MODELLING OF THE SHOT-PEENING PROCESS
A THEORETICAL APPROACH

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ABSTRACT

This paper examines the shot-peening process in some detail identifying pertinent
parameters that influence process efficiency. The mechanics of the shot-peening
is considered from the perspective of Hertzian theory of contact and discusses the
requirement for modelling with theoretical/numerical methods. A new parametric
modelling methodology is finally presented which allows for a number of shot-
peening parameters. The models enable the investigation of single and multiple
indentations and provide predictions of the residual stress field.

1. INTRODUCTION

Components of mechanical systems more frequently than not, are subject to
complex loadings, seldomly static and primarily time dependent periodic or
random in nature. The mode of failure associated with these time dependent
loads is fatigue. Surveys into the causes of in service failures carried out over the
last twenty years* attribute approximately 80% of catastrophic fractures
to fatigue which consequently, has been identified as the largest single cause
of failure in structures and machine systems.

Many research programmes have dealt with the causes of fatigue and the
mechanics of damage. Furthermore, effort has been invested in the develop-
ment of methods aimed at fatigue alleviation and the prevention premature
failures. The latter have introduced a range of thermal and thermochemical
surface treatments such as induction hardening, nitriding, carburizing and
mechanical surface treatments such as cold rolling, surface grinding, polishing
and impact surface treatments, to mention but a few. The problems
associated with the behaviour of metals under repeated stresses are
becoming more acute with increases in the operational demands on machin-
ery such as enhanced efficiency, reliability and safety. Design strategies that
postulate high mechanical efficiency and adequate static and dynamic
strengths, for minimum structural weight, are becoming mandatory in view
of the rising costs of materials and energy. Such strategies dictate the
optimum use of materials that in turn demands sound understanding of the
material behaviour under operational loading conditions. In case of using any
post-machining treatments, their effects have to be quantified and accounted
for at the design stage.
The present paper deals with the theoretical modelling of the shot-peening process, in an attempt to provide the means for predicting residual stresses as function of a number of control parameters.

2. IMPACT SURFACE TREATMENT

Treatments of thermal or thermochemical nature have limited applicability as they appear to discriminate on the material type. Mechanical treatments do not discriminate on type of material, but their drawbacks are in terms of component geometry and shape. One mechanical surface treatment has been found to be not only nondiscriminatory but also highly versatile and adaptable regarding shape and size. This is the impact surface treatment, commonly known as shot-peening, which is characterized by versatility, high productivity and a notably low equipment capital investment cost with low energy requirements.

Employing shot-peening to improve the structural integrity of metallic components, necessitates thorough understanding of the mechanics of the process, the behaviour and intensity of induced residual stresses. The mechanism of protection against fatigue failure stipulated by impact treatments is widely attributed to cold work and accumulation of compressive residual surface and sub-surface stresses.

These stresses must be sufficiently large, compressive and their distribution uniform and continuous in order to suppress the initiation and inhibit the growth of surface cracks.

Shot-peening is a cold working surface treatment widely used in the aerospace, automotive, gas turbine, as well as pump and power industries primarily for improvement of the fatigue structural integrity of metallic components. These results are accomplished by bombarding the surface of metallic materials with small spherical shots made of cast high carbon steel, iron, conditioned cut-wire, glass or ceramic beads at high impinging velocities. Each shot acts as a peenhammer and impact with the exposed surface produces localised stretching of the surface layer and cold working to a depth of 127-508μm. Upon completion of the process a compressive residual stress field is left on the workpiece that has been found to be highly effective in preventing premature failure of components subject to cyclic loads, Kyriacou et al., 1993 and 1996.

3. SHOT-PEENING CONTROL PARAMETERS

As previously mentioned, the beneficial effects of shot-peening depend upon the work hardening of surface layers and formation of compressive residual stresses, caused by the bombardment of the workpiece with shot. It has been found that great benefits can be obtained if the intensity of residual stresses and the depth of penetration of work hardening are maximised. Evidently, the effectiveness of the shot-peening process is dependent upon the energy transfer that occurs during the impact of shots with the target surface and the
uniformity of the induced compressive residual stresses. In practice the process efficiency is evaluated by means of intensity, saturation and coverage, Meguid (1983), Simpson & Chiasson (1986).

* Intensity, correlates the amount of energy being transferred during the impact of a typical shot with the workpiece and it is related to the kinetic energy of the blast stream.

* Saturation, deals with the number of particles that impinge upon the target, which can be manipulated by means of altering the exposure time.

* Coverage, is a means of quantifying the uniformity of residual stresses by visually examining a small area of the treated surface, and is a qualitative measure.

Clearly, a large number of variables control the efficiency of the shot-peening process. These variables can be classified in three groups: shot parameters, target parameters and flow parameters as follows.

i. Shot Parameters
   - Size, shape, integrity, density, hardness, yield strength, modulus of elasticity...

ii. Target Parameters
   - Hardness, yield strength, modulus of elasticity, work hardening characteristics, material chemical composition, prestress condition...

iii. Flow Parameters
   - Mass flow rate, velocity, angle of impingement, stand-off distance...

Although an array of pertinent parameters governing the shot-peening process has been presented, it must be remembered that the shot impact process by its nature is random and thus much more complex to control...

4. CONTACT MECHANICS FUNDAMENTALS

Shot-peening mechanics is a complex problem due to the large number of variables involved and the nonlinear nature of impact-contact phenomena and associated elastoplasticity. However, some understanding of the process can be gained by considering the ideas of contact mechanics and in particular the available solution associated with the axisymmetric indentation of an elastic surface by a spherical indenter.

Explicit theoretical solutions for the contact of elastic bodies were developed by Hertz and presented in his pioneering work considered as the foundation of contact mechanics, Johnson (1982). The Hertzian elastic solution shows that the contact area between two elastic axisymmetric bodies is a circle whose projected radius is given by the expression,

\[ a = \left[ \frac{3QR}{4 \left( \frac{1}{E_1} + \frac{1}{E_2} \right)} \right]^{1/3} \]  

(1)
where $Q$ is the applied load, $E$ is the equivalent contact modulus and $R$ the relative radius of curvature defined respectively as,

$$1 = \left(1 - \frac{v_1^2}{E_1} + \frac{(1 - v_2^2)}{E_2} \right) \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \quad (2)$$

The Hertzian pressure distribution within the circular contact area is parabolic with the maximum pressure $P_{\text{max}}$ present at the centre of the indentation. The contact pressure $P(r)$ varies along the indentation radius according to,

$$P(r) = P_{\text{max}} \left[1 - \left(\frac{r}{a}\right)^2\right]^{1/3} \quad (3)$$

$$P_{\text{max}} = \frac{3}{\pi a^2} \frac{Q}{E} = \frac{6Q\pi E^2}{\pi^3 R^2}$$

The surface stresses ($z=0$), generated by the elastic spherical indenter both inside and outside the circular contact area can be evaluated by the following expressions, Johnson (1989).

$$\sigma_b = \frac{P_{\text{max}}}{3} \left[\frac{a}{r}\right]^2 \left[1 - 1 - \left(\frac{r}{a}\right)^2\right]^{3/2} - \frac{1 - \left(\frac{r}{a}\right)^2}{a} \left[1 - \left(\frac{r}{a}\right)^2\right]$$

$$\sigma_t = \frac{2v - 1}{3} \left[\frac{a}{r}\right]^2 \left[1 - 1 - \left(\frac{r}{a}\right)^2\right]^{3/2} - 2v \left[1 - \left(\frac{r}{a}\right)^2\right]$$

$$\sigma_z = -\frac{1 - \left(\frac{r}{a}\right)^2}{a}$$

Furthermore, expressions have been developed for the axisymmetric sub-surface contact stress distribution, Huber [7].

$$\sigma_b = \frac{\sigma_b}{P_{\text{max}}} = \frac{(1 + v) \left[1 - \frac{z}{a} \tan^{-1} \left(\frac{z}{a}\right)\right] + 1 \left[1 + \left(\frac{z}{a}\right)^2\right]}{2}$$

$$\sigma_z = \frac{(1 + \frac{z}{a})}{a} \quad (5)$$

The solution for the contact between a spherical indenter and an elastic surface is incapable to provide the information relevant to shot-peening, i.e. residual stresses (magnitude, distribution), depth of penetration of the plastic zone, depth of work hardening. This is due to the assumption made by Hertz that the contact is elastic. Further, the solution is axisymmetric and as such cannot deal with the issues of multiple indentations or oblique loading. However, the elastic theory can provide fundamental information that could be used in investigating shot-peening mechanics by means of numerical methods, Finite or Boundary
5. SHOT-PEENING, THEORETICAL MODELLING

The aim of modelling is to produce a parametric representation able to adequately delineate the shot-peening process and further,

* provide quantitative information (residual stress distribution and magnitude...)
* allow changes in variables (velocity, shot size, shape, angle of impingement...)
* accommodate material properties (elastic, elastoplastic, strain hardening...)

Clearly, such a model should be validated against experimental results. However, development of the ideal model is profoundly complex and verges on the limit of impossibility as the number of variables and their combinations is large.

Over the last fifteen years several modelling efforts have been reported in the technical literature. In all cases the developed models aim to predict the residual stresses, utilising suitable theoretical or numerical schemes, Guechichi et al. (1986), Bernasconi & Roth (1987), Al-Obaid (1990) and Meguid & Klair (1985) Although the models have been validated against experimental measurements and show good agreement, they assume the indenter to be perfectly spherical (Guechichi et al., 1986; Al-Obaid, 1990) and in most cases are unable to account for multiple indentation, with the exception of (Meguid and Klair, 1985).

New computational models have been developed aiming to enhance the modelling capabilities already available and advance the understanding of the mechanics of the shot-peening process. The models are based upon the use of Finite Element Methods and take advantage of the availability of interactive pre-processing software, and highly specialised solvers designed specifically for the solution of nonlinear problems in contact and elastoplasticity. These have been developed over the last ten years by the author and contributions from his graduate students, Kyriacou (1987), Sierra (1992), Alapont (1993).

Two model types have been developed, i.e., axisymmetric, for the analysis of single ball indentations and II, three dimensional, for the analysis of multiple indentations. The models generated enable the representation of the indenter as a rigid or elastic body. The target material can be modelled as an elastoplastic continuum with varying strain hardening characteristics, linear or Kinematic strain, hardening. The most simplified form of model can deal with a single ball indentation in quasi-static conditions and does not account for the presence of the indenter represented by an equivalent pressure distribution. A finite element model is designed that provides a suitable fine and focused mesh in the area of contact. The size of the contact area is predetermined by considering the Hertzian theory of contact, equations (1-5). Noting that the single indentation problem is symmetric along the axis of load application, for normal contact, and taking advantage of the exhibited symmetry, a half, quarter or smaller sector of the model could be used, see Figure 1.
Fig. 1. Single Indentation 3D Finite Element Model

Fig. 2. Typical 3D Model for the Study of Multiple Indentations

An appropriate pressure distribution calculated using equations (1-3) is applied on the model as element face loading. An obvious benefit of the modelling method discussed is, that it can easily be modified in order to model multiple indentation. This is achieved by modelling half the contact area i.e. a quarter of the whole system. A typical mesh configuration for the study of two
indentations is shown in Figure 2.

![Hertzian Distribution](image)

**Fig. 3. Hertzian and Idealized Contact Pressure**

Single indentations can be modelled more efficiently by means of axisymmetric representations as long as normal contact is assumed. If the Finite Element package includes contact elements then the indenter may be included and modelled either as elastic or rigid. A typical axisymmetric model that includes an elastic indenter is depicted in Figure 4. The mesh is fine and focussed in the area of the anticipated contact. The advantage of this type of model is that the F.E. algorithms calculate the contact area as part of the solution thus, providing a more accurate contact area. In addition the development of such a model requires less time for preparation.

The most advanced model is a 3D representation of the workpiece that includes the indenter, as a 3D discretization. This type of model could only be utilised if three dimensional contact elements were available in the solver. The development of such F.E. models is bound by severe difficulties associated with modelling the spherical indenter and incorporating the 3D contact elements. A typical F.E. mesh of this type is shown in Figure 5. Modelling of multiple indentations is possible with this modelling technique but one should remember that complex 3D problems demand very powerful computer hardware in addition to the sophisticated pre- processor software.

Evidently, in the case of the last two modelling representations, Figures 4 and 5, it is possible to foresee models where an indenter of a different shape and not only spherical could be considered. Furthermore, modelling the indenter in three dimensions provides the potential for studying not only the normal indentation, but also the oblique contact. However, the oblique contact should
also account for friction between the indenter and the workpiece surface which has been found to affect the elastic solutions, Alapont (1993).

Fig. 4. Axisymmetric Single Indentation Model

These modelling techniques have been validated in the elastic range utilising 3D photo-elastic techniques, stress-freezing. Figure 6, depicts the isochromatic stress pattern, contours of maximum principal stress difference, in stress frozen models of single and multiple indentations as observed in a transmission polariscope using monochromatic sodium light.

The sub-surface stress distributions obtained from elastic finite element solutions, utilising all modelling methods already discussed, are compared with the Hertzian theory and photo-elasticity, Figure 7. The model predictions are evidently in very good agreement with theory and experiment.
The graphical presentation of the results from the various models; Figure 7, clearly indicates that models where the indenter has been included as part of the model, \( \text{symbols} \), give a better agreement with the Hertzian theory \( \text{(1)} \); The 3D solution been better than the axisymmetric. The results of photoelasticity \( \text{(*)} \), exhibit the overall trend however, they give a higher values of non-dimensional shear stress \( \left( \frac{T_{\text{max}}}{P_{\text{max}}} \right) \) and location \( (y/a) \) of the maximum value. This may be associated with experimental measurement errors, as the isochromatic fringes were very closely packed in the vicinity of contact, making it difficult to identify their order and exact location.

![3D Model, Target and Indenter](image)

**Fig. 5. 3D Model, Target and Indenter**

Investigating the shot-peening process inevitably requires prediction of the residual stresses developed in the workpiece for a given set of parameters. This could be achieved by means of a solution capable of accounting for material elastoplasticity. The models presented could provide such a solution with ease as the workpiece material properties could be modified to include post-yield information. As an example of this capability, an investigation of the effect of
workpiece material behaviour on the development of residual stresses, due to a given shot size and velocity considering a single and double quasi-static indentations is presented herein.

Fig. 6. Isochromatic Fringe Patterns, Single and Multiple Indentations

![Isochromatic Fringe Patterns, Single and Multiple Indentations](image)

Fig. 7. Comparison of F.E. Modelling, Photo-Elastic and Theoretical Results

The material was a medium carbon steel with, $E = 210.0$ GPa, $v = 0.30$ and $\sigma_{y_{\text{mat}}} = 600.0$ MPa. Idealised post yield material models were used, perfectly-plastic ($H^* = 0.0$) and linearly strain hardening with $H^* = 0.1$ and $H^* = 0.2$. The term $H^*$ is defined as the strain hardening modulus, $H^* = E', E$, where $E'$ is the tangent and $E$ the elastic modulus, respectively. This case aims to examine
the residual stress depth and distribution as a function of workpiece material hardening and indenter separation. A suitable model for the case could be assembled with any one of the methods previously discussed.

The modelling method used in this example analysis of the single and multiple indentations, is that of 3D Finite Elements without the indenter, see Figures 1 and 2. The loading was represented with an idealised Hertzian pressure distribution, applied incrementally so that the first load increment was sufficient to bring the material to the threshold of plasticity, \( t_{\text{max}} = 0.95 \sigma_{\text{yield}} \). Subsequent load increments raised the load in steps of no more than 10% of the final load, whilst the material was undergoing plastic deformation. Application of the full load was followed by a single step unloading. A diagram of the load history is shown in Figure 8.

![Solution Time](image)

**Fig. 8. Load History**

The residual \( \sigma_{xx}, \sigma_{yy} \) stress distribution along the z-axis in the centre of the single indentation is shown in Figure 9, for the three strain hardening models used. Definitions of the directions are defined in Figures 1 and 2. Clearly, the residual \( \sigma_{xx}, \sigma_{yy} \) stresses are almost zero on the surface and become compressive below the surface.

From the data depicted it is apparent that the strain hardening modulus affects the residual stress distribution. In fact the higher the value of \( H' \) the lower the peak compressive residual stress. The effects of strain hardening modulus are summarised in the Table below.

<table>
<thead>
<tr>
<th>( H' )</th>
<th>( \sigma_{xx} ) peak residual</th>
<th>( z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.90 ( \sigma_{\text{yield}} )</td>
<td>0.95 a</td>
</tr>
<tr>
<td>0.1</td>
<td>0.74 ( \sigma_{\text{yield}} )</td>
<td>0.60 a</td>
</tr>
<tr>
<td>0.2</td>
<td>0.53 ( \sigma_{\text{yield}} )</td>
<td>0.55 a</td>
</tr>
</tbody>
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With regard to the problem of multiple elastoplastic indentations two cases are presented. In the first case the indentations were very close to one another.
(d=2.3a), and in the second case they were further apart, (d = 4.0a). Where a is the radius of the indentation and d is the centre to centre distance between the indenters. In these cases the assumptions made, methodology and load history, were identical to those used in the single indentation study.

Fig. 9. Residual $\sigma_{xx}$ Stress Distribution at the Centre of a Single Indentation

The Von Mises stress contours, from an elastic solution, for the two cases are depicted in Figure 10. It is apparent that an interference of the contours occurs beneath the surface when the indenters are near one another, confirmed by photo-elasticity, see Figure 6. This postulates that the plastic zones should meet beneath the surface and residual stresses form in this region after unloading.

The elastoplastic analysis has provided some interesting results regarding residual stresses. In the centre of the indentations the $\sigma_{xx}$ residual stress is compressive as expected however; the $\sigma_{yy}$ residual stress is predominantly tensile on and below the surface, but of a very low magnitude. These observations are shown in Figures 11, 12 for $d = 2.3a$; Similar results were obtained for $d = 4.0a$. Furthermore, considering the residual stresses at mid-distance between indenters revealed some remarkable trends, especially for large separation between spherical indenters. These residual stress distributions are shown in Figures 13 & 15 for $d = 2.3a$ and Figures 14 & 16 for $d = 4.0a$.

Examination of the $\sigma_{xx}$ residual stress distributions at mid-distance between indenters, Figures 13 & 14, clearly shows that in the case of small separations the stresses are compressive on the surface, attaining a maximum value below the surface. However, for a larger separation the trend changes dramatically and although the surface residual stresses are compressive they rapidly decay

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to xero. Considering the $\sigma_{yy}$ residual stress components the results are significantly different, Figures 15 & 16. The surface residual $\sigma_{yy}$ stresses are always tensile irrespective of the separation distance. The magnitude of $\sigma_{yy}$ residuals is significantly higher when separation is small, and decreases to near zero as the separation increases. Evidently, the separation of the indenters affects the residual stresses developed in the target material. With reference to the shot-peening process these results are important as they show that, although incomplete coverage is undesirable, some surface compressive residual stresses could exist even in uncovered areas. However, in practice incomplete coverage has been found to be detrimental, and this could now be explained with the results revealing the presence of damaging tensile residual stresses.

Fig. 10a. Von Mises Stress Contours, $d = 2.3a$

Fig. 10b. Von Mises Stress Contours, $d = 4.0a$
Fig. 11. $\sigma_{xx}$ Residual Stress Distribution at Centre of Indentation, $d = 2.30a$

Fig. 12. $\sigma_{yy}$ Residual Stress Distribution at Centre of Indentation, $d = 2.30a$
Fig. 13. $\sigma_{xx}$ Residual Stress Distribution at Mid-Distance, $d = 2.30a$

Fig. 14. $\sigma_{xx}$ Residual Stress Distribution at Mid-distance, $d = 4.0a$
Fig. 15. $\sigma_{yy}$ Residual Stress Distribution at Mid-distance, $d = 2.30a$

Fig. 16. $\sigma_{xx}$ Residual Stress Distribution at Mid-distance, $d = 4.0a$
6. DISCUSSION

The modelling methodology herein presented, utilised advanced Finite Element Methods for the study of the shot-peening process. It has been demonstrated that the methods developed are capable of dealing with the problem of contact accounting for single and multiple indenters. The elastic solutions of single and multiple indentations have been compared with results from shot-elasticity and the agreement has been found to be very favourable. This has provided confidence in Finite Element modelling.

A number of different procedure could be utilised in modelling, that may or may not, include the indenter. The simplest technique is that of a 3D model of the target and representation of loading by an idealised Hertzian pressure distribution. The most advanced models could account for the presence of the indenter, which allows the accurate calculation of the contact area as part of the solution procedure. These models take two forms, axisymmetric or fully three dimensional. The latter, require the use of three dimensional contact elements and very sophisticated Finite Element algorithms. Furthermore, the inclusion of elastoplasticity adds to the requirement for powerful computer hardware. During the development of these modelling methods a variety of meshes were tested with different commercial software packages. It has been found, as anticipated, that the use of linear elements i.e. four noded quadrilaterals or three noded triangular, axisymmetric or linear bricks, demands the utilisation of a large number of elements for accurate solution. However, using parabolic elements improves the accuracy of solution and reduces the number of degree of freedom.

Incorporating elastoplasticity and suitable load incrementation schemes in the solutions, provides the unique capability of predicting the residual stresses, and consequently enables the study of the effects of various parameters involved in the shot-peening process. The example analysis presented has demonstrated this capability. Although, in this investigation idealised elastoplastic material models have been used, this need not be the case. If real material mechanical properties are available these may be inserted in the models.

7. CONCLUSIONS

The theoretical modelling allowed the representation of contact phenomena related to the shot-peening process. The models were validated against theoretical and experimental methods and were found to accurately represent elastic contact conditions.

Elastoplastic analysis has shown that the strain hardening behaviour of the peened material affects the residual stress field. In fact the higher the strain hardening modulus $H'$, the lower the maximum compressive sub-surface residual stress. Another interesting finding is the presence of small magnitude tensile residual stresses in the uncovered area between indentations. It has been revealed that their magnitude depends upon the distance of separation.
between indenters. Furthermore, for small separation ratios some compressive sub-surface residual stresses are also present and their magnitude increases as the separation between indentations is reduced.

Modelling with Finite Element Methods has been found to be very versatile and a powerful means for investigating the shot-peening process. Although modelling cannot substitute experiments it provides the means for improving understanding of the mechanics of the shot-peening process. Research in this area is by no means complete as this far quasi-static models have been developed which require further experimental validation.

REFERENCES

Effect of Shot-Peening on the Fatigue Life of Axially Loaded Notched Components

Investigation of the Effects of Shot-Peening on Partially Fatigued Notched Components
Submitted to ICSP-6


One Hundred Years of Hertz Contact

Contact Mechanics
Cambridge University Press.

Huber, M.T. 1904.
Zur Theorie der Berührung fester elastische Körper
Ann. Der Phys., 14, 153

Predicting Residual Stresses due to Shot-Peening

Bernasconi, J. and Roth, M. 1987.
The Niku-Lari Method and the Stress Source Method: Application to Residual Stress Distribution of Shot-Peened Plates
Advances in Surface Treatments, Pergamon Press, 4: 221-250

Al-Obaid, Y.F. 1990.

An Examination of the Relavance of Co-indentation Studies to Incomplete Coverage in Shot-Peening Using the Finite Element Method
Journ. of Mech. Working Technology, 11: 87-104

The Mechanics of the Shot-Peening Process
MSc Thesis, Cranfield Institute of Technology, UK.

Shot-peening Mechanics a 3-Dimensional Finite Element Study
MSc Thesis, Cranfield Institute of Technology, UK.

Alapont, I. 1993.
Theoretical Analyses into the Mechanics of the Shot-Peening
MSc Thesis, Cranfield Institute of Technology, UK.
ON THE AREA COVERAGE OF GRIT BLASTING

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1. INTRODUCTION

Full coverage i.e. completely covered with dent is a base of grit blasting. Now a days, area coverage is usually calculated by next formula, \( C = 1 - (1 - C)^1 \) [1]. Although this formula means that full coverage didn't reach, but we know that full coverage is easily reached on ordinary process.

The purpose of this paper is to obtain the relation between blasting conditions and area coverage including full coverage. Grit blasting was performed for plain carbon steel (0.45% C) under several conditions. Measured factors are area coverage and full coverage.

2. FORMER THEORY

Now, area coverage may be calculated with the next equation by SAE,

\[
C_n = 1 - (1 - C_1)^n
\]

(1)

Fig. 1. Influence of blasting time on area coverage. (SAE)

This equation does not lead full coverage till infinite time as shown in Fig. 1.