SURFACE TOPOGRAPHY CREATION OF MACHINE ELEMENTS AFTER CARBURIZING PROCESS WITH APPLICATION OF BURNISHING METHOD

KSZTAŁTOWANIE TOPOGRAFII POWIERZCHNI ELEMENTÓW MASZYN PO NAWĘGLANIU Z WYKORZYSTANIEM METODY NAGNIATANIA

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Abstract

Various types of bushings or pins are widely used in the machinery industry, i.e. in the automotive industry, agricultural machinery and production lines. Such machine components operate in a diverse environment, not infrequently in polluted or dusty environments and these components may be subjected to intensive wear. Particles circulating in various types of machine kinematic pairs contribute to accelerated or even emergency wear of the equipment. One way to prevent such dangerous failures is to use an additional machining to create dimples in the surface, which are a place to collect lubricant but also abrasive particles. The article presents a method of burnishing a cylindrical surface after carburizing treatment and after hardening, after which the hardness of the surface layer was about 60 HRC. As a result of using appropriate tools, it was possible to create regular and reproducible dimples in the surface. A surface topography parameter was also proposed, which makes it possible to evaluate the increase in oil capacity of the created cavities quickly and with high quality standards.

Keywords: carburizing, texturing, burnishing, surface topography, analysis of variance

Streszczenie

Różne rodzaje tulei lub sworzni są szeroko stosowane w przemyśle maszynowym, tj. w przemyśle motoryzacyjnym, maszynach rolniczych i liniach produkcyjnych. Takie elementy maszynowe pracują w zróżnicowanym otoczeniu, nierzadko w środowisku zanieczyszczonym czy zapylonym, a elementy te mogą być narażone na szybkie zużycie. Cząstki krążące w różnego rodzaju kinematycznych węzłach maszyn przyczyniają się do przyspieszonego lub nawet awaryjnego zużycia urządzeń. Jednym ze sposobów zapobiegania takim niebezpiecznym awariom jest stosowanie dodatkowej obróbki w celu ukształtowania wgłębień w powierzchni, które są miejscem gromadzenia substancji smarującej, ale również cząstek ściernych. W artykule przedstawiono sposób nagniatania powierzchni walcowej po obróbce nawęglaniem i po hartowaniu, po których twardość warstwy wierzchniej wynosiła około 60 HRC. W wyniku zastosowania odpowiednich narzędzi udało się ukształtować regularne i powtarzalne wgłębienia w powierzchni. Zaproponowano również parametr topografii powierzchni, który umożliwia szybką i spełniającą wysokie standardy jakościowe, ocenę wzrostu pojemności olejowej kształtowanych wgłębień.

Słowa kluczowe: nawęglanie, teksturowanie, nagniatanie, topografia powierzchni, analiza wariancji

1. Introduction

The bushings and pins are found a variety of sizes and shapes, allowing them to be widely used in industry. These elements are used in many branches, such as automotive, aviation, agricultural machinery, construction and often specifically in the construction of assembly equipment. The requirements of machine elements that work in the environment of high contamination and under high load is to limit the abrasive wear. One of the methods to prevent the wear is the carburizing process, which is applied to low-

alloy steels in order to modified the properties of the surface layer of the material in further processing phases. After carburizing process the hardening and tempering is used to increase the hardness of the surface layer and the core retains of high ductility. In some applications such treatment is sufficient, but in special cases it may not be enough. For example in sliding pairs of mono-materials of types: steel-steel or steel-cast iron which are susceptible to adhesive wear. Taking into account the mechanism of seizure we may counteract by dimples creation on the sliding surface. One postulate for creation a favorable surface layer to reduce seizure is to form such a micro-geometry that allows for adequate oil capacity and frequent interruption of frictional contact (Nosal, 1998; Nosal, 2002). It is worth to notice that the valleys creation was firstly applied to cylinder liners and it was the honing process. Nowadays, the laser method is usually used for dimple texturing in the zones of cylinder where is a slow motion of piston (Anderson et al., 2007; Dumitru et al., 2003). The wear resistance of textured surfaces is greater than those with the coated surfaces with CrN and DLC of high hardness (Etsion et al., 2006). In most cases the dimples are in spherical shape but they may be in various sophisticated shapes, because the shape is important factor that influence the performance. Results presented by (Galda, 2008; Galda et al., 2010) showed that the dimple in shape of drop oriented deeper side to the movement direction were superior to those of spherical dimple and to untextured surfaces in the tests of seizure resistance of sliding pair consisted of steel and cast iron elements. A degree of surface coverage with dimples is also very important factor and strongly effects on tribological characteristics. At high load and low speed the most favorable outcome were found with the texture coverage of about 10% (Galda et al., 2011). Only on untextured surfaces were observed deep scratches after seizure. Textured surfaces contained some small, it is shallow and short scratches which were stopped by dimples and in some cases seizure did not occur. Research conducted with sliding pair of type steel-steel with one textured element at medium load, low speed and starved lubrication conditions resulted in more than twice reduction in friction coefficient (Galda et al., 2016). On the textured surface no signs of wear were observed, while untextured surface (after grinding) was locally deformed, mainly the peaks were flattened. In these conditions the texture coverage of 3% was superior to other cases. Depth of dimples is another aspect that should be analyzed and selected according to the operating conditions, but there might be a problem with creation dimples on hard materials. The dimples usually are from a few to several tens of micrometers and the machining of the hard-to-

machine materials may be difficult or sometimes impossible with some machining methods. Typically, it is assumed that materials of hardness greater than 45 HRC are in group of the hard-to-machine materials. Hardness of materials after carburizing and hardening is of about 60 HRC, but taking into account the advantages in wear resistance increase is worth to try to create dimples on such surfaces.

This paper presents the results of a study on the burnishing process of 16MnCr5 steel after carburizing and hardening to obtain dimples on sliding surfaces in specific depth and arrangement.

2. Research methodology

In the article the burnishing process of carburized surface layer of 16MnCr5 steel is examined. Steel 16MnCr5 is a structural steel for parts that are surface-hardened and which is most often used in the construction of machinery operating in hard conditions, subjected to wear.

The chemical composition of 16MnCr5 steel is given in Tab. 1.

Table 1. Chemical composition of 16MnCr5 steel
(PN-EN ISO 683-3:2022-07)

C (%)	Si (%)	Mn (%)	P (%)
0,14-0,19	$\leq 0,40$	1,00-1,30	$\leq 0,025$
S (%)	**Cr (%)**	**Fe (%)**	
$\leq 0,035$	0,8-1,1	rest	

In Table 2 the selected properties of steel 16MnCr5 are presented.

Table 2. Selected properties of steel 16MNCr5 (http, 2024)

Hardness after softening annealing	≤ 207 HB
Hardness after carburizing, hardening and tempering	≥ 60 HRC
Tensile strength Rm, after hardening and tempering at 200°C	820 MPa ($16 < $ d, mm ≤ 40)
Density	7,85 g/cm^3
Temperature of carburizing	880–980ºC

Hardness of about 60 HRC after complex treatment of carburizing, hardening and tempering concerns the surface layer and the depth of the layer is usually up to 2 mm.

Samples in shape of shafts in diameter of 30 mm were subjected to carburizing, hardening and tempering and the obtained hardness of surface layer was

approximately of 58 HRC. A precision turning process was used to remove a scale after the heat treatment. Then the burnishing process was used with application a specific burnishing head (Gałda L., Koszela W., 2018). This tool was designed to be easily mounted on universal machines. Figure 1 shows the scheme of the burnishing head. In order to cause the impact of the burnishing element on the surface with high energy, the head uses a cam mechanism and a statically pressed spring. Drive of the cam is carried out by a motor, which is included in the head.
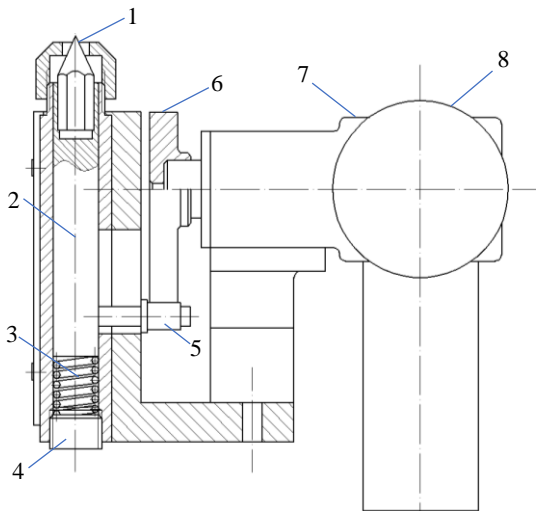

Fig. 1. Scheme of the burnishing head: 1 - burnishing element, 2 – holder, 3 – spring, 4 – adjustment screw, 5 – holder lug, 6 – cam, 7 – gearbox, 8 – motor (Gałda L., Koszela W., 2018)

For the texturing, the tooling used was a cemented carbide G10 burnishing element with a hardness of 1400 HV30. The depth of dimples formed on hard materials depends mainly on the energy of the burnishing element impact. In this case, a hard heavy burnishing element (Fig. 2) and a spring with high stiffness were used, which made it possible to realize texturing effectively.

Fig. 2. Photo of burnishing element from cemented carbide G10

Diameter of dimple is a result also of the burnishing element tip radius. The arrangement of dimples on processing surfaces depends on the technological parameters such as feed, number of cams and rotation speed of cam(s). Thus, there are several technological parameters that can be controlled in order to achieve the appropriate surface topography after burnishing process.

After complex processing of the shaft made from steel 16MnCr5, its surface was subjected to burnishing process at different technological parameters. The photos of the exampled burnished surfaces are shown in Fig. 3.
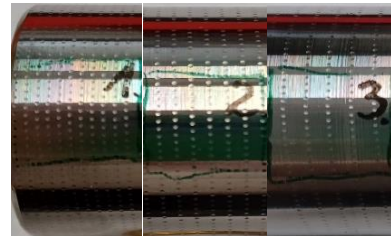

Fig. 3. Photos of shaft surfaces after burnishing with three different feed rate

The technological parameter of burnishing process that was assumed to control was the feed at three levels of variation in the range of 1 - 2 [mm/rev] (Tab. 3).

Table 3. Values of feed during the burnishing process

Surfaces number (fig. 3)	feed f [mm/rev]
1	1
2	1.5
3	2

After burnishing process of carburized surface of steel 16MnCr5 the surface topography was studied with application of an instrument the Form Talysurf i-Series PRO (Taylor Hobson).

To obtain an representative areas of each burnished surfaces, the measured zone was 5 mm x 5 mm. Because the aim of this research was to assess the possibility to form dimples on hard surface after carburizing process, mainly surfaces topography parameters connected with the valleys were analyzed: Svk (reduced valleys depth), Svi (coefficient of keeping the fluid in valleys) and Vvv (void volume per assumed area). The values of selected surface topography parameters were quoted according to standard PN-EN ISO 25178-2:2022. Also some important geometrical parameters of selected dimples were assessed and compared to values of surface topography parameters obtained at different feed rates.

An optical microscope of type Axio Vert.A1 (Zeiss) was used to observe the cross-section of surface layer after carburizing. The image of the cross--section was taken at 12.5x magnification (Fig. 4).

Fig. 4. Image of the cross-section after complex heat treatment with carburizing of steel 16MnCr5 (12.5x magnification)

Depth of the hardened surface layer after complex heat treatment with carburizing process was approximately equal to 600 μm.

3. Results and discussion

Figure 5 shows photos, images and Sk family parameters with shape of Abbott-Firestone curves (bearing area curves) of each burnished surface at varying feeds. Analyzing the surface data, one may noticed that the dimples in circle shape and in regular arrangement are clearly visible on each photos and images, so without any doubts this burnishing method is effective in dimples creation on very hard materials.

The distance between lines of dimples increase with the feed increase and is exactly as the feed value. The number of dimples in lines is on average the same in each case and in further calculation is assumed constant and integer and equal to 6. After removing the form of the measured surface (from shaft) the height is quite comparable, so the depth of dimples should be similar. The reduced depth of valleys is much greater in value than the reduced height of peaks but also from the surfaces core. The shapes of Abbott-Firestone curves are characteristic for the surfaces with valleys presence.
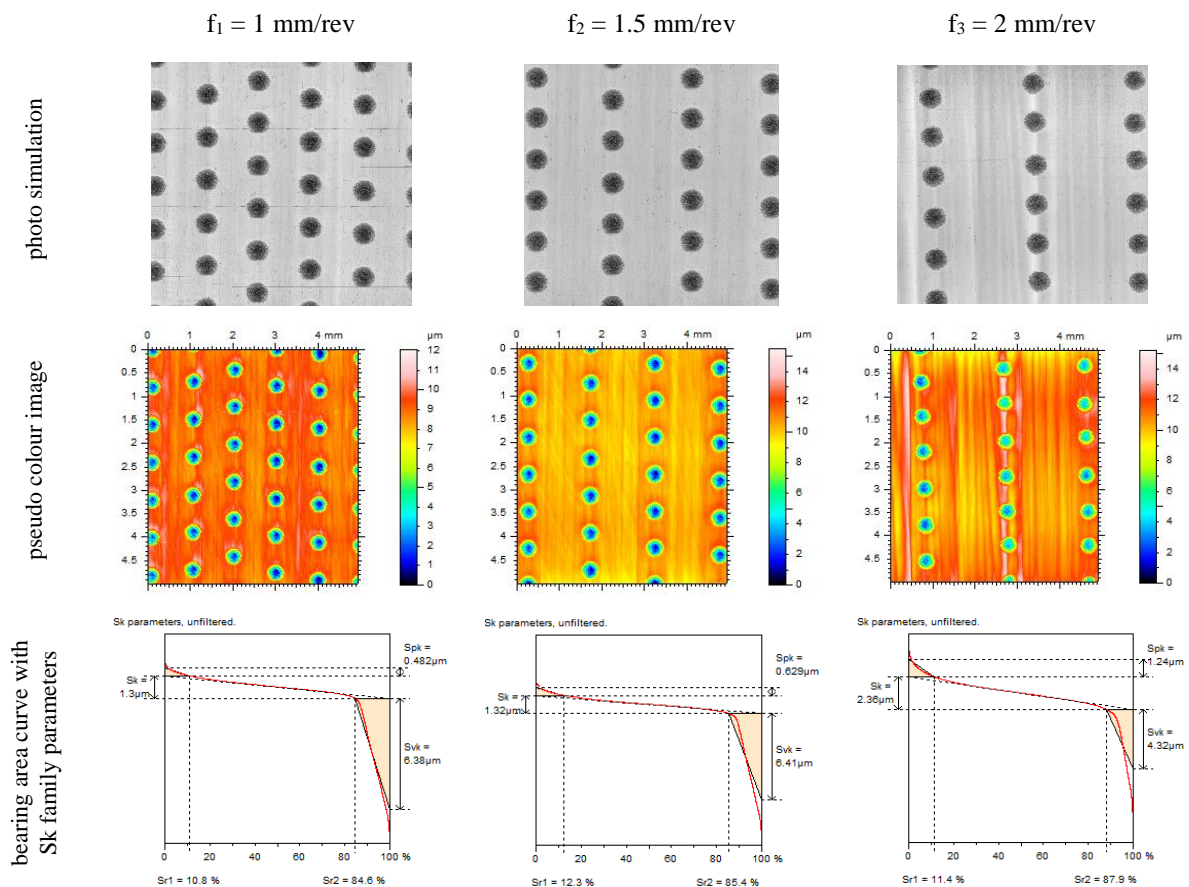

Fig. 5. Selected surface photos, images and bearing area curves after burnishing process with different feeds:
$f_1 = 1$ mm/rev, $f_2 = 1.5$ mm/rev, $f_3 = 2$ mm/rev

It would be convenient to assess the oil capacity of created dimples with adequate surface topography parameters. In order to verify the suitability of the selected surface topography parameters for determining

the changing cavity volume, the dimensions of individual cavities were determined and the volume of created by burnishing process cavities was calculated. A view of single dimple analysis for surface and volume calculation are presented in Fig. 6 and a selected profile for depth and width identification is presented in Fig. 7.
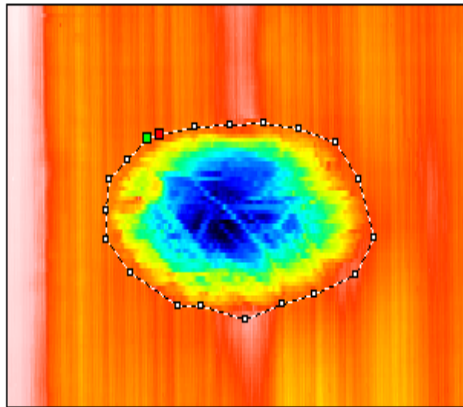
	Hole	Peak
Surface [mm^2]	0.132	0.0122
Volume [μm^3]	516022	2474
Max. depth/height [μm]	9.11	1.16

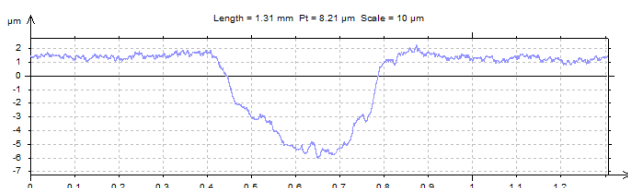**Fig. 6.** View of single dimple created in burnishing process

Fig. 7. Profile extracted from a single cavity at its deepest point

Calculations of individual dimple surface and volume were made with Mountains application and it was enough to point the analyzed zone. The dimple depth was assessed with surface profile application (parameter Pt), but to evaluate the dimple width the function measurement in Mountains application was used.

The important geometrical parameters of individual cavities after burnishing process at different feed with statistical analysis are presented in Tab. 4.

There are known solutions for creating textures in hard materials by grinding the surface with specially constructed grinding wheels (Stępień, 2006). The dimples reached 30 μm and their shape on the surface resembled scratches rather than gently rounded circles or ellipses.

A technique for creating dimples in sliding surfaces that has found widespread use in industry is laser surface texturing. Depending on the type of material, it is possible to produce textures of varying

depths but usually no larger than a few tens of micrometers and in almost any shape (Etsion, 2005).

Table 4. Values of geometrical parameters of single dimples after burnishing process of carburized steel 16MnCr5

feed f [mm/rev]	geometrical parameters of cavities			
	depth [μm]	width [μm]	surface [mm^2]	volume [μm^3]
1	8.74	431	0.127	454 169
	9.70	432	0.137	520 144
	9.23	432	0.131	496 510
average	**9.22**	**431.7**	**0.132**	**490 274**
standard deviation	0.48	0.58	0.005	33 427
1.5	10.10	438	0.143	569 823
	10.10	440	0.141	576 379
	9.88	431	0.143	546 013
average	**10.03**	**436.3**	**0.142**	**564 072**
standard deviation	0.13	4.73	0.001	15 979
2	9.24	427	0.132	516 022
	9.07	436	0.131	514 546
	10.20	435	0.130	509 163
average	**9.50**	**432.7**	**0.131**	**513 244**
standard deviation	0.61	4.93	0.001	3610
difference of average values %	**8.7**	**1.1**	**8.7**	**15.1**

An effective method, but less commonly used than laser texturing, is abrasive blasting. Using blasting, dimples of up to several tens of micrometers and in any shape depending on the cover used can be achieved (Wakuda, 2003). To texture the carburized surface the prototype burnishing tool was used and it was important to assess also the results repeatability. As one may see primary survey data, the standard deviation values are quite small and the difference of average values is 8.7% (for dimple depth) and only 1.1% (for dimple width). It seems to be the acceptable level. The differences between the transformed values are larger (8.7% for dimple surface and 15.1% for dimple volume), but still in these cases it is acceptable.

It is also useful to illustrate on the graph the changes of selected values with the feed changes in the assumed range (Fig. 8).

As analyzing the raw data of depth and width of single dimple, the stable average values and small standard deviations are observed taking into account results at given feed and with increase feed values. Similar observations were taken in case of transformed data, it is of dimple surface but a little greater spread of volume values was noticed. It seems to be acceptable level of repeatability of dimple dimensions

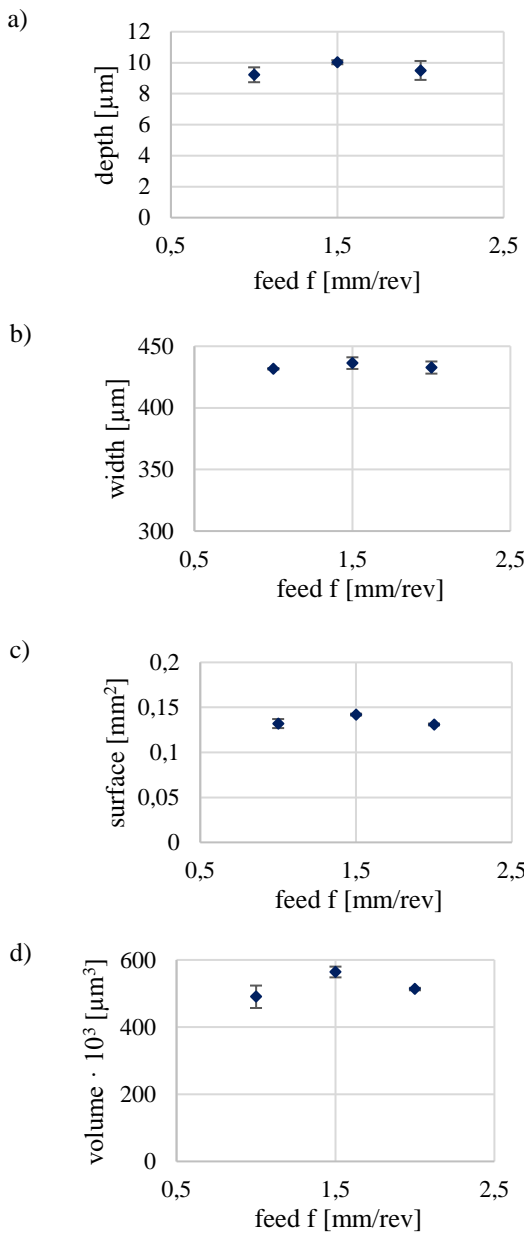after texturing the carburizing surface with burnishing application.

a)

b)

c)

d)

Fig. 8. Average values of depth (a), width (b), surface (c) and volume (d) of single dimple with increasing the feed during burnishing process

To verify this statement another method of data analysis was adopted and it was the one-factor analysis of variance. The input factor was the feed in the range of $1 - 2$ mm/rev at three levels. The output factors were the geometrical parameters of single dimple created in burnishing process. A significance level of $\alpha = 0.05$ was assumed. Some more details about this statistical method and also the example of implementation are presented in (Gałda et al., 2022). In Tab. 5 the results of the one-way analysis of variance for four selected geometrical parameters of single dimple are presented.

Table 5. One factor (feed) variance analysis for single dimple geometry parameters

output parameter	F	F_{cr}	p-value
depth	2.42		0.169
width	1.15	5.14	0.376
surface	13.15		0.006
volume	9.27		0.014

Compering the results of calculation one may see that the empirical values F obtained for the dimple depth and width are smaller than the critical value F_{cr} and also p-values are greater than 0.05. It means that the technological parameter (feed) has no significant effect on these geometrical parameters of single dimples. Statistical one-way analysis showed the significant effect of feed on the surface and volume of single dimple, because empirical values F exceed the critical value F_{cr} and p-values were smaller than 0.05, but one should be cautious with the assessment of the influence on transformed parameters. Especially in this case when the exceed is rather small and the process was realized with prototype tool.

The results of the measurements of selected surface topography parameters are shown in Tab. 6.

Table 6. Values of selected parameters of surface topography after burnishing process of carburized steel 16MnCr5

feed f [mm/rev]	surface topography parameters			
	Sa [μm]	Svk [μm]	Svi [-]	Vvv $\cdot 10^3$ [mm^3/mm^2]
1	1.05	4.67	0.305	0.528
1.5	1.02	3.49	0.281	0.505
2	1.00	3.03	0.205	0.328
difference %	**5.00**	**54.13**	**48.78**	**60.98**

It was assumed that the dimples depth should be similar, so with the decreasing the number of dimples the average amplitude parameters should also decrease, but probably not too much. Taking into account the most popular amplitude parameter Sa that defined an average arithmetical deviation of surface irregularities, the decrease in Sa value is of 5% comparing surfaces of the biggest and smallest number of dimples. From functional parameters the Svk and Svi were selected and the decrease in reduced depth of valleys Svk was of over 54% while the coefficient of storing the fluid in valleys Svi decreased of almost 49% with the increase of feed in burnishing the surface. Another functional parameter of surface topography that may be more adequate for comparing the fluid accommodation in surface valleys that was

analyzed it was Vvv. This parameter is defined by valley volume per square millimeter. As the feed rate increased, the volume Vvv decreased by almost 61%, caused by the reduced number of cavities. Summarizing, the analysis of surface topography parameters, one may conclude that the average height parameter was changed insignificantly (5%) and selected functional parameters connected with the dimple depth or volume decreased significantly of about 49-61%. It also means that with changing the feed one may control the oil capacity of dimples created in burnishing process.

To compare values of surface topography parameters connected with dimples, the volume of single cavities should be multiply by numbers of created cavities in burnishing process. In this analysis values from the 5 mm x 5 mm area were compared and the results are presented in Tab. 7.

Table 7. Number of dimples after burnishing process in the assumed zones and total volume of cavities

feed f [mm/rev]	parameters of cavities	
	number of dimples, n	total volume, $V \cdot 10^3$ [μm^3]
1	30	14 708
1.5	24	13 538
2	18	9 239
difference %	**66.67**	**59.20**

Decreasing the feed during burnishing the number of dimples increased significantly, in the analyzed case it was of over 66%, what resulted in the total volume increase of textured dimples of almost 60% in the analysed zone. Comparing this increase with these obtained with the surface topography parameters application, the highest similarity is obtained with the parameter Vvv, which is equal to 60.98%. Parameter Vvv expresses the oil capacity in mm^3 per mm^2 of surface area and probably that is the reason that correlates strongly with calculated separately dimples volumes. Summarizing, the parameter Vvv can be used to quickly assess the increase in oil capacity with high measurement accuracy after burnishing process with different technological parameters processing.

4. Conclusions

The burnishing process may be used to effectively form the dimples in the surface of a hard surface layer after carburizing. Obtained texture was with acceptable repeatability and in expected shape. The arrangement of the dimples depends on the technological parameters. With smaller feed, the number of dimples is greater, what effects on the oil capacity increase.

Instead of calculation individual dimples geometrical parameters, which is time consuming, the surface topography parameter Vvv may be used to assess the increase in oil capacity caused by texture creation with satisfactory accuracy.

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