Surface roughness formation during shot peen forming

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Abstract. Shot peen forming (SPF) is used for forming panels and skins, and for hardening. As a rule, shot peen forming is performed after milling. Surface roughness is a complex structure, a combination of an original microrelief and shot peen forming indentations of different depths and chaotic distribution along the surface. As far as shot peen forming is a random process, surface roughness resulted from milling and shot peen forming is random too. During roughness monitoring, it is difficult to determine the basic surface area which would ensure accurate results. It can be assumed that the basic area depends on the random roughness which is characterized by the degree of shot peen forming coverage. The analysis of depth and shot peen forming indentations distribution along the surface made it possible to identify the shift of an original center profile plane and create a mathematical model for the arithmetic mean deviation of the profile. Experimental testing proved model validity and determined an inversely proportional dependency of the basic area on the degree of coverage.

1. Introduction

In aircraft building, shot peen forming is widely used for generation of complex curvilinear surfaces of panels and skins and also for hardening [1-3].

When a shot flow acts on the surface machined, a specific surface roughness profile is formed on the part surface. It has numerous shot peen forming indentations of different diameters and depths. Distribution of indentations on the surface machined is chaotic (random). Shot peen forming can be preceded by mechanical machining or any other machining with their especial surface and roughness parameters. As a result, shot peen forming indentations can be observed on the surface microlief formed by a precedent operation, due to which the new microlief is formed. Thus, a systematic mechanical machining profile (process) is superimposed by a random process which is a set of chaotically arranged shot peen forming indentations with different depth values. Integration of these processes forms a new surface microlief with properties of a random process. Depth values of most shot peen forming indentations are larger than roughness depths values resulted from previous machining processes. A number of indentations with sizes exceeding an original surface microlief increases part surface roughness values and shift the centerline of a 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 peen forming, a coverage degree (a relation of the total shot peen forming indentation area in the sector under study to the whole sector area) can be used as a parameter which indicates the density of surges.

Previous research of the authors [4] 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 peen forming.

2. Determining roughness parameters for the base area

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%, and for shot hardening - of 100%. There is no doubt that at any degree of coverage surface, roughness formation after shot peen forming is a random process. The number and depth of shot peen forming indentations 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 a conditioned shot peen forming indentation profile along the previously milled surface.

![Figure 1. The scheme of a conditioned shot peen forming indentation profile, where hi – shot indentation depth from center plane Po; hi’’ – distance from original center plane Po to center plane after shot peen forming P0; hi’ – shot indentation depth to center plane P0; Ri – radius of the shot; ri – shot indentation radius in original center plane P0; ri’ – indentation radius in center plane Pi; Vi’’ – volume of the indentation between center planes Po and Pi; Vi’ – volume of the indentation below center plane Pi.](image)

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 of admissible roughness values.

To determine roughness parameters for the base area, it is necessary to find center plane $P_i$ after shot peen forming. According to the methods used for determining a center plane of the three-dimensional surface topography and roughness parameters for the base area [5] (where the base area is a square with a side equal to the base length), the center plane is a plane with equal volume of the material above and volume of voids below within the base area. As far as shot peen forming causes indentations mostly along the part surface, which depths exceed an original roughness depth value, it can be assumed that the center plane after shot peen forming is below the original center plane of the milled surface.

If $P_o$ is a center plane of the original milled surface before shot peen forming, and roughness of the milled surface is rather uniform regarding the center plane, an entire body is formed under $P_o$, as the total volume of mentioned-above material $P_o$ compensates for the total volume of voids below $P_o$.

If $F_b$ is a base area, the total volume of the material to center plane $P_i$ is determined as in equation (1).
\[ \sum \text{volume of voids below } P_i = \sum \text{volume of material above } P_i \]  
\text{i.e. volume of the indentation below center plane } P_i, \text{ } V_i', \text{ is calculated as in equation (2):} 
\[ \sum_{i=1}^{n} V_i' = F_b \cdot h_i'' - \sum_{i=1}^{n} V_i'', \]  
where \( F_b \) – base measured area.

Here the volume of the indentation between center planes \( P_0 \) and \( P_i \) is calculated as in equation (3):
\[ \sum_{i=1}^{n} V_i'' = \sum_{i=1}^{n} V_i - \sum_{i=1}^{n} V_i', \]  
where \( V_i \) – total volume of the valley of indentation \( i \).

Then \( V_i' \) is calculated as in equation (4):
\[ \sum_{i=1}^{n} V_i' = F_b \cdot h_i'' - \left( \sum_{i=1}^{n} V_i - \sum_{i=1}^{n} V_i' \right) \]  
or in equation (5):
\[ \sum_{i=1}^{n} V_i = F_b \cdot h_i'' \]

Distance \( h_i'' \) from original center plane \( P_0 \) to center plane after shot peen forming \( P_i \) is determined as in equation (6):
\[ h_i'' = \frac{\sum_{i=1}^{n} V_i}{F_b}. \]

As far as the valley is nearly spherical [4], the volume of each indentation \( i \) is a volume of the segment of a sphere with height \( h_i \), i.e. as in equation (7):
\[ h_i'' = \frac{\sum_{i=1}^{n} V_i}{F_b} = \frac{1}{F_b} \cdot \sum_{i=1}^{n} \pi \cdot h_i^2 \left( R_s - \frac{1}{3} h_i \right), \]  
where \( R_s \) – radius of the shot.

It is known that the arithmetic mean deviation of the profile within the base area can be determined by formula (8):
\[ Sa = \frac{1}{F} \int \int |\eta(x, y)| \, dx \, dy, \]
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 the center plane; \( \int \int |\eta(x, y)| \, dx \, dy \)
describes the total volume of the material above the center plane and the total volume of voids below the center plane.

As the roughness of the part surface after shot peen forming is undefined, it is difficult to find a uniform function of roughness deviation from the center plane. The center plane should be divided into \( m \) sectors, in which the surface profile deviation follows function \( F(u_j) \). Then the volume of the material of sector \( j \) is determined as in equation (9) [5]:

\[
V(u_j) = \int_0^u F(u_j) \, du_j,
\]

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

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

\[
\sum_{j=1}^m V(u_j) = \sum_{j=1}^m \int_0^u F(u_j) \, du_j,
\]

where \( m \) – number of sectors within the base area.

As far as the total volume of the 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 in equation (11):

\[
S_a = \frac{1}{F} \iint |\eta(x, y)| \, dx \, dy = \frac{1}{F_b} \sum_{j=1}^m \int_0^u F(u_j) \, du_j = \frac{2}{F_b} \sum_{l=1}^n V_l' \]

Based on formula (3) and a close-to-spherical shot indentation dimple, there is equation (12):

\[
S_a = \frac{2}{F_b} \sum_{l=1}^n V_l' = \frac{2}{F_b} \sum_{l=1}^n \pi \cdot (h_l')^2 \cdot \left( R_s - \frac{1}{3} h_l' \right) = \frac{2\pi}{F_b} \sum_{l=1}^n (h_l - h_l'')^2 \cdot \left( R_s - \frac{1}{3} (h_l - h_l'') \right)
\]

Formula (12) determines \( S_a \) after shot peen forming without regard to original surface roughness. Based on the original surface roughness, the average arithmetic mean deviation of the profile can be determined by formula (13):

\[
S_{a_t} = 0.5 S_{a_m} + \frac{2\pi}{F_b} \sum_{l=1}^n (h_l - h_l'')^2 \cdot \left( R_s - \frac{1}{3} (h_l - h_l'') \right),
\]

where \( S_{a_t} \) – total average arithmetic mean deviation of the profile within the base surface area; \( S_{a_m} \) – average arithmetic mean deviation of the profile within the base surface area

3. Proposed Roughness model validity check

To check model validity based on the arithmetic mean deviation of the profile within the base area, shot indentations depth were measured for four areas (7 x 7 mm, 10 x 10 mm, 15 x 15 mm, 20 x 20 mm). To this end, a Bruker Contour GT-K1 profilometer was used. It outputs a digital model of the surface, roughness parameters, a microprofile in any longitudinal or lateral section of the sample, allows one to calculates the number of indentations and depth of every indentation.
The surface radius of each indentation was determined in AutoCAD. The sample was made from B95, milled and machined with a 3.5 mm diameter shot. A surface microrelief after shot peen forming was measured from one point with a gradual increase in length and width of the scanned sector in the range of 7 to 20 mm.

Figure 2 shows the plan view of the scanned sample of 20 x 20 mm and its microprofile in target sections. The degree of coverage is about 11%.

![Figure 2.](image)

As can be seen, the depths of shot indentations significantly exceed milled surface roughness values. The indentations are practically not overlapped. Lapping of the material near the indentations resulted from the plastic deformation does not exceed peak-to-valley deviations of the milled sample surface.

It is evident that a new surface microrelief is formed due to shot indentations, so their sizes determine surface roughness parameters.

Based on the measured indentation depth values, distances from the original center plane to center plane $P_i$ were calculated by formula (6) for each surface sector. Arithmetic mean deviation $S_{a_i}$ was determined by formula (13). Target values $S_{a_t}$ for each scanned area were compared with similar values determined with an optical profilometer.

Measurement and calculation results are presented in Table 1.

| Scanning area, (mm x mm) | Number of indentations (units) | Original roughness value ($R_{a_{m}}$, µm) | Average value of indentation depth, (µm) | Distance $h''$, (µm) | Target value $S_{a_t}$, (µm) | Measured average value $Ra$ along the scanned area, (µm) | Deviation of target value $S_{a_t}$ from measured value $Ra$, (%) |
|-------------------------|-------------------------------|------------------------------------------|----------------------------------------|------------------|------------------|---------------------------------|-------------------------------|
| 7 x 7                   | 39                            | 0.40                                     | 13.9                                   | 1.96             | 3.69             | 2.88                           | 21.9                          |
| 10 x 10                 | 57                            | 0.41                                     | 17.8                                   | 1.65             | 3.15             | 2.704                           | 14.1                          |
| 15 x 15                 | 120                           | 0.406                                    | 18.3                                   | 1.70             | 3.25             | 2.743                           | 15.6                          |
| 20 x 20                 | 189                           | 0.402                                    | 18.8                                   | 1.62             | 3.14             | 2.884                           | 8.1                           |

When calculating $S_{a_t}$, original average $R_{a_{m}}$ along the whole scanned area was taken as $S_{a_{m}}$. For the milled surface, due to microrelief homogeneity and uniformness arithmetic mean deviation of the profile within the base length along the scanned area and the base area is the same.
Table 1 shows that within the area of 7 x 7 mm, the roughness value for the surface after shot peen forming is significantly larger than for every other surface. As far as roughness formation during shot peen forming is random, increase in the scanned area and its approximation to the base one makes the process steadier and stabilizes roughness values. In the example under study, at a given degree of coverage, the base area is a sector of 15 x 15 mm. When the sizes of scanned sectors increase, probable roughness deviation values will decrease, but the measurement volume sharply rises due to the large number of indentations.

4. Conclusions
A mathematical model of the relationship of the surface arithmetic mean deviation of the profile after shot peen forming and total volume of the dimple of indentations within the base area was developed. Sizes of the base area for monitoring roughness parameters vary inversely as the degree of coverage.

References
[1] Pashkov A E 2005 Tehнологические связи в процессе изготовления длиномерных листовых деталей [Technological relations when manufacturing long sheet components] (Irkutsk: Irkutsk State Technical University) p 138
[2] Pashkov A E 2011 О создании комплексной технологии формообразования крупногабаритных панелей [On the creation of a complex forming method for large panels] In: Highly efficient technologies of designing, design-engineering preparation and manufacturing of airplanes. All-Russian Scientific and Practical Workshop with International Participants p 103-10
[3] Pashkov A E 2013 Автоматизированная технология комбинированного формообразования панелей самолетов [Automated combined forming of aircraft panels] Proceedings of Samara Scientific Center of the Russian Academy of Sciences 15(6-2) 453-457
[4] Koltsov B P, Le Tri Vinh and Starodubtseva D A 2017 Определение степени покрытия после дробедарной обработки [Determining the coverage degree after shot peen forming] Bulletin of Irkutsk State Technical University 21 11(130) 45-52
[5] Khusu A P, Vitenberg Y R and Palmov V A 1975 Шероховатость поверхности: теоретико-вероятностный подход [Surface roughness: theoretical probabilistic approach] (Moscow: Nauka) p 344