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ORIGINAL ARTICLE

Machinability and manufacturing cost in low-lead brass

Fredrik Schultheiss[1] · Christina Windmark[1] · Stefan Sjöstrand[1] · Magnus Rasmusson[1] · Jan-Eric Ståhl[1]

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Abstract

Today, commercially used brasses commonly contain 2 to 4 wt% lead. As the availability of low-lead and lead-free brass increases, there are environmental incentives for investigating the consequences of replacing the lead-containing brasses with lead-free equivalents. Generally, lead-free brass is expected to have a lower machinability than its lead-alloyed counterpart, implying a higher manufacturing cost. Thus, the aim of this study has been to quantify the added manufacturing cost by replacing a standard brass alloy with a low-lead alternative. This was done through a case study performed at a Swedish SME which replaced CuZn39Pb3 (3.3 wt% Pb) with low-lead CuZn21Si3P (< 0.09 wt% lead) for a select part. Since CuZn21Si3P is almost twice as expensive as CuZn39Pb3, the material cost was found to have a substantial influence on the manufacturing cost. Additionally, the lower machinability implied a longer cycle time and higher losses while machining CuZn21Si3P, resulting in a 77% overall increase in manufacturing cost when using the low-lead material. Arguably, the difference in material cost, and thus manufacturing cost, may decrease over time making production of low-lead and lead-free brass products a viable option, especially when considering the environmental incentive for decreasing the amount of lead in circulation.

Keywords Machining · Brass · Lead · Machinability · Manufacturing cost

1 Introduction

Lead is a common additive in free-machining brasses. According to European legislation, copper alloys, e.g., brass, are currently allowed to contain up to 4 wt% lead [1]. The addition of lead in brass is considered as improving the machinability through improving chip breaking, lowering cutting forces, decreasing tool wear, and permitting better surface roughness and tolerances [2]. However, as the importance of sustainable production is increasingly recognized, interest for decreasing the amount of lead in circulation is growing. Further legislative actions, decreasing the amount of lead in brass, are likely in the future as emphasized by Nobel et al. [3] even if none has thus far been published.

Lead (Pb) is a heavy metal which is toxic even at low exposure levels and has been found to have acute and chronic effects on human health. In nature, lead is toxic to plants, animals, and microorganisms [4]. The International Lead and Zinc Study Group, formed by the United Nations 1959, has estimated that 115,000 t of lead was used in different alloys during 2003 by the countries reporting to the organization, estimated as being equivalent to roughly 80% of the world consumption during the same time period [4]. Lead is soluble in molten brass but precipitates into the grain boundaries during solidification commonly forming particles 1 to 10 μm in diameter [5]. Trent and Wright [5] found that addition of lead in brass greatly reduces the cutting forces, shortens the chips, and decreases the tool wear.

Due to the detrimental effects of lead on the environment, several alternative alloying elements have been proposed. For example, La Fontaine and Keast [6] evaluated the possibility of substituting lead with bismuth in brass with promising results. Later, Li et al. [7] proposed the addition of a small amount of titanium in the bismuth-alloyed brass. However, the high price of bismuth and titanium compared to other alloying elements has discouraged any further use. Another possible solution is to substitute lead with silicon although this has been perceived as somewhat reducing the machinability as summarized by Taha et al. [8], thus conceivably increasing the manufacturing cost.

To assess the impact of changing workpiece material, i.e., machinability, manufacturing cost may well be a crucial

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✉ Fredrik Schultheiss
fredrik.schultheiss@iprod.lth.se

[1] Production and Materials Engineering, Lund University, 221 00 Lund, Sweden

parameter to compare. This is because costs often are the basis for informed decisions concerning the production system and because there are manufacturing cost models incorporating performance, enabling an overall analysis on the effects of changing the process prerequisites. Hence, manufacturing cost can be used comparing different developmental scenarios, such as substitution of workpiece material. Previous research by the authors have proven that it is possible to machine parts in brasses with varying lead content, although proper considerations are required while selecting the process conditions [9]. Since the manufacturing process must be adapted for the different workpiece materials, i.e., lead-containing, low-lead, and lead-free brass, this will imply a variation of the manufacturing cost. It is also plausible to assume that this variation of workpiece materials will influence the loss parameters during machining, i.e., scrap rate, downtime rate, and production rate loss. Thus, the aim of the study described in this paper has been to investigate the monetary effect of transitioning to low-lead brass from a production perspective. This knowledge can then be weighed against the envisioned environmental benefits, possibly encouraging an increased use of environmental friendly materials, and thus contributing to sustainable production.

2 Manufacturing cost calculation

Several different models for calculating the manufacturing cost have been published through the years. Summaries and reviews have for example been published by [10–13]. Based on the cost models review done by Jönsson [13] and later extended by Ståhl [12], an overview of cost models available for assessing manufacturing has been compiled (Table 1). As stated by Tipnis et al. [24], these models can usually be divided into microeconomic models and macroeconomic models. Typically, microeconomic models specify the influence of specific process parameters on the manufacturing cost. In the bottom right corner of Table 1, models related to microeconomic considerations can be seen to have a considerably higher number of parameters connected to the process level. Such models for machining operations have for instance been published by Colding [22] and Alberti et al. [24] among others. For example, these models can describe how the cutting data, i.e., cutting speed, feed, and depth of cut, influences the manufacturing cost. In contrast, in a macroeconomic model, several of these process parameters have been aggregated in order to form a more holistic model. A typical example of this could be to only base macroeconomic models on cycle time and not the individual factors influencing the cycle time. Groover [19] has published a macroeconomic model that only takes one production loss parameter into consideration, the scrap rate. Ravignani and Semeraro [20] have developed a model which combines micro- and macroeconomic factors by including both cutting conditions and the batch size. However, their model does not take any loss parameters into consideration. Overall, microeconomic models are specific for the manufacturing process in question, requiring numerous different models depending on circumstances. In comparison, a macroeconomic model may be used for different manufacturing process, although it inhibits evaluation of how specific process conditions influence the manufacturing cost. This problem is partly overcome by using the manufacturing cost model introduced by Ståhl et al. [18], and later improved by Jönsson et al. [27]. Their model, Eq. (1), can be described as a macroeconomic model with the added benefit of considering selected microeconomic parameters. The selected microeconomic parameters are performance parameters on a system level instead of the process level, see Table 1, giving the speed rate based on ideal cycle time, the downtime rate, and quality rate of a produced product. The economic quality cost model published by Chiadamrong [16] also incorporate microeconomic parameters into a macroeconomic model, e.g., quality, idling, and downtime in equipment, but does not take speed rate losses into consideration. The model is extensive and include vital aspect of production, compared with the model presented by Ståhl et al. [18]. The complexity of the model is vastly surpassed, which impedes the usability.

$$k=\frac{k_A}{N_0}+\frac{k_B}{N_0}\left[\frac{N_0}{1-q_Q}\right]+\frac{k_{CP}}{60N_0}\left[\frac{t_0\cdot N_0}{\left(1-q_Q\right)\left(1-q_P\right)}\right]+\frac{k_{CS}}{60N_0}\left[\frac{t_0\cdot N_0}{\left(1-q_Q\right)\left(1-q_P\right)}\cdot\frac{q_S}{1-q_S}+T_{su}+\frac{1-U_{RP}}{U_{RP}}T_{Pb}\right]+\frac{k_D}{60N_0}\left[\frac{t_0\cdot N_0}{\left(1-q_Q\right)\left(1-q_P\right)}\cdot\left(1+\frac{q_S}{1-q_S}\right)+T_{su}+\frac{1-U_{RP}}{U_{RP}}T_{Pb}\right] \tag{1}$$

The following denotations are used in Eq. (1): part cost k, tool cost k_A, material cost k_B, machine cost during production k_{CP}, machine cost during downtime k_{CS}, personnel cost k_D, nominal batch size N_0, nominal cycle time t_0, scrap rate q_Q, downtime rate q_S, production rate q_P, setup time T_{su}, machine utilization U_{RP}, and production time of a batch T_{Pb}.

3 Machinability of brass

Brass, a copper-zinc alloy, is a common engineering material used for an array of different products. Many so-called free-machining brasses contain up to 4 wt% lead, although

Table 1 Summary of manufacturing cost models

	Macroeconomic models						Microeconomic models						
	Koltai et al. [14]	Ozbayrak et al. [15]	Chiadamrong [16]	La Diega et al. [17]	Ståhl et al. [18]	Groover [19]	Ravignani and Semeraro [20]	Jung [21]	Colding [22]	Cauchick-Miguel and Coppini [23]	Alberti et al. [24]	Branker et al. [25]	Orji and Wei [26]
Parameters	System level												
Material		x	x		x	x	x	x	x	x	x	x	x
Scrap price			x										
Indirect material			x		x					x		x	x
Mass/volume of product													x
Inventory	x	x					x		x				
Production volume	x	x	x		x	x		x		x			
Production period			x		x					x			x
Equipment depreciation	x	x	x	x						x		x	
Equipment life		x			x			x					
Equipment costs					x	x	x	x	x		x		x
Fixture costs		x		x	x				x				
Computer		x		x								x	
Floor space		x			x					x			
Building cost		x			x								
Building life		x											
Utilities (not specific)			x		x					x		x	
Energy costs		x			x								x
Tool costs	x	x		x	x		x		x	x		x	
Labor costs: direct		x	x		x	x		x	x	x	x	x	x
Labor costs: indirect		x	x		x				x		x	x	
Maintenance	x	x	x		x	x				x		x	
Repairs			x										
Material handling	x	x	x	x								x	
Rework		x	x				x			x			
Overhead costs		x	x			x		x		x			
	System capability												
Downtime		x	x		x			x	x				
Speed losses					x								

Table 1 (continued)

	Macroeconomic models						Microeconomic models						
	Koltai et al. [14]	Ozbayrak et al. [15]	Chiadamrong [16]	La Diega et al. [17]	Ståhl et al. [18]	Groover [19]	Ravignani and Semeraro [20]	Jung [21]	Colding [22]	Cauchick-Miguel and Coppini [23]	Alberti et al. [24]	Branker et al. [25]	Orji and Wei [26]
Setup	x	x	x		x			x	x	x		x	
Waiting		x	x	x									
Idling			x	x	x								
Quality: scrap from process					x								
Quality: prevention			x										
Quality: rejects/failure		x	x		x	x			x				
Quality: appraisal	x		x						x	x			
Equipment utilization				x	x								
Environmental aspects												x	x
	Process level												
Cycle time			x	x	x	x	x	x	x	x	x	x	x
Tool engaging time							x	x	x	x	x		x
Idling in cycle						x		x	x		x	x	x
Cutting data							x	x	x	x	x		x
Tool life					x		x		x	x	x	x	
Tool maintenance										x		x	

Table 2 Chemical composition according to nominal standards (wt%) [28, 29]

Material	Cu	Zn	Pb	Si	P
CuZn39Pb3	57.3	Balance	3.3	–	–
CuZn21Si3P	76	Balance	< 0.09	3	0.05

an increasing amount of low-lead and lead-free brasses is becoming commercially available. The permissible amount of lead in a lead-free brass is disputed, but the authors have chosen to designate levels of lead < 0.05 wt% Pb as “lead-free” and < 0.2 wt% Pb as “low-lead.” The implication is that there are few lead-free brasses commercially available, arguably partly due to the difficulty of removing lead from brass scrap during recycling. As a technique for illustrating the difference in machinability between a conventional free-machining brass and a low-lead brass, a comparison between CuZn39Pb3 (3.3 wt% lead) and CuZn21Si3P (< 0.09 wt% lead) has been made. The chemical composition for each of these materials can be found in Table 2 and examples of the microstructures can be found in Fig. 1. The dark spots in each micrograph in Fig. 1 constitutes lead particles randomly distribute throughout each material. Both brasses are dual-phased where CuZn39Pb3 contains roughly 70% α-phase and 30% β-phase while CuZn21Si3P contains roughly 60% α-phase and 40% κ-phase [30].

Machinability is a multi-faceted parameter generally evaluated through combining several different process behaviors during the machining process. Although the exact definition varies somewhat between different sources, many authors include most or all of the following process behaviors: (1) surface integrity, (2) chip geometry and properties, (3) energy consumption and cutting forces, and (4) tool deterioration [31]. In order to make an initial comparison of the machinability for the two evaluated materials, CuZn39Pb3 and CuZn21Si3P, a series of experimental machining operations have been performed [9], as summarized in the following sections.

3.1 Surface integrity

Surface integrity has a wide definition pertaining to all material properties influenced by the machined surface such as surface roughness, fatigue life, corrosion resistance, and residual stresses [32, 33]. Although all of these properties are important, primarily the surface roughness is measured in industry. An initial comparison of the arithmetic mean surface roughness R_a was made after longitudinally turning CuZn39Pb3 and CuZn21Si3P at varying theoretical chip thicknesses, h_1, while using coated CNMG120404, CNMG120408, CNMG120412, and CNMG120416 cemented carbide cutting tools with four different nose radii, r_ε (Fig. 2). During all experiments, a cutting speed of $v_c =$ 400 m/min and depth of cut $a_p = 1.5$ mm were used without the application of any cutting fluid.

As can be seen in Fig. 2, the surface roughness is markedly better while machining CuZn21Si3P for small values of h_1. The difference decreases for large values of h_1, essentially becoming negligible for $h_1 = 0.2$ mm although some differences between the tools with different radii may persist. Thus, in this comparison, the machinability of CuZn21Si3P appears better when compared to that of CuZn39Pb3 owing to the possibility of producing smoother surfaces.

3.2 Chip geometry

Each of the two investigated materials, CuZn39Pb3 and CuZn21Si3P, was machined at varying process conditions while using uncoated DNGA150708 cemented carbide cutting tools in order to investigate the obtained chip geometry. During this investigation feed, $f = 0.05$, 0.10, 0.15, 0.20, 0.25, and 0.30 mm/rev, and depth of cut, $a_p = 0.5$, 1.0, 1.5, 2.0, and 2.5 mm, was used. The cutting speed was kept constant at $v_c =$ 400 m/min and no cutting fluid was used during these experiments as to be comparable with commercial processes. Consistently for the investigated process conditions, it was found that CuZn39Pb3 mostly produced discontinuous chips and CuZn21Si3P produced longer, lamellar chips. As expected, CuZn21Si3P displayed better chip breaking at higher

Fig. 1 Optical micrograph on the structure of the evaluated materials. CuZn39Pb3 (left) and CuZn21Si3P (right)

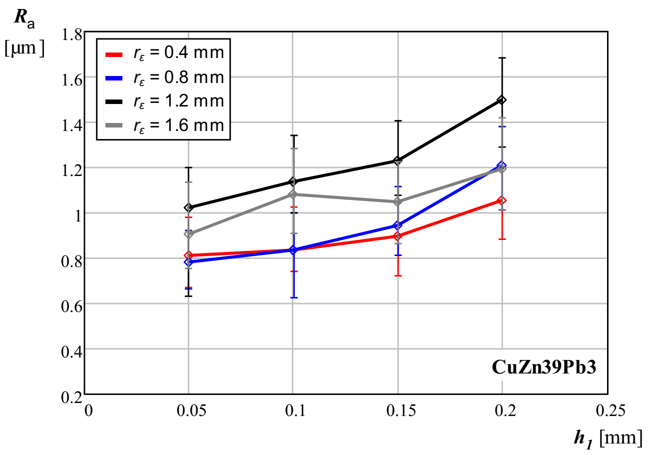


Fig. 2 Measured R_a values for varying tool nose radii

feeds and depths of cut. Machining of CuZn39Pb3 produced discontinuous chips for the whole range of process conditions evaluated with no major variation in chip geometry observed for this material. Chip cross sections from each material at $f =$ 0.30 mm/rev and $a_p = 2.5$ mm can be found in Fig. 3.

3.3 Cutting forces

The cutting forces were measured for the same process conditions as used for the previously described chip geometry experiments. In each case, the cutting force components, the main cutting force F_c, the feed force F_f, and the passive force F_p were measured. Figure 4 illustrates a comparison of the measured main cutting forces F_c for the two investigated materials. As can be seen in Fig. 4, the main cutting force is slightly higher when machining CuZn21Si3P as compared to CuZn39Pb3, even though the overall force values are low if for instance comparing to steels. Because of the higher cutting forces, a slightly faster tool deterioration could potentially be expected while machining CuZn21Si3P due to the slight increase in mechanical loads.

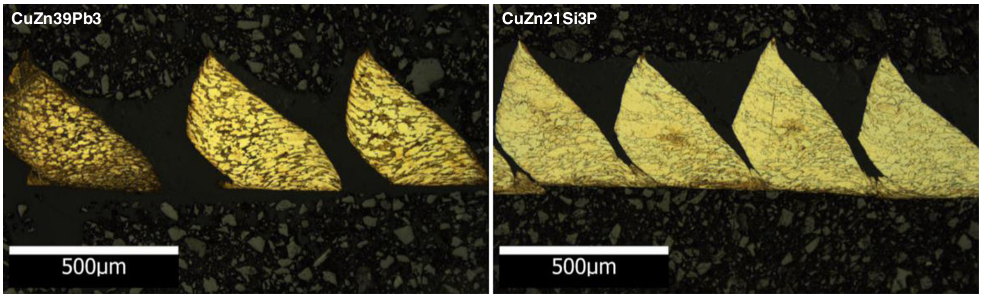
3.4 Tool deterioration

As a method for comparing the tool deterioration, a comparative study was made while longitudinally turning each workpiece material at $v_c = 400$ m/min, $f = 0.20$ mm/rev, and $a_p = 0.8$ mm using uncoated DNGA150708 cemented carbide cutting tools. The tool wear was measured incrementally throughout the whole test by using optical microscopy. Based on these measurements, a noticeable difference was observed for the two workpiece materials where the tool failed after 142 min of machining for CuZn21Si3P. In a separate study [34], the primary wear mechanism was found to be diffusional wear on the rake face of the cutting tool. As a comparison, no measurable tool wear was observed after 160 min of machining CuZn39Pb3, after which the experiment was terminated due to lack of workpiece material. A qualitative comparison of the attained tool wear can be found in Fig. 5.

4 Case study at a Swedish SME

As a mean for evaluating the consequence of workpiece material substitution on the manufacturing cost, a case study was performed at a Swedish SME. The selected company manufactures products for heating of buildings, such as thermostatic radiator valves, radiator manifolds, fittings, and control values. Many of the included parts in these products are manufactured from various brass alloys, among others CuZn39Pb3. Due to the strive towards sustainable production,

Fig. 3 Chip cross sections at $v_c =$ 400 m/min, $f = 0.30$ mm/rev, and $a_p = 2.5$ mm. CuZn39Pb3 (left) and CuZn21Si3P (right)



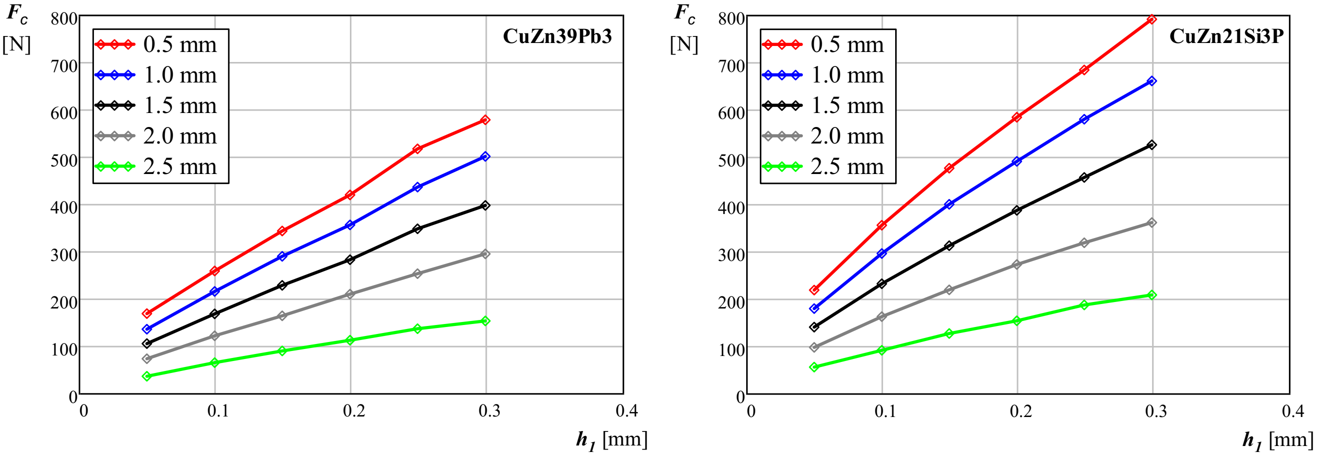


Fig. 4 Main cutting force F_c at $v_c = 400$ m/min for varying depths of cut as a function of h_1. CuZn39Pb3 (left) and CuZn21Si3P (right)

the company is evaluating the possibility of substituting this workpiece material with low-lead CuZn21Si3P. As previous research by the authors have shown, the machining of low-lead brass requires slightly modified process conditions as compared to machining of the lead-containing brass varieties; thus, a difference in manufacturing costs can be expected. If also including the material cost, as is commonly the norm, a substantial difference in manufacturing cost could be anticipated as the material cost of CuZn21Si3P is roughly twice that of CuZn39Pb3. The manufacturing process used at the participating SME primarily includes hot forging, machining, coating, assembly, and quality control. All of these processes, possibly with the exception of assembly and quality control, will in some way be influenced by the substitution of workpiece material. However, during this research, it was decided to focus on the machining operations since these were envisioned as being the most directly influenced by the substitution of workpiece material.

4.1 Case study outline

In order to evaluate the impact on the manufacturing cost of substituting the workpiece material, production of a brass socket was investigated. The socket constitutes a central part of the thermostatic radiator valve assembly, manufactured in large quantities by the company. The socket was originally made from CuZn39Pb3 which was substituted with CuZn21Si3P as part of the current study. The sockets are machined from solid brass bars until acquiring their final geometry, roughly 20 mm in length (Fig. 6).

During this investigation, data was ascertained through a combination of interviews and documentation supplied by the company. The level of detail of the data was not sufficient to use a microeconomic model, and hence the choice of manufacturing cost model has to be a macroeconomic model. As it is important to incorporate the performance of the process in terms of cycle time, downtime rates, and scrap rates, the model introduced by Ståhl et al. [18], Eq. (1), was implemented to compare the outcome of the different workpiece material alternatives. The reason for choosing this manufacturing cost model was the envisioned benefit of taking both macro- and microeconomic factors into consideration as sought during this study. It is worth mentioning that the company has been producing parts in CuZn39Pb3 and other similar, lead-containing brasses for an extended period of time. As a result, they have obtained an extensive knowledge on suitable production procedures and have had plenty of time to fine-tune their manufacturing process for these materials. In comparison, machining of low-lead brasses is a comparatively new experience for the company,

Fig. 5 Optical micrograph of the accumulated tool wear for $v_c =$ 400 m/min, $f = 0.20$ mm/rev, and $a_p = 0.8$ mm

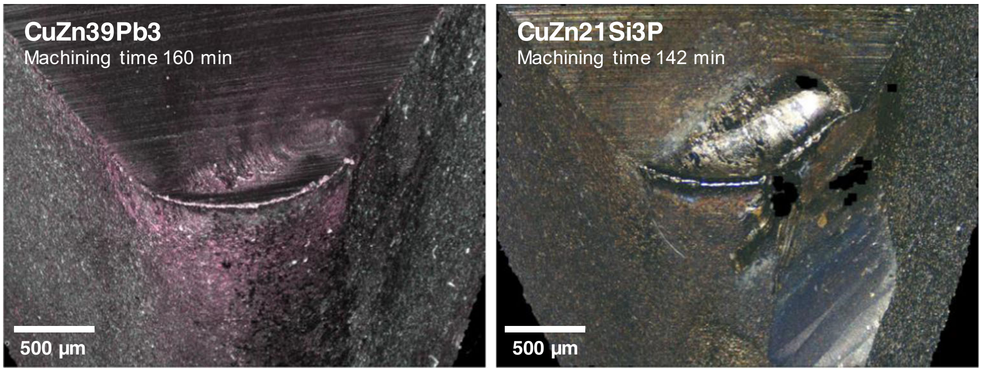


Fig. 6 Examples of the roughly 20 mm long socket. The left socket is produced in CuZn39Pb3 and the right in CuZn21Si3P

amounting to less than a year of experience on commercial production. Thus, it is likely that the production process for these low-lead materials can be further improved in the future, plausibly resulting in a decrease of the manufacturing cost over time.

4.2 Results and analysis

During the current case study, the average process characteristics were determined through a series of interviews with relevant personnel, i.e., operators, technicians, and the production manager, and internal documentation provided by the company. Overall, an average value for each process parameter and material was used due to the lack of more comprehensive data. Also, to simplify the analysis, it was assumed that no losses occurred in relation to the production rate, i.e., $q_P = 0$, and that the machine tool was fully utilized, i.e., $U_{RP} = 100\%$. The obtained values are summarized in Table 3.

As can be observed in Table 3, although the values for several process parameters are similar for the two materials, some noteworthy exceptions exist, consistently implying a higher manufacturing cost for the low-lead material. Several different factors contribute to the higher manufacturing cost, not least the higher purchasing price of the CuZn21Si3P material. The lower machinability of CuZn21Si3P also has a noticeable impact through the increase of the production loss parameters, i.e., scrap rate and production rate, while at the same time implying a longer cycle time and higher tool cost. Through using these input values while calculating the manufacturing cost by using Eq. (1), the following results were attained (Table 4). Although the added manufacturing cost only adds up to €0.10 per part, given the batch size of 88,000 parts, this will acquaint to roughly €9000 for a single batch. Thus, over time, the discrepancy will add up to a substantial difference in absolute numbers. If excluding the material cost from the calculation, roughly the same relative increase in manufacturing cost can be observed. This indicates a substantial influence of the production loss parameters on the manufacturing cost in the current comparison. Higher scrap and downtime rates in combination with a longer cycle time while machining CuZn21Si3P will imply increasing manufacturing costs, which, although small in absolute terms, constitutes a substantial increase of the manufacturing cost for the product in question.

5 Discussion

As found during the current study, the machinability of CuZn21Si3P is generally lower than that of CuZn39Pb3 primarily due to the sustainable difference in tool wear behavior and larger cutting forces. It can also be noted that machining of CuZn21Si3P will result in longer chips, although easily broken, the removal of which may cause issues during some machining operations. However, the more ductile behavior of

Table 3 Process parameter variation during manufacturing of sockets in varying workpiece materials

Description	Variable	Old material CuZn39Pb3	New material CuZn21Si3P
Nominal batch size (parts)	N_0	88,000	88,000
Nominal cycle time (s)	t_0	3.9	6.8
Tool cost (€/part)	k_A	0.009	0.012
Material cost (€/part)	k_B	0.096	0.168
Machine cost during production (€/min)	k_{CP}	0.175	0.175
Machine cost during downtime (€/min)	k_{CS}	0.106	0.106
Personnel cost (€/min)	k_D	0.258	0.258
Scrap rate (%)	q_Q	0.20	2.20
Downtime rate (%)	q_S	0.50	4.8
Production rate (%)	q_P	0	0
Setup time (min)	T_{su}	480	480
Machine utilization (%)	U_{RP}	100	100
Batch production time (min)	T_{Pb}	6211	10,678

Table 4 Manufacturing cost for the socket

	Old material CuZn39Pb3	New material CuZn21Si3P	Relative increase
Manufacturing cost (€/part)	0.13	0.24	77%
Manufacturing cost (excluding material cost) (€/part)	0.04	0.06	72%

CuZn21Si3P resulted in a better surface roughness on some occasions, especially for low theoretical chip thicknesses ($h_1 \leq 0.15$ mm).

Based on the attained results, substitution of lead-containing brass workpiece materials with low-lead varieties entails a substantially higher manufacturing cost due to the decrease in machinability. In this study, a 77% increase of the manufacturing cost was estimated when substituting CuZn39Pb3 with CuZn21Si3P during commercial production. This increase was primarily found to be due to the increase in workpiece material cost and process parameters related to the decrease in machinability for the low-lead material. As the investigated SME still is relatively inexperienced on the machining of low-lead brass with less than 1 year's commercial production, it is likely that the production process for this material will be improved in the future, somewhat decreasing the manufacturing cost. It is however doubtful that the manufacturing cost for parts in CuZn21Si3P ever will be as low as that for CuZn39Pb3. Arguably, manufacture of low-lead or even lead-free brass products may become a viable option in a macroeconomic sense if customers would be willing to accept higher prices for these products. Similarly, future legislative actions may inhibit further use of lead-containing brasses, although none has yet been announced. Given such circumstances, the research reported in this paper may be seen as an indication that manufacturing of parts in low-lead brasses is a viable, although more expensive, option. Thus, the use of low-lead and lead-free brass needs to be assessed on a case-by-case basis.

6 Conclusions

In general, low-lead brass displays an overall worse machinability when compared to a conventional, lead-containing variety. Overall, substituting CuZn39Pb3 with CuZn21Si3P will result in higher cutting forces, larger tool wear, and longer chips. This discrepancy in machinability will result in a higher manufacturing cost when machining the low-lead material. The higher material cost for the low-lead brass as compared to the lead-containing brass will further increase the difference in manufacturing cost. As a result, during the presented case study, the manufacturing cost for a specific product increased by 77% when substituting the traditionally used CuZn39Pb3 brass with low-lead CuZn21Si3P at a Swedish SME. Several different parameters contribute to this increase in manufacturing cost, not least the increased cost of the low-lead workpiece material. Other factors intimately related to the decreased machinability of the low-lead material also increase the manufacturing cost, e.g., longer cycle time, higher tool cost, larger scrap rate, and longer downtime. Thus, from a purely manufacturing-economic standpoint, substitution of lead-containing brass with a low-lead alternative does not appear to be an economically viable option. At the same time, the research demonstrates that it is technically possible to commercially produce products in CuZn21Si3P if a need should arise, for example as a result of future legislative actions.

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