Effect of copper addition at a rate of 4 % weight on the machinability of ZA-21Al cast alloy by CNC milling

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Abstract. Little work is published on the effect of copper addition to zinc-aluminium ZA-21Al alloy on its surface quality machined by milling. In this paper, the effect of copper addition at a rate 4 % weight to the ZA-21Al alloy on its hardness and surface quality is investigated. It was found that the addition of 4% Cu resulted in 18.3% enhancement in microhardness whereas the mechanical characteristics were reduced (softening) about 14.5% at 0.2% strain. It was found that the best surface finish for this alloy before copper addition ZA21 was achieved at a feed rate of 100 mm/min and 1.25 mm depth of cut whereas the best surface finish for ZA21-4% Cu was achieved at feed rate 250 mm/min, 1600 rpm cutting velocity and 1.25 mm depth of cut.

1. Introduction
The demand for high quality and fully automated production notes in industry utilizing the fully automated processes focuses attention on dimensional accuracy and surface quality. These normally affect product appearance and function during their lives services. For these reasons it is important to maintain consistent tolerance and surface quality. Among several industrial materials removal processes, milling is a fundamental machining operation. End milling is the most common metal removal operation encountered. It is widely used in a variety of manufacturing industries including the aerospace and automotive sectors, where quality is an important factor in the production of slots and dies. Several factors influence the final surface quality of the end milling operation. Independent factors such as tool geometry, spindle speed, feed rate, and depth of cut that control the cutting operation can be setup in advance, whereas dependant factors such as tool wear, and type of chip formed are uncontrolled. One should develop techniques to predict the surface roughness of a product before milling in order to evaluate the quality of machining parameters such as feed rate or spindle speed for keeping a desired surface. Zn-based alloys have a number of advantages over traditional bearing materials [1, 2, 3]. These advantages can be summarized as high resistance to wear, excellent castability and low cost [4, 5, 6]. Among the monotectoid-based alloys, the best mechanical and wear performance was obtained with the Zn–40Al–2Cu alloy [7, 8]. Selection of cutting tools and cutting conditions represents an essential element in process planning in machining. This task traditionally carried out on the bases of the experience of the process planner with the help of the data from machining handbooks and tool catalogs. Process planners continue to experience great difficulties due to lack of performance data on the numerous new commercial cutting tools with different materials, coating geometry and chip- groove configurations for high wear resistance and effective chip breaking.
The main objective of this present work is to investigate the effect of copper addition at a rate of 4% to ZA21 on the surface quality of the machined surfaces by the milling process under different cutting conditions of speed, depth of cut, and feed rate.

2. Materials and experimental procedures

2.1 Materials
High purity, zinc, copper powder and commercially pure aluminum were used in preparing the ZA21 alloy and the ZA21-4%Cu. The chemical analysis of the prepared alloys ZA21 and ZA21-4%Cu are shown in tables 1 and 2 respectively. The density of ZA21 is (6.23) g/cm³ and the melting point ranges from 380-386 °C.

| Element | Al    | Mg    | Fe    | Pb    | Cd    | Sn    | Zn     |
|---------|-------|-------|-------|-------|-------|-------|--------|
| %, Wt   | 20.3-21.3 | 0.03-.08 | 0.1   | 0.005 | 0.004 | 0.003 | Bal    |

| Element | Al  | Cu  | Mg   | Fe   | Pb   | Cd   | Sn   | Zn   |
|---------|-----|-----|------|------|------|------|------|------|
| %, Wt   | 20.3-21.3 | 4   | 0.03-.08 | 0.1  | 0.005 | 0.004 | 0.003 | Bal  |

2.2 Experimental procedures

2.2.1 Preparation of the ZA21-4% copper
The ZA21 alloy was prepared by melting the pre-calculated amounts of the 99.99% Zn powder and the commercially pure aluminum under caryolite flux in a graphite crucible and stirred with graphite rod at 550 °C. The melt was kept at this temperature for 5 minutes and then poured to solidify in a brass mould of 50*50*25 mm manufactured for this purpose as shown in figure 1, where the machining set up is shown in figure 2.

![Figure 1. Brass mould for producing the square section of milling specimens](image1)

![Figure 2. Machining process](image2)

The ZA21-4% Cu was prepared by adding the precalculated amount of the high purity copper powder into the ZA21 melt at 550 °C and kept in the crucible inside the furnace for 5 minutes and finally stirred with graphite rod before it was poured to solidify in the thick brass die. Test specimens from each alloy, namely the ZA21 and the ZA21-4%Cu were prepared for the microhardness, mechanical behavior and metallurgical examination tests.
2.2.2 Machining and surface quality tests

The machining tests on both ZA21 and ZA21-4%Cu were carried out on CNC milling machine type (KM3000) Excel of 0.1 μm resolution. The tests were carried out at different speeds, depth of cut and feed rates as shown in Table 3, under dry condition. A total of 64 machining runs using a 9 mm diameter cutter with four edges, after each run. The average surface roughness of the machined surface, after cleaning, was measured at two locations from which the average surface roughness, Ra, was determined, noting that the measurements were taken close to but not at the edges to avoid grain size at the edges, The average roughness (Ra) measurement was based on cut off distance = 0.8 and ISO 13565 (Rk), after each machining test. All milling tests were performed under dry cutting conditions. The path of the cutter with respect to the surface of the work piece is shown in figure 3.

| Table 3. Cutting Conditions for both the ZA-21 and ZA-21-4% Cu |
|---------------------------------------------------------------|
| Depth of cut (t) (mm) | 0.5 | 1.25 | 2 | 2.75 |
| Cutting speed (v) (rpm) | 750 | 1300 | 1600 | 2000 |
| Feed rate (f) (mm/min)  | 100 | 150 | 200 | 250 |

![Figure 3. Path of the cutting tool from A to B](image)

3. Results and discussion

In this section, the effect of copper addition on the microstructure, microhardness, mechanical strength and the machining parameters on the surface quality produced from CNC milling of ZA21 cast alloy before and after 4 % Cu will be presented and discussed.

3.1. Effect of copper addition on the microstructure of ZA21 cast alloy

Microphotographs of figure 4 shows the optical microphotographs of ZA21 and ZA21- 4%Cu, it can be seen that the microstructure consists of primary aluminium-rich α zinc-rich η and copper-rich ε phases. This is in consistence with the previous work of other researchers,[2,3,4].

![Figure 4. Photomicroscan of ZA21 and ZA21-4%Cu alloys at magnification of 250x](image)
structure of the alloys. It was observed that the ε phase was formed in the interdendritic region of the alloys containing more than 2% Cu. This type of microstructure seems to be ideal for bearing materials which usually have two phases, one of which is hard and the other one soft, [4]. In zinc-aluminum-copper alloys, the aluminum-rich α phase having a face-centered cubic (FCC) crystal structure exhibits excellent ductility [10,11,12]. The zinc-rich η phase having a hexagonal-close-packed (HCP) crystal structure with a large (c/a) ratio.

3.2 Effect of copper addition on the microhardness and mechanical characteristics of ZA21 cast alloy

It is obvious from figure 5 that the addition of 4 % copper resulted in enhancement in the microhardness however, 18.3 % have been achieved. The results are consistence with the previous work which was observed that the hardness of the alloys increased continuously with increasing copper content up to 5%. Microhardness of the aluminium-rich α phase was also affected by the copper content in a manner similar to that of the tensile strength. It was found that the wear loss of the alloys decreased with increasing copper content and reached a minimum at 2% Cu for a sliding distance of 700 km. However, the coefficient of friction and temperature due to frictional heating were found to be generally less for the copper containing alloys than the one without the element. The effect of copper on the wear behaviour of the alloys was explained in terms of their microstructure, hardness, tensile strength, percentage elongation and microhardness of the α phase [13]. It can also be seen from figure 6, that the mechanical properties after 4 % Cu addition were decreased, however the structure become softer, the maximum reduction is about 14.5 % at 0.2% strain. This result is in consistence with the previous work, which indicates that the tensile strength increased with increasing copper content up to 2%, but above this level the strength decreased as the copper content increased further [13], due to the structural softness of the morphological change of (α+η) phase from fine lamellar structure to coarse equiaxed grains [14]. According to hall-pitch equation, the strength of microstructure with lamellar or equiaxed grains morphology is inversely proportional to the grain size or interlamellar spacing. On the other hand the softness is related to two opposite defects; solid solution hardening of α phase and weakening effect through cracking tendency to ε phase, the later is more effective at copper counted beyond 3 % addition [15].

![Figure 5. Microhardness of ZA alloys](image1)

![Figure 6. True stress-true strain for ZA21 and ZA21-4% Cu](image2)

3.3 Effect of copper addition on surface roughness of ZA-21 Alloys

The effect of cutting parameters on the surface roughness of machine surfaces of the ZA21 alloy without and with addition of 4% copper was investigated by varying the main cutting parameter namely the rotational cutting speed from 750 rpm to 2000 rpm at different depth of cut ranging from 0.5 to 2.75 mm and different values of feed rate ranging from 100 mm/min to 250 mm/min and the
surface roughness was measured at each cutting condition. The results are presented in Fig. 7 to Fig. 22 inclusive. It can be seen from these figures that increasing the rotational cutting speed from 750 rpm to 2000 rpm at low feed rate, 100 mm/min, and small values of depth of cut, 0.5 mm, the surface roughness of the machined surfaces of both alloys decrease up to 1600 rpm beyond which it starts to increase of the cutting speed. Furthermore, it can be seen that addition of 4% copper to ZA21 alloy resulted in better surface quality i.e. lower values of surface roughness at all cutting speeds. Also increasing the depth of cut from 0.5 to 2.75 mm did not change the trend. These figures also indicate that variation of feed rate is more effective than variation of depth of cut, which agrees with the findings of previous researchers [16]. On the whole the produced surface roughness within the limitation of experimental work of speed and depth of cut resulted in surface roughness ranging from 0.5 to 1 micrometer except at 750 rpm for the ZA2-4%Cu alloy and from 0.9 to 1.4 micrometer for the ZA21 alloy i.e. without copper addition. These values of surface roughness even at highest values fall within the acceptable value in industrial applications. Finally, it can be concluded that, within the limitations of experimental work, addition of 4% Cu to ZA21 alloy resulted in better surface quality at all cutting speeds, depth of cut and feed rates, which may be attributed to the grain refining caused by the copper addition which also resulted in improvement of its hardness, both of which reduces surface roughness i.e. improves surface quality. This agrees the findings reported in references [14, 15].

Figure 7. $d = 0.5$ mm, $F=100$ mm/min

Figure 8. $d = 1.25$ mm, $F=100$ mm/min

Figure 9. $d = 2$ mm, $F=100$ mm/min

Figure 10. $d = 2.75$ mm, $F=100$ mm/min
Figure 11. \( d = 0.5 \text{ mm}, F=150 \text{ mm/min} \)

Figure 12. \( d = 2 \text{ mm}, F=150 \text{ mm/min} \)

Figure 13. \( d = 2.75 \text{ mm}, F=150 \text{ mm/min} \)

Figure 14. \( d = 2.75 \text{ mm}, F=150 \text{ mm/min} \)

Figure 15. \( d = 0.5 \text{ mm}, F=200 \text{ mm/min} \)

Figure 16. \( d = 1.25 \text{ mm}, F=200 \text{ mm/min} \)
Figure 17. \( d = 2 \) mm, \( F = 200 \) mm/min

Figure 18. \( d = 2.75 \) mm, \( F = 200 \) mm/min

Figure 19. \( d = 0.5 \) mm, \( F = 250 \) mm/min

Figure 20. \( d = 1.25 \) mm, \( F = 250 \) mm/min

Figure 21. \( d = 2.0 \) mm, \( F = 250 \) mm/min

Figure 22. \( d = 2.75 \) mm, \( F = 250 \) mm/min
3.4 Effect of copper addition on the characteristics of chip

It can be seen from figure 23(a) and (b) that the formed chip in the ZA21 alloy before and after addition of the 4% Cu is of the discontinuous type. This is expected, because the type of chip in the milling process is function of the process and not affected by process parameters. Furthermore, the discontinuous chip formed in case of AZ21-4% Cu is finer than that of the alloy before the addition. This may be attributed to the increase in the hardness of the alloy after copper addition.

![Figure 23. Type of chips, (a) ZA21, (b) ZA21-4 %Cu](image)

4. Conclusions

It can be conclude the following points:
- The mechanical strength was decreased at 4 % copper addition, the structure become softer.
- The microhardness increased at 4% copper addition this may attributed to the intermetallic compounds Al2Cu.
- It can be concluded that the best surface finish for ZA21 was achieved at feed rate 100 mm/min and 1.25 mm depth of cut.
- It can be concluded that the best surface finish for ZA21-4% Cu was achieved at feed rate 250 mm/min, 1600 rpm cutting velocity and 1.25 mm depth of cut.
- The chip in general was discontinuous; the formed chip after copper addition was finer than the ZA21.
- 6-increase in surface roughness had occurred at higher values of feed rates.

5. References

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