Formation of shot dimples during shot peening

V P Koltsov¹, Le Tri Vinh¹, V B Rakitskaya¹ and E V Tardybaeva²

¹Irkutsk National Research Technical University, 83, Lermontov str., Irkutsk, 664074, Russia
²Baikal State University, 11, Lenina str., Irkutsk, 664003, Russia

E-mail: kolcov@istu.edu

Abstract. In the aircraft industry, the technology of shot peen treatment is successfully used for the manufacture of long panels and sheaths, both for forming and finishing hardening. Shot dimples increase the roughness of the treated surface, so after the shot peening, the surface should be grinded with flap wheels to improve the roughness values by partially removing the traces of shot impact. To assess the quality of shot peening as a monitoring indicator, in practice the degree of coverage of shot dimples on the treated surface is used, which is determined by the percentages of the total area of shot dimples to the total area of the considered treatment part. To assign the modes of subsequent grinding with flap wheels, it is necessary to determine the allowance for grinding, which is determined by the value of the maximum depth of the largest dimple within the base area of the treated surface. The paper presents a method of creating a mathematical model to determine the size of dimples in shot peening, as well as modeling and engineering analysis of the shot peening process with the finite element method.

1. Introduction
To obtain complex curvilinear forms of the surfaces of panels and sheaths, as well as hardening operations, shot peening and shot peen hardening are widely used [1-7]. Grinding with abrasive flap wheels is a mandatory part of the technological process of forming long large-sized surfaces such as panel and sheath [8-10]. It is carried out in order to improve the quality of the initial surface obtained after shot peening. The degree of coverage with shot dimples and the depth of the largest dimple in the treated surface are important parameters that determine not only the degree of forming, but also the amount of allowance for grinding.

In practice, the actual data of parameters is determined only after processing, which makes it difficult to assign a rational processing mode for both shot peening and subsequent grinding with a flap wheel. Therefore, the purpose of this work is to theoretically study the formation of a shot dimple during operation of a contact-type shot peen device and to develop a mathematical model for determining the size of dimples on the treated surface under a shot impact, depending on the processing mode and properties of the machining material. The results of the research will be useful for subsequently determining the degree of coverage with shot dimples and assigning an allowance for subsequent grinding with a flap wheel.

2. Analytical determination of the size of the shot dimples during shot peening
To study and determine the size of the shot dimple on the treated surface during shot peening, a model of the impact of a spherical shot on the surface of a metal plate was constructed.
Figure 1 presents a model of impact of the ball 2 with radius R on the surface of the plate 1. To simplify the calculations, following assumptions in our model are accepted:

- The shot is spherical and absolutely rigid without deformation when hitting the surface of the plate.
- The roughness of the panel surface and the shot is not taken into account when determining the depth and area of the shot dimple on the panel surface.
- Due to the high attack speed and the small distance between the surface of the panel and the shot peen wheel of contact type shot peen device, the speed loss is not taken into account and it is taken equal to the circumferential speed of the shot at the exit of the shot peen wheel.
- Due to the low height of the metal influx around the shot dimple after impact, the size of the shot dimple is determined by the original surface of the panel before the shot impact.

![Figure 1. Model of impact of shot on the panel surface, where: 1 is a panel, 2 is a spherical shot, R is a shot radius, r is a radius of the shot dimple on the panel surface, h is a depth of the dimple after impact, V₀ is the initial velocity of the shot before impact, V₁ is the speed of rebound of shot after impact, α is the angle of attack of the shot against the normal to the panel surface, β is the angle of rebound of shot after impact on the panel surface.](image)

According to the law of energy conservation, when leaving the shot peen device, the shot has kinetic energy, part of which is transferred to the panel on impact and causes deformation, the rest causes the shot to bounce in the opposite direction. The equation of energy balance in this case can be expressed with the following formula:

\[
m \frac{V₀^2}{2} \cos^2 \alpha - m \frac{V₁^2}{2} \cos^2 \beta = \int_{0}^{h} F_{res}(x) \, dx,
\]

where: m is the mass of the shot, \( F_{res}(x) \) is the resistance force of the panel material when the shot is indented in its surface, h is the depth of the shot dimple. The mass of the shot is determined by the following formula:

\[
m = \frac{4\pi R^3}{3} \rho,
\]

where: \( \rho \) is the density of the shot material, \( \int_{0}^{h} F_{res}(x) \, dx \) is the work of the resistance force of the shot indentation to the depth h, while:

\[
\int_{0}^{h} F_{res}(x) \, dx = \int_{0}^{r_x} \sigma_{0.2} \pi r_x^2 \, dx,
\]

where: \( \sigma_{0.2} \) is the yield strength of the panel material, \( r_x \) is the radius of the dimple at the indentation of the x-th value.

Given the lack of deformation of the shot and absolute smoothness of shot surface and the panel without considering the influx of metal around the dimple (Figure 2), the function of the dimple radius during the shot indentation into the panel is determined by the formula (4):
Figure 2. To the definition of the shot indentation depth

\[ r^2(x) = R^2 - (R - x)^2 \]  

(4)

Substituting (4) into (3) we obtain

\[
\int_0^h F_{res}(x)dx = \pi \sigma_{0.2} \int_0^h (R^2 - (R - x)^2) \, dx = \pi \sigma_{0.2} \int_0^h (2Rx - x^2) \, dx
\]

\[ = \pi \sigma_{0.2} (R^2h - \frac{1}{3}h^3) \]

Thus

\[ \frac{mv_0^2}{2} \cos^2 \alpha - \frac{mv_1^2}{2} \cos^2 \beta = \pi \sigma_{0.2} (R^2 - \frac{1}{3}h^3) \]  

(5)

or

\[ \frac{2}{3}R^3 \rho (V_0^2 \cos^2 \alpha - V_1^2 \cos^2 \beta) = \sigma_{0.2} (R^2h - \frac{1}{3}h^3) \]

That is

\[ h^3 - 3Rh^2 + \frac{2}{\sigma_{0.2}}R^3 \rho (V_0^2 \cos^2 \alpha - V_1^2 \cos^2 \beta) = 0 \]  

(6)

Given that the dimple has a spherical shape, the area of the dimple on the panel surface can be determined by the following formula:

\[ S = \pi (2Rh - h^2) \]  

(7)

Equation (6) can be solved at a known velocity and angle of shot rebound after impact.

Solving equation (6) gives the value of the depth of the dimple depending on the initial velocity of impact, the angle of attack of the shot and the properties of the panel material.

3. Determination of the size of the shot dimple on the surface to be processed during shot peen treatment with the finite element method

Theoretically determining the actual values of dimple size on the panel surface during shot peen treatment is challenging, as not all the shot kinetic energy is given for the deformation of the processed material, the recovery process of the dimple after the rebound of shot occurs in a complicated manner depending on the properties of the panel material, impact velocity, angle of attack, friction and slip shot to the panel surface, etc.

Currently, there are various computer programs for modeling and engineering analysis, which allow to obtain fairly reliable results in the study of such complex dynamic processes as shock, which take into account most of the factors that affect the final results.
To solve the problem of determining the actual depth and area of the shot dimple, the Ansys modeling and engineering analysis program with module "Explicit Dynamics" was used. In the study, the following parameters of the model were adopted: as a shot, a ball with different diameters used for shot peening of aircraft panels and sheaths (2.5, 3.5, 4.5 mm) was taken. A plate is taken as a panel 15*15*5 mm aluminum alloy B-95T.

Figure 3 presents a typical finite element model of the ball and panel with a mesh size of 0.25 mm.

The initial velocity of the ball (attack speed), was directed generally at an angle $\alpha$ to the upper surface of the plate (Figure 4). The value of the attack speed of the ball was given as the values of vector velocities $V_y = V \cos \alpha$ and $V_x = V \sin \alpha$ at $\alpha = 0 \div 12$ degrees (Table 1).

The remaining initial parameters for the model are also presented in Table 1. Figure 5 shows a typical result of modeling the impact in the plate cross section through the center of the dimple. By results of modeling it is possible to determine depth and the area of shot dimple.

Figures 6-11 represent the dependence of the depth and area of the shot dimple on the angle of the shot attack with respect to the normal to the panel surface when modeling the impact of a ball with a diameter of 2.5, 3.5 and 4.5 respectively (with an approximation accuracy of 100%).
From the dependency analysis on the Figures 6-11, it follows that the larger the size of the shot and the attack speed, the larger the size of the shot dimple on the treated surface. This is due to the fact that increasing the size of the shot and the speed of its attack increases the kinetic energy of the shot, which leads to greater plastic deformation of the panel surface. With the same attack speed and shot size, the maximum depth and area of the shot dimple is achieved at an attack angle of 0 degrees.

In addition, as a result of the simulation, the values of the speed of rebound of the ball after impact can also be obtained. In our case the angle of rebound according to the simulation results varies slightly compared to the angle of attack.

Table 1. Initial speed of ball flight

| Frequency of rotation of shot peen wheel, rpm | Radius of outer surface of shot wheel, mm | The angle of shot attack, degree. | Shot attack speed $V_x$, m/s | Shot attack speed $V_y$, m/s |
|----------------------------------------------|------------------------------------------|----------------------------------|-----------------------------|-----------------------------|
| 600                                          | 200                                      | 0                                | 0                           | 12.566                      |
|                                              |                                          | 6                                | 1.314                       | 12.497                      |
|                                              |                                          | 12                               | 2.613                       | 12.291                      |
| 800                                          | 200                                      | 0                                | 0                           | 16.755                      |
|                                              |                                          | 6                                | 1.751                       | 16.663                      |
|                                              |                                          | 12                               | 3.484                       | 16.389                      |
| 1000                                         |                                          | 0                                | 0                           | 20.944                      |
|                                              |                                          | 6                                | 2.189                       | 20.829                      |
|                                              |                                          | 12                               | 4.355                       | 20.486                      |

Figure 5. Stress-strain state of the panel after the shot impact
Figure 6. The depth and area of the shot dimple vs the angle of shot attack with shot diameter 2.5 mm

Figure 7. The depth and area of the shot dimple vs the angle of shot attack with shot diameter 2.5 mm
Figure 8. The depth and area of the shot dimple vs the angle of shot attack with shot diameter 3.5 mm

Figure 9. The depth and area of the shot dimple vs the angle of shot attack with shot diameter 3.5 mm
Figure 10. The depth and area of the shot dimple vs the angle of shot attack with shot diameter 4.5 mm.

Figure 11. The depth and area of the shot dimple vs the angle of shot attack with shot diameter 4.5 mm.
In relation to the constructed model (dependencies 6 and 7), when determining the size of the dimples, the values of velocities and rebound angles were taken as a function of the angles of attack of the shot from the simulation. Approximate results of calculations of the area of dimples by the formula (7) on the basis of depth of a dimple from the formula (6) and results of modeling at an angle of attack of 0 degrees depending on diameters of shot of 2.5, 3.5 and 4.5 mm are presented in Figures 12, 13 and 14.

**Figure 12.** Dimple area vs shot diameter with a speed of shot peen wheel fn=600 rpm, where the red line is the result of theoretical calculations, blue – simulation result

**Figure 13.** Dimple area vs shot diameter with a speed of shot peen wheel fn=800 rpm, where the red line is the result of theoretical calculations, blue – simulation result
Figure 14. Dimple area vs shot diameter with a speed of shot peen wheel fn=1000 rpm, where the red line is the result of theoretical calculations, blue – simulation result

Deviations of the dimple area values obtained by the formula (7) and in the finite element modeling are within the permissible limit (not exceeding 13%). These data can be used for preliminary calculations of the size of the shot taking into account the modes of shot peen processing and properties of the processed material to predict the required quality of the workpiece surface.

4. Conclusion
The finite element method is the best tool to date for determining the size of shot dimple on the workpiece surface during shot peen processing.

A mathematical model is proposed to determine the depth and area of the shot dimples depending on the processing modes and properties of the processed material in the case of shot peening on a contact-type shot peen device. This model is useful for subsequent determination of the degree of coverage with shot dimples during shot peening and assigning the allowance value for subsequent grinding with flap wheels.

References
[1] Pashkov A E 2005 Technological Relationships under Long Sheet Metal Part Manufacturing (Irkutsk: Irkutsk State Technical University)
[2] Pashkov A E and Chapyshnev A P 2003 Accounting machining zone structure effect under shot peening forming, in: Interuniversity collection of scientific articles “Technological mechanics of materials” (Irkutsk: Irkutsk State Technical University) pp 22–27
[3] Likhachev A A, Gerasimov V V and Pashkov A A 2015 Implementation of shot peening control system on contact type installations Vestnik of Irkutsk State Technical University 12(107) 19-25
[4] Pashkov A A 2015 Automation of large scale panels shotblasting process morphogenesis on contact type installations Vestnik of P. A. Solovyov Rybinsk State Aviation Technical University 4 34-39
[5] Vinh L T, Starodubitseva D A, Koltsov V P and Nguyen T H 2018 Determination of the degree of shot coverage after shot peening by image processing Systems. Methods. Technologies – Scientific Journal of Bratsk State University 2(38) 32-37
[6] Koltsov V P, Vinh L T and Starodubtseva D A 2019 Determination of the allowance for grinding with flap wheels after shot peen forming Material of Int. Conf. on Innovations in Automotive and Aerospace Engineering 632

[7] Diak A U 2015 Determination of the coverage by the automated method Vestnik of Irkutsk State Technical University 12(107) 19-25

[8] Diak A U 2014 Promising methods to determine surface coverage under shot peening Vestnik of Irkutsk State Technical University 7(90) 12-17

[9] Dimov U V and Poashev D B 2015 Cutting forces in machining by elastic abrasive wheels Vestnik of Irkutsk State Technical University 7(102) 47-55

[10] Dimov U V and Poashev D B 2015 Cutting zone temperature under elastic fap disc machining Vestnik of Irkutsk State Technical University 2(97) 38-42