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STOCHASTIC ANALYSIS OF GRINDING WEHEEL LOADING

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Abstract

The accumulation of workpiece material on the grinding wheel surface is monitored having a random nature, a stochastic approach is adopted.

Discrete models are fitted to eight sets of experiments. Using the model parameters, wheel saturation level, loading factors and the amalgamation process are described, such measures are related to the grinding wheel performance and the occurrence of capping and tangling processes, saturation and post bond fracture. The need of grinding wheel automatic dressing is also introduced.

Nomenclature

a_t's	White noise	
d_w	Workpiece diameter	mm
K_d	Deloading coefficient	$0.07\ sec.^{-1}$
K_l	Loading coefficient	$\%\ /mm^3/mm.sec.$
$L_a\ (t)$	Average loading level at time t	% age area
l	Distance along the wheel circumference	mm
m_n's	Special moments	
N_w	Woekpiece speed	rpm
S_n	Infeed rate per revolution	mm/rev.
V_g	Grinding wheel surface velocity	m/sec.
W_l	The average wave length of loading area	mm
X	The percentage area loaded by workpiece material at any distance along the grinding wheel circumference.	

Greek Letters

Δ	Sample interval	
δ_k	Kroncher delta function	
η_{am}	Amalgamation coefficient	% m
θ_1, θ_2,	Moving average parameter.	
τ_t	$0.32 - 0.00533\ t$ for $0.0 < t < 60.0$	sec.
ϕ_1, ϕ_2,	Autoregressive parameters	

Introduction

Grinding wheel loading can be defined as the deposition of workpiece material on the wheel surface during the grinding process. It has been shown experimentally [1] that loading exists on the wheel surface in two forms, capping and tangling.

Capping is the process in which metal adheres to the top of the grit surface, while tangling is the filling of the void spaces inbetween the grits.

It has been stated [2] that the increased loading may be observed whenever ductile materials are ground. The amount of loading also depends on the grinding wheel structure; for example, a hard wheel surface is subjected to less wear and therefore tends to accumulate more workpiece material.

One of the effects of loading is to alter the geometric relations of the active grain edges, on which the initial build-up of loading particles occurs. These variations, in grain geometry, result in higher levels of frictional forces occuring in the chip formation process, and result in an increased specific cutting force acting on a single grit.

Loading also changes the frictional system between the grinding wheel and workpiece from Al_2 0-steel to steel-steel, thus increasing the levels of the frictional forces. When the grinding wheel is heavily loaded and the grinding forces increase, a breakdown of the grinding wheel structure will occur, leading to a reduction in the grinding force. In this phase the rate of wheel loading decreases because of the effect of a deloading factor, which is dependent on the amount and distribution of loading on the grinding wheel and wheel specifications [3].

The increase of grinding force component due to the attritious wear (glazing) on a grit plateau [4,5,6] shows the same trend as that of loading however, it depends on the grinding wheel hardness. Since it has been proven that the loading process, if it exists, occurs faster than the wheel glazing or the attritious wear, the former will have a stronger influence on the grinding process [1 ,4].

Since loading phenomenon is directly related to the grinding forces, it controls the rate of fracture wear and increases the real area of contact, which in turn affects the rate of metal removal.

The general equation representing the loading build-up, for any grinding condition and constant dressing variables have been determined experimentally [7], based on the average values of loaded areas, and can be written as follows:

$$\overline{L_a(t) = V_g K_l [\Pi d_w N_w S_n - \tau_l](1 - \exp(-k_d t))}$$

This equation identifies the loading mechanism, and the particular value of the average loading, at any time, can be determined.

It also shows that, the loading build-up is close to an exponential trend before reaching the saturation level; thereafter the relation of loading/deloading is linear (equilibrium level).

It has been stated also in [7] that the mechanism of adhesion between the wheel and the workpiece material depends on the rate of metal removal; i.e for a rate of metal removal, less than 0.5 mm^3/mm. sec., no evidence of metal adhering to the grinding wheel surface has been found, and only attritious wear occurs; for a rate of metal removal less than 5 mm^3/mm. sec. the equilibrium level of loading on the wheel surface is dependent on the rate of metal removal; but for a higher rate than 5 mm^3/mm. sec. The equilibrium level is independent on the grinding conditions.

The experimental results reported in [7] shows that the average loading level increases with the increase of the wheel dressing depth, depth of grinding, workpiece speed and grinding wheel speed.

The proposed model, in [7], show that the loading, changing the stability criteria of grinding, is a time dependent. Therefore in order to achieve a quantitative agreement between predicted and experimental results of grinding instability, it is necessary to obtain a more detailed knowledge for the loading mechanism, using a stochastic approach to give a detailed description of this phenomenon as a function of grinding wheel characteristics such as grade, grit number, dimensions and materials, grinding conditions, and workpiece materials and dimensions. Stochastic technique has been adopted for the analysis of random signals representing the actual process behaviour especially for the grinding process [8-12]. However a great deal of work has been applied in the field of grinding dynamics [13-17].

In the above mentioned work grinding is viewed as a random process whose events are generated by the interactions between the abrasive grains and workpiece, the used approach in these papers depends on the sample spectrum of the workpiece profiles/cutting force signals or grinding wheel wear. Analysis of the above signals allowed the dynamic characteristics of the grinding process to be determined. As for the grinding wheel topography, a great deal of stochastic analysis has been done to investigate the role of topography on the cutting performance of the abrasive tools [18-23]. However random process analysis has been applied to the working surfaces of grinding wheels to asses its resultant wear [24].

The different variables involved in assessing the wheel wear are grit size and type, wheel structure, wheel hardness, dressing tool type and dressing conditions. From this analysis [24], grinding wheel wear has been identified as occurring in three main modes, mainly, attritious wear, partial fracture and complete dislocation of the grits. The results of this work [24] where nearly the same as those reported earlier [25 - 28], however, the use of stochastic method gives a quantitative values of the different wear modes, compared with the purely qualitative technique such as optical examination.

The role and importance of grinding wheel loading on the process performance is quite clear. The method used for the analysis of loading, reference [7], is based on the averaging of the loading signals.

Due to the random behaviour and fluctuations on the loading, the average cannot represent the exact loading characteristics of the workpiece material. Therefore, in this paper, a further extension, in order to shed more light on this particular pehnomenon, has been proposed. Stochastic models, that capture all the variations in the loading signals are firstly fitted. Spectral analysis, using the model parameters, are also adopted to describe the intensity of peaks of heavily loaded areas, rate of loading and the amalgamation process.

Characterization Of Grinding Wheel Loading

When the continuous signal of grinding wheel loading is uniformly sampled at an interval Δ, the well known autoregressive - moving average model can be fitted to the discrete data. Such a model is denoted by ARMA (m, n) [29]

where

$$X_t - \Phi_1 \cdot X_{(t-1)} - \ldots\ldots \Phi_n \cdot X_{(t-n)} = a_t - \theta_1 \cdot a_{(t-1)} \ldots\ldots \theta_n \cdot a_{(t-n)}$$

$$E(a_t) = 0.0 \quad . \quad E(a_t, a_{(t-k)}) = \delta_k \sigma_a^2$$

Using the modelling procedure of reference [29] a second order model was found adequate for the grinding wheel loading, see Table 1. The power spectrum is then estimated from.

$$P(f) = \frac{\sigma_a^2}{\left| 1.0 - \sum_{(m=1)}^{n} \Phi_n(m) \exp(-2\Pi i f m) \right|^2}$$

The spectral moments mo, m2, m4 are then calculated from,

$$m_n = 2 \int_0^{(1/2\Delta)} f^n P(f) \cdot df$$

The probability of peak of heavily loaded areas, at different loading levels; X [30] is given by,

$$P(X) = \frac{\delta}{2\Pi} \cdot \left[e^{(-X^2/2\delta^2)} + \sqrt{\Pi}\, \Xi\, e^{(-1/2X^2)} (1 + erf(\Xi)) \right]$$

where

$$\delta = \left[\frac{(\alpha - 1)}{\alpha} \right]^{(1/2)}$$

$$\alpha = m_0 m_4 / m_2^2$$

$$\Xi = \left[\frac{1 - \delta^2}{2\delta^2} \right]^{(1/2)} X$$

The maximum intensity of peaks of heaviliy loaded area is taken as the wheel saturation level. For a new dressed wheel, that level is zero.

The distribution of profile slopes dX/dl represent the chip accumulation on the grinding wheel surface. For a given loading signal, the expected rate of loading (loading factor) occurs at a rate represented by the peak in the probability distribution function describing dX/dl

$$P\left(\frac{dX}{dl}\right) = \frac{dX/dl}{m_2} \exp\left(-\left(\frac{dx}{dl}\right)^2 / 2m_2\right)$$

To shed more light on the loading phenomenon, the average number of loading - profile crossings, at the mean loading level per unit length is calculated as,

$$MNZC = \frac{1}{\Pi}\left[\frac{m_2}{m_o}\right]^{(1/2)}$$

The average wave length W_1 is taken as

$$W_l = \frac{1.0}{2(MNZC-1)}$$

The average wave length, together with the scatter index $\sqrt{m_o}$ is used to determine the area of profile spikes. This area is noted as the amalgamation coefficient, η_{am}, Fig. (1).

$$\eta_{am} = 3W_l\sqrt{m_o}$$

Higher values of η_{am}, represent a larger loaded areas and hence, the possibility of steel-steel friction .

Table (1) Grinding Wheel Loading Model Parameters

ID	Time (sec)	Model Order	Φ_1	Φ_2	Residual sum of squares $x10^4$	Scatter Index $\sqrt{m_o}$	Average Values X
1	32	AR(2)	0.644 0.591 0.539	-.0830 -.1195 -.5160	0.6693	5.4	14.3
2	64	AR(2)	0.539 0.478 0.419	-.1630 -.1716 -.2070	1.046	6.53	27.0
3	80	AR(2)	0.603 0.555 0.50 0	-.1540 -.2009 -.2480	0.8404	5.89	29.45
4	144	AR(2)	0.570 0.525 0.480	-.0565 -.0213 -.0990	.3477	3.82	30.70
5	160	AR(2)	0.566 0.518 0.471	-.0650 -.0920 -.4710	.3894	4.67	30.40
6	224	AR(2)	0.832 0.764 0.696	-.1030 -.1287 -.1540	.2290	3.64	29.66
7	281	AR(2)	1.080 1.041 1.000	-.1260 -.1573 -.1890	.1536	4.83	29.50
8	304	AR(2)	1.090 1.059 1.020	-.1510 -.1740 -.1970	.1853	5.38	28.40

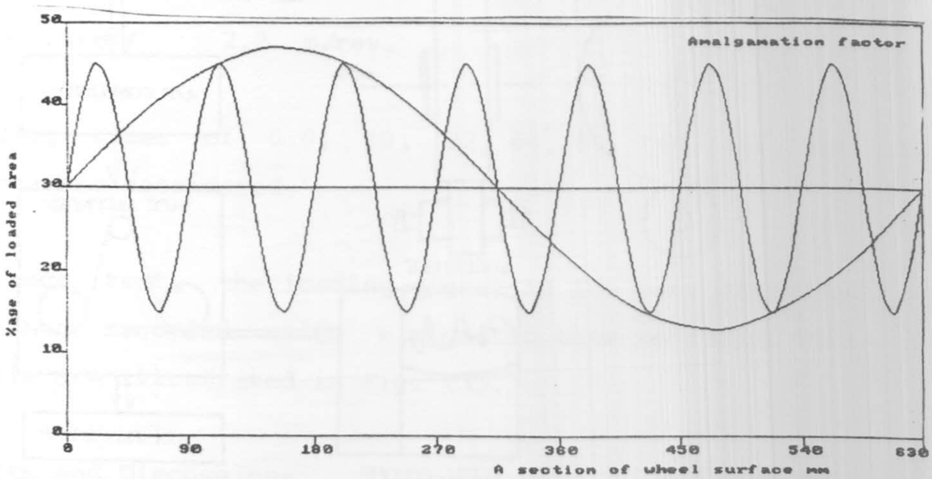

Fig. (1) Representation of the Amalgamation factor

Experimental Conditions And Data Acquisition

Grinding tests were performed on the Matrix Okuma GP 33x900 plain cylinderical grinder. The main specifications of such a machine are described in reference [7].

The wheel head spindle is supported on hydrodynamic bearings which are expected to give higher rigidity during the grinding process.

An inprocess measuring system for loading has been developed and incorporated to the grinding machine, Fig. (2).

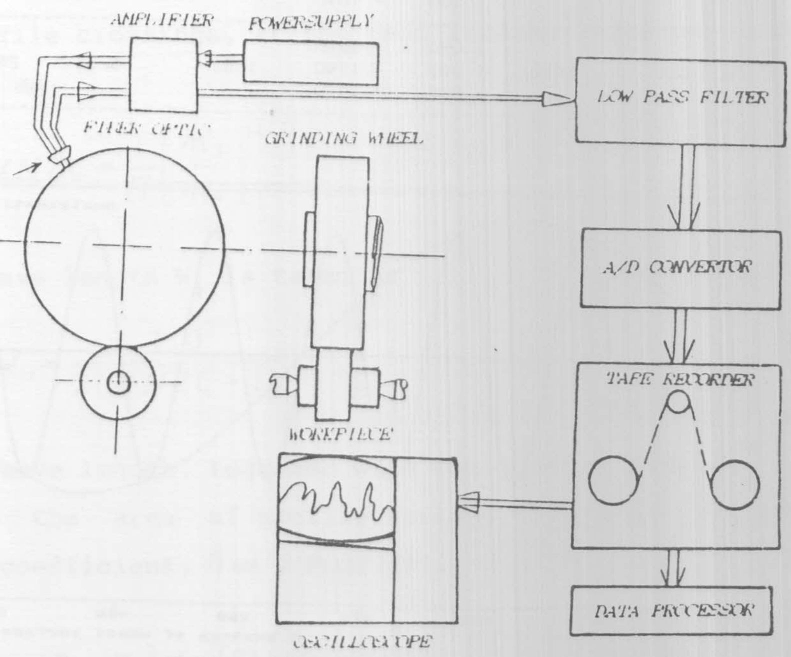

Fig. (2) Experimental set up and data acquisition of grinding wheel loading. [7]

The chip accumulation on the grinding wheel surface was detected using fibre optics [7] which are arranged to measure the percentage area covered by workpiece material. Since the probe diameter was 5.0 mm a sample interval of about 5.625 mm was taken, thus allowing the recording of 320 data points along the wheel circumference, the other working conditions employed during these tests are:

Grinding Wheel

Type	:	BA46Q5VFBLU, (Carborundum)
Dressing	:	Wet.
Speed	:	30 m/sec.

Workpiece

Type	:	EN56B Steel
Speed	:	0.4 m / sec.
Width	:	52 mm
Infeed rate:		2.2 m/rev.

Grinding times of 0.0, 16, 32, 64, 80, 144, 180, 224, 281 and 304 seconds are considered.

For each test, the loading signal is low pass filtered, digitized and then recorded using a magnetic tape recorder. Plots of loading signals are illustrated in Fig. (3).

Results and Discussions

Fig. (3) shows the variations on the percentage of loaded area, along

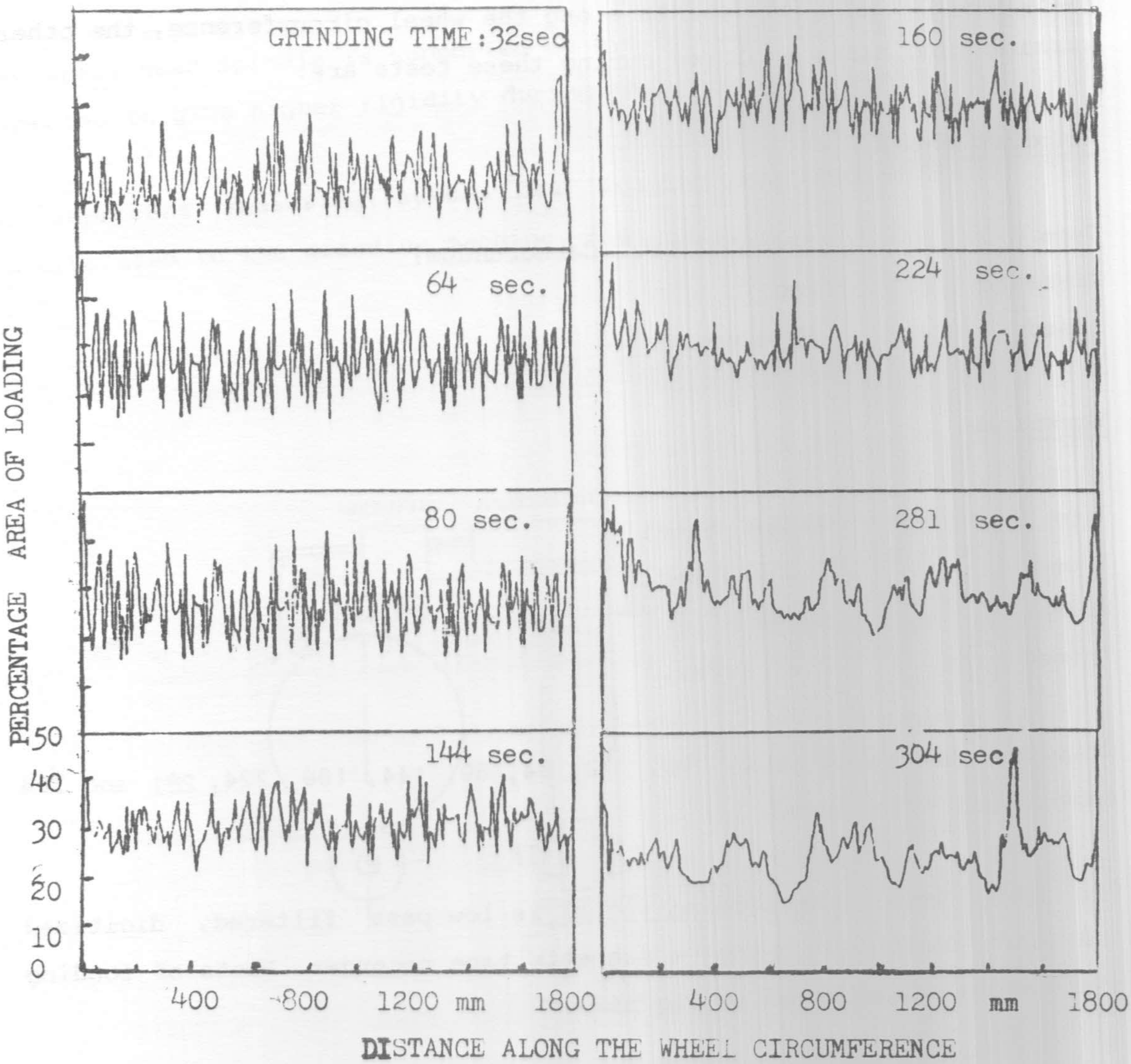

Fig. (3) Variation of grinding wheel loading at different grinding times. [7]

the wheel circumference, at different machining times. The random nature of this phenomenon is evident. It is also difficult to distinguish, fully, the differences among these records using the average valuesdescribed in reference [7].

When the autoregressive models of order 2, AR(2), are fitted to the data, the differences among the model parameters and are observed, see table 1.

The distribution of peaks of heavily loaded areas is presented in Fig (4). For a newly dressed wheel, the percentage area covered by workpiece material is zero. As the machining time progresses, the workpiece material accumulates on the wheel surface. Heavily loaded area with a percentage ranging from 0 - 32 % for t = 32 seconds with a maximum intensity of peaks (saturation level) at 19% can be noticed. For 80 seconds, the average level, scatter index, Table 1 and the saturation level becomes higher. A further increase in machining time reduces the scatter index and the saturation level, see Fig. (3).

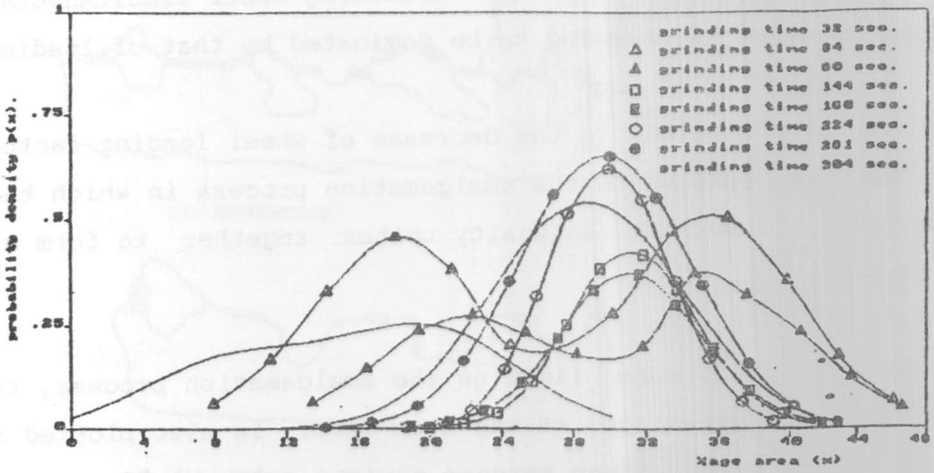

Fig. (4) Density of peaks of heavily loaded area at different grinding times.

The grinding wheel saturation level is plotted against the grinding time in Fig. (5). It is clear that the saturation level increases with time up to 70 seconds beyond which a further decrease with time is shown. Under such a condition (70 seconds), the grinding wheel acceptability to accomodate workpiece material, by both capping and tangling effects, is maximum, Fig (6).

Beyond 70 seconds, the wheel saturation level declines. This behaviour is however anticipated and could be related to the occurrence of post-bond fracture due to the increased frictional forces [7].

The distribution of loading-profile slopes, representing the rate of chip accumulation on the wheel surface is shown in Fig. (7). The peaks of Fig. (7) represent the loading factor. Fig. (8) represents the variation of the wheel loading factor with time, the wheel loading factor/ acceptability is maximum at a time of 70 seconds. The low values reported at a grinding time greater than 70 are, again, related to the fracture of heavily loaded particles under the effect of the high friction forces caused between the workpiece and the grinding wheel. Since both loading and deloading occur simultaneously, the loading mechanism is expected to be dominated by that of loading.

A further explanation to the decrease of wheel loading factor, with time, may be related to the amalgamation process in which the small peak/spikes of maximum intensity unites together to form a larger bands/spikes, Fig. (3).

In order to shed more light on the amalgamation process, the mean number of zero crossings, at the mean level, is also plotted in Fig. (8). The number of crossings reaches maximum value at 70 seconds, thus

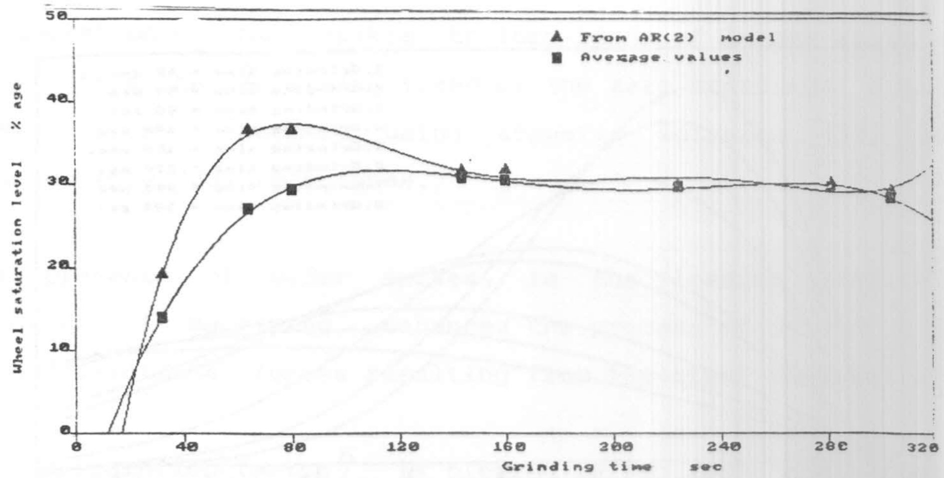

Fig. (5) Grinding wheel saturation level at different grinding times.

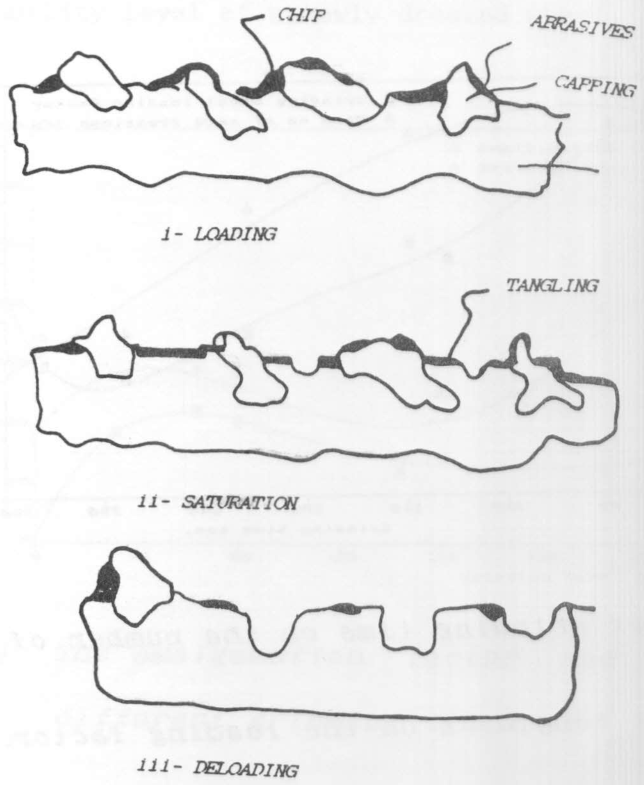

Fig. (6) Grinding wheel loading mechanism.

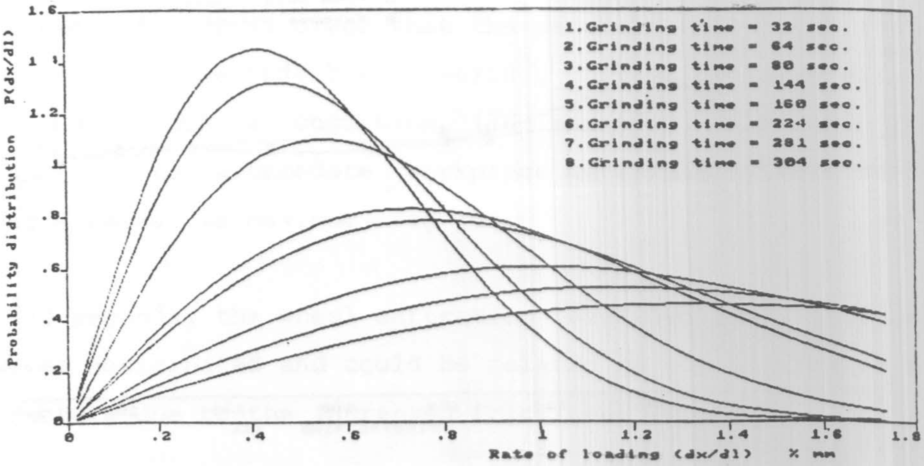

Fig. (7) Loading profile slopes for different grinding times.

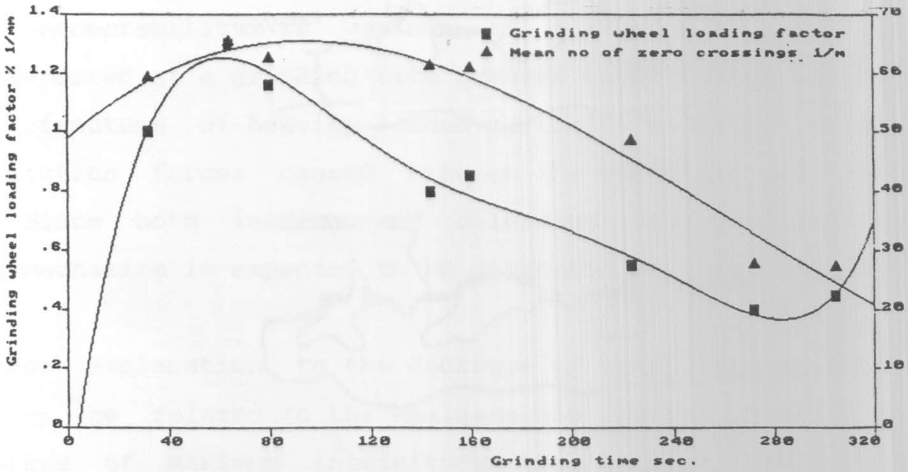

Fig. (8) Effect of grinding time on the number of crossings per unit length, & on the loading factor.

representing a minimum spike width in the loading profile. The accumulation of small spikes to form bands of larger spike widths is clear from the decreasing trend of the zero crossings. Similar trends have been observed using acoustic emission [32] and X-ray fluorescence [33] techniques.

The presence of wider spikes, in the loading profile, with the progress of machining, enhances the process of deloading due to the raised frictional forces resulting from the steel-to-steel contact [2].

The amalgamation factor η_{am} is plotted in Fig. (9). Accordingly three distinct zones could be identified:

i. Less than 70 seconds, η_{am} increases with time due to the high acceptability level of a newly dressed wheel.

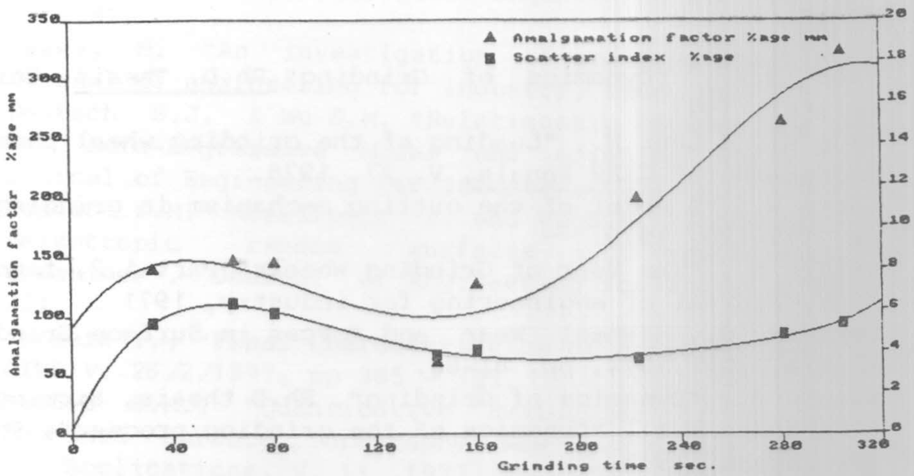

Fig. (9) The amalgamation factor and scatter index at different grinding times.

ii. In the range 70 - 160 seconds the deloading action is the major reason behind the decrease of η_{am} with time.

iii. 160 - 304 seconds the amalgamation factor rises due to the fromation of larger areas at the expence of small spots. However this behaviour is expected to be associated with an increased rate of deloading. Under such circumstantial conditions, the need of grinding wheel redressing arises. For that purpose, machining should be terminated in order to avoid grinding wheel damage.

Conclusions

1. Grinding wheel loading obeys a second order autoregressive process, AR (2).
2. Grinding wheel need for redressing could be anticipated using the amalgamation factor.

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