

Step-by-step surface roughness formation during shot peening and subsequent grinding with flap wheels

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Abstract – Shot peening is widely used in forming panels and sheaths. Due to a shot peen impact on a processed surface, a specific microgeometry is formed, a characteristic feature of this microgeometry is the numerous traces of shot (in shape of the dimples) with different diameters and depths. A presence of these dimples causes deterioration of surface roughness parameters. Therefore, after shot peening the mandatory requirement is implementation of surface grinding with flap wheels for partial removal of the dimples. A size of the assigned allowance for grinding depends on the quality requirements of the part surface. At the same time, a depth of the dimples is determined by the part surface roughness requirements. After grinding, the new surface microgeometry as a combination of micro-roughness from previous types of processing and the remaining dimples from impact of shot is formed.

In this work the analytical description about formation of microgeometry of surface layer of the samples after shot peen forming and subsequent grinding with flap wheels was presented. The parameters of surface roughness were measured by the method of three-dimensional optical scanning. In the measurement result, the mathematical model of formation of the surface micro-profile during shot peening and grinding with flap wheels was formulated.

Keywords – shot peening; grinding with flap wheels; dimple; optical method of three-dimensional scanning; surface roughness during shot peening; surface roughness during grinding with flap wheels

I. INTRODUCTION

In aircraft building, for generation of complex curvilinear surfaces of panels and sheaths and also for hardening, shot peening (SP) is widely used. Grinding with flap wheels is a mandatory technological operation during forming the long-sized and large-sized surfaces of panels and sheaths, this operation is carried out in order to improve the quality of the initial surface obtained after shot peen forming [1-5].

When a shot flow acts on the surface machined, a specific surface roughness profile is formed on the part surface. It has numerous shot peening dimples of different diameters and depths [6-9]. At this time, a distribution of dimples on the surface machined is chaotic (random) and the depth values of most shot peening dimples are larger than the roughness depths values resulted from previous machining processes.

The operation, preceding shot peening treatment, as a rule, is machining (usually milling) with its own characteristics and parameters of surface roughness. As a result, on the surface microrelief formed by a previous operation, the traces of shot peen impact are applied, and a new profile of micro-roughness is formed on this surface.

The dimples as the traces of shot on the new microrelief have different diameters and depths, which significantly exceed the level of micro-roughness from previous machining. At the same time, a distribution of these dimples on the treated surface is chaotic (random) [10]. An actual combination of microreliefs of these operations allows one to form a new microrelief of the part surface. Thus, a systematic mechanical

machining profile (process) is superimposed by a random process which is a set of chaotically arranged shot peening dimples with different depth values. Practical integration of these processes forms a new surface microrelief with properties of a random process.

The presence of the set of dimples, the value of which exceeds the initial level of surface microroughness, increases the values of surface roughness parameters of the part, which causes displacement of the original center plane of surface roughness profile.

When measuring roughness parameters for a three-dimensional surface topography with properties of a random process, a basic surface area ensuring accurate results should be determined. The value of the basic surface area should depend on the density of random surges. In shot peening, a coverage degree (a relation of the total shot peening dimples area in the sector under study to the whole sector area) can be used as the parameter which indicates the density of surges.

Previous researches of the authors [7] identified dependencies of the basic sector area on the degree of coverage. It is evident that the base surface area for the available coverage degree is crucial for determining the surface roughness after shot peening.

II. DETERMINING ROUGHNESS PARAMETERS FOR THE BASE AREA AFTER SHOT PEENING

The theoretical degree of coverage can range from 0 to 100 %. For shot peen forming, the degree of coverage falls within the range of 30-40 %, and for shot hardening – of 100 % [11, 12]. There is no doubt that at any degree of coverage a surface roughness formation after SP is a random process. The number and depth of shot peening dimples in the controlled surface sector influences roughness parameters. Roughness parameters, measured along the area which is smaller than the basic one, are different. When the area of the controlled sector approximates to the base one, roughness parameters are stable, and when the controlled area increases, they are more constant.

Figure 1 shows the scheme of the conditioned profile of the shot peening dimple with the original surface (after applying profiles milled and machined by shot peening).

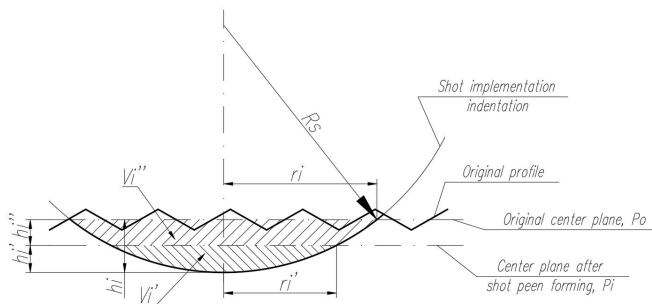


Fig. 1. The scheme of profile after shot indentation on milled surface

Figure 1 includes the following designations: R_s – radius of shot; h_i – shot indentation depth from center plane P_0 ; h_i'' – distance from original center plane P_0 to center plane after shot peening P_1 ; h_i' – shot indentation depth to center plane P_1 ;

r_i – radius of shot peening dimple in original center plane P_0 ; r_i' – dimple radius in center plane P_1 ; V_i'' – volume of dimple between center planes P_0 and P_1 ; V_i' – volume of dimple below center plane P_1 .

The base surface is used to assess roughness parameters. It is a part of the nominal part surface which is a part surface set without regard to admissible roughness values.

In order to determine roughness parameters within the base area, it is necessary to find a center plane of surface profile P_1 after shot peening. According to the methods used for determining a center plane of three-dimensional surface topography and roughness parameters within the base area [10, 13] (where the base area is square with side equal to base length), a center plane is a plane with equal volume of material above and volume of voids below within the base area. As far as shot peening causes dimples along the part surface most whose depths exceed the original roughness depth value, it can be assumed that the center plane after SP is below the original center plane of the milled surface.

If P_0 is the center plane of the original milled surface before SP, and the roughness of milled surface is rather uniform regarding to center plane, an entire body is formed under P_0 , as the total volume of material above P_0 compensates for the total volume of voids below P_0 .

If F_b is the base area, the total volume of material to center plane P_1 is determined as (1):

$$\sum \text{volume of voids below } P_1 = \sum \text{volume of material above } P_1 \quad (1)$$

i.e.

$$\sum_{i=1}^n V_i' = F_b \cdot h_i'' - \sum_{i=1}^n V_i'' \quad (2)$$

Here

$$\sum_{i=1}^n V_i'' = \sum_{i=1}^n V_i - \sum_{i=1}^n V_i', \quad (3)$$

where V_i – total volume of the valley of i -th dimple.

Then:

$$\sum_{i=1}^n V_i' = F_b \cdot h_i'' - \left(\sum_{i=1}^n V_i - \sum_{i=1}^n V_i' \right) \quad (4)$$

or

$$\sum_{i=1}^n V_i = F_b \cdot h_i'' \quad (5)$$

Distance h_i'' from original center plane P_0 to center plane after SP P_1 is determined as (6):

$$h_i'' = \frac{\sum_{i=1}^n V_i}{F_b} . \quad (6)$$

As far as the valley form is nearly spherical [7], the volume of each i -th dimple is the volume of sphere segment with the height h_i (7):

$$h_i'' = \frac{1}{F_b} \cdot \sum_{i=1}^n \pi \cdot h_i^2 \cdot \left(R_s - \frac{1}{3} h_i \right) . \quad (7)$$

It is known that [10] the arithmetic mean deviation of the profile within the base area can be determined by formula (8):

$$Sa = \frac{1}{F_b} \iint |\eta(x, y)| dx dy , \quad (8)$$

where Sa – arithmetic mean deviation of the profile within the base area; F_b – base area; x, y – coordinates; $\eta(x, y)$ – function of roughness deviation from center plane; $\eta(x, y)$ describes a total volume of material above center plane and a total volume of voids below center plane.

As the roughness of the part surface after SP is undefined, it is difficult to find a uniform function of roughness deviation from center plane. The center plane should be divided into m sectors, in which the surface profile deviation follows some continuous function $F(u_j)$. Then the volume of material of j -th sector is determined as (9), [10]:

$$V(u_j) = \int_0^u F(u_j) du_j , \quad (9)$$

where $V(u_j)$ – volume of area restricted to field $H(x, y)$ (surface) and plane which is parallel to coordinate plane (x, y) at distance u .

If the above center plane is plane (x, y) , and u ranges from 0 to u_{max} (maximum value of each profile peak or valley), the total volume of material or voids above or below center plane P_i is determined as (10):

$$\sum_{j=1}^m V(u_j) = \sum_{j=1}^m \int_0^u F(u_j) du_j . \quad (10)$$

As far as the total volume of material above the center plane is equal to the total volume of voids below it, the arithmetic mean deviation of the profile from the center plane within the base area can be written as (11):

$$Sa = \frac{1}{F_b} \cdot \sum_{j=1}^m \int_0^u F(u_j) du_j = \frac{2}{F_b} \cdot \sum_{i=1}^n V_i' . \quad (11)$$

Based on formula (3) and a close-to-spherical dimple of shot peening, we have (12):

$$\begin{aligned} Sa &= \frac{2}{F_b} \cdot \sum_{i=1}^n \pi \cdot (h_i')^2 \cdot \left(R_s - \frac{1}{3} h_i' \right) = \\ &= \frac{2\pi}{F_b} \cdot \sum_{i=1}^n (h_i - h_i'')^2 \cdot \left(R_s - \frac{1}{3} (h_i - h_i'') \right) . \end{aligned} \quad (12)$$

The formula (12) determines Sa after SP without regard to original surface roughness. Based on the original surface roughness, the total arithmetic mean deviation of the profile Sa_t can be determined by formula (13):

$$Sa_t = 0.5Sa_m + \frac{2\pi}{F_b} \cdot \sum_{i=1}^n (h_i - h_i'')^2 \cdot \left(R_s - \frac{1}{3} (h_i - h_i'') \right) \quad (13)$$

where Sa_m – arithmetic mean deviation of the profile within the base surface area after milling.

To check the validity of the proposed mathematical models (13) it was necessary to measure the depth of dimples on different parts of the surface scanning by optical method [13]. The results of measuring the depths of dimples at the stage of shot peening, as well as the depths of dimples after shot peen forming. Comparison of the results of calculations with the results produced by the optical profilometer confirmed the reliability of mathematical models.

III. DETERMINING ROUGHNESS PARAMETERS WITHIN THE BASE AREA DURING SHOT PEENING – GRINDING WITH FLAP WHEELS

The surface after shot-peen forming is subject to mandatory subsequent grinding in order to partially remove the traces because of impact of shots and to ensure the specified parameters of surface quality.

Regarding to the surface structure after shot-peen forming, the allowance value a , characterizing the value of removal of the dimples, is determined by the depth of the dimple (Fig. 2), [14].

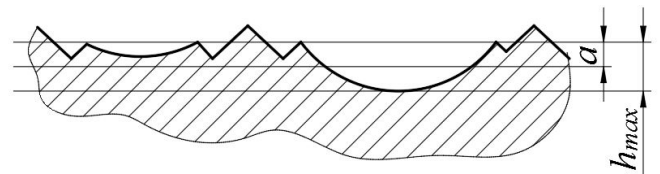


Fig.2. Schematic representation of the part surface treated by shot peening, where h_{max} – maximum depth of dimple; a – allowance, which will be removed during grinding

The maximum value of dimple depth h_{max} in the investigated sector of the surface at stage of grinding must be reduced by the allowance amount a for compliance with the requirements of design documentation and tolerance of the part. In this case, a removal of all traces of shot is not necessarily and in the result after grinding, a large number of shot dimples is remained.

Figure 3 shows the result of the optical profilometer scan (with Bruker Contour GT-K1 model) of the typical milled sample surface area, followed by shot peen forming with the shot radius of 1.75 mm at the shot-peen wheelspeed of 800 rpm and the longitudinal feed of 2 m/min. Figure 4 shows the surface profile through one of the largest shot peening dimple in the investigated area. While (Ra 3.981 μm , while Rp , which characterizes the magnitude of the highest peak of profile 18.711 μm , deepest valley profile Rv 41.249 μm).

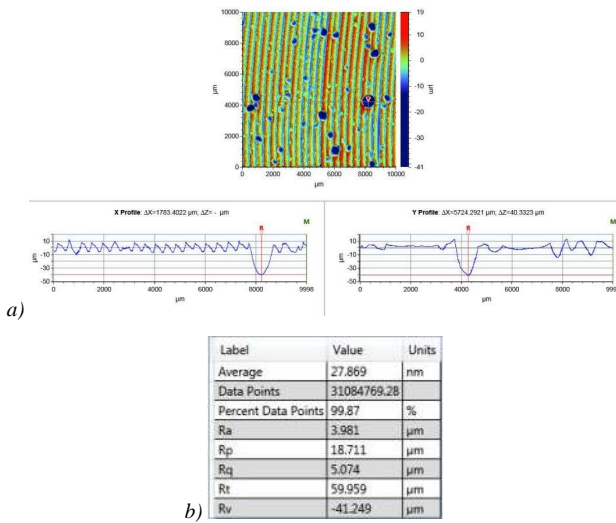


Fig. 3. Scan results of sample surface after shot peen forming, a) scanned surface profile of largest dimple after shot peening, b) measurement result

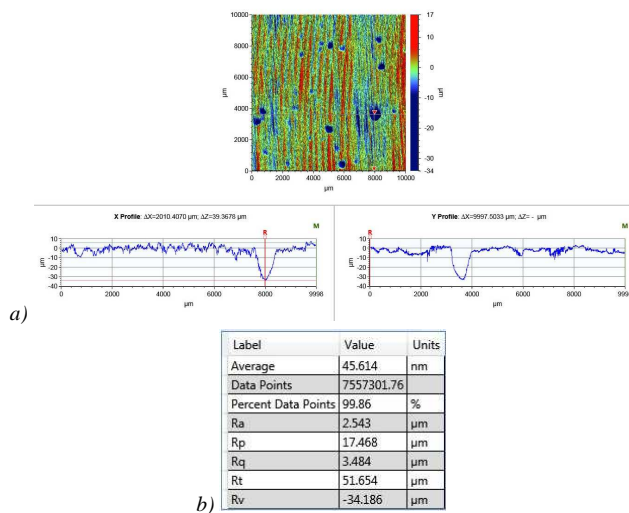


Fig. 4. Scan results of sample surface after shot peen forming and subsequent grinding with flap wheels, a) scanned surface profile of largest dimple after grinding with flap wheels, b) measurement result

Figure 4 shows the profile of the same scanned surface after shot peening in mutually perpendicular planes passing through the same shot dimple. Grinding is done with the 350×100×45 mm flap wheel made of abrasive flap KK751 P60 at the flap wheel speed of 1200 rpm, the longitudinal feed of 1.2 m/min and the radial deformation of abrasive flap during contact with machining surface of 2.5 mm according to the technology used in practice.

After shot peening, the average value Ra within the investigated area amounted to 2.543 μm , Rp 17.468 μm , Rv decreased to 34.186 μm . It should be noted that the average value of the Ra parameter within the investigated area during grinding did not exceed the allowed value (Ra 3.2) during processing of panels and sheaths.

In result of data review in figures 3 and 4 we can conclude that even in this slight removal of the allowance by flap wheels, on machining part the new surface micro-relief is formed, as combination of micro-roughness formed by successive stages of processing, including mechanical machining, shot peening and grinding. That is, after grinding, there are still many large dimples that are directly involved in forming the surface roughness of machining part.

Thus, the original center plane of surface profile formed by milling, is shifting down after shot peening [13]. In subsequent grinding the center plane also moves down when the material layer within the allowance is removed. That is, the center plane of profile after grinding is below the center plane of profile after shot peening.

Figure 5 presents the graphical diagram of location of main parameters of surface profile after milling, shot peening and grinding. At the same time, the basic parameters of surface roughness after grinding are determined on the basis of location of the center plane P_k .

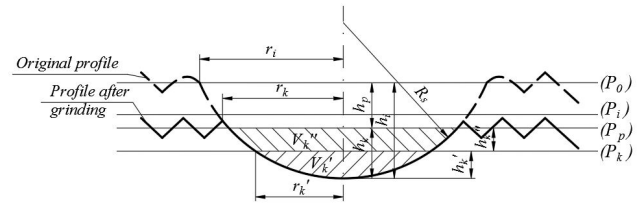


Fig 5. Diagram of main parameters of profile of machining part after milling, shot peening and grinding with flap wheels

Figure 5 includes the following designations: h_i - depth of k -th dimple; h_p - allowance value removed during grinding; h_k -dimple depth after grinding; h_k' - dimple depth from center plane after grinding, including shot peen forming; h_k'' - distance between center plane after grinding without taking into account shot peen forming (P_p) and center plane after grinding (P_k); r_i -radius of dimple in center plane after milling (P_0); r_k -radius of dimple in terms of center plane P_p ; r_k' - radius of dimple in terms of center plane P_k ; V_k -volume of voids in dimple after grinding under center plane P_k ; V_k'' - volume of voids in dimple after grinding over center plane P_k .

If there are still a lot of dimples remained after grinding, then similarly to the method of determining the center plane after shot peen forming [13], the final position of center plane after grinding is determined by the following form (14):

$$h_k'' = \frac{\sum_{k=1}^t V_k}{F_b} = \frac{1}{F_b} \cdot \sum_{k=1}^t \pi \cdot h_k^2 \cdot \left(R_s - \frac{1}{3} h_k \right), \quad (14)$$

where t is the number of dimples remained after grinding with depths exceeded the level of original micro-relief; V_k – the volume of voids of the k -th dimple under the center plane P_p ;

Herewith,

$$\sum_{k=1}^t V_k = \sum_{k=1}^t V_k' + \sum_{k=1}^t V_k'' \quad (15)$$

$$h_k = h_i - h_p \quad (16)$$

So

$$h_k'' = \frac{1}{F_b} \cdot \sum_{k=1}^t \pi \cdot (h_i - h_p)^2 \cdot \left(R_s - \frac{1}{3} (h_i - h_p) \right) \quad (17)$$

Similarly to the method proposed for determining roughness after shot peen forming, the arithmetic mean deviation of the profile within the base area after grinding is determined by the formula (18). The obtained dependence determines the value of Sa after shot peen forming without taking into account original surface roughness.

$$\begin{aligned} Sa &= \frac{2}{F_b} \cdot \sum_{k=1}^t V_k' = \frac{2}{F_b} \cdot \sum_{k=1}^t \pi \cdot (h_k')^2 \cdot \left(R_s - \frac{1}{3} h_k' \right) = \\ &= \frac{2\pi}{F_b} \cdot \sum_{k=1}^t (h_i - h_p - h_k'')^2 \cdot \left(R_s - \frac{1}{3} (h_i - h_p - h_k'') \right) \end{aligned} \quad (18)$$

The final formula for calculating the total arithmetic mean deviation of the profile within the base area after shot peen forming and grinding Sa_t , taking into account the original roughness is determined as follows (19):

$$Sa_t = 0.5 Sa_{gri} + \frac{2\pi}{F_b} \cdot \sum_{k=1}^t (h_i - h_p - h_k'')^2 \cdot \left(R_s - \frac{1}{3} (h_i - h_p - h_k'') \right), \quad (19)$$

where Sa_{gri} is the arithmetic mean deviation of the profile within the base area after grinding, excluding shot peen forming.

Formula (19) is only valid with the condition of availability of sufficient number of the remained dimples. Otherwise, when the allowance value is close to the value of depth of the

greatest dimples, the remained dimples of shot peening do not have a significant impact on roughness formation of treated surface after grinding. That is, the formation of surface roughness during grinding can be considered as a process of roughness formation during traditional processing with flap wheels.

However, when using shot peening with subsequent grinding with flap wheels, the parameters of surface roughness is largely determined by traces of shot peen impact.

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