Computer assisted coverage simulation

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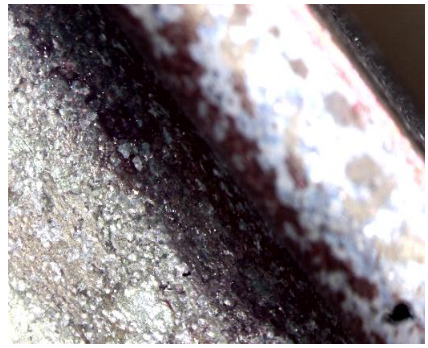
Keywords: Almen intensity, artificial image, coverage curve, coverage rate, crater area, crater depth, crater size, craters population density, indent, overlapping map, shot size, shot-peening, simulation.

Introduction

Depending on the target material ductility, peening parameters and component geometry, coverage evaluation can be very subjective. I.e.: when peening a very hard target material, after a first peening operation and using fine and light shot with low intensity. Mathematical models for Almen intensity and surface coverage determination [1], are now adopted in the SAE standards. Computer calculation programs have been proposed. Beyond simple calculation, a full computer mastering of a flat component surface coverage process is here produced.



Pict. 1: microscope picture of the internal beam radius of a con'rod. Despite the surface was covered, before peening, with red marker for whiteboard, the geometry makes the coverage evaluation difficult.

Objectives

- Building the coverage curve and predicting the coverage rate vs. peening time,
- Creating artificial, but realistic reference coverage pictures, helping for evaluation of the real surface coverage rate,
- Characterizing individual craters [2], crater population density and distribution of craters overlapping numbers across a reference area,
- Providing the peening operators and controllers with automatic and accurate guidance.

The purpose is restricted to geometric and topographic aspects, not taking into account any other aspect of the shot peening process, such as residual stress distribution, microstructure changes, hardness evolution, etc. The Almen intensity is also part of the program, but not the topic in this paper.

Methodology

- Individual Crater

Coverage starts with isolated craters formed during the shot impacts, randomly spread from the peening stream.

The contact begins when the shot hits the surface and starts penetrating the target until the material reaction is strong enough to stop it and send it bouncing away. The stress induced during the contact phase is large enough to over pass the target yield strength, which creates a permanent, plastic deformation, which is like "memorizing" the shot shape as a "crater" into the target.

The size (d) (1) and depth (h) (2) of each crater are depending on individual shot characteristics and peening parameters (Fig. 1): specific shot gravity, shot size (D=2R), shot and target mechanical properties, peening intensity, impingement angle, etc.

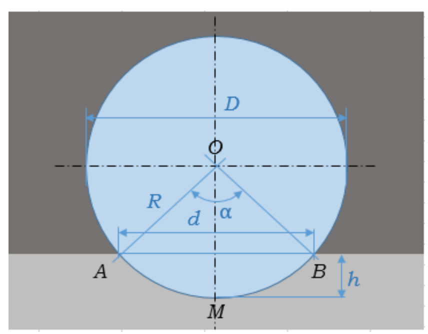


Fig. 1: representation of crater size (d) and depth (h) vs. shot size (D).

How then, correlating the peening parameters and material characteristics with the crater geometry? The shot size analysis is translated into crater size distribution

$$(1)\quad d = 2\sqrt{h(D-h)}$$

$$(2)\quad h = 1/2\,(D - \sqrt{D^2 - d^2})$$

and randomly spread across a reference surface area. According to the peening intensity, the calibration is made by measuring the crater size with a microscope. For poor crater population, most of the craters are isolated. For a given peening intensity, it is then easy measuring each actual crater size under the microscope and correlating with a given set of peening parameters (Fig. 2) [2].

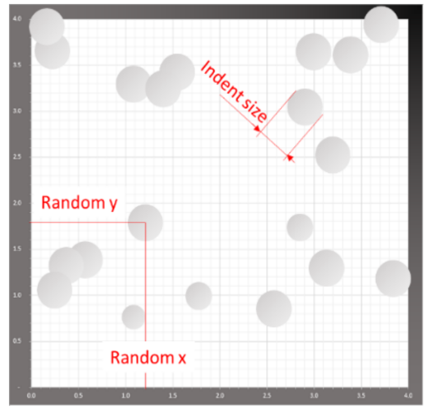


Fig. 2: simulation of random crater distribution and calibration.

- Craters Combination

The crater coordinates are randomly generated by "Monaco" principle. Impact after impact, the craters combination is creating a complex surface topography, with some overlapping happening, even for low coverage rates (Fig. 3) [2]. The artificial picture advantages are that the coverage quantification is a simple summation and it is not subjective.

Fig. 3: cross section of a fully covered surface, clearly showing craters overlapping and the subsequent peaks and folds creation.

- Coverage Rate Calculation

Coverage rate is expressed in % and defined as the ratio of the surface area covered with craters vs. the total reference surface area (3). I.e.: the square area of a picture taken from a microscope.

. Before starting the peening process, the surface is virgin from craters and the coverage is 0%.

. At the beginning of the peening process, the probability for hitting a virgin area is close to 100%.

. When the worked surface area equals the virgin surface area, the coverage is 50%.

. At the end of the peening process, it becomes easier hitting a worked area, creating craters overlapping, than hitting a virgin area. Therefore, 100% coverage is theoretically impossible to reach: 100% is the horizontal asymptote to the coverage curve.

$$(3) \quad C_{\%} = 100\,\frac{Indented\ surface\ area}{Reference\ surface\ area}$$

Based on the Johnson-Mehl-Avrami-Kolmogorov equation, known as "JMAK" Law (4) [1] [3], algorithms are producing artificial pictures, representing the surface after a given number of shots have randomly reached the target surface, creating craters. The "JMAK" law is well describing the coverage progression vs. peening time *t*. *t* is the time for which we would like to know the coverage rate and $t_0 \neq 0$, is the time for which the coverage rate has been measured (chart 1).

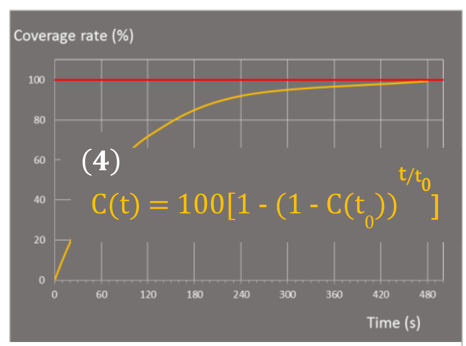


Chart 1: coverage progression vs. peening time, according to "JMAK" law.

The coverage rate *Cn*, for *n* passes, can also be expressed vs. n (4a). I.e., nozzle strokes or peening passes, where C_1 is the coverage rate measured after one peening pass. When C_1, the coverage for one pass, has been measured, the number of peening passes, n, required to reach 98% coverage, is given by solving $0.98=1-(1-C_1)^n$. The solution (5), is displayed in chart 2.

$$(4a) \quad C_n = 100[1 - (1 - C_1)^n]$$

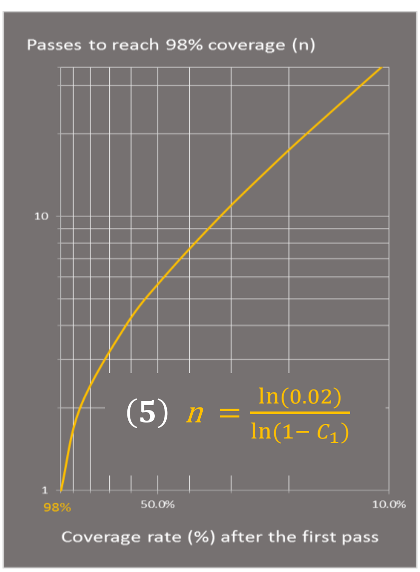


Chart 2: number of passes to reach 98% coverage vs. coverage after the first peening pass, C_1.

- Craters population density

$$(6)\quad a_i = \pi\frac{{d_i}^2}{4}$$

Each crater projected area, a_i is given in formula (6), where d_i is the individual crater diameter. For a given number of craters n, the craters population density, D_c (7) is then defined as the ratio between the sum of all individual crater surface areas and the reference surface area, with $1 \leq i \leq n$. n is depending on the shot mass flow rate, peening time and the mass of each shot particle. When the surface is free from any crater, $D_c=0$. When the sum of individual crater areas is equal to the reference surface area, then $D_c=1$. Since craters are randomly overlapping each other, in this case, the reference surface cannot be fully covered with craters: C=63.3%. The time can then be replaced with D_c in the coverage calculation (8) (chart 3).

$$(7)\quad D_c = \frac{\sum_n a_i}{Ref.Surface\ Area}$$

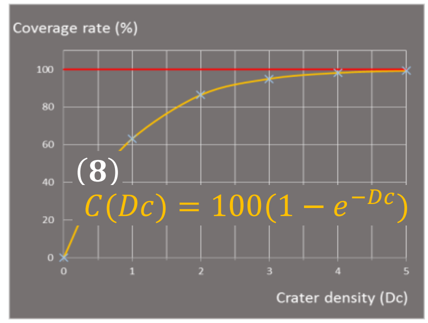


Chart 3: coverage rate vs. crater population density, D_c.

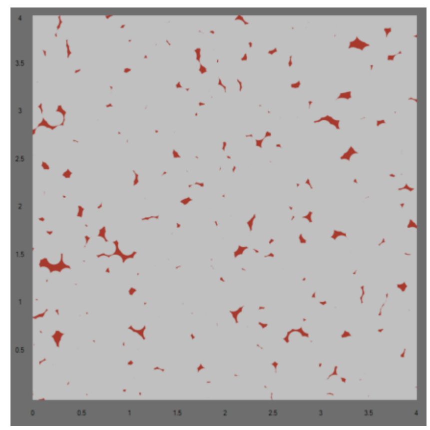
- Full coverage definition

Practically, beyond a given amount of craters, the reference area is almost fully covered with craters. Almost no area remains virgin and the practical coverage rate is 100%, or even higher. When the peening operation is continued, the coverage rate cannot be quantified any further.

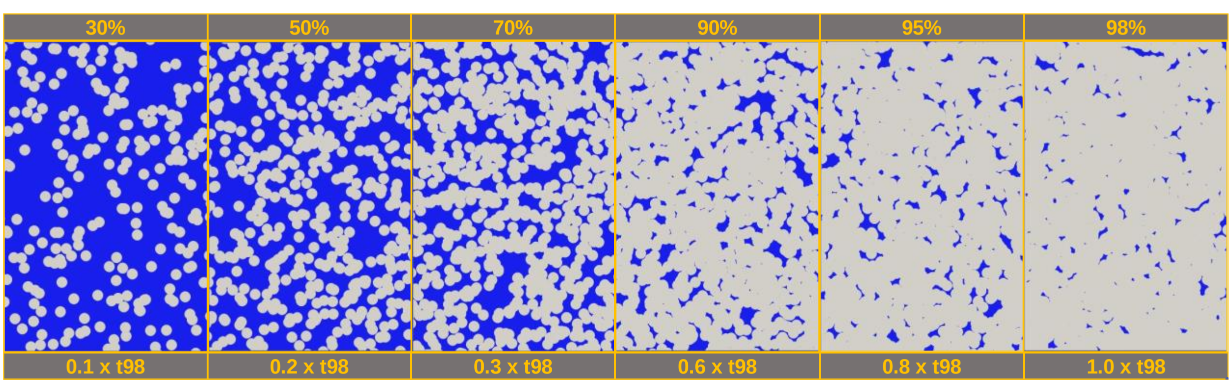
- Specified coverage definition

The convention is to stop measuring the coverage rate at 98% (Pict. 2) and consider only the peening time in order to specify the coverage rate beyond 98%, as being the number of times the surface has been peened at 98% coverage. I.e.: 200% specified coverage cannot be measured, but it is defined as reached for twice the peening time providing 98% measurable coverage rate. Some interesting values are 118% specified coverage that brings 99% physical coverage and 178% specified coverage that brings 99.9% physical coverage.

Furthermore, the coverage can be expressed vs. the rate of the 98% physical coverage time, which allows easy understanding that 50% of the 98% coverage time corresponds with 86% coverage (Pict. 3, Chart 4).



Pic. 2: computer generated picture 98% coverage. Background simulation of red marker for whiteboard.



Pict. 3: example of a reference gauge, made from artificial pictures produced using the software, for coverage rates from 30 to 98%. The time base is the time to reach 98% coverage. Background simulating blue ink tracer.

- Main practical aspects

. Shot Size and Shot Density

The number of shots per litre is only depending on the shot size (Chart 5). Whatever is its density, if the shot size is divided by 2, then, the amount of shots/l is multiplied by $2^3 = 8$; i.e.: there are 42.3 million of 0.3 mm shots in one litre and “only” 5.3 million of 0.6 mm shots.

For a given shot size, the number of shots per mass unit is decreasing when the shot density is increasing. If steel shot is taken as reference, the density ratio is approximately 1/2 for ceramic shot and 1/3rd for glass beads, i.e., for 0.3 mm shot there are: 28.3 million glass beads/kg; 18.4 million ceramic shots/kg; 9.3 million steel shots/kg.

. Influence of shot wear and Almen intensity

Picture 4 is simulating coverage, using 0.6 mm cut wire shot, as new. Pictures 5 and 6 are showing the coverage rate variation, with shot size reduction and then, Almen intensity increase, using always the same 180 craters production. The artificial background is simulating fluorescent coverage tracer.

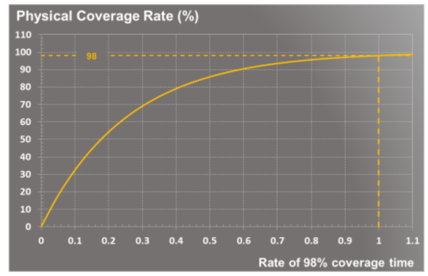


Chart 4: physical coverage vs. rate of 98% coverage time.

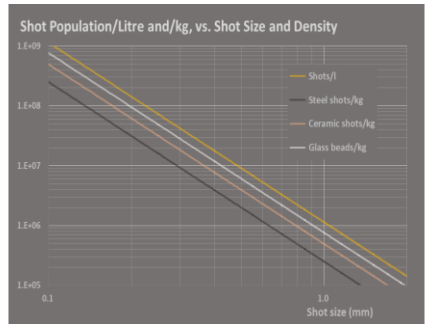
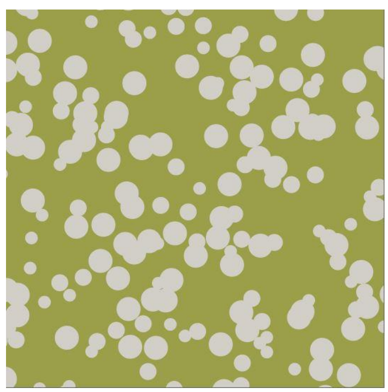


Chart 5: shot population vs. shot density and size.

Pict. 4: 50% coverage, simulating 0.600 mm cut wire shot, as new.



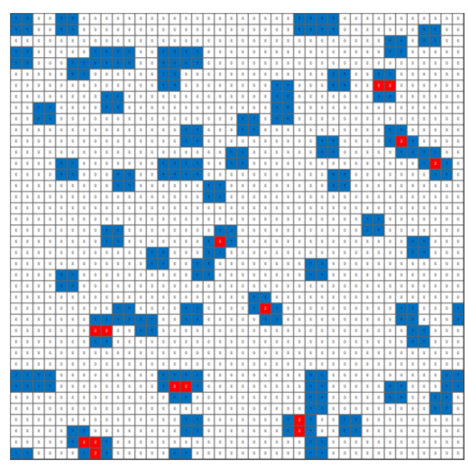
Pict. 5: 30% coverage, simulating the wearing down to 0.480 mm.

Pict. 6: 80% coverage, simulating the use of higher intensity.

- Overlapping map

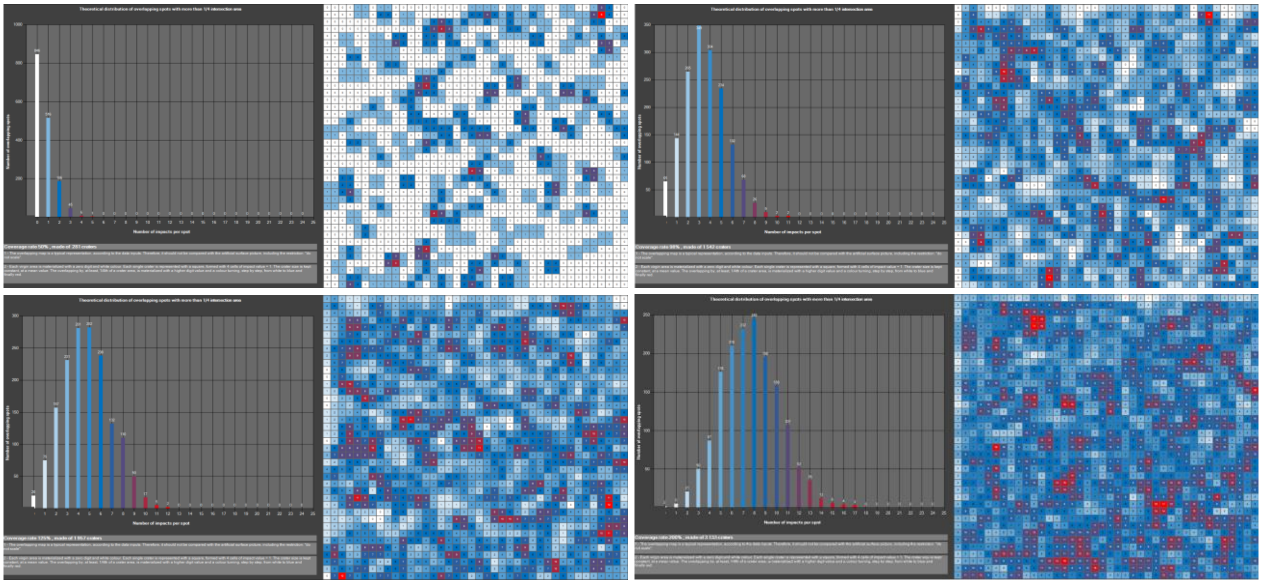
The mapping area is gridded, using 40 x 40 = 1600 cells (spots). Each crater is randomly located and represented with 4 cells, each having a value of “1” (Pict. 7).

Real craters are nearly round and may have intersection area from almost 0 to 100%. The square crater shape is a good approach to make the computation faster. Then, the minimum intersection area is 25%. Therefore, intersection possibilities are 25, 50 or 100%. This approach is also eliminating small overlaps that are not inducing significant surface defects. When overlapping occurs, inside the intersection area, the cells values of each crater are added. This process is easy to understand when coverage is low (Pict. 7).



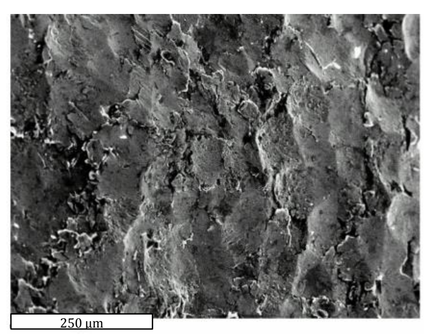
Pict. 7: overlapping map, using "4 square cells" crater model.

For a given amount of coverage, the number of impacted cells, among the 1600 total ones, that are different from zero, can easily be calculated, using the proportional law. Then, by Monaco principle, the individual craters are randomly located and each of their 4 cells receive a value taking into account the intersections with the other ones. The cells are then coloured from white for "0", to blue for medium overlapping value and to red for "maximum overlapping value.



Pict. 8: screen shots of overlapping map and distribution evolution for coverage rates from 50 to 200%.

. For poor coverage, below 50% (Pict. 8, top left), the overlapping spectrum is squeezed at the left, with 2 tall bars representing "no overlapping", with no, or 1 impact per cell. No cell showing more than 4 impacts.
. For 98%, coverage, (Pict. 8, top right), the overlapping spectrum is moved to the right and well balanced. Since this is the 98% coverage definition, 40 cells over 1600 remain virgin. 70% of the area is overlapped with 2 to 5 impacts at the same spot. No cell with more than 9 impacts; red portion represents now more than 7% of the area showing 7 to 9 impacts at the same spot.
. For 125% coverage, (Pict. 8, bottom left), which is a very common specification, the overlapping spectrum starts widening with 85% of the area showing overlapping with 2 to 7 impacts at the same spot. 10% of the area is overlapped with 8 to 12 impacts at the same spot. No cell showing more than 12 impacts.
. For 200% coverage, (Pict. 8, bottom right), which is not recommended and hardly specified, except for low intensity peening or in very specific purpose, the spectrum is very wide, but still 0.25% of the area is virgin. The maximum overlapping value is 18. This creates a significant gap with the majority of the surface, showing 5 to 10 impacts at the same spot. Under high intensity, the risk is folding, crack initiation, scaling and cavity creation, potentially sheltering corrosion (Pict. 9)...

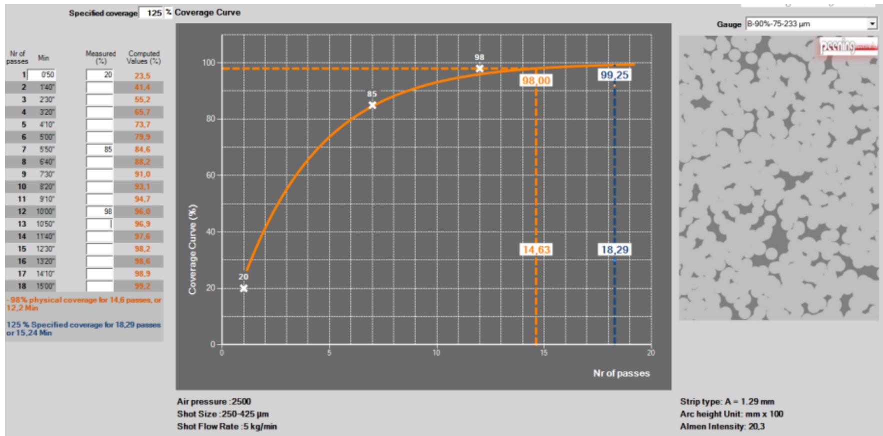


Pict. 9: SEM picture of high strength steel surface, peened with 100% specified coverage rate, using high peening intensity. Folding and crack initiation are visible.

- Coverage prediction

To start coverage characterization (Pict. 10), the operator estimates and inputs the coverage for a given peening amount, not necessarily one pass. In case when several assessments are made for the same peening amount, only the average value will be input. Based on this 1st value, the software immediately proposes coverage values for each peening amount and draws the curve accordingly, predicting the time to reach the 98% physical, as well as specified coverage. Then, the operator inputs, at least, 2 other coverage values for different peening amounts. The recommendation is to include a measurement value around 98%.

To help in the coverage rate evaluation, some real or artificial reference pictures from archives, are displayed at the screen right.



Pict. 10: screen shot of coverage curve creation using the software predictions and reference pictures.

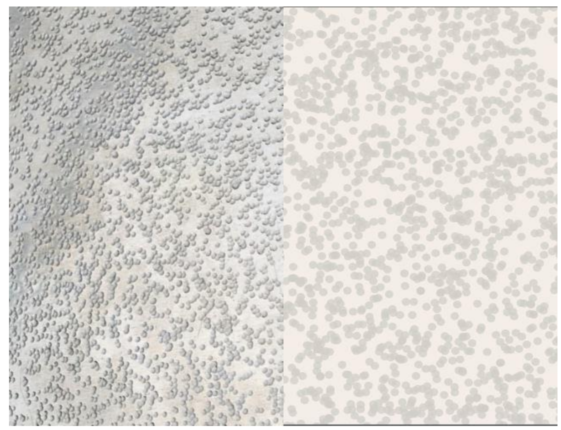
Results and analysis

The computer program is fully describing and quantifying, how the peening process is randomly covering a flat surface with craters, including overlapping map and their distribution.

For reference and comparison, the program also stores artificial and real surface pictures (Pict. 11) and overlapping maps (Pict. 8).

In a first step, for artificial pictures, the software only takes into account a flat component surface. A future evolution, using CAD data, could take into account the local component geometry.

The limitation to 1/4th intersection of the square crater model allowed reasonable computation time for the overlapping map. This can be improved, using much higher computer calculation capacity, with a finer crater definition, up to 24 pixel (Fig.4). 20% better crater area filling can be achieved using 12 or 24 pixels, but craters intersection possibilities are then growing exponentially, with no significant benefit and poor map readability.


Pict. 11: Aluminium surface after 50% coverage; real microscope picture (left) and artificial picture from the software (right).

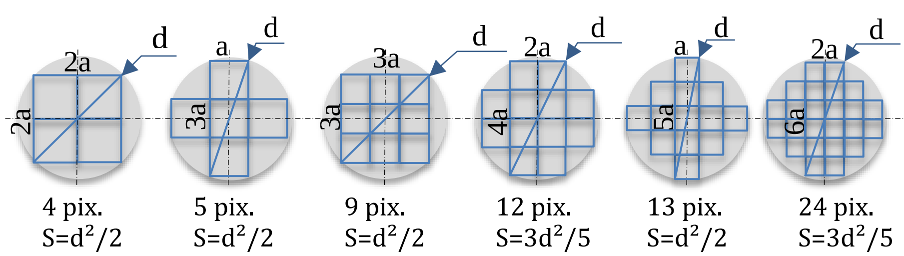


Fig. 4: Pixel arrangement possibilities, where S is the crater simulated area. Beyond the 4 pixels, 12 is providing the 1st better area filling, by 20% higher.

References

[1] SAE Standard J2277, Shot Peening Coverage Determination, revised 2013-04.
[2] Knotec O. and Elsing R., Computer simulation of different Surface Topographies of Metals Produced by Blasting Process, ICSP3, p361-368, 1987.
[3] Avrami M, J. Chem. Phys., 7, 1103, 1939; Ibid., 8, 212, 1940; Ibid., 9, 177, 1941.