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THE ROLE OF LEAD IN THE MACHINABILITY OF COPPER ALLOYS USED FOR DRINKING WATER INSTALLATIONS

ABSTRACT

The machinability of two copper alloys with lead: CuZn40Pb2 and CuSn5Zn5Pb2, was assessed. Turning tests were performed based on the selection of parameters that will result in the tool being worn out after 1 minute. Tool wear was assessed by observing dimensional and microstructural changes in the blade. When assessing machinability, power consumption, chip shape, changes in the surface layer and surface roughness were taken into account. The research aims to determine the custom machinability index of materials used in SANHA Polska. A publicly available index must be adapted to a given application, and such adaptation is often quite time-consuming. Therefore, a 1-minute test was carried out as a quick and cheap alternative to a large fleet of machines with various machining properties. The developed methodology and the results obtained are the basis for further research conducted as part of the implementation doctorate, the aim of which is to implement the production of well-machinable lead-free materials for drinking water installations, characterized by good solderability and corrosion resistance. As a result of the conducted research, the role of lead in the machining of copper alloys was identified, which is important due to European restrictions on the elimination of this element and its replacement in a way that allows for precise removal processing.

Keywords: ***M****achinability; tool wear; copper alloys with lead; surface layer*

INTRODUCTION

Brasses with lead are characterized by a number of positive properties such as: high corrosion resistance, electrical conductivity, very good formability and mechanical properties. However, their main industrial application is their high machinability [1-3]. The microstructure and phase composition of brass alloys, including grain size and boundary misorientation, play a crucial role in their machinability and fracture resistance [4].Thanks to this, these materials are easily used for elements such as, for example, fittings for drinking water installations. Bronzes, on the other hand, are characterized by resistance to corrosion and high temperatures, excellent forgeability and ductility. They are also resistant to rapid wear. They are used to make fittings for

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stainless steel and copper pipes used in water and sewage and gas installations [5]. In lead bronzes, the morphology of Pb inclusions is important, as it affects mechanical properties and machinability. The morphology of lead inclusions is influenced by cooling rates during casting. Spheroidal lead inclusions, which are formed at low cooling rates, are preferred [6]. Moreover zinc sulfide formation in lead-free bronze castings affects machinability. Lower zinc sulfide ratios improve machinability, and the presence of tin and nickel has minimal impact on zinc sulfide ratios [7].

Brass fittings are characterized by good machinability due to the lead content [5]. Lead promotes discontinuous chip formation by deforming into flake-like shapes, which act as crack initiation points, reducing cutting forces, friction, and process temperature [8]. Moreover lead acts as a natural chip breaker and reduces tool wear, facilitating better chip control and lower cutting forces [9]. The size and distribution of lead globules in leaded brass significantly influence cutting performance, with better-distributed lead leading to improved machinability [1]. Lead content significantly affects the cyclic stress response, cyclic ductility, and low-cycle fatigue life of copper alloys. Alloys with higher lead content exhibit specific fatigue characteristics, such as intergranular fracture along grain boundaries [10]. Higher lead content improves the wear resistance of copper alloys, with optimal performance observed up to a certain lead percentage (e.g., 35 wt.%) [11].

Despite its many positive properties, environmental and health regulations require a reduction in lead content, which necessitates the development of lead-free alternatives. [4, 9, 12]. Silicon and graphite have been explored as alternative alloying elements to improve the machinability of lead-free brass. For instance, adding graphite particles to brass can enhance machinability similarly to lead [13, 14]. Whereas increasing silicon content in brass alloys can change chip type from continuous to discontinuous, reducing cutting force but increasing tool wear and surface roughness [14]. When comparing leaded brass with lead-free brass, it can be seen that leaded brass (e.g., CuZn39Pb3) shows significantly better machinability compared to lead-free alternatives, with lower tool wear and better chip control [9, 15-16]. Moreover lead-free brass alloys, such as CuZn21Si3P, exhibit higher tool wear and cutting forces, leading to longer cycle times and increased manufacturing costs [15, 17]. In addition to modifications to the chemical composition, ongoing research is being conducted to investigate the influence of plastic processing and heat treatment on the machining properties of Pb-free copper alloys. It was observed that the variation in the degree of work hardening and heat treatment influences the machinability properties of the material and can have a significant influence on the underlying chip formation mechanisms and the resulting chip shape, particularly during interaction with the selected process parameters [18].

The term machinability describes the susceptibility of the processed material to machining [19]. The machinability of a material depends on many factors such as geometry, workpiece material, type of cutting tool, type of machine tool, applied machining technique and machining conditions [20]. In the case of copper alloys, cutting force, surface roughness, chip shape and tool wear are often used to assess machinability [3, 20-21]. Determining the machinability rating based on tool wear involves machining the material at a constant cutting speed that gives a predetermined tool life of 60 min [22].

Copper and its alloys can be broadly divided into three categories based on their machinability, as evaluated by parameters such as chip shape, tool wear, and microstructure:

- Type I: alloys with excellent machinability:

This group includes copper-based materials that contain lead (Pb), tellurium (Te), or sulfur (S), often referred to as "chip breakers." These elements promote short, easily manageable chips during machining, reducing tool wear and increasing machining efficiency. Alloys in this category typically have a homogeneous or non-homogeneous microstructure and are used in applications where high precision and smooth surfaces are necessary. Leaded brass, like CuZn40Pb2, belongs to this category, making it a prime choice for applications that require excellent machinability.

- Type II: alloys with moderate to good machinability

This category primarily includes lead-free copper alloys. These materials exhibit moderate tool wear and produce medium-length chips during machining. They often have a heterogeneous microstructure and are harder than Type I alloys, allowing them to be cold-formed more easily. Alloys in this category offer a balance between machinability and mechanical strength, making them suitable for applications where both machining and forming operations are required.

- Type III: alloys with poor machinability

Materials in this group have a single-phase microstructure and are highly cold-workable, leading to higher cutting forces during machining. They produce long, ductile chips that are more challenging to manage and can cause rapid tool wear. This group includes copper-based materials containing zinc, tin, nickel, or aluminum in solid solution, as well as low-alloy strain-hardened copper alloys and high-strength copper-aluminum alloys. These materials are more challenging to machine but offer excellent mechanical properties and corrosion resistance. Type III also includes materials with a heterogeneous microstructure, such as low-alloy strain-hardened copper alloys and high-strength copper-aluminum alloys [20].

The problem of removing lead from machining materials remains relevant. Many researchers have identified problems with such machining [15, 18, 21-22], especially with regard to the technological scope, i.e., the process windows necessary for mass production. The novelty of this article is the systematic approach to identifying the role of lead in copper alloys, taking into account the machining process within acceptable industrial ranges and the selection of processes for the production of lead-free fittings for drinking water.

The aim of this work is to develop a procedure for quick preliminary testing of the machinability of various materials used in drinking water installations. This procedure is designed for use in a production environment, where rapid assessment is crucial. The primary criterion for evaluation is tool wear after 1 minute of machining tests. The study focuses on the machinability of two copper-lead alloys: CuZn40Pb2 (brass) and CuSn5Zn5Pb2 (bronze). The evaluation of these materials included the following key parameters: power consumption, chip shape and microstructure, changes in the surface layer, surface roughness. This approach ensures a comprehensive evaluation of the machinability characteristics of the alloys, providing a quick and practical method for assessing materials in real-world manufacturing scenarios.

MATERIALS AND METHODS

The test materials used for the machining study were two solid rods in their initial states: CuZn40Pb2 (brass) and CuSn5Zn5Pb2 (bronze). CuZn40Pb2 rod was drawn and thermally annealed with a diameter of 61 mm. The annealing process have softened the material, reducing internal stresses and making it easier to machine, while the drawing process have improved the surface finish and dimensional accuracy. CuSn5Zn5Pb2 rod was cast with a larger diameter of

81 mm. Casting generally results in a coarser grain structure compared to drawn materials, which may affect its machinability and mechanical properties, including a higher tendency to strengthen during machining. The chemical composition and mechanical properties of these alloys are provided in Table 1 and Table 2, respectively. The CuZn21Si3P alloy was used as a lead-free reference material, the chemical composition and mechanical properties of which are also given in Table 1 and Table 2.

Table 1. *Chemical composition of the tested materials*

Material	Element content, % by mass											
	Cu	Zn	Sn	Pb	Fe	Al	Ni	Si	Mn	S	Sb	As	P
CuZn40Pb2	57.7	rest	0.2	2.1	0.2	<0.01	0.05	<0.01	<0.01	0.001	0.004	-	-
CuSn5Zn5Pb2	86.92	5.18	4.47	2.73	0.10	0.002	0.50	0.004	0.002	0.027	-	0.008	0.007
CuZn21Si3P[1]	76.0	rest	0.02	0.05	0.05	<0.01	0.01	3.3	<0.01	-	-	-	0.05

[1]reference material

Table 2. *Mechanical properties of the tested materials*

Material	Rm, MPa	$Rp_{0.2}$, MPa	A, %	HV5
CuZn40Pb2	360	150	20	92-95
CuSn5Zn5Pb2	300	138	27.9	66.6
CuZn21Si3P[1]	612	275	40.5	143

[1]reference material

The microstructure of both materials was revealed using a 10% aqueous solution of ammonium persulfate and is presented in cross-section in Figure 1. The microstructure images were taken using an OLYMPUS BX53M light microscope from Evident, connected to a computer equipped with OLYMPUS Stream Essentials 2.4 software allowing digital recording of images.
CuZn40Pb2 brass is characterized by a heterogeneous microstructure consisting of α and β phases. Lead does not dissolve in this alloy and occurs mainly at grain boundaries. On the other hand, CuSn5Zn5Pb2 is characterized by a microstructure consisting of mixed α dendritic crystals, a homogeneous solution of tin and zinc in copper, eutectoid (α+δ) and Pb particles insoluble in the microstructure.

a) b)

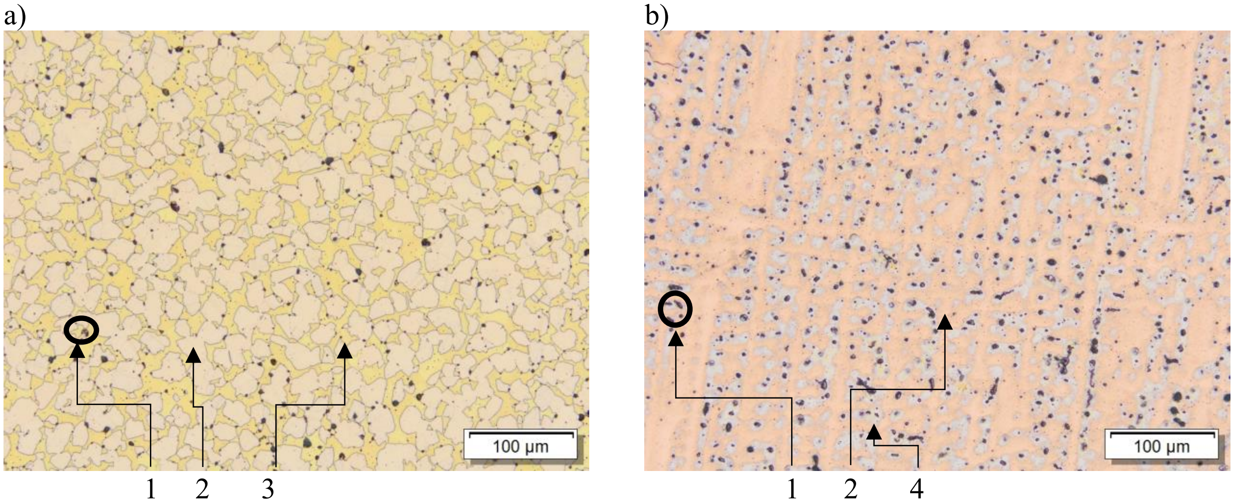

Fig. 1. Microstructure of alloys with marked microstructural components: a) CuZn40Pb2, b) CuSn5Zn5Pb2, where: 1 - lead precipitations, 2 – alpha-phase, 3 – beta-phase, 4- (α+δ)-eutectoid

Standard methods used for machining copper alloys are: turning, milling, drilling, grinding, Electrical Discharge Machining (EDM), laser or water jet cutting. CNC machining is considered the best due to: precision and consistency, the ability to machine a wide range of copper alloys with complex shapes, efficient cooling, the ability to select parameters that reduce tool wear and obtain parts with high surface quality.

The tested materials were subjected to an external longitudinal turning operation on a Haas VM-3 universal lathe from Haas Automation. This is the most common operation during the production of connectors in the plant. The DWLNR2525M08 cutter was used for the tests, with a WNMG080408-MF4 carbide insert, grade CP500 (Secotools tools), with a corner radius of 0.8 mm. This type of insert is used for machining low-alloy steels and copper alloys used in the company. The longitudinal turning operation was performed on pieces of bar 130 mm long each, of which the working surface was 100 mm, 30 mm was used to secure the samples in the machine holder. For technological reasons related to accelerating the production of components, it is important to determine the highest speed that gives acceptable surface roughness effects. So, the tests were performed in 4 passes so that the machining time was 1 minute. In addition, in order to wear out the tool, significantly higher cutting speeds were used than those recommended by the tool manufacturer. The values used in relation to the recommended by the tool manufacturer to machining copper alloys using carbide insert (grade CP500) ones are listed in Table 3. In addition, in Table 3, the turning parameters of the lead-free material as a reference material are given to assess the effect of the presence or absence of lead on the machinability. The cutting speed recommended by the tool manufacturer was used when cutting the lead-free material. The process was carried out with cooling by means of a water-based emulsion. During the tests, the following were taken into account: power consumption, tool wear, surface roughness and chip shape. The changes in the surface layer were also assessed.

Table 3. *Turning parameters*

Material	Axial cutting depth ap, mm	Cutting speed Vc, m/min	Feed, mm/rev
CuZn40Pb2	2	290 (117-213)[1]	0.22 (0.273-0.440)
CuSn5Zn5Pb2	2	280 (110-199)[1]	0.31 (0.273-0.440)
CuZn21Si3P[2]	2.5	170	0.2

[1]recommended by the tool manufacturer [23], [2]reference material

Power consumption during turning has a direct impact on the machinability of the material. Materials with better machinability are characterized by lower power consumption [6]. This parameter was recorded by reading the value directly from the device, after the process stabilization. Then the obtained values were averaged. The tool was analyzed by observing the rake surface using the OLYMPUS BX53M light microscope from Evident, connected to a computer equipped with OLYMPUS Stream Essentials 2.4 software allowing digital recording of images. The tool analysis is intended to confirm that the turning parameters were selected in accordance with the test assumptions. To measure the surface roughness after machining, a MarSurf PS1 from Mahr mobile surface roughness measuring device was used. The obtained results were classified in accordance with PN-EN ISO 1302:2004 [24]. In the case of parts made of copper alloys in the company, Ra should not exceed 6.3 μm. The evaluation of the shape and size of the chip was performed in accordance with PN-ISO 3685, by taking pictures using a Panasonic Lumix DMC-LS2 digital camera of chips arranged on graph paper. Both the shape and size of the chip are important due to the quality of the finished product and the efficiency of the removal process. The most advantageous are short chips that take up little space and can be easily removed from the cutting zone. Thanks to this form, the chips do not get tangled on the workpiece and the tool, do not scratch the surface of the part and take up little space compared to the material before machining [7]. The assessment of changes in the surface layer was carried out using the OLYMPUS BX53M light microscope from Evident, connected to a computer equipped with OLYMPUS Stream Essentials 2.4 software allowing digital recording of images and by measuring microhardness with an Innovatest Falcon 500 device using the Vickers method at a load of 100 gf at a distance of 1.5 mm from the sample surface into the material.

RESULTS AND DISCUSSION

Characteristics of the machining material

Figure 2 shows the microstructure of the surface layer of CuZn40Pb2 and CuSn5Zn5Pb2. CuZn40Pb2 brass is characterized by a heterogeneous microstructure consisting of α and β phases.

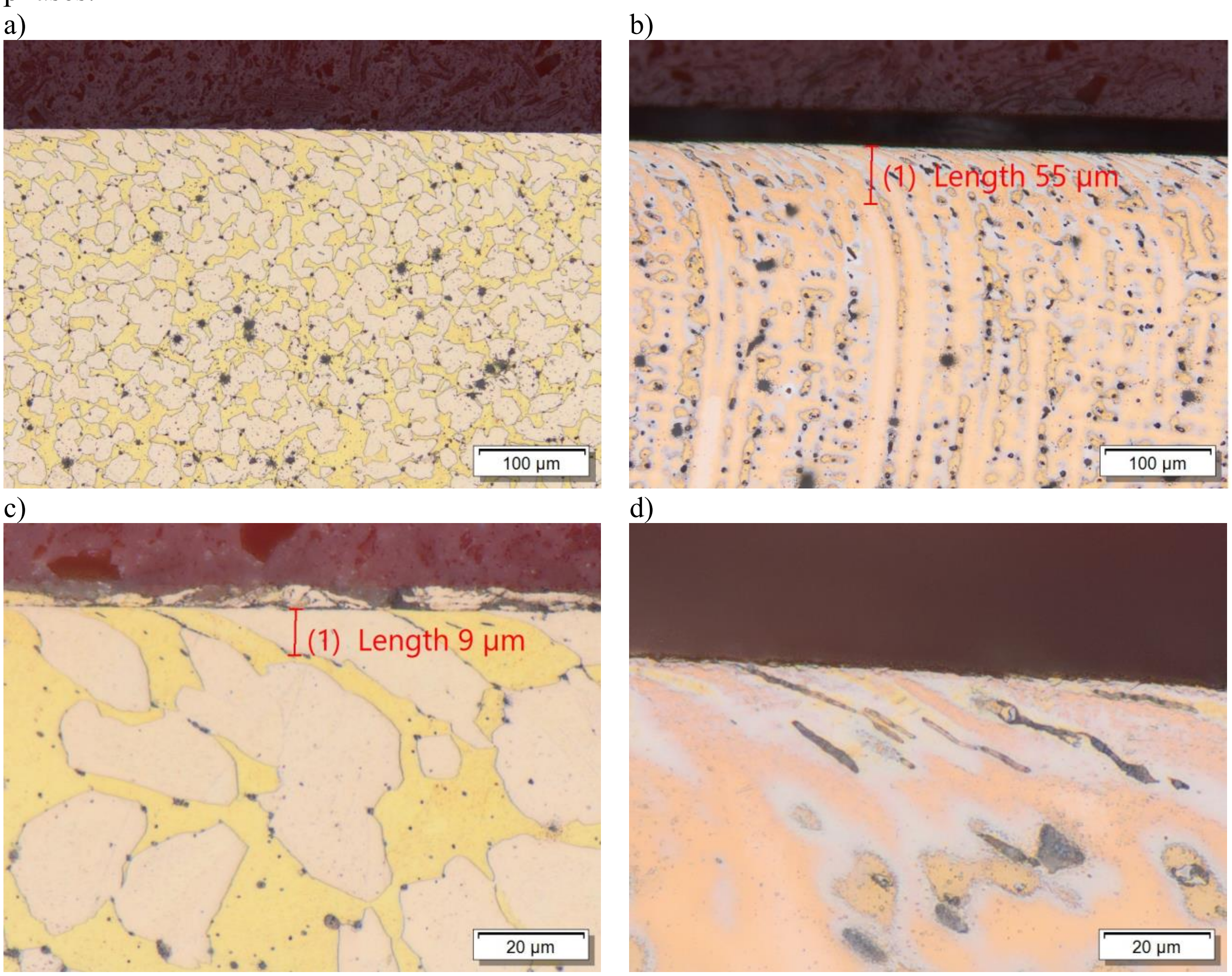

Fig. 2. Microstructure of the surface layer after turning: a) CuZn40Pb2 with the undeformed area, b) CuSn5Zn5Pb2 with the maximum deformation depth marked, c) CuZn40Pb2 with the maximum deformation depth marked, d) CuSn5Zn5Pb2 deformed area

Lead is insoluble in this alloy and occurs primarily at grain boundaries. As a result of machining, the maximum deformation depth of the surface layer is approximately 9 µm. In contrast, CuSn5Zn5Pb2 is characterized by a microstructure consisting of mixed α dendritic crystals, a homogeneous solution of tin and zinc in copper, eutectoids (α + δ), and lead particles insoluble in the microstructure. As a result of machining, the deformation depth is significantly greater than in brass, reaching approximately 55 µm.

In order to confirm the obtained values, microhardness measurements were performed from the surface into the depth of the material, as shown in Figure 3. The measured hardnesses confirm that in the case of CuZn40Pb2 the influence of turning on the properties of the surface layer is insignificant, whereas in the case of bronze an increase in hardness is visible to a depth of approx. 0.4 mm.

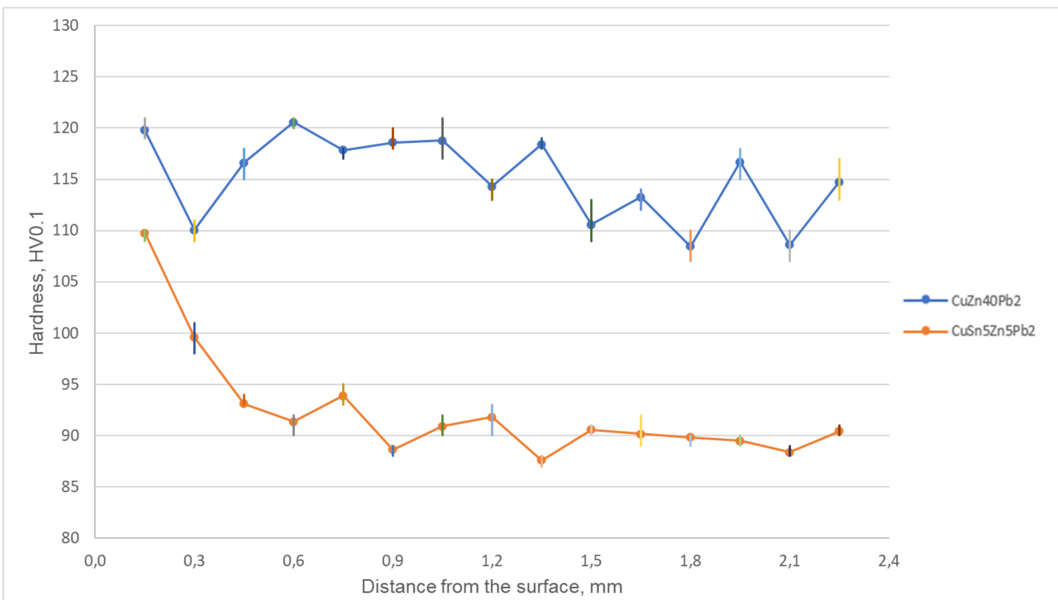

Fig. 3. Diagram of microhardness distribution from the surface into the material for the tested copper alloys

Figure 4 illustrates the different chip formations resulting from the machining of CuZn40Pb2 (brass) and CuSn5Zn5Pb2 (bronze). In CuZn40Pb2 the chips produced are type 8, characterized as needle. These chips are flat and relatively small, reflecting the material's ability to deform into discontinuous, manageable shapes, which helps in smoother machining with reduced chip congestion. The chips obtained are of the same type as those obtained for the CuZn39Pb3 material in another study [25]. In contrast, the chips produced from bronze are type 6.2, described as loose arc chip. These chips are cylindrical in shape, likely resulting from the more ductile nature of bronze, which allows for the formation of tubular structures before the chips break off. The difference in chip morphology between the two materials highlights their distinct machining behaviors. Brass tends to form flatter chips that break easily, while bronze generates more three-dimensional tubular chips, which may require different handling or chip removal strategies during machining.

Analyzing the microstructure of the chips obtained (Fig. 5) in the case of CuZn40Pb2, one can see the way in which the chips were formed – the chip microstructure at the point of contact with the tool is characterized by a strongly deformed grain. In the case of CuSn5Zn5Pb2, the chips formed, in addition to grain deformation, are characterized by numerous cracks at the place of chip formation, which indicates that the cutting force for this material is too high.

a) b)

Fig. 4. Chip appearance after turning: a) CuZn40Pb2, b) CuSn5Zn5Pb2

As a result, the material is locally strengthened above its plastic limit and the material continuity is broken. In the case of machining of bronze, the hardening and tendency to cracking of chips should be considered advantageous because these mechanisms facilitate the separation of the chip, which will not tend to stick to the tool. In order to confirm this, chip microhardness measurements were performed. 4 chips were measured for each material. For brass, microhardness ranges from 164 HV0.1 to 187 HV0.1, while for bronze from 192 HV0.1 to 218 HV0.1. It can be seen that the microhardness of the CuSn5Zn5Pb2 chip increased approximately 3 times compared to the hardness of the material before turning.

Process characteristics and tool wear

The power consumption during machining is clearly different between the two materials. In the case of brass (CuZn40Pb2), the power consumption was measured at 5.4 kW. Brass has a higher tensile strength and higher hardness than bronze, and as a result, brass is easier to machine due to lower deformation and less strain hardening, which results in lower cutting forces and consequently lower energy requirements. In the case of CuSn5Zn5Pb2, on the other hand, the power consumption was higher at 6.5 kW. Bronze has a lower tensile strength and lower hardness. The increased power requirement is attributed to the tendency of bronze to locally strengthen more during the machining process. This strain hardening effect increases the material's resistance to cutting, requiring more energy to overcome the strengthened surface layer. The higher energy consumption of bronze indicates that it is more difficult to machine than brass, primarily due to its greater tendency to work harden under mechanical stress, which increases cutting forces and energy requirements. Comparing the influence of different lead contents and its morphology, it should be noted that despite the higher lead content, bronze is characterized by a coarse-grained cast structure, which affects its worse machinability than CuZn40Pb2 - after annealing, characterized by a much finer grain with small lead precipitations mainly on the grain boundaries.

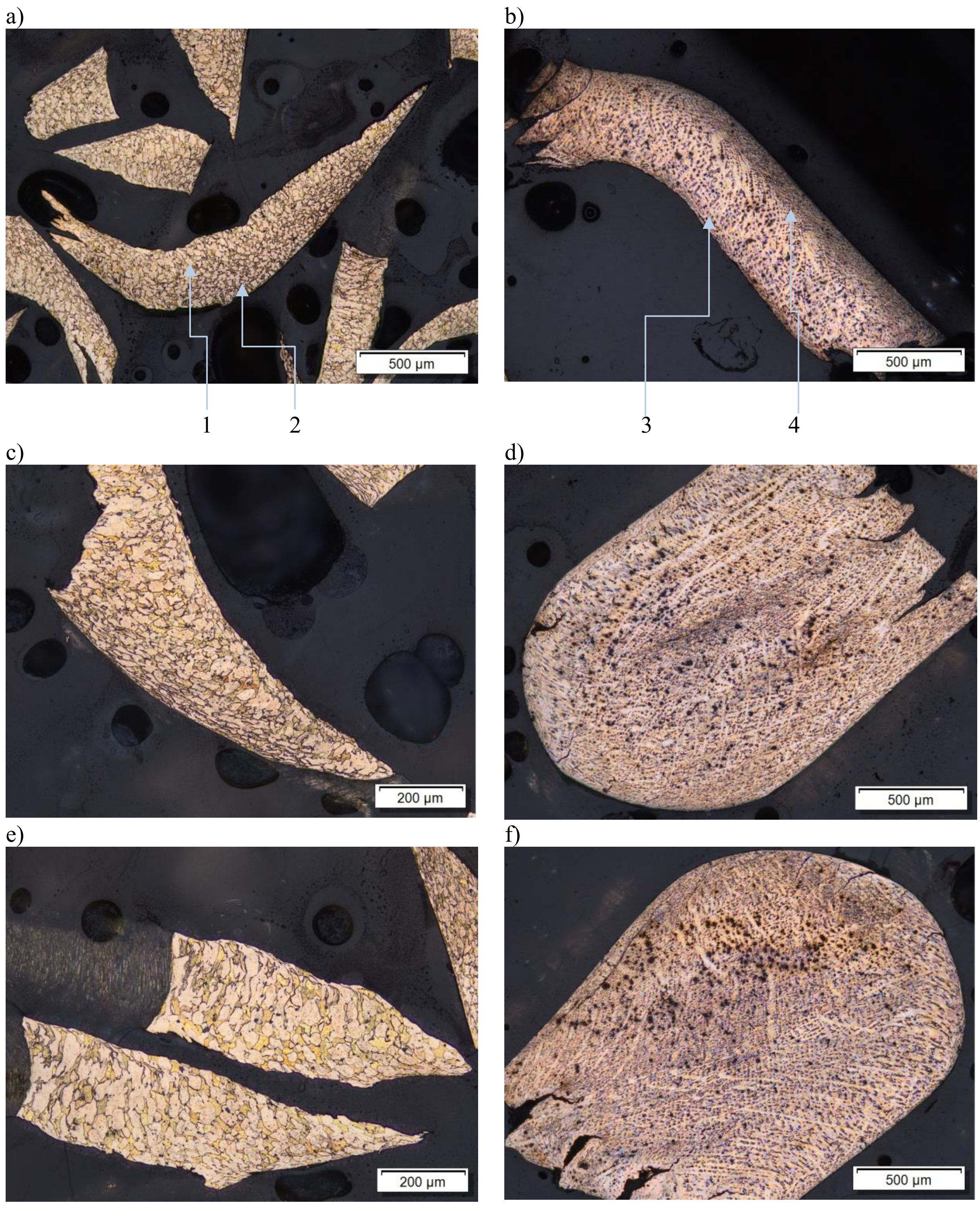

Fig. 5. Chip microstructure: a, c, e) CuZn40Pb2; b, d, f) CuSn5Zn5Pb, where: 1- 164-169 HV0.1; 2- 177-187 HV0.1; 3- 192-201 HV0.1; 4- 207-218 HV0.1

While turning a reference material (CuZn21Si3P), a power consumption of 6.7 kW was measured. It should be noted that despite the lower cutting speeds, lead-free CuZn21Si3P has a higher power consumption than bronze and brass with lead. The increased power consumption for lead-free materials is consistent with the results of other studies [15, 17, 25].

When analyzing the surface quality obtained after turning, it can be seen that in both cases the obtained values are very similar and are characterized by high surface quality. For brass, the Ra parameter was 0.665 µm – class 7, while for bronze – 0.686 µm – also class 7. Figures 6 and 7 show the wear of the cutting insert. After turning CuZn40Pb2, delamination of the titanium nitride coating on the insert is visible. Numerous adhesions of the machined material are also visible. In the case of CuSn5Zn5Pb2, numerous cracks in the coating on the rake face and slight adhesion are visible. Table 4 summarizes the obtained results.

a) b)

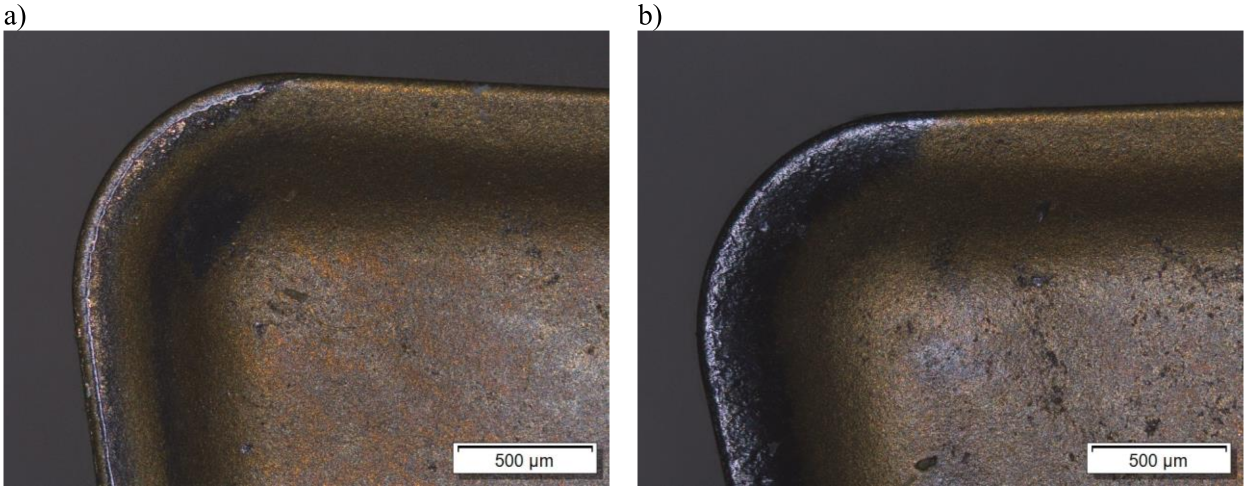

Fig. 6. Tool wear - flank surface: a) CuZn40Pb2, b) CuSn5Zn5Pb2

Table 4. *Summary results*

Parameter	CuZn40Pb2	CuSn5Zn5Pb2
Changes in the surface layer	9 µm	55 µm
Shape and size of chips	Type 8 – needle chip	Type 6.2 – loose arc chip
Chip microhardness	164 – 187 HV0.1	192 – 218 HV0.1
Power consumption	5.4 kW	6.5 kW
Roughness	Ra 0.665 µm (class 7) Rz 3.13 µm	Ra 0.686 µm (class 7) Rz 4.14 µm
Cutting insert wear	Visible damage to the coating, delamination, sticking	Multiple cracks in the rake surface, minor sticking

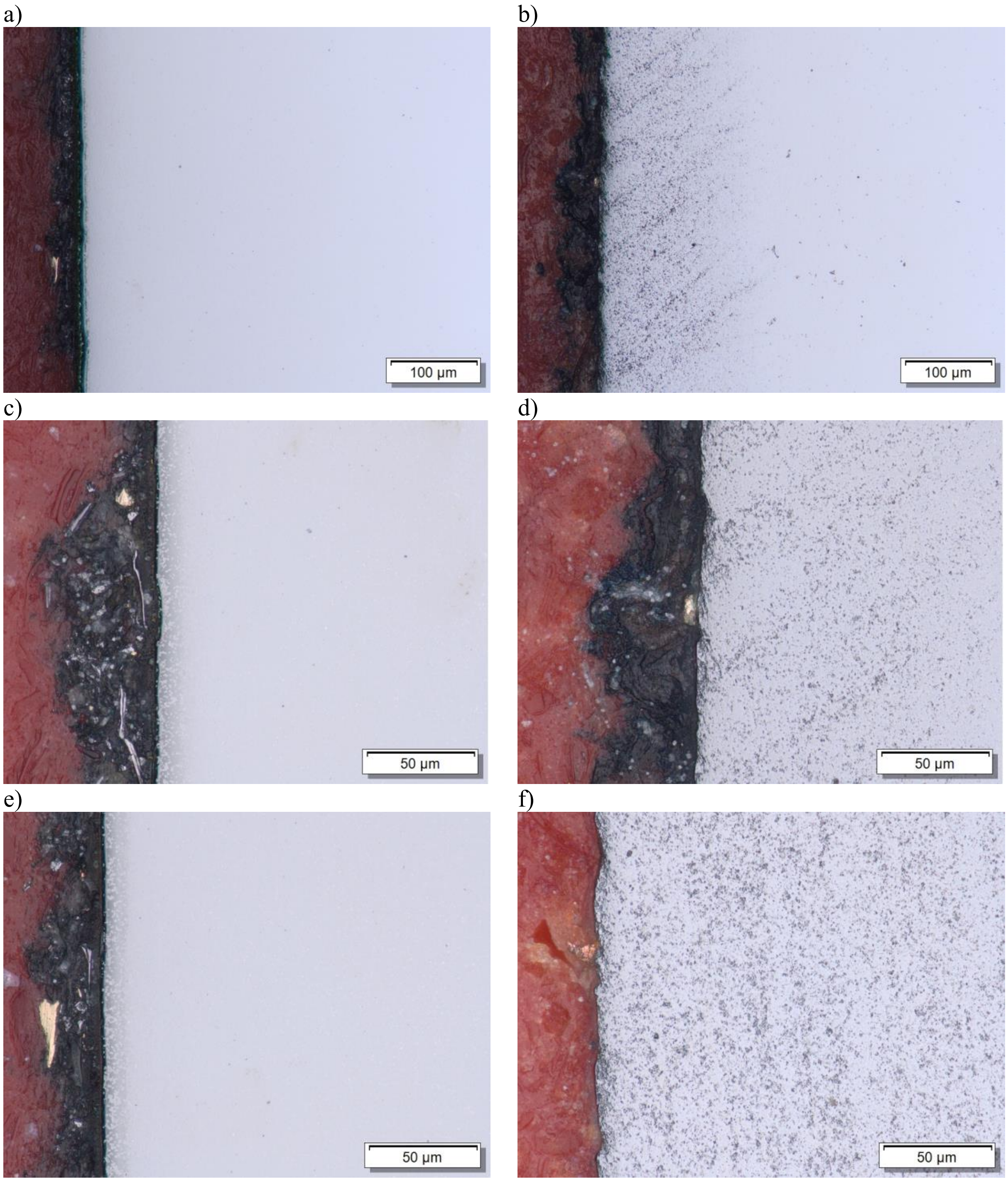

Fig. 7. Tool wear – cross-section through the flank surface: a, c, e) CuZn40Pb2; b, d, f) CuSn5Zn5Pb

CONCLUSIONS

The objective of this research was to create a procedure for a quick preliminary test of the machinability of various materials, focusing specifically on those suitable for drinking water installations. While most traditional methods of assessing machinability require much longer machining times, this method is intended for rapid assessment and compares material machinability within 1 minute of turning. The proposed procedure was tested on two copper-lead alloys: CuZn40Pb2 and CuSn5Zn5Pb2. As a result of the conducted research, the role of lead in the machining of copper alloys was identified, which is important due to European restrictions on the elimination of this element and its replacement in a way that allows for precise removal processing.

Key Findings:

- Tool Wear: After 1 minute of machining, both materials showed distinct patterns of wear, achieving the research goal of quickly assessing machinability. However, the wear mechanisms differed: After CuZn40Pb2 machining the titanium nitride coating on the tool showed delamination and numerous instances of material sticking. This type of wear indicates some adhesion of the workpiece material to the cutting tool, potentially due to the material's properties and machining conditions. After CuSn5Zn5Pb2 machining the tool showed numerous cracks on the rake surface, but only minor sticking of the workpiece material. Despite having a higher lead content, bronze displayed poorer machinability than brass.
- Chip Shape and Microstructure: Brass produced better chip formation (needle chip) with no cracks, while bronze chips were loose arc type and presented cracks. Good chip formation is critical for efficient material removal and preventing tool damage.
- Surface Layer Changes: Brass exhibited less impact on the surface layer after machining, suggesting minimal deformation and a more stable surface quality compared to bronze, which showed greater surface layer changes.
- Surface Roughness and Power Consumption: Brass showed better surface roughness and required less power (5.4 kW) during machining, contributing to its superior machinability. Brass has a higher tensile strength and higher hardness than bronze, and as a result, brass is easier to machine due to lower deformation and less strain hardening, which results in lower cutting forces and consequently lower energy requirements. Bronze required more power (6.5 kW), despite being a softer material. This anomaly is attributed to bronze's tendency to strengthen during cutting, increasing the energy needed for machining.
- Machining: It should be noted that the materials with lead have a lower power consumption than the lead-free material CuZn21Si3P. Based on the tests, can be concluded that CuZn40Pb2 has the best machinability, followed by CuSn5Zn5Pb2, and then CuZn21Si3P.

The study met its primary objective of developing a quick, 1-minute machinability test. The findings indicated that CuZn40Pb2 exhibited better machinability compared to CuSn5Zn5Pb2, with more favorable chip formation, lower surface impact, smoother surface finish, and lower power consumption. The machining method used is characterized by precision and repeatability, the ability to process a wide range of copper alloys with complex shapes, efficient cooling, the ability to select parameters that reduce tool wear and allow you to obtain parts with high surface quality. The research lays the groundwork for further testing of lead-free copper alloys to assess their machinability for drinking water installations.

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Conflicts of Interest

The authors declare that they have no competing financial interests or personal relationships that could have seem to influence the study reported in this paper.

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