Determination of the allowance for grinding with flap wheels after shot peen forming

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Abstract. Shot peening is widely used in forming long panels and sheaths. Due to the impact of shot on the processed surface, the specific microgeometry is formed, the characteristic feature of this microgeometry is 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 surface grinding with flap wheels for partial removal of the shot dimples. Allowance for grinding depends on the requirements for the quality of the surface of the part. As a rule, the depth of dimples in magnitude significantly exceeds the valleys of micro-irregularities formed owing to 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 shape of a combination of traces of the impact of abrasive grains of flap wheels and the remains of the dimples from the shot peening. Since the dimples have a spherical shape with a much larger radius of curvature than their depth, they have a special effect on the amount of metal removed and on the roughness of the treated surface. The paper presents an analytical description of the process of quantitative removal of metal and the formation of roughness during grinding with flap wheels of the surface treated with a shot peening. Based on the results of research, mathematical models are constructed to determine the amount of material removed from the surface treated with shot peening during grinding with flap wheels, and a numerical method for determining the allowance for obtaining the required roughness is proposed.

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 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].

From the impact of shot flow, a specific surface roughness profile is formed on the surface of the workpiece, which is characterized by numerous dimples of shots with different diameters and depths [4, 5]. At the same time, the distribution of dimples on the treated surface is chaotic (random) [6].

The results of the study of numerous samples treated with a shot in the shot peen forming showed that owing to a low degree of coverage (up to 40%) during shot peen forming the metal influx around the dimples was commensurate with the height of the microrelief of the surface treated by milling before shot peen processing. There is practically no overlap with each other's dimples [6, 7]. When grinding, first of all, a layer of the surface microrelief from the previous operation (milling) and the influx formed as a result of shot peen processing is removed, and when the grinding process is continued, the
subsequent layers of the surface are removed in areas not covered with the dimples. The dimples in the form of voids have a shape close to spherical with radii of shot (1.5-3 mm) [4], much larger than the depth of dimples (tens of microns). So the volume of dimples has a significant impact on the volume of the metal removed. At the same time, when increasing the thickness of the removed layer of material during grinding, the coverage area of the remaining dimples decreases. That is, the degree of coverage becomes less and more than the number of abrasives grains of flap wheels simultaneously participating in the grinding process, which leads to a constant increase in the forces and cutting power. Cutting forces and power are stabilized as traces of dimples are removed. At the same time, by increasing the thickness of the removed layer of material during grinding, the coverage area of the remaining dimples decreases (Fig. 1) and the number of grains of flap wheels simultaneously participating in the grinding process becomes larger. This leads to a constant increase in the forces and cutting power when grinding. Cutting forces and power are stabilized as we approach the complete removal of traces of dimples.

Figure 1. The result of scanning the surface area of the sample after shot peening – grinding with flap wheels

2. Removal of metal and formation of roughness when grinding with flap wheels

Fig. 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 introduces the following symbols: $R_s$ is radius of shot; $P_0$ – center plane after milling; $P_i$ – center plane after grinding without taking into account shot peening; $h_i$ – depth of $i$-th dimple of shot from the original center plane $P_0$; $h_p$ is the depth of the $i$-th dimple of shot from the original center plane $P_0$ to the center plane $P_i$; $h_0$ – distance from center plane $P_i$ to the bottom of dimple; $r_i$ – radius of $i$-th dimple of shot in the center plane $P_0$; $r_p$ 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 (1):

\[ Q_{peen} = \rho \cdot F_b \cdot h - \rho \cdot \sum_{i=1}^{n} V_i, \]

where \( \rho \) – the volume weight of the panel material; \( h \) – thickness of the panel to the center plane \( P_0; \) \( n \) – the number of dimples on the control area after shot peening; \( V_i \) – the volume of empty part of the \( i \)-th dimple.

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

\[ Q_{gr} = \rho \cdot F_b \cdot (h-h_p) - \rho \cdot \sum_{i=1}^{m} V_i', \]

where \( h_p \) – 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 with \( m < n, m \in n. \)

Thus, the quantity of the removed material (in kg) during grinding can be defined by the following formulas (3, 4):

\[ Q_m = Q_{peen} - Q_{gr} \]  

\[ Q_m = \rho \cdot F_b \cdot h_p - \rho \cdot \sum_{i=1}^{n} V_i + \rho \cdot \sum_{i=1}^{m} V_i'. \]

The amount of material to be removed when grinding (5):

\[ V_m = F_b \cdot h_p - \sum_{i=1}^{n} V_i + \sum_{i=1}^{m} V_i'. \]

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

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

However, \( h_k \) 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:

\[ h_k = h_i - h_p. \]

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

\[ Q_m = \rho \cdot \left( F_b \cdot h_p - \sum_{i=1}^{n} \pi \cdot h_i^2 \left( R_s - \frac{1}{3} h_i \right) + \sum_{i=1}^{m} \pi \cdot h_i^2 \left( R_s - \frac{1}{3} (h_i - h_p) \right) \right). \]
$Sa = 0.5Sa_{gr} + \frac{2\pi}{F_b} \sum_{i=1}^{m} \left( R_S - \frac{1}{3}(h_i - h_p - h_k) \right) \cdot (h_i - h_p - h_k)^2$  \hspace{1cm} (9)

where $Sa_{gr}$ – the arithmetic mean deviation of the profile within the base area of the surface treated by grinding without taking into account the shot dimples; $h_k''$ – the distance from the center plane of roughness without taking into account the shot dimples to the center plane of the surface roughness after grinding [8] with taking into account the remaining dimples.

Distance $h_k''$ is determined by the following expression [8], (10):

$h_k'' = \frac{1}{F_b} \sum_{i=1}^{m} \pi \cdot \left( R_S - \frac{1}{3}(h_i - h_p - h_k) \right) (h_i - h_p)^2.$

(10)

In this case, equation (9) is valid only if there is a sufficient total volume of voids of the remaining dimples after grinding, which provides a displacement of the center plane downwards, that is:

$\frac{2\pi}{F_b} \sum_{i=1}^{m} \left( R_S - \frac{1}{3}(h_i - h_p - h_k) \right) (h_i - h_p - h_k)^2 \gg 0.5Sa_{gr}.$

(11)

The results of experimental studies of numerous authors of the roughness of the surface treated by grinding with flap wheels after milling (without shot peen processing) showed that after removal of the complete roughness of the milled surface, regardless of the time of further grinding (with preservation of the processing mode), an achievable roughness with a practically constant value is formed on the treated surface. Therefore, in formula (9), the arithmetic mean deviation of the profile within the base area varies depending only on the total volume of voids of the remaining dimples, which in turn depends on the thickness of the layer being removed (allowance).

Thus, the dimples of the scanned surface are treated with shot peening and equations (9) and (10), depending on the values of a specified allowance. In the range from $Rz_{mi}$ – the average height of the roughness of the milled surface before treatment with shot peening to the value of the difference is $Rq_{peen} - Rz_{gr}$, where $Rq_{peen} –$ the maximum depth of the dimples on the control area, $Rz_{gr} –$ the average height of the roughness of the surface processed by grinding, excluding shot dimples. Thus, numerically we find the remaining dimples and their size, coordinates of center plane $h_k''$ and numerically dependence of $Sa(h_p)$ values of the roughness on the thickness of removal material. Further, with the help of the found dependence $Sa(h_p)$ and equation (8), we find the mass of the material to be removed from the workpiece by the required roughness corresponding to a specific thickness value – the allowance for grinding with flap wheels.

**Figure 3.** The actual dependence of the displacement of the center plane and the arithmetic mean deviation of the profile on the allowance

Figure 3 shows a typical result of the calculation of the displacement of the center plane and the arithmetic mean deviation of the profile $Sa(h_p)$ on the value of allowance for grinding with flap wheels...
without taking into account the roughness of grinding ($S_{ar}$).

The calculation was carried out for the base area of $15 \text{ mm} \times 15 \text{ mm}$ [4] of the sample of aluminum alloy BT95. According to the technology of fabrication of large curved aircraft panels and skins, the sample was first milled to a surface finish $Ra$ 0.4, after being processed by shot peening with steel shot with a diameter of 3.5 mm on the equipment for shot peening of contact type DUF-4M. The following processing mode was used. Frequency of rotation of the shot peen wheel was 1200 rpm, longitudinal feed - 2.5 m/min. After shot peening, the treated surface of the sample was scanned on a three-dimensional optical profilometer to obtain the necessary data about the dimples. In this case, these were a total of 120 dimples with a depth from 3.2 to 90.5 microns, the total degree of coverage by dimples was 10.66%.

The value of roughness in Fig. 3 was obtained taking into account only the dimples and the nominal surface for a specific value of the allowance. To obtain the final value of the roughness on the surface to be treated, when grinding after the shot peen forming, it is necessary to take into account the roughness of the part of the surface without dimples cleaned with flap wheels (9).

Based on the graph formula in Fig. 3 (with an approximation error of not more than 1%) it is not difficult to determine the required allowance to provide the required value of the arithmetic mean deviation within the base area. And with the help of formula (8), the necessary metal removal is determined when grinding after shot blasting in accordance with this allowance.

3. Conclusion

The dimples, formed as a result of shot peen forming, as well as the degree of shot coverage, play a crucial role in the formation of roughness and removal of the material from the treated surface in the implementation of the technology of shot peen forming with subsequent grinding with flap wheels.

The proposed method for determining the allowance for grinding and removal of the material during grinding with flap wheels after shot peening ensures the necessary surface roughness.

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