

Study of Physical Aspects of Changes in the Morphology Parameters of the Surface Layer After Machining Using LFV Technology

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Doi: [10.12693/APhysPolA.149.S28](https://doi.org/10.12693/APhysPolA.149.S28)

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The article presents an analysis of changes in the physical properties of the surface layer after the process of shaping difficult-to-cut materials. Obtaining the appropriate structure of the surface layer during machining is crucial for achieving the desired properties of the element, such as hardness, resistance to wear, corrosion, material fatigue, or friction. The surface layer is not only a geometric surface; it is also a zone with modified physicochemical properties, the formation of which is controlled by physical phenomena occurring during cutting. Thermal phenomena occurring in the contact zone during its formation cause structural changes in the subsurface layer, hardening or softening it. Dynamic phenomena occurring during the machining process deteriorate surface quality, causing waviness and microcracks. The paper presents the effect of surface shaping using vibration cutting, analyzes the physical aspects of surface morphology, and evaluates the nature of the influence of process parameters, i.e., functional parameters of the surface layer. Experimental studies were carried out on four materials with different physical and structural properties: 1.4404 stainless steel, S235 structural steel, M1E electrolytic copper, and EN AW-6060 aluminum alloy.

topics: low-frequency vibration (LFV) technology, surface physical parameters, surface functional parameters

1. Introduction

The development of construction materials is primarily related to the search for materials with better mechanical properties, increasing their durability and environmental resistance, as well as reducing their impact on the environment in which they will be used, lowering production costs, and improving processing efficiency. Another very important feature that must be considered is the ability of materials to shape and obtain a favorable surface structure. Forming the geometric structure of the surface through the cutting process causes various types of defects that can have a negative impact on the functional properties of the final product [1–3]. During the turning of difficult-to-cut materials, long, continuous chips are created, which must be removed from the machining space. They can become entangled in the workpiece or tool, making it difficult to implement full automation and thus reducing efficiency [4–6]. Difficult-to-cut materials require an appropriate tool, careful selection of cutting parameters, and appropriate lubricating and cooling fluids. In many cases, all

this is not enough, so additional special machining techniques must be used to properly fragment the chips and obtain the required surface quality after machining. In order to solve the problem occurring during turning, research has been carried out in recent years on vibratory cutting, which involves subjecting the tool to vibrations to perform the cutting process [7, 8]. A. Miyake et al. [9] developed a machining process simulation to define vibration conditions that can minimize workpiece roundness errors. It is then possible to control the contour profile of the machined parts during low-frequency vibration (LFV) operation. A new geometry of the low-frequency vibratory turning tool blade presented in [10, 11] resulted in reduced surface roughness and improved average roundness. M.C. Cosenza et al. [12] described numerical studies demonstrating the use of 1D vibrations in the feed direction during Inconel turning. In [13], a low-frequency vibration cutting technology was developed in which vibrations are generated in the tool feed direction and spindle rotation direction. The vibrations consist of a combination of two vibration axes, the X -axis and the Z -axis of the lathe. Unlike conventional vibration cutting, it can be used for

TABLE I
The chemical composition of 1.4404 steel.

Alloying element	[%]	Alloying element	[%]	Alloying element	[%]
C	0.03	P	0.045	Mo	2.0
Si	1.0	S	0.03	Ni	10.0
Mn	2.0	Cr	16.5	N	0.11

TABLE II
The chemical composition of S235 steel.

Alloying element	C	Mn	P	S	N
[%]	0.17	1.40	0.045	0.045	0.009

turning any shape, including cones or arcs. This paper proposes a model of motion conditions for chip breaking using LFV operating parameters. In [14], the effect of low-frequency vibrations on tool life in turning operations for carbon steel, stainless steel, and titanium alloys was investigated.

This paper presents the results of research analyzing the impact of technological and modeling parameters of LFV machining on surface quality parameters. For selected materials, LFV machining parameters were optimized to improve roughness parameters while simultaneously generating the appropriate chip shape.

2. Materials and methods

Samples were machined on CNC lathe Miyano BNA42GTY by Mitsubishi with dedicated Alkart programming software [15]. The samples on which the tests were carried out were 20 mm diameter shafts made of the following materials: stainless steel 1.4404 (Table I), S235 steel (Table II), electrolytic copper CW004A (Table III), and aluminum alloy EN AW-6060 (Table IV).

For turning samples made of 1.4404 and S235 steel, Walter WSM20S carbide inserts with the DCMT11T302-MM4 and DCMT11T304-MM4 geometry were used, and for samples made of electrolytic copper CW004A and aluminum alloy EN AW-6060, the DCGT11T302-PM2 and DCGT11T304-PM2 inserts made of the material designated according to the manufacturer WK1 [16] were used. The inserts used for the tests were mounted in the SDJCR 2020 K11 tool holder. A constant cutting depth of $a_p = 2$ mm and feed rates of 0.01, 0.02, and 0.03 mm/rev were assumed for the tests. For the given feed rates, the tool vibration amplitude along the feed axis was selected in the range of 30–50 μ m. The frequency is directly influenced by two parameters, namely the number of vibrations per spindle revolution and the spindle speed.

TABLE III

The chemical composition of electrolytic copper CW004A.

Alloying element	[%]	Alloying element	[%]	Alloying element	[%]
Cu	min 99.9	Sb	0.002	Fe	0.005
Ni	0.002	Pb	0.005	As	0.002
Sn	0.002	Zn	0.003	Bi	0.001

TABLE IV

The chemical composition of aluminum alloy EN AW-6060.

Alloying element	[%]	Alloying element	[%]
Si	0.3	Mg	0.35
Fe	0.2	Cr	0.05
Cu	0.1	Zn	0.15
Mn	0.1	Ti	0.1

The choice of these parameters is dictated by an attempt to match the appropriate LFV frequency. Phase synchronization in the LFV technology cycle is characterized by the fact that the tool should properly cut off a specific volume of material, causing effective chip breaking. In the case of a mismatch, vibrations may overlap, surface quality may deteriorate, and instability and chip balling (no chip breaking) may occur. In order to achieve optimal quality of surface layer structure and obtain appropriate chips (i.e., short, splintering ones), the feed rate should be synchronized with the vibration amplitude, and so the number of chip breaking cycles per spindle revolution should be determined. In the case of the applied control, parameter D defines the number of vibration cycles per spindle revolution, and parameter Q determines the ratio of amplitude to feed. For the applied spindle speeds n in the range of 764–1146 rpm with the D parameter of 3.1, the obtained frequencies used for machining were 40–60 Hz. The surface structure was examined using a Taylor Hobson New Form Talysurf 2D/3D 120 profilometer, which is equipped with a head with an interferometric transducer with a resolution of 0.6 nm. A measuring tip in the form of a cone-ball-shaped diamond needle (radius 2 μ m and cone angle 90°) was used for the measurements. On each sample, the measurement of roughness parameters was performed six times at different positions of the sample, and the averages of these measurements were used for the analyses. In the case of surface topography measurement on all samples, the measurement was carried out on a surface of 2 \times 4 mm². Surface topography analysis was performed using TalyMap Platinum software from Taylor Hobson.

3. Results and discussion

After machining in accordance with the established strategy of setting the tool in relation to the surface of the samples, tests were carried out to determine the effect of selected technological parameters on the quality parameters of the machined surface. First, the samples subjected to the test were machined using a variable feed, while the constant values were the revolutions of 1146 rpm and the coefficients modeling the machining in the LFV system, $Q = 2.5$ and $D = 3.1$. It was noticed that with the increase in the feed, and consequently the vibration amplitude, using the LFV system, the roughness increases.

The increase in roughness for the machining case presented in the experiment is caused by the increase in the non-contact area, i.e., the insert re-rubbing the place already machined in the previous rotation of the material (the place of chip detachment). This is due to the increase in the amplitude of the movement, which causes the distance between the peak of the oscillatory movement of the current machining and the machining from the previous rotation of the material to increase. Among the materials tested, the EN AW-6060 grade machined with a cutting insert with an R0.4 corner was characterized by the largest average increase in the Ra surface roughness parameter at the level of $0.7463 \mu\text{m}$ (Fig. 1a). In turn, for the R0.2 corner, the largest average increase in the Ra roughness parameter was obtained by the S235 material and amounted to $0.6304 \mu\text{m}$ (Fig. 1b).

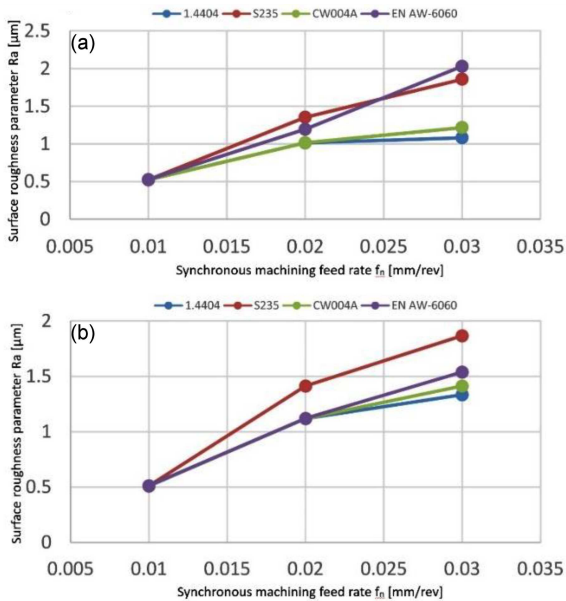


Fig. 1. The influence of feed on the surface roughness of the machined materials using an insert with a corner radius: (a) R0.4, (b) R0.2.

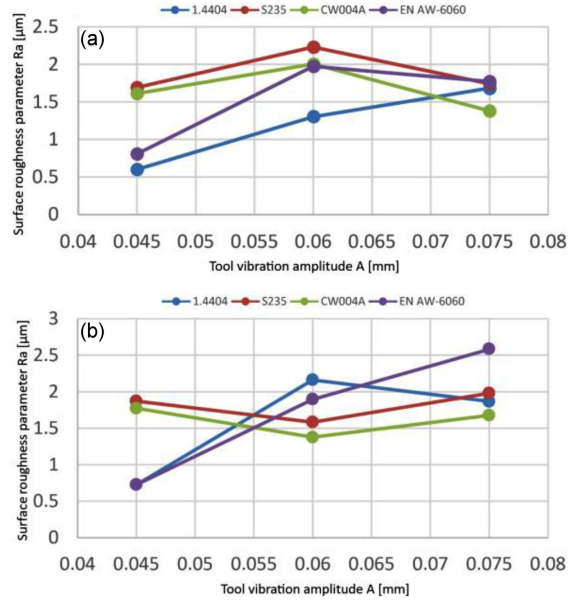


Fig. 2. The influence of the tool vibration amplitude on the surface roughness for the materials used with the use of an insert with radius corners: (a) R0.4, (b) R0.2.

In the next study, samples made with varying tool vibration amplitude along the feed motion were analyzed. The constant parameters were: feed $f = 0.03 \text{ mm/rev}$, speed $S = 955 \text{ rev/min}$, and $D = 3.1$. The studies considered were performed for turning using a cutting insert with a corner radius of R0.4 and a corner radius of R0.2.

Analyzing the values of the surface roughness parameter Ra presented in the graph (Fig. 2a) for turning using an R0.4 insert for the material 1.4404, one can observe an increase in the roughness parameter value with increasing vibration amplitude, with the largest average increase in this parameter being $1.0812 \mu\text{m}$. For the other materials tested, within the vibration amplitude range of $0.045\text{--}0.075 \text{ mm}$, the Ra roughness parameter values increased and then decreased. When using a turning insert with an R0.2 corner to prepare the test samples (Fig. 2b), different trends in changes in the roughness parameter were observed with changing the tool vibration amplitude. Only for the EN AW-6060 material, increasing the vibration amplitude across the entire test range causes an increase in the Ra roughness parameter, yielding the largest average increase of $1.8546 \mu\text{m}$. For the S235 and CW004A materials, the Ra roughness parameter values decrease and then increase with increasing vibration amplitude. However, for the 1.4404 material, the trend is reversed.

In the next study, the analyzed samples were made using a variation of the rotational speed, which also causes a change in the tool vibration frequency in the direction of the feed movement. The constant values in this process were the feed rate

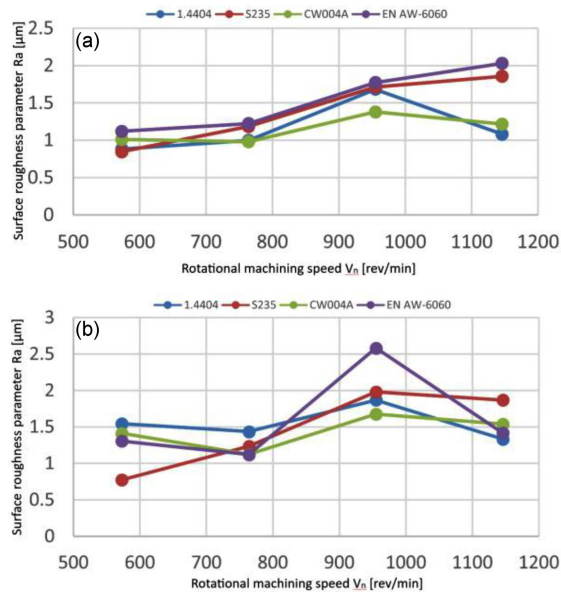


Fig. 3. The influence of rotational speed and vibration frequency on surface roughness for the materials used with the use of a corner radius insert: (a) R0.4, (b) R0.2.

of 0.03 mm/rev and the parameters $Q = 2.5$ and $D = 3.1$. The considered samples were made for the case of turning using a cutting insert with the R0.4 corner and the R0.2 corner.

The highest average increase in the Ra parameter for the sample made using the R0.4 corner insert was obtained after machining the 1.4404 material, obtaining result of $0.4671 \mu\text{m}$, while for the R0.2 corner, using the EN AW-6060 material, it was $0.9378 \mu\text{m}$ (Fig. 3). In the attempts to machine selected materials using conventional turning, only in the case of S235 steel it was possible to conduct continuous machining, during which a directional or spalling chip was formed. The roughness parameters were better compared to machining using the LFV technology. This is due to the good machinability of this steel. Manufacturing elements from other grades required additional involvement from the operators, aimed at removing the resulting chip, which prevented the continuation of machining operations. Analyzing the surface morphology of the samples, it can be noticed that there are regular grooves on the surface of the workpiece after conventional turning (Fig. 4). When we apply low-frequency vibrations (Fig. 5) in LFV technology, periodic surface textures with sharp troughs and ridges are clearly visible. This is primarily due to the effect of overlapping tool space trajectories during vibrations.

Based on the measurement results obtained using the TalyMap Platinum software and the acquired support curves presenting information on the shape of unevenness, an analysis was made of the effect of changes in machining parameters on changes in the functional parameters of the surface

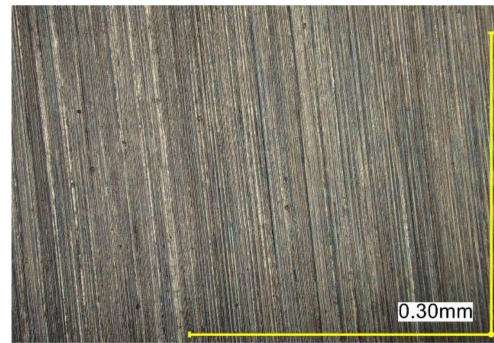


Fig. 4. Surface after turning without LFV technology 1.4404 steel with parameters $f_n = 0.03 \text{ mm/rev}$ and $V_n = 869 \text{ rev/min}$; view of the sample at x100 magnification on Keyence VHX-900F.

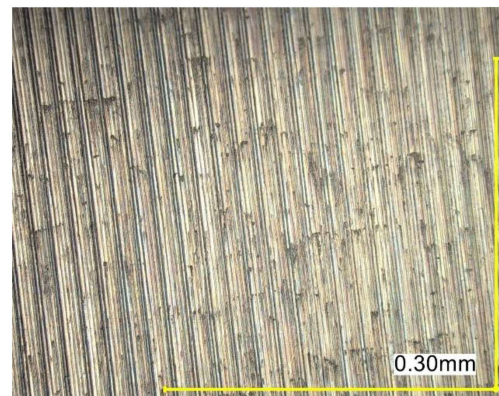


Fig. 5. Surface after turning 1.4404 steel using LFV technology after machining with parameters $f_n = 0.03 \text{ mm/rev}$, $V_n = 869 \text{ rev/min}$, $a_p = 2 \text{ mm}$, $Q = 2$, $D = 3.5$; view of the sample at x100 magnification on Keyence VHX-900F.

layer. Figure 6 shows an example of material distribution along the surface profile after turning 1.4404 steel using LFV technology, with parameters $f_n = 0.02 \text{ mm/rev}$, $V_n = 1146 \text{ rev/min}$, $a_p = 2 \text{ mm}$, $Q = 2$, $D = 3.1$.

Based on the data obtained in the conducted tests and after analyzing the material share curves for samples made of the 1.4404 material using a cutting insert with a corner radius R0.4, it was noticed that when using variable feed values in the range of 0.01–0.03 mm/rev for constant speed values of 1146 rev/min, as well as a constant value of parameter $Q = 2.5$, parameter c_1 initially decreases from 1.07 to $0.853 \mu\text{m}$, and then increases to $1.44 \mu\text{m}$. In turn, parameter c_2 obtains increasing values with the use of increased feed from 2.99 to $5.99 \mu\text{m}$.

From the Sk graphs, the value of the upper bearing surface Sr_1 (material share in the place where the elevation zone passes into the core zone) increases from 9.58% to 27.2%. However, changing the speed from the range of 573–1146 rpm, while

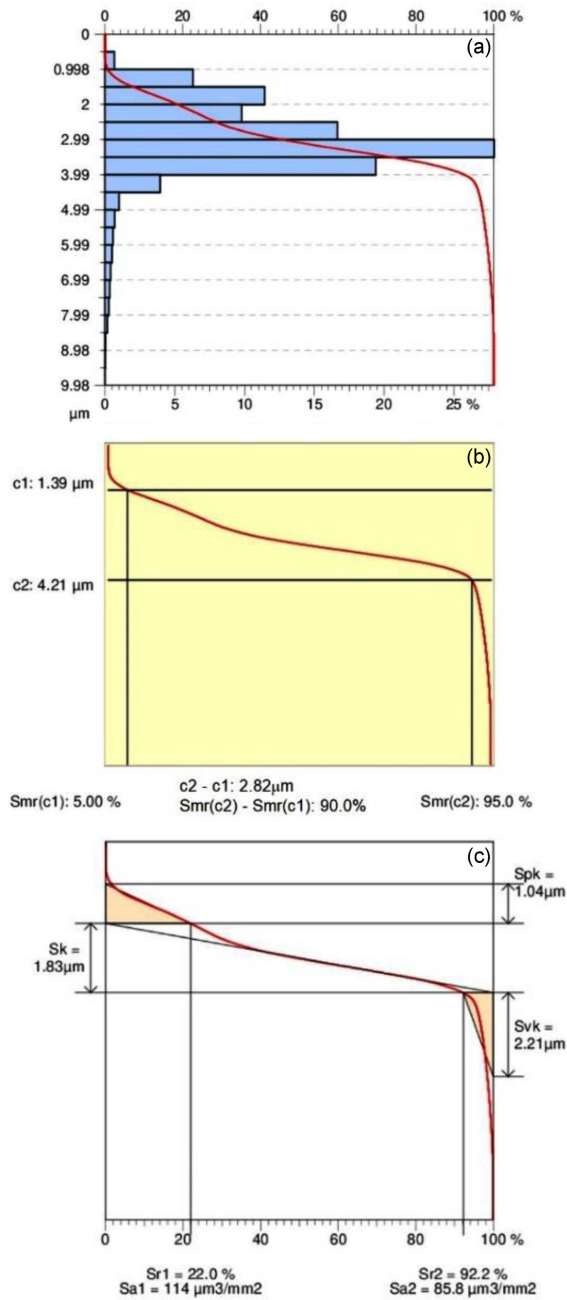


Fig. 6. Graphical representation of the material distribution along the surface profile after turning 1.4404 steel using carbide insert with corner radius R0.4, at the parameters $f_n = 0.02$ mm/rev, $V_n = 1146$ rev/min, $a_p = 2$ mm, $Q = 2$, $D = 3.1$: (a) Abbott–Firestone curve with designated profile ordinates, (b) interactive Abbott curve, (c) material share curve.

maintaining constant feed values at the level of 0.03 mm/rpm, as well as the parameter $Q = 2.5$, causes the initial increase in the parameter c_1 from 1.18 to 2.66 μm at a spindle speed of 955 rpm. Then this value decreases to the level of 1.44 μm . We notice a similar characteristic for the parameter c_2 , i.e., its values initially increase from 3.75

to 7.16 μm , then decrease to 5.99 μm . With the increase in speed, the upper bearing surface Sr_1 initially increases from the value of 10.60% to 28.90% when reaching the speed of 955 rpm, then decreases to 27.2%. It was found that with the increase in the Q parameter, the c_1 parameter increases from 1.56 to 2.66 μm and the c_2 parameter from 5.0 to 7.16 μm , and there is also a slight increase in the upper bearing surface from 25.9% to 28.90%.

The next material analyzed in terms of material fraction curves is EN AW-6060. The tests were carried out for samples made using a turning insert with an R0.4 radius corner, as well as an R0.2 corner. For samples made using an insert with an R0.4 corner, it was found that when applying variable feed values in the range of 0.01–0.03 mm/rev for constant speed values of 1146 rev/min and a constant value of parameter $Q = 2.5$, there is an average increase in parameter c_1 from 0.388 to 1.61 μm and parameter c_2 from 2.334 to 5.06 μm . In turn, in samples made using a cutting insert with a corner equal to R0.2, the surfaces are characterized by an increase in parameter c_1 in relation to the increase in feed, with average values from 0.8 to 2.15 μm and parameter c_2 from 3.014 to 6.20 μm . Analysis of speed changes in the range of 573–1146 rpm while maintaining constant feed values at 0.03 mm/rev, as well as parameter $Q = 2.5$, showed that with an increase in speed for the sample made using an R0.4 corner radius, the average value of parameter c_1 decreases from 1.65 to 1.61 μm , in contrast to parameter c_2 , which increases with an increase in speed from 4.96 to 5.06 μm . Samples made using the R0.2 insert corner are characterized by a decreasing trend for both parameter c_1 and c_2 , ranging from 3.23 to 2.15 μm and from 7.3 to 6.2 μm , respectively (example in Fig. 7). When analyzing the c_1 index in terms of the effect of increasing the Q parameter, it was found that both for samples made using the R0.4 and R0.2 insert radius corners, the value of parameter c_1 decreases from 1.93 to 1.31 μm and from 3.53 to 2.09 μm , respectively. However, in the case of parameter c_2 , a noticeable change of 15% (from 7.46 to 6.28 μm) applies only to samples made using the R0.2 insert corner. The functional parameters of the obtained samples were also assessed. It was observed that when the feed rate increased in the range of 0.01–0.03 mm/rev while maintaining a constant rotational speed of 1146 rev/min and the parameter $Q = 2.5$, the average values of the upper bearing surface Sr_1 for both types of samples decreased. In the case of samples made with a cutting insert with a R0.4 corner, the average Sr_1 values ranged from 22.06% to 14.52%, while for R0.2, from 19.1% to 14.68%.

In the case of samples made of CW004A material using a cutting insert with an R0.4 corner, it was noticed that with an increase in the feed value in the range of 0.01–0.03 mm/rev while maintaining constant speed values of 1146 rev/min and a constant value of parameter $Q = 2.5$, parameter c_1

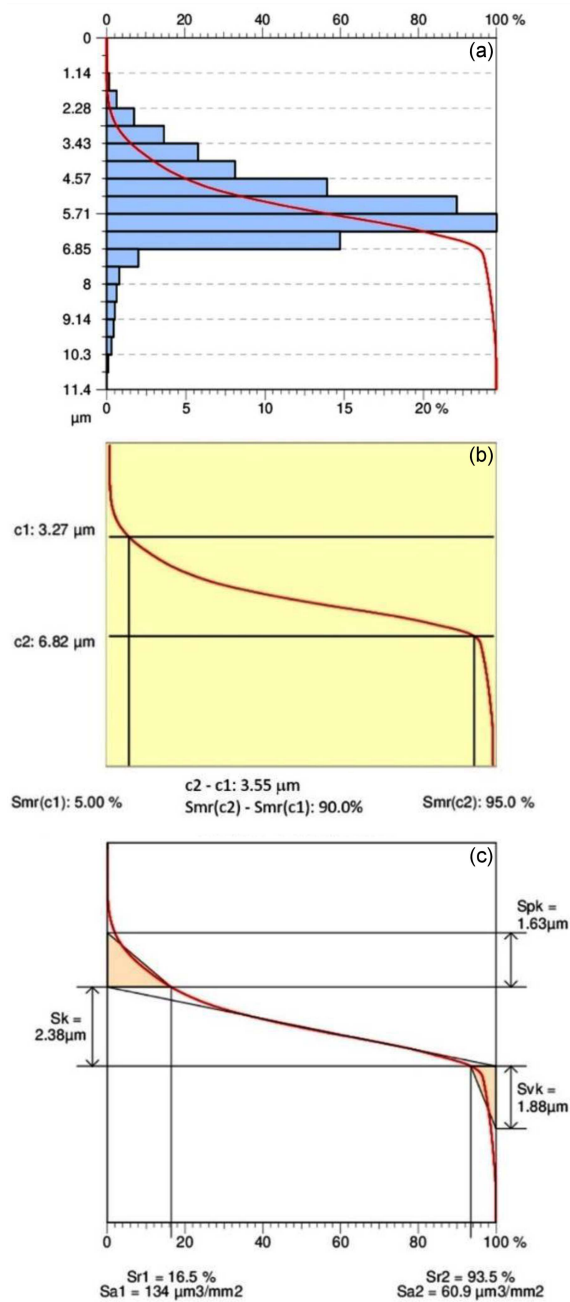


Fig. 7. Graphical representation of the material distribution along the surface profile after turning EN AW-6060 material with LFV technology using a cutting insert with an R0.2 corner, at the parameters $f_n = 0.03$ mm/rev, $V_n = 955$ rev/min; $a_p = 2$ mm, $Q = 2.5$, $D = 3.1$: (a) Abbott-Firestone curve with designated profile ordinates, (b) interactive Abbott curve, (c) material share curve.

increases from $1.3356 \mu\text{m}$ to $1.98 \mu\text{m}$, and parameter c_2 also obtains increasing values from 3.342 to $5.06 \mu\text{m}$. The same relationship occurs for the tested samples made using an R0.2 insert corner. The results obtained parameter c_1 values from 1.031 to $1.85 \mu\text{m}$. In turn, increasing the spindle speed

in the range of 573–1146 rpm for both cases of the tested samples using a constant feed rate of 0.03 mm/rev and parameter $Q = 2.5$ leads to a decrease in the values of parameters c_1 and c_2 . The same effect was also observed when increasing the Q parameter using other variable technological parameters. The effect of individual variables on the value of the upper flank surface Sr_1 was also considered. It was found that the increase in feed has the greatest impact on the value of parameter Sr_1 . While maintaining a constant rotational speed of 1146 rpm and parameter $Q = 2.5$, there is a change from 11.99% to 21.46% for samples obtained when turning using an insert with an R0.4 corner. In turn, for samples made using an insert with an R0.2 corner, the value of parameter Sr_1 changed from 13.30% to 15.35%. An increase in the Sr_1 value was also noted when increasing the spindle speed while maintaining a constant feed rate and the Q parameter. These changes for the R0.4 and R0.2 inserts were from 15.3% to 21.46% and from 5.13% to 15.35%, respectively.

When analyzing the data obtained from measurements of samples processed in LFV technology and made of other tested materials, the same correlation of changes in functional parameters with respect to technological parameters was observed.

4. Conclusions

The use of low-frequency vibration technology, i.e., an intermittent process of turning small-diameter elements, has led to a significant reduction in the susceptibility of difficult-to-machine materials such as 1.4404 stainless steel, CW004A electrolytic copper, and EN AW-6060 aluminum alloy to the ability to form C-shaped chips and small spiral pieces, which is beneficial for their removal and prevents chips from wrapping around the tool. This has reduced the need for the machine operator to remove chips after each machining operation, increasing productivity.

Based on the observations of sample machining, the parameter Q , which determines the ratio of amplitude to feed in LFV technology, should be at least equal to 2 for 1.4404 stainless steel and 1.5 for CW004A electrolytic copper and EN AW-6060 aluminum, in order to form a short, splintered chip, enabling smooth and stable machining.

The best surface quality parameters after turning with LFV using a tool with a corner radius of R0.2 were obtained with parameters $Q = 2.5$ and $D = 3.1$. Obtaining optimal surface quality parameters while simultaneously creating the appropriate chip shape during the cutting process depends on the type of material being processed, the tool, the technological and modeling parameters of machining in the LFV system, and the turning diameter. Analyzing the influence of individual

technological parameters, such as cutting speed and feed in turning with the use of LFV technology, on the quality parameters of surface roughness, one can observe similar relationships as in the case of conventional turning.

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