Abstract: In this work, a simple non contact method for monitoring of the drying process of painted surfaces using dynamic laser speckle interferometry is presented. During the drying process of paint, intensity signals and related correlation functions changes significantly. The variation of time history of intensities of dynamic laser speckle pattern helps to monitor the drying process. Temporal variation of the peak height of the cross-correlation function between successive frames taken with a fixed interval is plotted until the peak maintains a stationary maximum value. The peak value reaches maximum when the surface becomes completely dry. This is a non-destructive low cost simple method to study the drying process of coatings.

Key words: dynamic laser speckle pattern, paint drying process, image correlation.

I. INTRODUCTION

Drying is the part of coating process and therefore knowledge of the drying process has practical applications. Industries require the non contact monitoring of drying process of painted surfaces and coatings of substrates. It is very important to establish the shortest time necessary for drying of the first layer before the application of the second layer. After applying paint, the initial drying process consists of a constant slope falling period of loss of mass. Many techniques are there to evaluate drying times or studying the curing properties of coatings. For example, in the BK record test the length of a line, left by the needle drawn through the drying film at a known rate gives the drying time. This technique suffers from subjective interpretation of results and poor reproducibility. The other methods solvent scrub test, paper test, the cotton fiber test etc., but these methods are labour-intensive, tedious to carry out and show user variability. Differential Scanning Calorimetry, Dynamic Mechanical Analysis offers more quantitative results. They are not suitable for measuring the build-up of properties in situ in drying films under realistic conditions of solvent evaporation and on the appropriate substrate. In this article, a new technique using detection of the dynamic change of speckle patterns that appear when the surface is illuminated by a laser beam. A speckle pattern shows random movement that indicates change of microscopic surface structures and disappears when they cease to move after drying.

Dynamic behaviors of speckle have been investigated for deterministic movement of a rough surface on the basis of cross-correlation of the patterns [1]. The technique called diffusing wave spectroscopy (DWS), an extension of the classical dynamic light scattering (DLS) to concentrate and opaque media [2, 3]. A laser light points at the coating sample. Part of the incident coherent light is absorbed into the sample and the other part is scattered out detected by a camera. At the single condition that the sample is a diffuser the camera monitor shows a peculiar image of a granular appearance [4]. The detailed structure of this granularity bears no obvious relationship to the macroscopic properties of the illuminated object, but rather it appears chaotic and disordered with an irregular pattern that is best described by the methods of probability theory and statistics. This phenomenon is known as “laser speckle” [5, 6]. The geometrical structure of this granularity bears no obvious relationship to the macroscopic and microscopic properties of the illuminated sample; it is only related to the size and shape of the laser spot and the distance between the sample and the camera. But when the sample undergoes time-dependent activity such as particle movements, refractive index changes etc., this activity causes temporal fluctuations in the scattered light and random changes of light intensity on the speckle image.
At that time of paint coating formation, the sample structure changes because of solvent evaporation, leveling and the diffusion of particles (latex particles, pigments, emulsion droplets etc). When fast changes occur inside the sample structure, fast changes of light intensity are observed on the speckle image. Now the appearance of the speckle pattern is similar to that of a boiling liquid [7]. The speed of light fluctuations (speckle rate) is directly related to the motion speed of the scatterers inside the sample. When no changes occur (when the film is completely formed), the average speckle rate remains constant. The rate of speckle image fluctuations during the drying process can therefore be measured and used to monitor structural changes in the film forming coating sample.

II. PRINCIPLES OF SPECKLE PATTERN

If a rough surface is illuminated by laser light, the light will be scattered back from every illuminated object point (Fig.1). If the object is viewed by an eye or the camera, the object surface seems to be covered with bright and dark spots, which are called speckle. These speckles result from the path differences of the light emitted by the laser and reflected to the camera via different surface points. When coherent light is incident on an optically rough surface, with height variations greater than the wavelength of the light, and is scattered from it, a pattern consisting of dark and bright spots known as speckles. The scattered waves interfere and form an interference pattern. This phenomenon is called the speckle effect. The speckle pattern is characterized by a random intensity and phase distribution. It is fundamentally a statistical process [8].

![Fig.1 Basics for Speckle image formation](image1)

The intensity $I$ is distributed according to the probability density function of a fully developed polarized speckle field as follows: 

$$P(I) = 1/I < I > \exp{-I/<I>} \quad I \geq 0 \ldots \ldots \ldots \ldots (1)$$

where $I$ is the mean intensity value. The intensity $I$ follows a negative exponential distribution (Fig.2). Dark speckles are thus more likely, but there are always some very bright ones. If the statistical properties of the speckle pattern are determined by the size of the illuminated spot, the pattern is called objective. Instead if the statistical properties of the speckle pattern are determined by the aperture of the imaging system, the pattern is called subjective. In the case of a rectangular aperture the in-plane speckle width is defined as:

$$\sigma_{x,y} = \lambda L/D \ldots \ldots \ldots \ldots \ldots \ldots (2)$$

where $\lambda$ is the wavelength of the light.

![Fig.2 Probability density functions of polarized speckle.](image2)
‘L’ is the distance between the aperture and the detector, ‘D’ is the width of the rectangular aperture. The speckle length is defined as: 
\[ \sigma_z = 7.31 \lambda (L/D)^2 \] .... (3). This means that the speckles have the shape of a cigar, since they have a larger size in the z-direction than in the x- and y-direction, unless for very large numerical apertures.

III. EXPERIMENTAL SETUP

Figure 3 shows a schematic of the experimental setup used to study the drying process of paint. Laser beam of 1 mm in diameter from a laser diode with wavelength 680 nm and output power of 0.5 mW is illuminated on the freshly painted glass plate. A charge-coupled device (CCD) is positioned at a suitable distance from it. The acquired pattern changes rapidly during the drying process frame after frame. We stored the frame into a personal computer successively at an interval of 1 s. The image processing and evaluation of the acquired images are done in MATLAB software.

For calculating the cross-correlation of speckle patterns in successive frames we used two algorithms. The first one is the normal cross-correlation that is numerically calculated based on the relationship:

\[ C_{12}(X, Y) = \int \int I_1(X', Y')I_2(X', Y + Y)dX'dY' \]
\[ = \mathcal{F}^{-1}[\hat{I}_1(\xi, \eta)\hat{I}_2^*(\xi, \eta)], \]

where the Fourier transform and its inverse are defined as:
\[ \hat{f}(\xi, \eta) = \mathcal{F}\{f(x, y)\} \]
\[ = \int \int f(x, y) \exp[i2\pi(\xi x + \eta y)]dx\,dy \]
\[ = \mathcal{F}^{-1}\{f(\xi, \eta)\} \]
\[ = \int \int f(\xi, \eta) \exp[-i2\pi(x\xi + y\eta)]d\xi\,d\eta. \]

The cross-correlation is:
\[ C_{12}(X, Y) = \mathcal{F}^{-1}\left[\frac{\hat{I}_1(\xi, \eta)\hat{I}_2^*(\xi, \eta)}{|\hat{I}_1(\xi, \eta)|^2}\right] \]
\[ \left[\frac{|\hat{I}_2(\xi, \eta)|^2}{|\hat{I}_2(\xi, \eta)|^2}\right] \]

This algorithm is not affected by variations of the mean intensity. We also calculated the variation of speckle contrast that is defined by:

\[ C = \frac{\sqrt{\langle[I(X, Y) - \langle I \rangle]^2\rangle}}{\langle I \rangle} \]

where \( \langle I \rangle \) denotes the spatial averaging. The useful parameter for measuring the fluctuations of intensity is the speckle contrast. The contrast is defined statistically as:
\[ C = \sigma / < I >. \]

Moreover we can divide the whole image into sub images which consist of 128 x128 pixels and were correlated. By this way we could compare the desired regions painted in different manners. The temporal activity of the sample appears as intensity changes in the horizontal direction. The rows represent different points of the object and the columns represent its time intensity variations [9]. Every row of the THSP images was used to calculate a value of the contrast. All the obtained values were averaged and we call this result the temporal contrast (TC) of the dynamic speckle pattern. So, when a phenomenon shows low temporal activity, time variations of the speckle pattern are slow and small. In each row of THSP, the speckle appears “stretched” in the time direction showing, horizontally, an elongated shape.
IV. RESULT AND DISCUSSION

In the limit, when there is no activity at all, the THSP shows no variation in the horizontal direction. In this case, the TC is of low value or zero. Conversely, when the phenomenon is very active, the THSP shows fast intensity variations that resemble an ordinary spatial speckle pattern. The intensity variations are caused by changes of phase in the wave-front.

Fig. 4 Low activity speckle

Fig. 5 High activity speckle

Fig. 6 Low activity speckle profile

Fig. 7 High activity speckle profile

Fig. 8 Low activity sub images of speckle

Fig. 8 High activity sub images of speckle

Fig. 9 Temporal variation of correlation peak height

Fig. 10 Temporal variation of correlation peak height
V. CONCLUSION
A simple low cost device based experiment has been done for monitoring of the drying process of painted surfaces. Successive speckle patterns arising from laser illumination of a painted surface were taken and a variation of peak-height of the cross-correlation function between successive frames was plotted. When the surface is dried, the peak value reaches the maximum value equal to unity. Other information such as dust-free, touch-dry and dry-hard times can also be extracted.

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