sciendo

DOI 10.2478/ama-2020-0001

acta mechanica et automatica, vol.14 no.1 (2020)

FEATURES OF MAGNETO-ABRASIVE MACHINING OF TAPS

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received 4 July 2019, revised 11 February 2020, accepted 14 February 2020

Abstract: The features of magneto-abrasive machining of taps for metric thread cutting were investigated. The calculation method of integral intensity of the magneto-abrasive machining of the working surfaces of the taps by the quantitative values of normal and tangential components of moving speed of the quasi-stable volumes of the magneto-abrasive tool was developed. Based on the results of calculations, it was possible to predict the probable influence of the taps' location in the working zone on the quality and efficiency of machining their working surfaces. The calculation method is relevant for taps of all diameters with a profile angle of 60°. The working surfaces of the tool would not be effectively machined if the location angle of taps to the plane of the working zone of the machine equals 20–60°. Depending on the expected major polishing or strengthening effect of magneto-abrasive machining, the taps are required to be located at an angle of 60–90° to the plane of the working zone of the machine.

Keywords: Tap, magneto-abrasive machining, cutting tools, machining intensity, polishing effect, strengthening effect

1. INTRODUCTION

Taps are widely used for the formation and machining of an internal metric thread. They are used on different types of machines that provide rotational and translational motions (Patel et al., 2011). However, while using taps, some problems do occur, such problems as rapid wear, teeth chipping, size loss, binding and breakdown of the tool due to inefficient removal of chips, high cutting forces or inadequate strength (Benga et al., 2009; Gultekin and Ihsan, 2016; Pereira et al., 2020; Piska and Sliwkova, 2015; Saito et al., 2016). One of the promising finishing technologies for improving the quality and working capacity of the cutting tool (CT) is magneto-abrasive machining (MAM) (Baron, 2008; Hashimoto et al., 2016; Jain et al., 2007; Mori et al., 2003; Singh et al., 2013; Vahdati and Rasouli, 2016). Investigation of influence of the MAM process on the state of microgeometry of details showed that it is appropriate to use at the final stages of production. This method allows the occurrence of combined influence on the state of the surface layer, controllably change its physical and mechanical properties, microgeometry as the working surfaces and the cutting edges of the tool (Baron, 2008; Denkena et al., 2014; Karpuschewski et al., 2009; Maiboroda et al., 2012a,b, 2017; Olt et al., 2018; Payam et al., 2016; Shadab et al., 2017; Tikal, 2009; Wu et al., 2016; Yamaguchi et al., 2014).

The geometry of working part of the taps, particularly their cutting edges, has a complex space shape. The modes and conditions of MAM of the taps will be significantly different from the machining modes of other cutting tools (Baron, 2008; Denkena et al., 2014; Karpuschewski et al., 2009; Keksin, 2013; Maiboroda et al., 2012, 2017; Maksarov and Keksin, 2018). A great influence on the quality indexes of the tools have features of location of the taps in the working zone of the machine, rotation speed, value of magnetic induction, type and fraction of the magneto-abrasive powder. Information on the study of influence of the location and rotation speed of taps during MAM process on the intensity and quality of machining their complex surfaces is lacking. The papers Dzhulii and Maiboroda (2008), Jayswal et al. (2005), Keksin (2013), Kim and Choi (1995) and Kwak (2012) give the methodology and certain results of the process simulation and determination of parameters of MAM, which have an influence on the quality of surfaces. Improvement of the calculation methodology, which is aimed at determining the intensity of machining of working surfaces of taps, depending on such parameters as the location in the working zone of the machine and the rotation speed, will allow performing prediction and optimization of the method of MAM of this tool.

The goal of the research is to study the features of MAM of taps in the ring-type working zone and conditions for effective machining of their working surfaces and cutting edges.

2. MATHEMATICAL MODEL OF THE MAM PROCESS OF THE TAPS

The mathematical model of the MAM process of the taps with an angle between the flanks equal to 60 degrees was developed for machines with a circular arrangement of the working area (Maiboroda et al., 2017). The model was developed to determine the probable normal V_n and tangential V_τ components of the moving speed of individual quasi-stable volumes of the magneto-abrasive tool (MAT), which come in contact with machined surface at each investigated point of working part of tap and for identifying specific zones during machining. The diagram of taps' positioning in this type of machine is shown in Fig. 1. On the diagram, *p* is the angle of mandrel inclination, which is measured in a tangent plane to the plane of the working zone of the machine, *q* is the angle of rotation of the mandrel relative to the tangent plane to the ring-type working zone. For the mathematical modelling of the MAM process, we set the following coordinate systems:

- the coordinate system $X_W Y_W Z_W$ is connected with a ring-type working zone and rotates with a frequency ω_W around Z_W axis;
- the coordinate system $X_M Y_M Z_M$ is connected with the mandrel. An axis Z_M is the axis of rotation of the mandrel. This coordinate system rotates around Y_W axis by an angle p, as well as around the vertical axis Z_W by an angle q, which allows inclining the tap by an arbitrary angle in the working zone. The coordinate system $X_M Y_M Z_M$ is offset relative to the vertical axis Z_W of the working zone of the machine by the value of A – the radius of the middle part of the annular working zone;
- the coordinate system $X_T Y_T Z_T$ is connected with the machined tap and rotates at a speed ω_M around the axis Z_M.

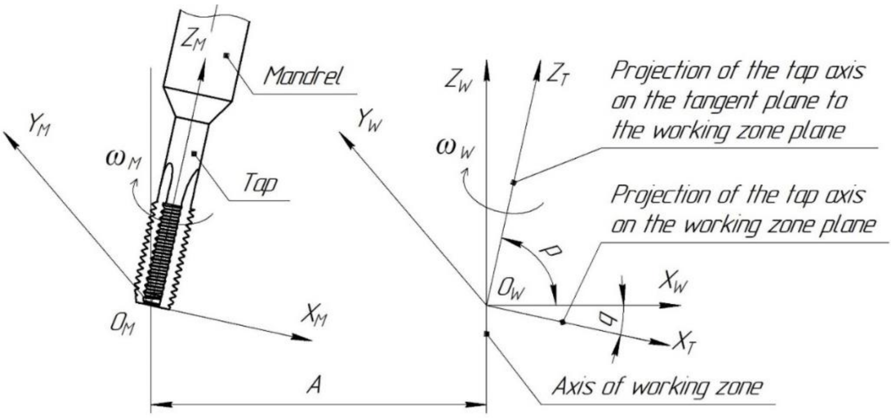

Fig. 1. Diagram of location of coordinate systems in mathematical modelling of the process

For determining the coordinates of a given point P and the direction of the vector of normal N in the coordinate system of the mandrel when the tap is rotated about its own axis by the angle ε, we use the rotation matrix of the vector by the angle $M(\varepsilon)$:

$$\mathbf{M}(\boldsymbol{\varepsilon}) = \begin{pmatrix} \cos\varepsilon & -\sin\varepsilon & 0 \\ \sin\varepsilon & \cos\varepsilon & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{3}$$

$$\mathbf{P}_{\boldsymbol{M}} = \mathbf{M}(\boldsymbol{\varepsilon}) \cdot \mathbf{P} \tag{4}$$

$$\mathbf{N}_{\boldsymbol{M}} = \mathbf{M}(\boldsymbol{\varepsilon}) \cdot \mathbf{N} \tag{5}$$

The coordinates of the given point P and the direction of the vector of normal N in the coordinate system of the annular working zone at the inclination of the mandrel by the angle p and the rotation by the angle q are defined as:

$$\mathbf{M}(\boldsymbol{p}) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \sin p & -\cos p \\ 0 & \cos p & \sin p \end{pmatrix} \tag{6}$$

$$\mathbf{M}(\boldsymbol{q}) = \begin{pmatrix} \cos q & -\sin q & 0 \\ \sin q & \cos q & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{7}$$

$$\mathbf{P}_{\boldsymbol{W}} = \mathbf{M}(\boldsymbol{p}) \cdot \mathbf{M}(\boldsymbol{q}) \cdot \mathbf{P}_{\boldsymbol{M}} + A \tag{8}$$

$$\mathbf{N}_{\boldsymbol{W}} = \mathbf{M}(\boldsymbol{p}) \cdot \mathbf{M}(\boldsymbol{q}) \cdot \mathbf{N}_{\boldsymbol{M}} \tag{9}$$

where $M(p)$ is the matrix of the rotation of the vector by the angle p; $M(q)$ is the matrix of the rotation of the vector by the angle q; A- radius of the annular working zone.

We determine the speed of moving the point around the axis of the annular working zone V_W using the equation:

$$\mathbf{R}_{\boldsymbol{W}} = \begin{bmatrix} (\mathbf{P}_{\boldsymbol{W}})_0 \\ (\mathbf{P}_{\boldsymbol{W}})_1 \\ 0 \end{bmatrix} \tag{10}$$

$$\mathbf{V}_{\boldsymbol{W}} = w_W \times \mathbf{R}_{\boldsymbol{W}} \tag{11}$$

where R_W is the distance from the given point on the working surface of the tap to Z_W axis of the annular working zone.

We determine the linear speed of moving the point around the axis of the mandrel V_M using the below equation:

$$\mathbf{R}_{\boldsymbol{M}} = \begin{bmatrix} (\mathbf{P}_{\boldsymbol{M}})_0 \\ (\mathbf{P}_{\boldsymbol{M}})_1 \\ 0 \end{bmatrix} \tag{12}$$

$$\mathbf{V}_{\boldsymbol{M}} = \mathbf{M}(\boldsymbol{p}) \cdot \mathbf{M}(\boldsymbol{q}) \cdot (w_M \times \mathbf{R}_{\boldsymbol{M}}) \tag{13}$$

where R_M is the distance from the point to the mandrel axis Z_M.

The absolute speed of moving of the point V is defined as:

$$\mathbf{V} = \mathbf{V}_{\boldsymbol{W}} + \mathbf{V}_{\boldsymbol{M}} \tag{14}$$

The angle β between the vector of speed and the vector of normal to the surface at the concrete point of the working surface is determined as:

$$\beta = \cos^{-1}\left(\frac{\mathbf{V} \cdot \mathbf{N}_{\boldsymbol{W}}}{|\mathbf{V}| \cdot |\mathbf{N}_{\boldsymbol{W}}|}\right) \tag{15}$$

Then, the value of normal Vn and tangential V_T components of the moving speed of quasi-stable volumes of MAT in the investigated point of the working surface of the taps is determined as:

$$V_n = |\mathbf{V}| \cdot \cos\beta \tag{16}$$

$$V_\tau = |\mathbf{V}| \cdot \sin\beta \tag{17}$$

Depending on the direction of the speed vectors of the probable relative movement of the quasi-stable volumes of the MAT, that are in contact with the surface of the taps, a different nature of their interaction is possible. Namely, there may be either a predominant polishing process, or a process of strengthening the surface layer, or even a machining process may be absent, when the surface of the tool is located in the ‘shadow zone’. This occurs when the angle between the normal vector to the surface in which this point or region lies, and the vector of speed V is greater than 90°. Thus, the active components of speed, where $V_n > 0$ and $V_\tau > 0$ can be defined as:

$$V_n act(\varepsilon) = |\mathbf{V}| \cdot \cos(act\beta_n(\varepsilon)) \tag{18}$$

$$V_\tau act(\varepsilon) = |\mathbf{V}| \cdot \sin(act\beta_\tau(\varepsilon)) \tag{19}$$

where $act\beta_n$ and $act\beta_\tau$ are the angles at which the surface is machined effectively. When the angle β is in the range 0–90°, then $act\beta_n$ and $act\beta_\tau$ is equal to it. In other cases, $act\beta_n = \frac{\pi}{2}$, $act\beta_\tau = 0$.

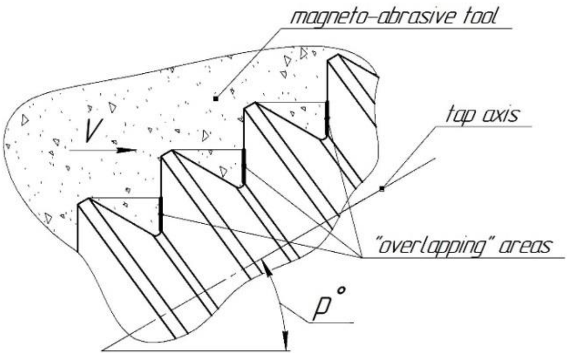

Fig. 2. The zone of ‘overlapping’ of the cutting edge by the teeth, which located in the front

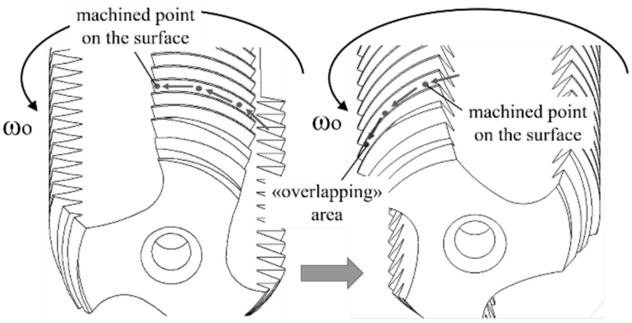

Fig. 3. Pass of the point on the surface to the ‘overlapping’ area

At the MAM of taps at different angles p to the working zone, there is an effect of ‘overlapping’ of the tooth and the cutting edge by other teeth, which are located in the front (Fig. 2, 3).

In this zone, there are no $V_n act(\varepsilon)$ and $V_\tau act(\varepsilon)$, so the MAO process is ineffective. To determine the quantitative evaluation of the active normal and tangential components of the speed of the working surfaces of the tap, it is necessary to determine the angles of rotation of the tool around its own axis, at which the zone of ‘overlapping’ of the machined points of the surface begins and ends. To determine the value of the angle φ of beginning of the ‘overlapping’, the graphical simulation of the formation of the ‘overlapping’ zone in the MAM was carried out (Fig. 4).

From the end surface of the tool, the plane P_1 on the figure shows the diameter of tap D and the diameter d along which the studied point of the surface moves. In plane P_2 and $P3$, the above diameters are represented by graphic modelling at an angle p to the plane of the machine working area. In figure, it is shown that R is the radius of the tooth of the working part of the tap, which overlaps with the next tooth during the machining; r is the radius on the surface of the overlapped tooth, on which is located the investigated point of the surface; a is the distance from the top of the tooth, which overlaps with the plane perpendicular to the tap axis, on which the investigated point is located.

At machining by the angle p to the plane of the working zone, the ‘overlap’ of the investigated point on the surface begins at the point H_3 and ends at a point, which is symmetrical to H_3 relative to the axis Y_3.

To determine the coordinates of the point of beginning of the ‘overlap’ H_3 in the X_3Y_3 coordinate system, it is necessary to find the intersection point of the two ellipses. For this purpose, we use the equation of these ellipses:

$$\frac{X_3^2}{R^2} + \frac{(Y_3 + a \cdot \sin p)^2}{(R \cdot \cos p)^2} = 1 \tag{20}$$

$$\frac{X_3^2}{r^2} + \frac{Y_3^2}{(r \cdot \cos p)^2} = 1 \tag{21}$$

Solving the system of equations from (20) and (21), we receive the coordinates of the point of beginning of the ‘overlap’ in the coordinate system X_3Y_3 and find the coordinates of the point of beginning ‘overlap’ H_1 in the coordinate system X_1Y_1:

$$X_1 = X_3 \tag{22}$$

$$Y_1 = \frac{Y_3}{\cos p} \tag{23}$$

For finding the angle φ by which it is necessary to rotate the tap so the point of the surface falls into the ‘overlapping’ area, we find the angle between the axis $\overrightarrow{O_1Y_1}$ and the vector $\overrightarrow{O_1H_1}$:

$$\cos\varphi = \frac{\overrightarrow{\mathbf{O_1Y_1}} \cdot \overrightarrow{\mathbf{O_1H_1}}}{\left|\overrightarrow{\mathbf{O_1Y_1}}\right| \cdot \left|\overrightarrow{\mathbf{O_1H_1}}\right|} \tag{24}$$

$$\varphi = \cos^{-1}\left(\frac{\overrightarrow{\mathbf{O_1Y_1}} \cdot \overrightarrow{\mathbf{O_1H_1}}}{\left|\overrightarrow{\mathbf{O_1Y_1}}\right| \cdot \left|\overrightarrow{\mathbf{O_1H_1}}\right|}\right) \tag{25}$$

At the MAM, with location of taps by the some angle to the plane of the working area p, the ‘overlap’ of the machined point of the tooth begins at the tap rotation around its own axis by the definite angle φ and ends when the angle of rotation reaches $(360°\text{-}\ \varphi)$.

Note that it is necessary to take into account the cases when the system of equations (20, 21) has no solution, that is, when the machined point is always in the ‘overlapping’ zone or never gets there.

This means that taking into account the presence of the ‘shadow zone’ and of the ‘overlapping’ zone, it is possible to determine the active normal and tangential components of the speed of quasi-stable MAT volumes relative to the back surface of the taps. In the investigated point, when the tap rotates at $\varphi \le \varepsilon \le (360° - \varphi)$, $V_n act = 0$ and $V_\tau act = 0$, in other cases, the active components are determined by (18, 19).

By determining the nature of the interaction of quasi-stable volumes of MAT with processed elements, we calculate the integral intensity of the machining as a quantitative estimate, which characterize the energy aspect of the interaction of grains and their groups with the machined surfaces by the values $V_n act(\varepsilon)$ and $V_\tau act(\varepsilon)$. They are defined as the sum of active speeds for a separate component for the point of the machined surface for the complete turn of the tap around its own axes.

According to the calculations of the integral intensity of the machining $V_n act(\varepsilon)$ and $V_\tau act(\varepsilon)$, one can predict the predominant nature of the machining. Therefore, in order to ensure efficient machining, it is necessary to control the ratio between the tangential and normal components of the interaction speed of the MAT with the working surfaces of the taps, which depend on the parameters of the tool location in the machines with the annular arrangement of the working zones.

The calculation method is relevant for taps of all diameters with a profile angle of 60°. The ratio of $V_n act(\varepsilon)$ to $V_\tau act(\varepsilon)$ will be the same regardless of the taps' diameter.

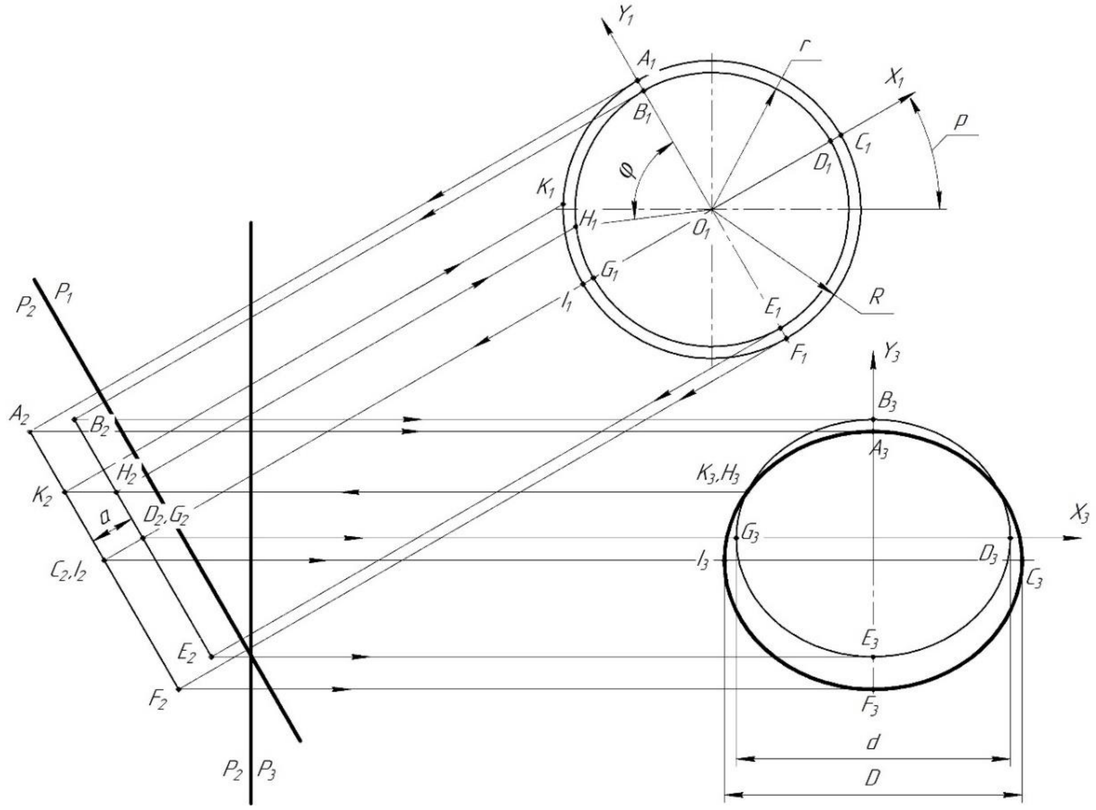

Fig. 4. Graphical diagram for determining the 'overlapping' zone

3. RESULTS OF ANALYTICAL CALCULATIONS

Integral intensities of machining on the back surface of taps M10, made according to DIN 352, at various values of angle *p* were calculated. The points at which were determined the integral intensities of components the machining speed on the back surface are shown in Fig. 5.

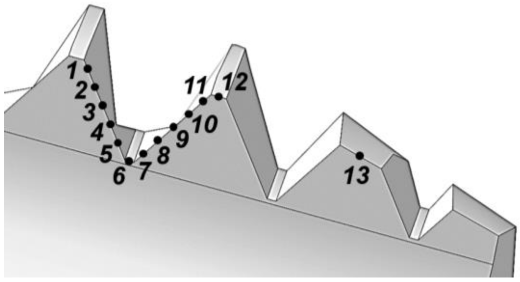

Fig. 5. Points on the cutting edge for which the calculations were made

Points 1–5 and 7–11 are located on the cutting edge of the tooth profile, points 6 and 12 on the cutting edge of the inner and outer diameters of the taps, respectively. Point 13 is located on the cutting edge of the taper lead; therefore, we consider that there is no 'overlapping' zone for this point.

The results of calculations of the integral intensity of the components of the machining speed according to the method described above on the back surface of the working part of the taps in the clockwise rotation mode at different angles of the taps' location to the plane of the working zone are presented in the form of histograms in Fig. 6, 7.

It is shown that effective machining of all surfaces of the working part of the taps occurs at the angle of the tool inclination to the plane of the working zone *p* = 60–90°. That is, the MAM of taps by *p* = 20–60° is not effective, because some of the surfaces are in the 'overlapping' zone where there is no active interaction with the MAT.

For the range of angle *p* = 60–90°, additional calculations of integral intensity were carried out for the full cycle of machining – both in the rotation mode of the taps clockwise and in the opposite direction. The results of calculations are presented in Fig. 8, 9.

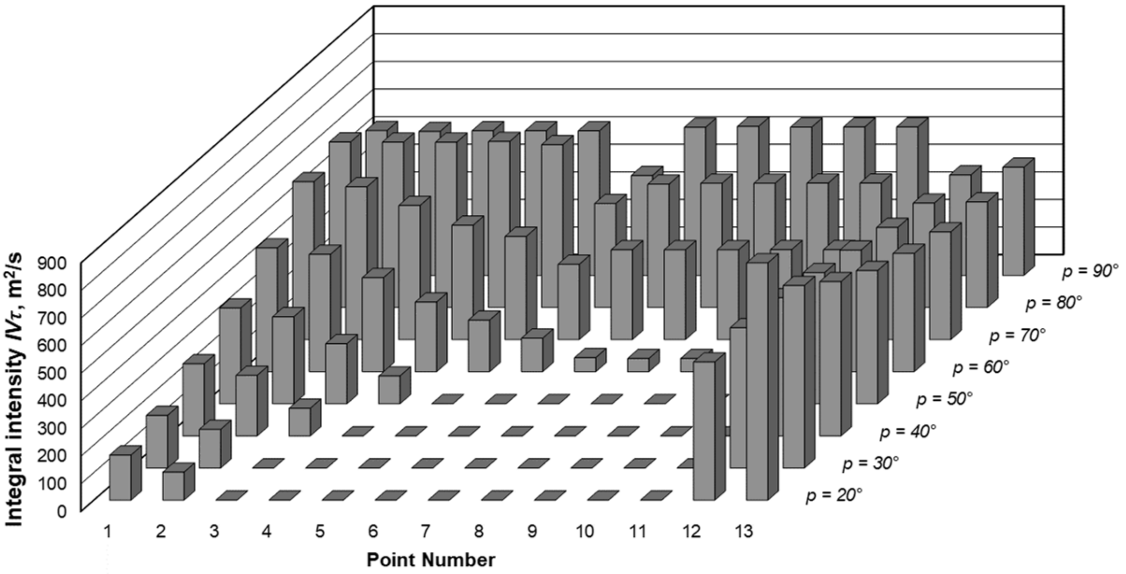

Fig. 6. Integral intensity of machining IV_τ on the back surface at *p* = 20–90°

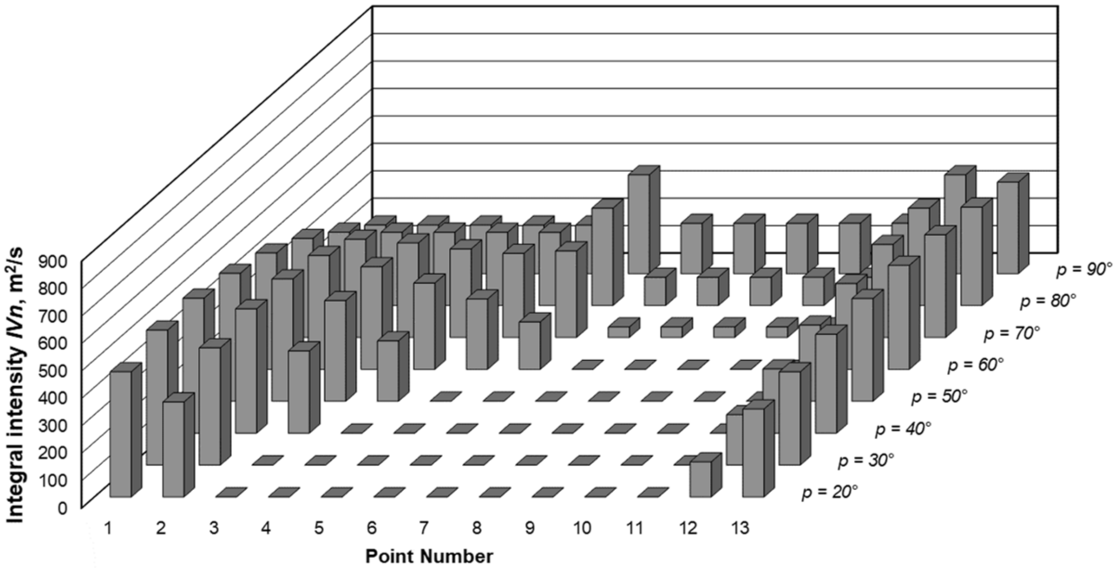

Fig. 7. Integral intensity of machining IV_n on the back surface at *p* = 20–90°

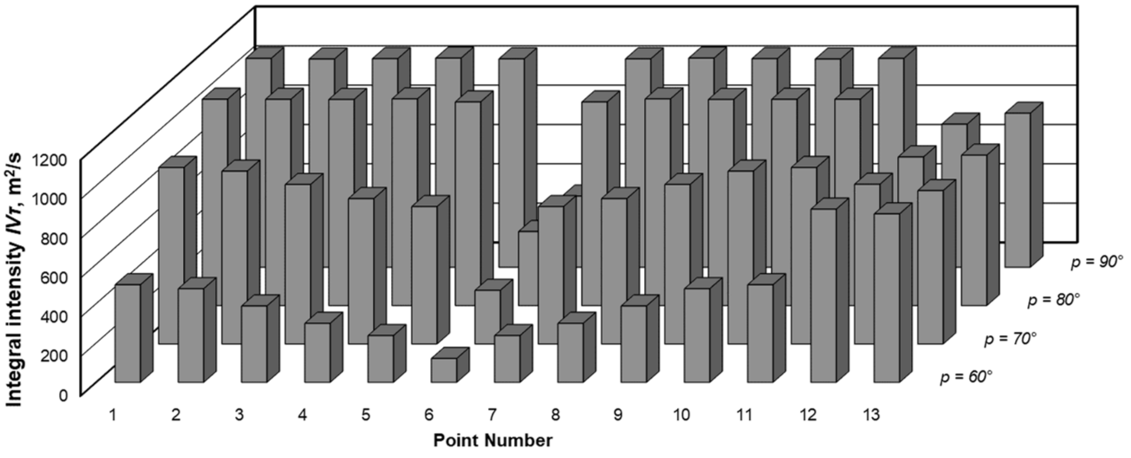

Fig. 8. Integral intensity of machining IV_τ on the back surface for the full cycle of machining at *p* = 60–90°

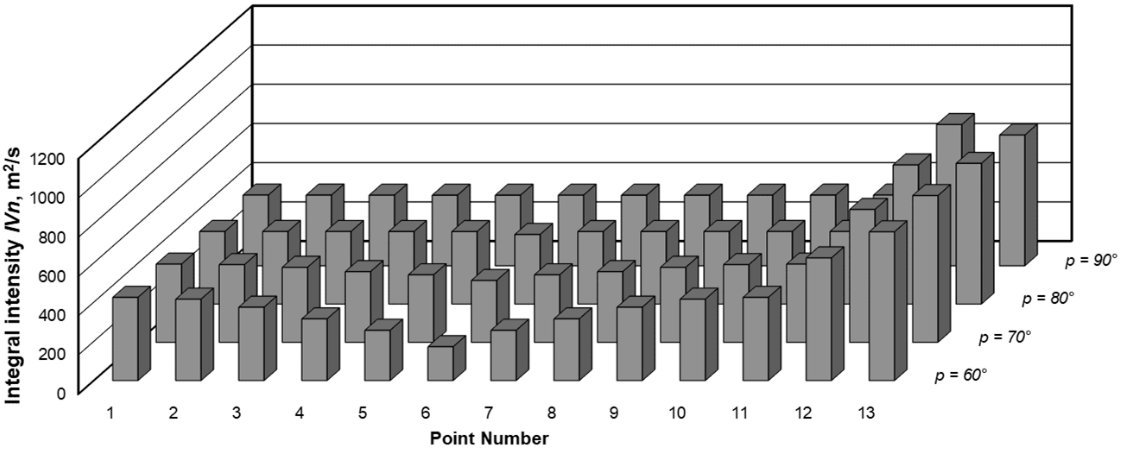

Fig. 9. Integral intensity of machining IV_n on the back surface for the full cycle of machining at *p* = 60–90°

Figure 10 shows the values of ratios of the integral intensities of processing *IVτ* to *IVn* at different points of the cutting edge of the taps, depending on the angle *p*.

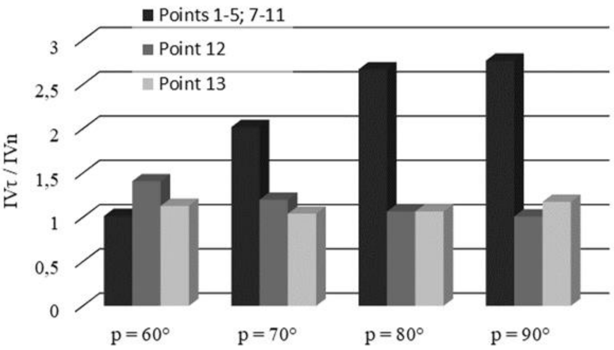

Fig. 10. Average value *IVτ I IVn*

It is established that at *p* = 60°, equal polishing and strengthening effect of MAT is observed on the flank surfaces of the teeth, and with increasing the angle *p*, the polishing is prevalent. On the cylindrical surface of the teeth, the polishing effect of the MAT decreases and aligns with the strengthening as the angle *p* increases. At taper lead, the prevailing polishing interaction of MAT with the surface is observed at *p* = 60° and *p* = 90°.

4. CONCLUSIONS

The method of calculating the quantitative assessment of action of the quasi-stable volumes of MAT on the working surfaces of taps during magneto-abrasive machining is developed. The peculiarities of the MAM process of the taps in the conditions of the ring type working zones, depending on the features of their location in the working zone, were determined. It was established that based on the results of calculations, it is possible to predict the probable effect of location of the taps in the working zone on the quality of machining their working surfaces. The calculation method is relevant for taps of all diameters with a profile angle of 60°. It was shown that when taps are located at the angle *p* = 20–60° to the plane of the working zone, not all surfaces would effectively interact with the MAT. Effective magneto-abrasive machining of taps is appropriate to perform under conditions of their location at an angle of 60–90° to the plane of the working zone. For receiving the prevalent polishing effect, the inclination angle of the taps should be equal to 80–90°, and for the strengthening, it should be equal to 60–70°.

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