To determination of removable material during grinding with flap wheels after shot peen forming

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Abstract. Shot peening are widely used in forming the long panels and sheaths. Due to impact of shot on the processed surface, the specific microgeometry is formed, the characteristic feature of this microgeometry are the numerous dimples of shot with different diameters and depths. The presence of these dimples causes deterioration of the surface roughness parameters. Therefore, after shot peening the mandatory requirement is implementation of grinding with flap wheels for partial removal of the shot dimples, the depth of which in magnitude significantly exceeds the valleys of micro-irregularities formed as a result of previous treatment. The value of the assigned allowance for grinding depends on the requirements for the quality of the surface of the part. As a result of grinding on the treated surface, a new microrelief is formed in the form of a combination of traces of the impact of abrasive grains of flap wheels and the remains of the dimples from shot peening. At the same time, the depth of dimples of shot after grinding is much larger than the values of valleys of the micro-surface formed as a result of impact of the grains of flap wheels. Since the dimples have a spherical shape with a much larger radius of curvature than their depth, they have a special effect on the volume of the removed metal with an increase in the size of the allowance.

1. Introduction
To obtain complex curvilinear forms of the surfaces of panels and sheaths, as well as hardening operations, shot peening is widely used. Grinding with abrasive flap wheels is a mandatory part of the process of forming of long-length large-sized surfaces. It is carried out in order to improve the quality of the initial surface obtained after shot peen forming [1-3].

Due to impact of shot flow, a specific surface roughness profile is formed on the part surface, which is characterized by numerous dimples of shots with different diameter and depth [4, 5]. At the same time, the distribution of dimples on the treated surface is chaotic (random).

The results of the study of numerous samples treated with a shot in the shot peen forming showed that thank a low degree of coverage (up to 40%) at shot peen forming the metal influx around the dimples does not actually exceed the height of the microrelief of the surface treated by milling before shot peen processing, and there is practically no overlap with each other's dimples [6, 7]. During grinding with flap wheels in several passages, at the beginning the microrelief layer from the surface of the previous treatment (milling) and the influx formed as a result of shot peening are removed, and during the subsequent passage the following layers of the surface between the dimples are removed. The dimples have the form close to spherical with the radius of shot (1,5-3 mm) [4], much greater than the depth of dimples (tens of micrometers), so the voids of dimples significantly affect the volume of the metal removed. At the same time, when increasing the thickness of removed layer of material...
during grinding, the coverage area of the remained dimples decreases, that is, the degree of coverage becomes less and the number of abrasives grains of flap wheels simultaneously participated in the grinding process becomes more, that leads to a constant increase in the forces and cutting power. Cutting forces and power are stabilized as traces of dimples are removed.

**Figure 1.** Result of scanning the surface area after grinding with flap wheels of the sample pre-treated with shot peen forming.

2. **Formation of metal removal during grinding with flap wheels**

The figure 2 shows the dimple-model formed on the surface pre-treated with milling during shot peening and grinding with flap wheels.

**Figure 2.** Dimple-model of shot after shot peening and grinding with flap wheels.

Figure 2 presents the following symbols: \( R_s \) is diameter of shot; \( h \) - thickness of the panel to the center plane \( P_0 \); \( h_i \) – depth of \( i \)-th dimple of shot from the original center plane \( P_0 \); \( h_i' \) is the depth of the \( i \)-th dimple of shot from the original center plane \( P_0 \) to the center plane \( P_i \); \( h_i'' \) – distance from center plane \( P_i \) to the bottom of dimple; \( r_i \) – radius of \( i \)-th dimple of shot in the center plane \( P_0 \); \( r_{ig} \) is the radius of the \( i \)-th dimple of shot in the center plane \( P_i \); \( V_i' \) is the void volume of a truncated part of the \( i \)-th dimple of shot between the planes \( P_0 \) and \( P_i \); \( V_i'' \) – the void volume of the \( i \)-th dimple of shot after grinding from \( P_i \).
If $F_b$ is control area, for which after shot peening the degree of coverage became stable.
Given that the influx around the dimples after shot peening does not exceed the height of the microrelief of the surface treated by milling before shot peening, the volume of the material of the treated panel after shot peening on the control area can be determined by the following formula:

$$Q_{pen} = \rho \cdot F_b \cdot h - \rho \cdot \sum_{i=1}^{n} V_i,$$

where $\rho$—the volume weight of the panel material,
$n$—the number of dimples on the control area after shot peening,
$V_i$—the volume of void of the $i$-th dimple.

After grinding with flap wheels a bottom section of the some dimples still remains (Figure 2), and the mass of the material on the control area can be determined by the following dependence:

$$Q_{wel} = \rho \cdot F_b \cdot (h - a) - \rho \cdot \sum_{i=1}^{m} V_i^*,$$

where $a$—the allowance for grinding,
$m$—the number of dimples remained after grinding, which is determined by measuring the depth of the dimples after shot impact and the specified allowance for grinding, herewith $m < n, m \in n$.

Thus, the quantity of the removed material (in kg) at grinding can be defined by the following formula:

$$Q_m = Q_{pen} - Q_{wel},$$

$$Q_m = \rho \cdot F_b \cdot a - \rho \cdot \sum_{i=1}^{n} V_i + \rho \cdot \sum_{i=1}^{m} V_i^*$$

or the volume of material to be removed during grinding:

$$V_m = F_b \cdot a - \sum_{i=1}^{n} V_i + \sum_{i=1}^{m} V_i^*.$$

Given that the shape of the dimples is close to spherical [4], then:

$$Q_m = \rho \left( F_b \cdot a - \sum_{i=1}^{n} \pi \cdot h_i^2 \left( R_s - \frac{1}{3} h_i \right) + \sum_{i=1}^{m} \pi \cdot h_i^2 \left( R_s - \frac{1}{3} h_i^* \right) \right).$$

However, $h_i^*$ for the number $m$ of dimples has a relation to the allowance $a$ and can be determined by the thickness of the material layer to be removed (allowance) and the depth of the dimples after shot peening.

$$h_i^* = h_i - a.$$

Thus, the mass of the removed material can be expressed by dependence:

$$Q_m = \rho \left( F_b \cdot a - \sum_{i=1}^{n} \pi \cdot h_i^2 \left( R_s - \frac{1}{3} h_i \right) + \sum_{i=1}^{m} \pi \cdot (h_i - a)^2 \left( R_s - \frac{1}{3} (h_i - a) \right) \right).$$

It follows that the task of determining the mass of the material removed during grinding is simplified, since it is not necessary to measure the depth of the dimples remained after grinding, but to use the data on the initial depth of the dimples after shot peening.

Formula 7 is used to determine the total removal for a given allowance $a$, for the subsequent passage of the flap wheels with allowance $b$, the removal of the material of this passage $Q_m(b)$ is determined as follows:
\[ Q_m(b) = Q_m(a + b) - Q_m(a) = \rho \left( F_b \cdot b + \sum_{i=1}^{k} \pi \cdot (h_i - a - b)^2 \left( R_s - \frac{1}{3} (h_i - a - b) \right) \right) - \sum_{i=1}^{m} \pi \cdot (h_i - a)^2 \left( R_s - \frac{1}{3} (h_i - a) \right), \] (8)

where \( k \) - the number of remained dimples after the subsequent passage of flap wheels with allowance \( b \).

However, during grinding with a constant allowance for all passages, the thickness of the removed material layer \( a \), which is the value is a function of the metal removal speed and the longitudinal feed of the flap wheels with passages number \( k \), can be showed by following:

\[ a = \frac{B}{f} \cdot v \cdot k, \] (9)

where \( B \)-the width of flap wheels, \( f \)-the longitudinal feed of flap wheels, \( v \)-the speed of removal of the metal layer during grinding (in mm/s), which can be determined experimentally or theoretically, depending on the properties of the panel material, the characteristics of flap wheels and the angular velocity of flap wheels.

Thus, the mass of the removed material during grinding is represented by the following expression:

\[ Q_m = \rho \left( F_b \cdot \frac{B}{f} \cdot v \cdot k - \sum_{i=1}^{n} \pi \cdot h_i^2 \left( R_s - \frac{1}{3} h_i \right) + \sum_{i=1}^{m} \pi \cdot \left( h_i - \frac{B}{f} \cdot v \cdot k \right)^2 \left( R_s - \frac{1}{3} \left( h_i - \frac{B}{f} \cdot v \cdot k \right) \right) \right). \] (10)

Since one of the important control parameters of the shot peening process is the degree of coverage of the dimples of shot, which in turn depends on the size of the dimples in the sample surface:

\[ \varepsilon_p = \frac{\pi \sum_{i=1}^{n} r_i^2}{F_b} \cdot 100\%; \quad \varepsilon_{wel} = \frac{\pi \sum_{i=1}^{m} r_i^2}{F_b} \cdot 100\%, \] (11)

where \( \varepsilon_p \), \( \varepsilon_{wel} \) - the degree of coverage after shot peening and grinding with flap wheels, respectively.

Thus, the mass of the removed material for the entire grinding cycle can be determined by the size of the dimples in the sample surface as follows:

\[ Q_m = \rho \left( F_b \cdot \frac{B}{f} \cdot v \cdot k - \sum_{i=1}^{n} \pi \cdot \left( R_s - \sqrt{R_s^2 - r_i^2} \right) \cdot \left( R_s - \frac{1}{3} \left( R_s - \sqrt{R_s^2 - r_i^2} \right) \right) + \sum_{i=1}^{m} \pi \cdot \left( R_s - \frac{B}{f} \cdot v \cdot k - \sqrt{R_s^2 - r_i^2} \right) \right) \left( R_s - \frac{1}{3} \left( R_s - \frac{B}{f} \cdot v \cdot k - \sqrt{R_s^2 - r_i^2} \right) \right). \] (12)

It is obvious that the metal removal during grinding not only depends on the longitudinal feed, the speed of metal removal by flap wheels, the number of passages of flap wheels, but also depends on the degree of coverage of dimples after shot peening.

Figure 3, 4 and 5 show the typical results of the calculations of the degree of coverage of the dimples, the volume of the removed material depending on the increase in the removal thickness, as well as the total volume of the removed material depending on the allowance (for clarity, regardless of the type of processed material, the calculations are carried out by volume).
Figure 3. Dependence of degree of coverage of dimples on allowance.

Figure 4. Dependence of degree of coverage of dimples on allowance.

Figure 5. Dependence of total volume of removed material on allowance for grinding.

The calculation is carried out for the base area of 15mm*15mm [4] of the aluminum alloy sample BT95. According to the manufacturing technology of large and curved aircraft panels and sheaths, the
sample was first milled to the purity of the surface $Ra_{0.4}$, after milling this sample is processed by a ball steel shot with a diameter of 3.5 mm on the shot peen machine of contact type DUF-4M with processing mode: the speed of the shot peen wheel - 1200 rpm, longitudinal feed - 2.5 m/min. After shot peening, the surface of this sample is scanned on a three-dimensional optical profilometer to obtain the necessary data about the dimples (in this case, 120 dimples with a depth of 3.2 to 90.5 microns are obtained on this sample and the initial degree of coverage of the dimples before shot peening is 10.66%).

Figure 4 shows that due to the curvature of the dimples after shot peen forming, the volume of the material being removed with the same allowance of the passage is not constant but changes along the logarithmic curve. However, in the Figure 5 the total amount of removed material is almost directly proportional to the allowance for grinding. This is due to the fact that in this case, due to the low initial degree of coverage (only 10.66%) after the shot peen forming and its sharp decrease during an increase in the allowance for grinding (Figure 3), the volume of voids of the dimples remained after each passage of the flap wheels is not significant comparing to the total volume of subsequent material layer to be removed, that does not significantly affects the total volume of the removed material.

3. Summary
The dimples formed after shot peen forming have a specific effect on the material removal during subsequent grinding with flap wheels.

A method for calculating the material removal during grinding with flap wheels after shot peen forming depending on the allowance for grinding, taking into account the degree of coverage after shot peen forming and each passage of the flap wheels is proposed.

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