viscosity level at time t, $\mathbf{u}_t(u_{1t}, u_{2t}, \ldots)$ are the inputs to the system, and a_t is a white noise series.

Based on past and current measurements, the behavior of the dynamic system can be predicted using the developed model. For example, the one step ahead forecast for Eq. (1) is given below:

$$\hat{x}_t(1) = \phi_1 x_t + \phi_2 x_{t-1} + \ldots + \phi_n x_{t-n} + \varphi_0 \hat{\mathbf{u}}_t(1) + \varphi_1 \mathbf{u}_t + \ldots + \varphi_n \mathbf{u}_{t-n} \quad (2)$$

The developed forecast equation can be transformed into a control equation by combining the target value and the one-step ahead forecasting. A control variable can be manipulated so that the expected output will be on target.

For one step-ahead forecasting, the response after control is:

$$x_t = a_t$$

The control efficiency is expressed as follows:

$$\text{Control Efficiency} = \frac{\text{Var}[x_t] - \text{Var}[a_t]}{\text{Var}[x_t]} \times 100 \text{ percent} \quad (3)$$

3 Manual Viscosity Control in Paint Mix Room

Currently, most paint mix room technicians use the Fisher cup for short-interval viscosity checking. For a Newtonian fluid, the efflux time has been shown to be positively correlated to the viscosity of the fluid [6]. Other viscosity measurement devices include Bohlin and Brookfield viscometers, and Cambridge in-line viscometer. Principles of these measurement devices, measurement error analyses, and correlation among them were shown in [7].

Figure 1 shows an example of viscosity data on Dark Blue Green Metallic waterborne basecoat collected on an hourly basis. As can be seen from the figure, the viscosity is disturbed by the addition of solvent and paint, and also changes over time.

A two-input one-output ARX model is used as the model structure. The inputs are the *solvent addition* in gallons (u_{1t}), and *paint transfers* (u_{2t}), also in gallons. Other variables, such as paint temperature, etc., are regarded as noise. A data set collected over four days was used to estimate the model order

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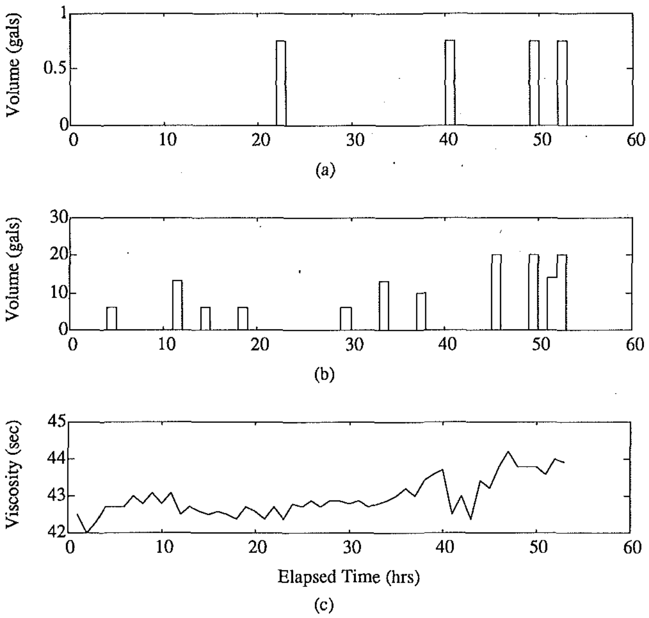

Fig. 1 Data collected on an hourly basis on dark blue green metallic waterborne basecoat: (*a*) solvent addition (gallons), (*b*) paint transfer (gallons), (*c* viscosity (seconds)

and parameters. A backward stepwise regression was used. It started from an assumed highest order (fourth order) and screened out the least significant term in the equation at each step. The procedure was repeated until all terms in the equation were statistically significant. After several iterations, the final model was obtained as follows:

$$x_t = 0.821 + 0.012T - 1.107u_{1t-1} + 0.017u_{2t-2} + 0.826x_{t-1} + 0.151x_{t-2} + a_t \quad (4)$$

where T is the sampling interval.

In the above model, a Time Interval Compensation (TIC) term is employed to compensate for the variation in sampling intervals. Although great efforts were made on the production floor to maintain a constant sampling interval of 30 minutes, some variations were unavoidable for human operators. For engineering purposes, instead of going through complicated non-uniform time series model, a TIC term was used for a locally linearized representation. The TIC term is statistically significant at 95 percent confidence. Also, the partial F value for the term "u_{2t-2}" (Paint Transfers at 2 time intervals ago) was 3.016 which was smaller than 4 and the 95 percent confidence interval includes 0. Both statistics suggested that this term should be removed from the model. Since this term was the last term associated with Paint Transfers left in the model, and it was significant at 90 percent confidence level, it was kept to represent the effects of new paint transfers on viscosity.

Based on Eq. (4), the one-step ahead prediction of viscosity can be expressed as:

$$\hat{x}_t(1) = 0.821 + 0.012T - 1.107u_{1t} + 0.017u_{2t-1} + 0.826x_t + 0.151x_{t-1} \quad (5)$$

Equation (5) was used to predict the behavior of the waterborne basecoat one week later. A comparison between measured viscosities and predictions are shown in Fig. 2. The prediction errors have a mean of 0.134 seconds and a standard deviation of .628 seconds. Compared with the viscosity specifications of ± 2 seconds, performance of this model is satisfactory.

Forecasting control can be pursued after validating the model. Since the controllable variable in this case is the amount of solvent added, and the new paint transfer is confined by the production consumption (i.e., the number of vehicles to be painted), and cannot be controlled manually, one can only

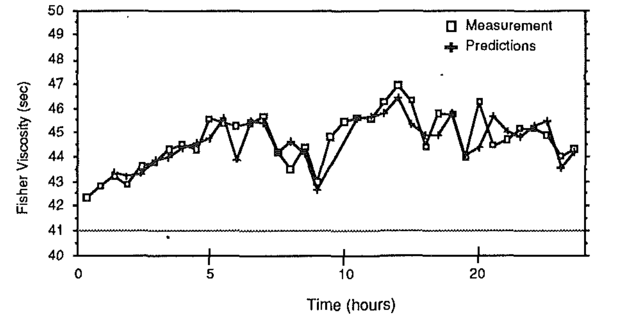

Fig. 2 Comparisons between one-step (30 minutes) ahead predictions and actual viscosity measurement for two days. The forecasting model is identified based on data a week earlier.

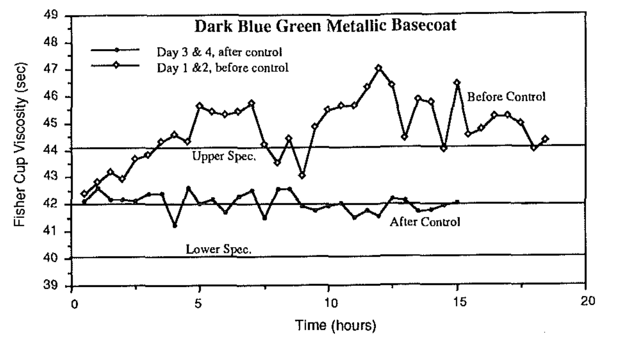

Fig. 3 Manual implementation of forecasting control of paint viscosity with a sampling interval of 30 minutes

lower the viscosity by adding solvent. Hence the target value was set at 42 Fisher seconds, which provides a 1 second "safe margin" for the specification of 41 seconds. With the target at 42 seconds and a time interval of 30 minutes, the control equation can be derived from Eq. (5) as:

$$u_{1t} = -36.85 + 0.015u_{2t-1} + 0.746x_t + 0.136x_{t-1}$$

and

$$u_{1t} \geq 0 \quad (6)$$

Equation (6) says that the amount of solvent needed to bring the viscosity to 42 seconds can be calculated from the amount of paint transfers in the past time interval, the current viscosity, and the viscosity one time interval ago. After implementing forecasting control, the system was brought back within specifications, as shown in Fig. 3.

There are some practical limitations to the direct application of forecasting control to daily plant floor operations. One limitation is the laborious work of taking viscosity readings and calculating the solvent addition every 30 minutes. One alternative is to design an automatic control system based on the above technique, which will be discussed in Section 4. In the mean time, the above manual control method has been simplified and implemented for immediate improvement of paint viscosity.

The first adjustment was to relax the time interval to 2 hours. A new model based on observations of every 2 hours was built, and the control equation derived. Results showed that the system can be controlled at the target value (42.0 Fisher seconds) with a range $\pm .8$ seconds, which is well within the specifications of ± 2.0 seconds.

The second adjustment was to eliminate the solvent addition calculations. A *Compensatory Control Table* was developed from the two-hour interval control equation [7]. The operator simply takes a viscosity reading, looks up the appropriate table entry, and makes a solvent addition. This procedure can be finished within 5 minutes.

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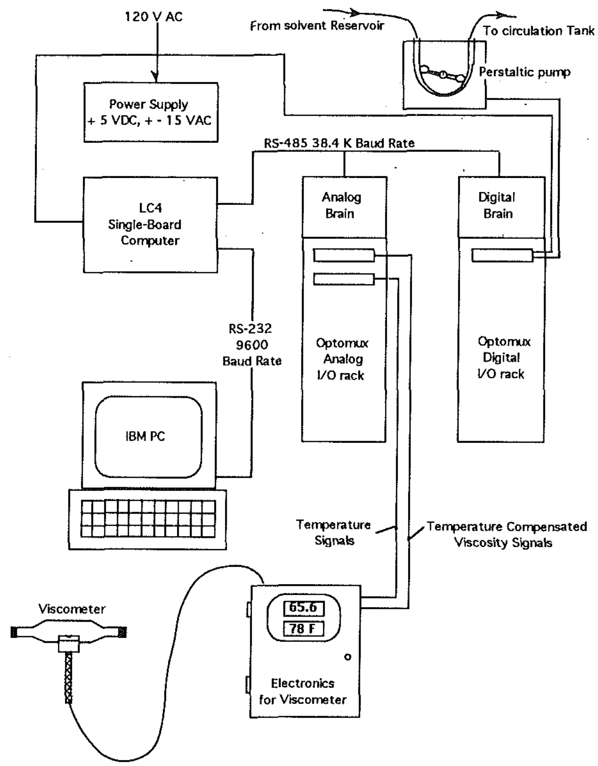

Fig. 4 A schematic diagram for closed-loop viscosity control setup

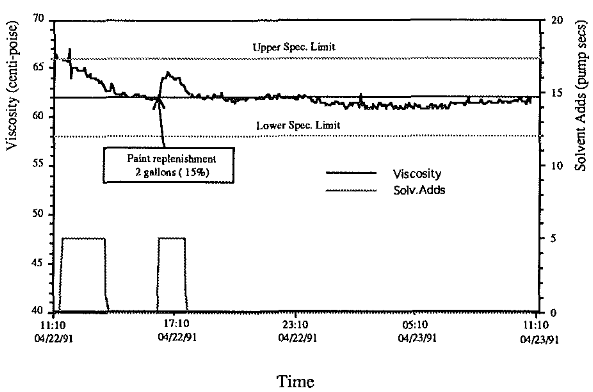

Fig. 5 Closed-loop automatic viscosity control

4 Automatic Viscosity Control System

An automated system has been set up in the Teach Booth to control the viscosity and the performance of the system has been evaluated. This experimental system consists of five parts: (*i*) a paint circulation system with a double-action air pump, (*ii*) a Cambridge in-line viscometer to measure the viscosity real-time, (*iii*) a peristaltic pump with Neoprene tubing for adding solvent to the system, (*iv*) an LC4 industrial single-board computer with analog/digital I/O boards, and (*v*) an IBM PC for programming the LC4 computer. Figure 4 shows a schematic diagram of the experimental setup.

A computer program was developed for automatic model order search, parameter estimation, and residual error analysis. Viscosities collected from the in-line viscometer along with paint and solvent additions are recorded as time series in a data file. The program will search through different model structures until the ARX model structure with the smallest AIC is found and parameters are estimated. With a sampling interval of 5 minutes, this program gives a much better model than the previous models based on either 30-minute or 2-hour intervals. The average error of the closed-loop system is .276 centipoise with a standard deviation of .711 centipoise, which gives a process capability C_p of 1.875. In conclusion, this system can continuously control the viscosity at the target level with small variation (Fig. 5).

5 Conclusions

A forecasting control scheme has been implemented to control the viscosity of waterborne basecoats in automotive paint mix rooms. The model developed is capable of predicting the dynamic behavior of viscosity and calculating the amount of solvent needed to control the viscosity at a desired target value. Application of manual control in the paint mix room resulted in a 67 percent reduction of standard deviations. An experimental computer-controlled system has also been developed and tested, and results show that it can control the viscosity to within ±2 centipoises. This approach provides an immediate and effective solution to the waterborne basecoat viscosity problem.

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Influence of Feed Variation on Tool Wear When Milling Stainless Steel 17-4Ph

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This paper presents the results of experimental studies on the influence of feed variation on tool wear during face milling. Experimental results on milling Stainless Steel 17-4PH show that it is possible to increase tool life substantially with a proper variation of the cutting feed rate throughout the cutting process. Experiments clearly demonstrate this phenomenon and show a decrease of approximately 30 percent of the tool wear. Comparison between constant and variable feed processes is based on the constant volume of material removed in a given time span, therefore maintaining a constant process efficiency

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