MATERIALS PHYSICS AND MECHANICS RESEARCH ARTICLE

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Experimental investigations on the milling characteristics of Cu alloys and additively manufactured CuCrZr

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ABSTRACT

Copper is one of the widely used materials in various fields such as automotive, electronics, aviation, etc. The inherent property of copper makes it useful in wide variety of applications. The features on different components using the copper material can be made using different manufacturing techniques. However, post processing is one of the inevitable steps in any manufacturing process. Machining is one of the widely used post processing. There are multiple varieties of milling process. Among them, end milling process is widely used for making the slots. Three important process parameters in end milling process are depth of cut, cutting rate and feed rate. In this experimental approach, the copper is subjected to end milling operation by varying the aforementioned input parameters. In this fast-moving world, any manufacturing industry aims to produce the features with good dimensional accuracy with minimal amount of tool wear. Hence, the output responses selected are surface roughness and the tool wear. This research investigates the machining behavior of pure copper (Cu) and additively produced CuCrZr alloys to assess how fabrication methods affect processability. Pure copper, recognized for exceptional thermal / electrical conductivity, is compared against additively manufactured CuCrZr, which retains copper's advantages while offering improved strength and wear resistance through alloy composition. During the milling process the following parameters such surface quality, cutting forces, tool degradation, and removal rates are reviewed through proper analysis. Compared to commercial copper, CuCrZr is more difficult to machine because it requires precise control over machining parameters to attain superior surface quality during milling. It is found that the CS and FR parameters balance material removal rate while controlling surface quality in both materials. As–built CuCrZr finds demand in high–performance applications such as heat exchangers, rocket engine components, and electrical contacts wherein strength, excellent thermal conductivity and additive manufacturability are critical.

KEYWORDS

CuCrZr • milling • as built • surface roughness • depth of cut

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Introduction

Widespread usage of copper across multiple industrial sectors is due to unique metal properties such as electrical conductivity, malleability, and thermal conductivity. In manufacturing, copper is employed in the production of industrial machinery [1], precision instruments, and heat exchangers. The transportation sector also depends on copper for the construction of vehicle radiators [2] and braking systems [3].

Machining copper presents numerous challenges due to thermal and electrical properties of the material. Copper is utilized majorly in various applications due to its electrical and thermal conductivity, plasticity, and elongation [4,5]. Notable complications are observed during the machining process of copper due to its electrical properties and the properties of softness and ductility. Optimal choice of tools and machining techniques and process parameters is imperative to minimise tool degradation, distortion, burr development and retain accurate dimension. Copper's maximum heat transfer capability develops complications during the time of machining, resulting in loss of material's integrity and tool degradation. Thermal management becomes essential by adopting efficient lubricant and coolant systems. Copper is susceptible to built-up edge (BUE) formation as it shows tendency to bond with cutting tool surfaces. Necessity for specialized tool coatings and optimized cutting velocities arises due to the occurrence of BUE, which results in acceleration of tool wear and degradation of surface quality [6]. It is difficult to process copper with significant advantages due to the following properties such as softness and malleability. Manufacturing techniques such as drilling, milling and turning are used for the fabrication of accurate components mostly used in safety critical application in aerospace domain. Maintaining a balance is essential during the copper matching due to copper's physical complexity for achieving appropriate integrity and accurate dimension for usage across various industrial sectors.

Machining procedures play a vital role in customizing copper (Cu) components for versatile applications across various spectrum of industries. Different techniques are deployed, each demonstrating its unique pros and cons. Machining processes classified under mechanical, facilitates the removal of material through mechanical modes, are widely adopted in copper machining. These processes involve drilling, turning, grinding, and milling. Milling is a machining technique that uses rotary cutters to remove material out of the workpiece. Milling offers several advantages while placing it as a preferred choice for Cu machining. It illustrates high precision, allowing for ease of fabrication of intricate shapes and profiles [7]. Besides, milling yields exceptional surface finishes, thereby eliminating any supplementary finishing procedures [8]. It illustrates high efficiency, and is well-suited for large scale production [9]. Advancements in tooling and cutting techniques have enhanced the tool life. Additionally, milling demonstrates adaptability through end and face milling, that offers distinct advantages. End milling, engages the bottom of the cutter, whereas face milling comprises of cutting with the sides of the cutter [10,11]. This features places milling as a potential machining process to handle a diverse range of tasks, that comprises machining flat surfaces, complex profiles and slots [12].

End milling presents is a prominent technique for the required ablation from raw materials. The variations of the key process parameters, controls the end milling of additively manufactured copper [13]. These parameters play a crucial role in the outcome of the machining process. Typically, a higher cutting speed (CS) can improve material removal efficiency and minimize tool contact time, thereby enhancing the surface finish. Optimizing the feed rate (FR) has the potential to influence tool wear and chip evacuation. Optimizing these parameters is essential to ensure efficient and precise machining. Tool wear and machined product evenness, measured in the form of roughness are important in the end milling for additively manufactured copper [14,15]. Lower surface roughness is preferred as it facilitates production of smoother and more precise parts. The tool wear impacts the tool longevity and the efficiency of the machining process. Higher tool wear forces frequent tool changes, leading to increased downtime and incurs additional costs. Henceforth it is imperative to monitor and regulate tool wear and surface roughness to attain successful end milling product.

After detailed literature survey, it may be observed that minimal work is presented on optimizing the end milling process parameters for copper-based materials. Hence, in this study, the copper is subjected to end milling operation by varying three input parameters. The input process parameters are varied in five levels. The impact of input parameters on the tool condition and product quality is reported. Further, Cu Cr Zr is additively manufactured and milling experiments are performed similar to those performed or Cu. The comparative results are presented in the paper. The experiments are designed based on the central composite rotable design technique.

Materials and Methods

The end milling experiments are carried out on the copper plate. During experimentation, steel tools with a wide speed range are deployed for the machining or ablation operation. FR, CS, and depth of cut (DoC) varied during the experimentations, and the tool wear and surface roughness are calculated. A systematic approach that considers the material properties and intended process outputs is considered when choosing machining settings for milling commercial copper (Cu) and CuCrZr that has been additively produced. The foundation for parameter selection also accounts for the milling behaviour of commercial copper and Cu Cr Zr alloys, such as the impact of process parameters on the resultant microstructures. Additionally, mechanical, thermal, and physical properties of the material are carefully examined, as are material-specific factors like porosity, work hardening, and anisotropy. The process parameter window is then fine-tuned by preliminary trials, and performance is subsequently optimized using structured experiments utilizing Taguchi factorial design. The parametric range is selected based on the tool catalogue and the initial preliminary trials calculated based on trial and error. Subsequently, the parameters are chosen from optimized parametric window based on the data obtained from the experiments. Consequently, the trials are carried out based on the central composite rotable methodology. Input process parameters are varied in five levels during the experimentation. Each experiment with a specific parametric set up

Fig. 1. Cu sample after milling operations

is repeated thrice, and the mean value is reported. The surface roughness is measured using a 3D profilometer (Make: Bruker) and the tool wear is estimated using the optical microscope (Make: Leica). Figure 1 shows the Cu sample after milling operations are performed.

Preliminary experimentation

The primary objective of the initial/preliminary experimentation is to determine the optimal range of the parameters in which the responses are effective. It is observed from the literature that FR has the most significant parameter that influences the product surface quality followed by CS and DoC. The variation of the FR during experimentation is in accordance to the tool makers catalogue. It is desirable to obtain the least surface roughness for the applications. It may be concluded that the range in which the FR can be varied may lie between 100 to 250 m/min.

Influence of FR on machined surface

The linear speed at which the cutting tool (represented by FR) moves along the workpiece during the process of milling, influences the resulting surface roughness in copper machining. Figure 2 provides valuable insights into the dependency of surface roughness on the FR with the key objective being the attainment of lower surface roughness, a major consideration in precision machining.

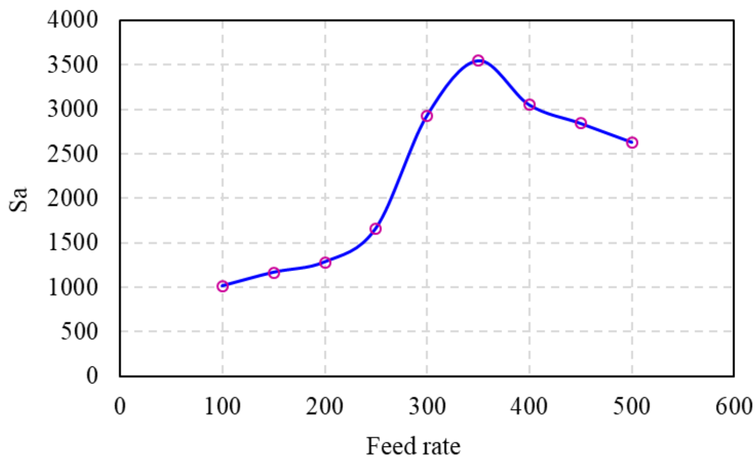

Fig. 2. Effect of FR on the 3D average S_a

From Fig. 2, it can be observed that mean S_a (machine surface quality) is increasing with the increase in FR from 100 to 350 m/min and then progressively decreases as the FR is increased to 500 m/min. This clearly indicates that higher FRs yield smoother surface finishes. It may also be noted that within the data, there is an occurrence of a peak in surface roughness at an intermediate FR, specifically at 350 m/min, where S_a reaches 3551.55 nm. This suggests that there exists an optimal range of FRs that minimizes surface roughness. Increasing the FR beyond this optimal point, may result in rougher surfaces due to factors such as increase tool wear or increased cutting forces, indicating a subtle balance between FR and surface finish.

Influence of CS on machine surface quality

3D surface roughness is measured and recorded using optical metrology tools by capturing the height variation (*z*-axis) across a defined area (*x*-*y* plane) of the sample surface. These values of height are processed to calculate area surface roughness parameters according to standards. CS (rpm) controls the resulting surface roughness in the machining processes of copper. Figure 3 shows the influence of CS on the average Sa. It is observed from the figure that the average Sa drops down with rise in CS from 950 to 2500 rpm and then decreases further as the CS is increased to 3000. Subsequently, a declining trend may be observed as the CS increases to 3500 rpm. It is preferred to obtain the least surface roughness for the applications. Therefore, the FR range can be varied between 500 to 3000 rpm.

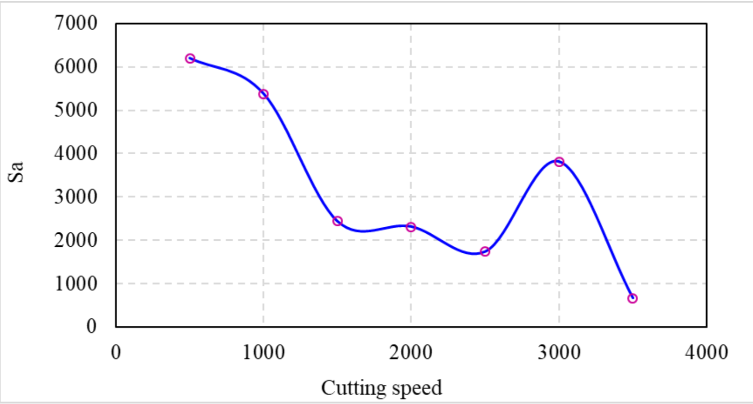

Fig. 3 Effect of CS on 3D average S_a

Analysing Fig. 3, it may further be note that initially, as the CS increases from 500 to 3000 rpm, there is a decline in surface roughness value. At a constant FR of 300 m/min and a DoC of 0.5 mm, S_a decreases progressively from 6197.25 to 1737.88 nm. However, it may be noted that a slight deviation is in the data at 3500 rpm, where surface roughness increases to 3812.33 nm. This anomaly may be due to the fact that there may be a threshold beyond which further increases in CS can have a detrimental effect on surface finish. Factors viz., tool wear, vibrations or excessive heat generation could be contributing to this deviation.

Influence of DoC on surface quality

DoC (measured in mm) is a key parameter in the machining processes of copper that governs the machined product quality. The impact of DoC on the average S_a is shown in Fig. 4. It may be observed that the average unevenness increases with the increase in cutting depth from 0.2 to 0.3 mm and on further increasing the depth, S_a decreases and then increases as the DoC is increased to 0.8 mm. It is preferred to have the least surface roughness for the applications. Therefore, the FR can be varied between 0.3 to 0.8 mm.

Analysing the data from Fig. 4, it is evident that as the DoC increases from 0.2 to 0.8 mm while maintaining a constant CS of 2000 rpm and a FR of 300 m/min, S_a exhibits a consistent decreasing trend. The reducing surface roughness with increasing DoC may be attributed to different factors. The depth of cut being larger allows for more efficient

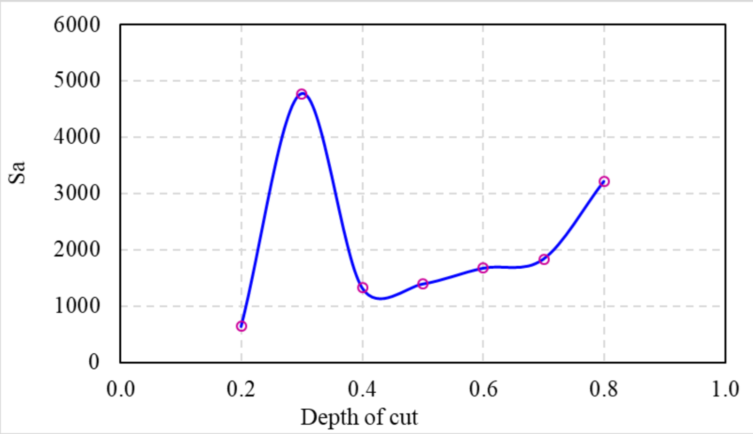

Fig. 4 Influence of DoC on the 3D average S_a

material removal, reducing the number of tools passes that is necessary to complete the machining operation. This will eventually minimize the cumulative effects of tool wear and cutting forces, leading to improved surface finish. Beyond a threshold point, increasing the depth of cut may result in diminishing returns or even deteriorating surface finish. This is due to the fact that increasing cutting forces, heat generation, and the potential for tool deflection, negatively impacts the surface quality.

CCRD results with discussion

The experiments are carried out using the central composite rotable design technique. Each input parameter is varied in five levels, and the output responses are record. The experimental design followed for the experimentation is shown (Table 1).

Table 1 Experimental plan according to central composite rotable design with surface roughness

Std	Run	CS, rpm	FR, m/min	Depth of cut, mm	3D-surface roughness (S_a), nm	Cutting forces		
						Fx	*Fy*	*Fz*
8	1	2500	200	0.7	3496.55	-11.64	-40.37	0.9
2	2	2500	100	0.4	1914.9	-6.54	-19.23	2.81
17	3	1750	150	0.55	2181.85	-12.05	-47.58	2.35
19	4	1750	150	0.55	2780.2	-6.87	-20.66	0.34
14	5	1750	150	0.8	4800.28	-22.16	-64.02	-0.08
20	6	1750	150	0.55	2495.16	-12.69	-24.4	-2.15
15	7	1750	150	0.55	2477.7	-17.01	-60.57	-4.82
6	8	2500	100	0.7	2377.25	-11.13	-29.92	0.59
18	9	1750	150	0.55	2507.8	-16.29	-70.83	0.59
12	10	1750	235	0.55	3972.4	-1.58	-8.55	-1.35
13	11	1750	150	0.3	1952.3	-2.01	-10.42	3.27
7	12	1000	200	0.7	5982.2	-5.76	-24.25	5.27
1	13	1000	100	0.4	2860.72	-2.91	-12.98	3.48
9	14	490	150	0.55	5440.6	-13.61	-41.84	1.63
4	15	2500	200	0.4	3279.59	-11.57	-31.72	2.35
10	16	3010	150	0.55	2802	-12.31	-31.1	3.09
3	17	1000	200	0.4	4501.15	-11.43	-32.08	4.48
11	18	1750	65	0.55	1530.7	-7	-19.82	1.88
5	19	1000	100	0.7	3386.05	-8.55	-26.53	-0.43
16	20	1750	150	0.55	2258.2	-7.42	-25.23	1.76

From the above data, an equation is generated. The equation is as follows: SA = +6437.66676 − 2.97654·CS + 7.10099·FR − 11785.15146·DoC − 0.005842·CS·FR − − 1.47452·CS·DoC + 11.83883·FR·DoC + 0.001051·CS^2 + 0.041299·FR^2 + 14768.16485·$D0C^2$.

Influence of FR on milled product evenness with varying DoC

Upon closer observation of the data in Fig. 5 it becomes evident that FR, when coupled with varying DoC, yields interesting reports on surface roughness. The dataset comprises of runs with FR ranging from 65 to 235 m/min, each carried out at various DoC settings.

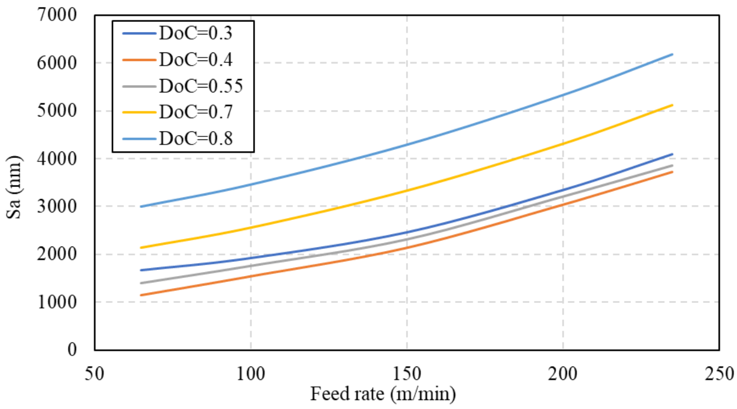

Fig. 5. Effect of FR on average area S_a at varying DoC

It may be noticed that for a given DoC, as FR increases, surface roughness decreases. Higher FR improve the more efficient chip evacuation and reduced tool contact time with the workpiece, resulting in reduced surface roughness. However, it is also to be noted that this trend is not uniform across all trials, and the influence of FR is also dependent upon DoC. The data reveals cases where the effect of DC on SA is prominent. In Run 5 with DoC of 0.8 mm, an increase in FR from 150 to 235 m/min results in a substantial rise in roughness (S_a) from 4800.28 to 5472.4 nm. This nonconformity from trend suggests that, for specific scenarios and DoC settings, higher FR yielding a lower surface roughness isn't certain as conditions vary.

Furthermore, it is recorded that the ideal FR for achieving lower roughness varies with the DoC cut. Runs 3 and 10, both executed at a DoC of 0.55 mm. While Run 3, with a FR of 150 m/min, yields a S_a value of 2181.85 nm, Run 10, with a higher FR of 235 m/min, results in a higher S_a value of 3972.4 nm. This discrepancy highlights the need for a systematic and cautious approach, that accounts not only FR but also the DoC during the process of optimizing the surface finish in copper machining.

One of the main reasons behind the decrease in S_a with higher FR is the effect on chip formation and evacuation. FR, measured in m/min, controls the rate at which the cutting tool advances through the workpiece. A higher FR leads to the generation of smaller, and more manageable chips. It is easy to evacuate these smaller chips from the cutting zone, reducing the likelihood of chip recutting and minimizing surface irregularities. Effective chip evacuation is a critical factor in accomplishing a smooth surface finish owing to the fact that the recutting chips may introduce unwanted imperfections and marks on the workpiece. With the increase in the FR, the rate at which chips are produced bring into line better with the tool's ability to evacuate them, that results in reduced recutting and enhanced surface quality.

Higher FR values reduce the dwell time (the duration of tool-workpiece contact) during each pass of the cutting tool. Shorter dwell time is desired. Firstly, it decreases the heat build-up at the cutting edge of the tool, that may lead to thermal distortion and negatively affect the surface quality. Secondly, by reducing the duration of tool-workpiece contact it minimizes tool wear.

Influence of FR on surface roughness with varying CS

From Fig. 6, it becomes evident that the combination of FR and the CS, is significant in accomplishing a particular surface quality of machined copper components. The dataset comprises of FR varying from 65 to 235 m/min, performed at different CSs. Typically, as FR increases, S_a machined product irregularities decrease. This establishes the importance of FR in accomplishing smoother surface finishes during copper machining. Higher FR facilitate the attainment of efficient chip evacuation and reduces the dwell time of the machining tool on the work surface, that contributes to the reduction in surface roughness.

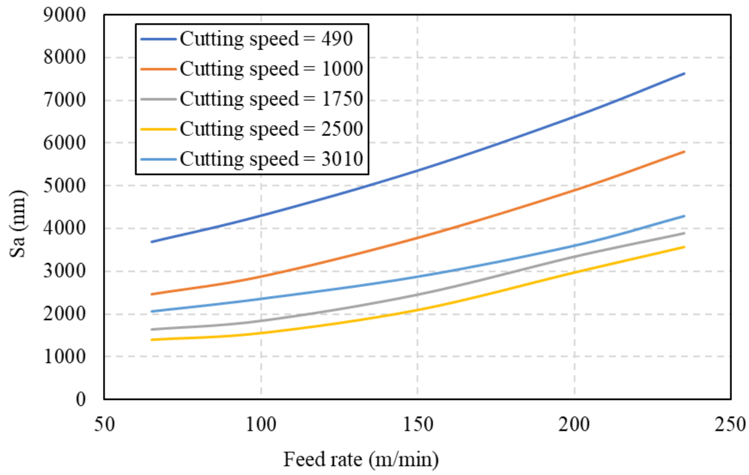

Fig. 6. Effect of FR on average S_a at varying CS

The data recordings also reveal that the impact of CS on S_a is prominent. In the case of Run 16 with a CS of 3010 rpm, an increase in FR from 150 to 235 m/min results in a significant decrease in surface roughness from 2802 to 3972.4 nm. This clearly demonstrates how the effect of FR can be altered by CS, and higher CSs can increase the impact of FR on surface roughness. Besides, it's vital to consider the interaction between CS and FR in achieving the desired surface finish. In the case of Run 14 with a CS of 490 rpm, a relatively low FR of 150 m/min leads to a high surface roughness of 5440.6 nm. Nevertheless, in contrast, Run 15 with a similar CS but a higher FR of 200 m/min results in a lower surface roughness of 3279.59 nm.

The key reason for the decrease in surface roughness with increasing FR is its effect on chip formation and evacuation. FR (m/min) controls the rate at which the cutting tool advances through the workpiece. Generation of smaller, more manageable chips is typically observed for a higher FR. It is easier to evacuate these smaller chips from the cutting zone, thereby reducing the chip recutting and minimizing surface irregularities. Efficient chip evacuation is a critical factor in accomplishing a smooth surface finish owing to the fact that recutting chips introduces unwanted marks and imperfections on the workpiece. Additionally, a higher FR led to the reduction in dwell time. It decreases the opportunity for heat to build up at the machining tool surface or the edge which can lead to thermal distortion and adversely affect surface quality. It also minimizes withering of the cutting tool by reducing the duration of tool-workpiece contact. Tool wear alters the sharpness of the tool and increases the friction, both of which may negatively impact surface finish.

Effect of CS on surface roughness with varying DoC

A careful examination of the plot (Fig. 7) reveals that the choice of CS, when clubbed with variations in DoC, majorly influences the surface roughness of machined copper components. The dataset comprises of trials carried out at a wide range of CSs, from 490 to 3010 rpm, with each run featuring different depth of cut settings. In general, as CS increases, S_a is observed to decrease. In the case of Run 16 with a CS of rpm and DoC of 0.55 mm, the resulting surface roughness is 2802 nm. This clearly establishes how higher CSs lead to smoother surface finishes by ensuring efficient material removal and reducing tool contact time with the workpiece. Nevertheless, the data also reveals that the effect of DoC on machined product surface evenness cannot be neglected. In case of Run 5 with a DoC of 0.8 mm, an increase in CS from 1750 to 2500 rpm results in a substantial rise in surface roughness, from 4800.28 to 3496.55 nm. This observation infers that the impact of CS on surface quality can be regulated by the DoC. Trials 2 and 17, carried out at similar CSs but with different DoC settings, illustrate this point. Run 2, with a DoC of 0.4 mm and a CS of 2500 rpm, yields a S_a value of 1914.9 nm. In contrast, Run 17, with a similar CS but a deeper DoC of cut of 0.4 mm, results in a notably higher S_a value of 4501.15 nm. One key factor driving the improvement of surface evenness at higher CS is the efficiency of material removal. As CS rises, the tool removes material more rapidly, leading to a reduction in the thickness of material left behind in each pass.

A higher CS accelerates material removal and minimises the negative effects of tool wear on surface quality. The reduction in surface roughness with higher CSs is also

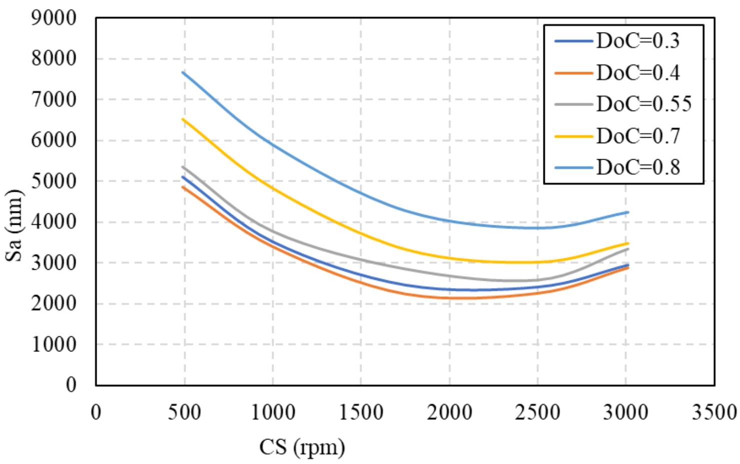

Fig. 7. Effect of feed rate on average S_a roughness at varying DoC

governed by the minimization of cutting forces. Cutting forces are the forces that are exerted on the tool during machining and those forces may cause tool deflection and workpiece deformation. When CS is increased, the duration of tool-workpiece contact is reduced, resulting in lower cutting forces. This reduction contributes to a smoother surface finish by reducing the instances of workpiece vibrations and deformations. However, the impact of CS on the surface should be determined along with the variation of DoC. DoC which specifies the thickness of material removed during each pass of the cutting tool, plays a vital role in regulating the correlation between them. With the increase in DoC, it may counter the benefits of higher CS.

A deep cut removes more material, even for a moderate CS. This results in a higher surface roughness, as observed in Run 5, where a rise in CS from 1750 to 2500 rpm led to a rise in surface roughness. The DoC in this case (0.8 mm) significantly influenced material removal, overshadowing the effects of increased CS. Furthermore, the interaction between CS and DoC governs the machined surface characteristics. Runs 2 and 17 illustrate this point, as both were carried out at a similar CS but with different DoC settings. In Run 2, with a DoC of 0.4 mm and a CS of 2500 rpm, a relatively low surface roughness of 1914.9 nm was accomplished. However, in Run 17, with a similar CS but a deeper DoC (0.4 mm), the roughness increased significantly to 4501.15 nm.

Effect of CS variation on Sa with varying feed rate

The dataset provided in Fig. 8 can be utilised to explore the dependencies between CS and surface roughness with the variations in the FR. The requirement of the copper milling process is lower surface roughness. The obtained data indicates that CS, when combined with changes in FR, goenrs the surface roughness of machined copper components. The dataset includes the experimental trails conducted with variation of CSs, ranging from 490 to 3010 rpm, with each run featuring different FR settings.

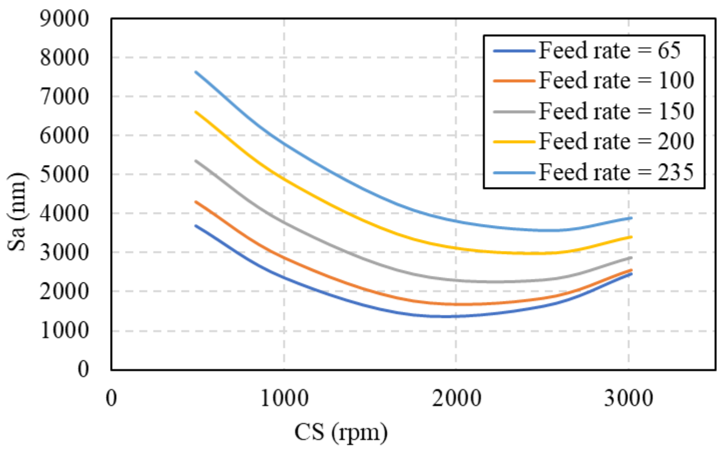

Fig. 8. Effect of CS on average S_a at varying FRs

As CS increases, roughness is observed to decrease. For instance, in Run 16 with a CS of 3010 rpm and a FR of 150 m/min, the resulting surface roughness is 2802 nm. This highlights the significance of higher CSs to promote smoother surface finishes by enhancing material removal efficiency and reducing tool contact time with the workpiece. However, the data also reveals that the impact of FR on product roughness should not be underestimated. For instance, in Run 15 with a CS of 2500 rpm, a lower FR of 100 m/min leads to a higher surface roughness of 3279.59 nm, whereas increasing the FR to 200 m/min results in a notably lower S_a value.

The reduction in Sa with increasing CS can be due to several key factors. Firstly, increased CS promotes the chip evacuation, ensuring prompt removal of the metal remnants from the cutting zone. Also, higher CSs reduce the dwell time of the cutting tool on the workpiece, minimizing the tool wear and heat build-up. The combination of these effects results in smoother surface finishes when CS is increased. FR has its own significance on the surface roughness, even with varying CS. In the trial 15, a CS of 2500 rpm is maintained, but the FR is varied. When the FR is set at 100 m/min, the resulting surface roughness is 3279.59 nm. However, when the FR is increased to 200 m/min, a notably lower Sa value is achieved. This observation infers that the effect of CS on Sa may be modulated by the chosen FR. In cases like Run 15, where the FR is increased, the reduction in Sa is significant, indicating that FR adjustments can compensate for variations in CS.

CS primarily affects material removal efficiency by determining the speed at which the cutting tool engages the workpiece. Higher CSs can help achieve smoother surfaces by reducing tool contact time and minimizing heat generation. The FR influences the rate at which the tool advances through the workpiece. A higher FR can promote chip evacuation, reduce tool wear, and mitigate heat-related issues. However, excessively high FRs can also lead to issues such as tool breakage or poor chip formation. Runs 2 and 8, executed at a similar FR but with different CSs, illustrate this point. Run 2, with a CS of 2500 rpm and a FR of 100 m/min, yields a S_a value of 1914.9 nm. In contrast, Run 8, with a similar FR but a higher CS of 2500 rpm, results in a S_a value of 2377.25 nm. This highlights the need to carefully balance both parameters to optimize surface quality in copper machining.

Effect of DoC on roughness of product with varying FR

The variation patterns observed in Fig. 9 illustrate the correlation of DoC and machined product roughness (S_a), considering variations in FR. The dataset comprises trials executed at varying DoC, ranging from 0.3 to 0.8 mm, each paired with different FR

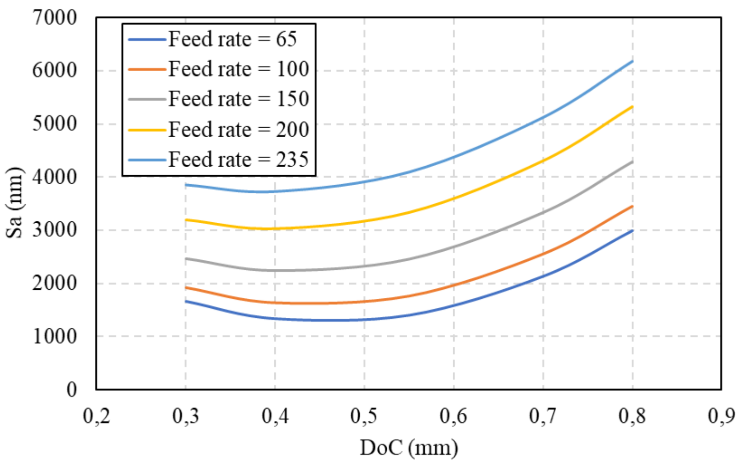

Fig. 9. Effect of DoC on average area surface roughness at varying FRs

settings. The DoC, in conjunction with changes in FR significantly influences the surface roughness of machined copper components.

As the DoC increases, surface roughness is observed to decrease. For example, in Run 5, with a DoC of 0.8 mm and a FR of 150 m/min, the resulting surface roughness is 4800.28 nm. Larger values of DoC contribute to smoother surface finishes by efficiently removing more material per pass and minimizing tool contact time with the workpiece. The variations also indicate the impact of FR variations on the machined surface at differing DoC. In Run 15, a DoC of 0.4 mm is maintained, but the FR is varied. When the FR is set at 100 m/min, the resulting surface roughness is 3279.59 nm. However, when the FR is increased to 200 m/min, a notably lower S_a value is achieved.

This observation suggests that the influence of DoC on Sa can be modulated by the chosen FR. In cases like Run 15, where FR is increased, the reduction in S_a is substantial, indicating that FR adjustments can compensate for variations in DoC. The correlation and combined effect of DoC and FR rate can be analysed by considering the balance between material removal and tool-workpiece interaction.

A comparative analysis of milling behaviour in copper and additively manufactured CuCrZr

Optimisation and selection of the optimal approach for machining for copper and additively manufactured CuCrZr requires comparative analysis of their properties. CuCrZr demands more precise machining parameters and tools, due to its enhanced properties [16,17]. This section describes the experimental analysis of 3D printing of Cu Cr Zr using laser powder bed fusion (LPBF) technique. This study involves the following procedures: 3D printing a 110 × 110 × 8 mm^3 plate; wire-cut EDM (electrical discharge machining) to reduce its dimension to 55 × 110 × 8 mm^3; milling operations.

Experiment

The chemical properties of CuCrZr materials and the mechanical properties of the as-built sample is presented in Tables 2 and 3. CuCrZr has high strength and good machinability. With these characteristics, it is commonly used in applications such as heat exchangers, electrical contacts, and aerospace components.

Table 2. Chemical composition of CuCrZr

Element	Min	Max
Cr	0.5	1.2
Zr	0.03	0.3
Fe		0.08
Si		0.1
Cu	Balance	

Table 3. Mechanical properties of as-built CuCrZr sample

Test	Unit	As-built	Remarks
Tensile strength	*Rm*, MPa	190 ± 20	Tensile test according to ISO 6892−1:2009B
Yield strength	R_pO, MPa	150 ± 20	
Elongation break	*A*, %	36 ± 4	
Modulus of elasticity	*E*, GPa	125 ± 20	
Vickers hardness	*HV10*	90 ± 2	Hardness testing according to DIN EN ISO 6507−1

LPBF printing technology for CuCrZr

CuCrZr material is prepared in the form of powder for the printing process. CuCrZr powder typically has a specific particle size distribution to ensure good flowability and density during printing. The LPBF process involves laser power to heat and fuse layers of CuCrZr powder to form the part. The laser moves in a precise pattern, layer by layer, to build up the part. The machine used for this study is STLE 400 (Fig. 10) and the parameters used for building the part is presented in Table 4. The typical layer thickness for LPBF is in the range of 20−100 µm, depending on the printer's capabilities and the desired part resolution. The initial 3D-printed plate is 110 × 110 × 8 mm³. The LPBF process allows for the creation of complex geometries, but in this case, a simple plate structure is being produced, which will subsequently be subjected to WEDM.

Fig. 10. STLR 400 machine deployed for preparing CuCrZr part

Table 4. Parametric Settings for as-built CuCrZr sample

Parameters	Value
Powder, W	370
Scan speed, mm/S	500
Hatch distance, µm	80
Layer thickness, µm	30
Spot size, µm	80
Build plate temperature, °	180

Wire-cut EDM process

EDM uses an electrically charged wire (usually copper or brass) to erode material from the workpiece. The wire is continuously fed through the part while submerged in a dielectric fluid (such as deionized water) to cool the process and flush away debris. Wire-cut EDM allows for very fine and intricate cuts with high precision and minimal thermal distortion. The wire acts as an electrode that removes material through rapid electrical discharges, leaving behind a very clean and accurate cut surface. In this study, after printing the 110 × 110 × 8 mm³ CuCrZr plate, the wire-cut EDM is used to trim the plate to a final dimension of 55 × 110 × 8 mm³. Figure 11 shows as−built CuCrZr sample subjected to milling with the numbers marked indicating the trials and the process parametric range used for them.

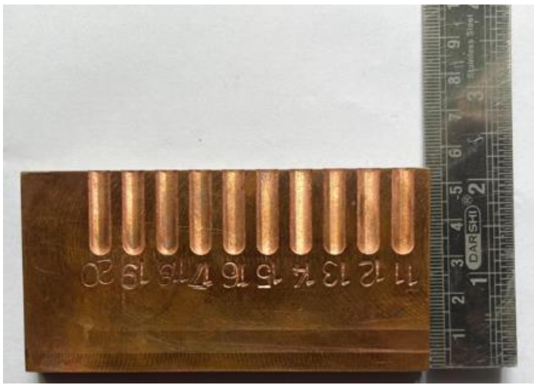

Fig 11. Sample as–built CuCrZr subjected to milling

Fig. 12. A section removed for analysis from as-built CuCrZr

The following caution was adopted during the experimentation:
1. CuCrZr has high thermal conductivity, which can lead to thermal stresses during the printing process. These stresses must be carefully managed through optimal printing parameters.
2. LPBF parts often require post-processing steps like wire-cut EDM or machining to achieve the final dimensions and surface finish. This can be time-consuming and costly.
3. CuCrZr powder can be expensive and handling the powder carefully to avoid contamination and ensure consistent quality.

Milling operation of as built-CuCrZr

Additive manufacturing (AM) of CuCrZr, a high-performance copper alloy with superior thermal and electrical conductivity, has become popular for the generation of intricate geometries in aerospace, automotive, and fusion technology [18–20]. Methods such as laser powder bed fusion (LPBF) are widely practiced, albeit with challenges owing to the high reflectivity and thermal conductivity of copper, necessitating high-power lasers and processing conditions to be optimized. Post-processing operations like heat treatment and hot isostatic pressing are commonly utilized to improve mechanical properties and remove porosity. CuCrZr milling is employed to obtain high dimensional precision and surface quality, particularly following AM, although the greater hardness of the alloy in the aged condition can contribute to tool wear [19,21,22]. The combination of AM and high-precision milling allows complex, high-performance parts with high tolerances and high-quality surfaces to be fabricated [23–26].

Experimentation involving the milling of as-built CuCrZr focuses on evaluating the significance and influence of various machining parameters, such as FR, CS, and cutting forces on product quality and DoC. cut. During the process of milling, copper's high thermal conductivity paves way for efficient heat dissipation, thereby minimizing the thermal loads on the workpiece and tool. Contrary to that, additively manufactured CuCrZr illustrates reduced and anisotropic thermal conductivity owing to microstructural variations that eventually lead to localized heat accumulation. This may have impact on the dimensional stability, tool wear, and surface quality. A thorough understanding of these thermal behaviours is essential for optimizing machining strategies. The goal is to optimize machining conditions for improved efficiency, precision, and durability of CuCrZr

Table 5. Experimental plan according to central composite rotable design with surface roughness for CuCrZr

Std	Run	CS, rpm	FR, m/min	Cutting forces			As-built CU	
				Fx	*Fy*	*Fz*	Depth of cut, mm	3D-surface roughness (S_a), μm
8	1	2500	200	−2.03	-19.43	-3.34	0.7	0.78
2	2	2500	100	−0.15	-14.57	-3.67	0.4	0.73
17	3	1750	150	-0.64	-27.15	-3.75	0.55	6.97
19	4	1750	150	-0.42	-15.36	-3.69	0.55	5.96
14	5	1750	150	-5.26	-54.6	-16.06	0.8	6.38
20	6	1750	150	-2.64	-24.44	-10.51	0.55	6.3
15	7	1750	150	-3.19	-26.54	-7.51	0.55	6.67
6	8	2500	100	-5.81	-30.98	-11.08	0.7	0.54
18	9	1750	150	-4.86	-58.44	-10.21	0.55	6.99
12	10	1750	235	-2.11	-21.91	-5.87	0.55	5.72
13	11	1750	150	-0.49	-12.52	-1.69	0.3	6.5
7	12	1000	200	-0.45	-19.39	-2.76	0.7	2.16
1	13	1000	100	-6.8	-10.24	-0.16	0.4	1.74
9	14	490	150	-9.67	-41.45	-10.55	0.55	2.93
4	15	2500	200	-5.21	-20.42	-4.32	0.4	1.15
10	16	3010	150	-7.15	-18.46	-3.54	0.55	0.57
3	17	1000	200	-13.85	-22.19	-4.55	0.4	2.32
11	18	1750	65	-11.89	-16.95	-2.06	0.55	6.05
5	19	1000	100	-14.6	-11.52	0.53	0.7	1.61
16	20	1750	150	-17.18	-15.67	-0.39	0.55	6.64

components in demanding industrial applications. The following table shows the experimental trials for milling of as-built CuCrZr based of design of experiments. Figure 12 shows CuCrZr sample where a milled portion is removed for analysing the DoC and product quality. Table 5 records the DoC and Sa for various trails of milling conducted on as-built CuCrZr. During milling, cutting forces were measured using a dynamometer which was mounted beneath the workpiece to record forces along all the directions. The dynamometer was connected to data acquisition system to capture real-time force signals during machining. Measurements were recorded for varying cutting parameters to examine their influence on machining behaviour.

Results and Discussion

Table 5 is analysed for understanding the parametric correlation between the process input parameters and output parameters which are the surface roughness and DoC. Correlation statistical algorithms are used to analyse the parametric interdependencies while Pearson's coefficient is used to arrive at a comparative heat map for milling parametric correlations and comparisons between Cu and CuCrZr samples. Figure 13 shows the relation between CS and surface roughness.

In milling operations of as-built CuCrZr, surface roughness typically decreases as CS increases, up to an optimal point. At higher CSs, the material is removed more efficiently,

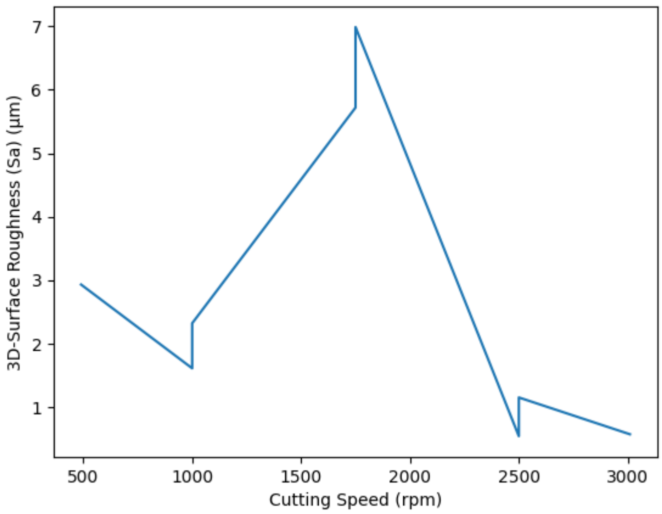

Fig. 13. Cutting speed vs. surface roughness

allowing for smoother cuts and reducing the likelihood of tool marks on the surface. However, if the CS is too high, it can cause excessive heat generation, leading to thermal damage, work hardening, and increased tool wear, which may worsen machined product quality. The relationship between CS and roughness is thus dependent on finding an optimal CS that balances material removal efficiency and tool performance while minimizing surface imperfections. Figure 14 shows the relation between FR and S_a.

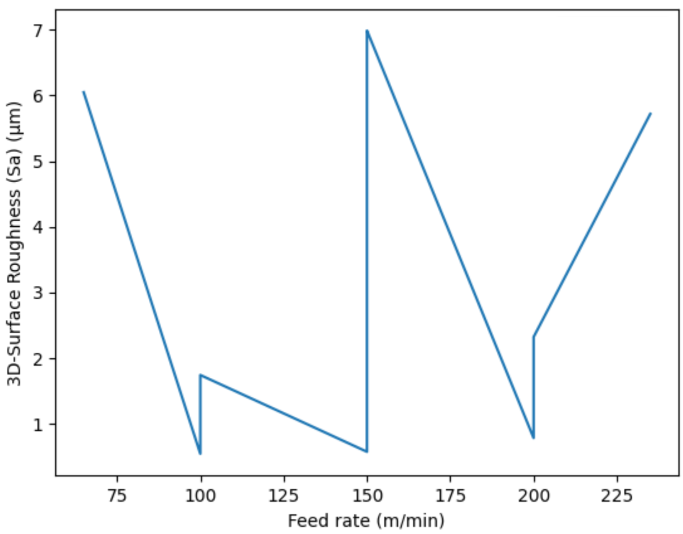

Fig. 14. Feed rate vs. surface roughness

The dependency of surface roughness on the FR for as-built CuCrZr (copper chromium zirconium) can be critical in determining the efficiency and quality of manufacturing processes such as milling or turning. Additive manufacturing (e.g., laser powder bed fusion) of CuCrZr may exhibit different surface roughness characteristics compared to traditional machining due to the material's microstructure and layer bonding. When studying the FR vs. surface roughness relationship for as-built CuCrZr, the key takeaway is that lower FRs generally result in better surface finishes (i.e., lower surface roughness), but at the cost of slower material removal. Understanding the interplay of machining parameters and material characteristics is critical for optimizing the process to balance efficiency and surface quality. The bar chart (Fig. 15) shows comparison of surface roughness (R_a) for commercial Cu and additively manufactured CuCrZr at varying feed rates, with error bars illustrating standard deviation. Highly anisotropic or harder materials like as-built CuCrZr result in rougher surfaces and higher tool loads as compared to softer materials like commercial Cu.

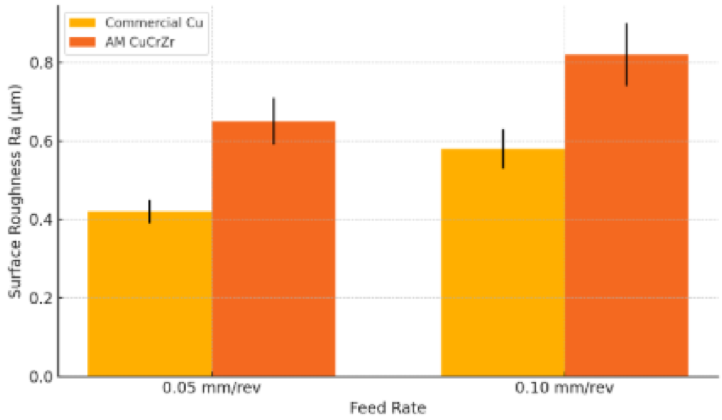

Fig. 15. Surface roughness comparison with deviation

Microscopic analysis of milled samples of Cu and as-built CuCrZr

SEM (scanning electron microscopy) analysis of the milled commercial Cu surface (Fig. 16(a)) illustrated smooth, continuous tool marks with negligible surface defects. This emphasizes stable chip formation and better heat dissipation owing to high conductivity. In contrary, the milled as-built CuCrZr surface demonstrated micro-tearing, smeared areas, and some material sticking, owing to its lower and uneven thermal conductivity, hardened microstructure and internal porosity. These characteristics reveal more tool-material contact and localized heat build-up during the process of machining.

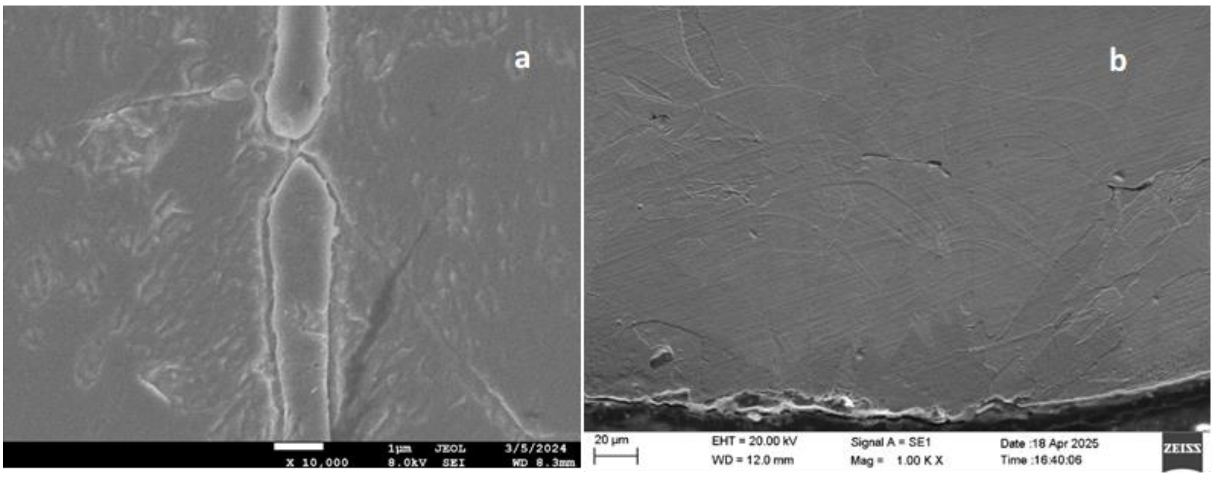

Fig. 16. SEM images of milled sample of Cu (a) and as-built CuCrZr (b)

Comparison between milling operation parametric performance for Cu and as-built CuCrZr

A Pearson correlation heat map is a visual representation of the correlation coefficients between multiple variables in a dataset. Each cell in the heatmap shows the correlation value between a pair of variables, with colour shading indicating the strength and direction of the correlation.

Analysis of the milling performance and parametric differences observed in copper (Cu) and as-built CuCrZr (copper chromium zirconium) in terms of dependency between CS and surface roughness and FR depicts the following observations:

1. Dependency of surface roughness on CS for Cu: surface roughness varies inversely with respect to CS increases, as higher speeds allow for finer, more continuous and uniform cuts. High thermal conductivity of copper causes efficient heat dissipation, thus minimizing tool wear resulting in maintaining surface finish at higher speeds [26,27]. Optimal CS needs to be maintained to avoid excessive heat generation and resultant thermal damage that may increase surface roughness. The less hardness property of copper makes this effect less significant.
2. Dependency of surface roughness on CS for CuCrZr: improvement in surface finish with increasing CS is less observed in CuCrZr, due to its nature of being stronger and harder than commercially available copper. This results in more heat generation due to its alloying elements, and is thus prone to significant thermal damage and tool wear. The optimal CS is thus lower compared to copper, to avoid poor surface finish due to work hardening and increased tool wear.

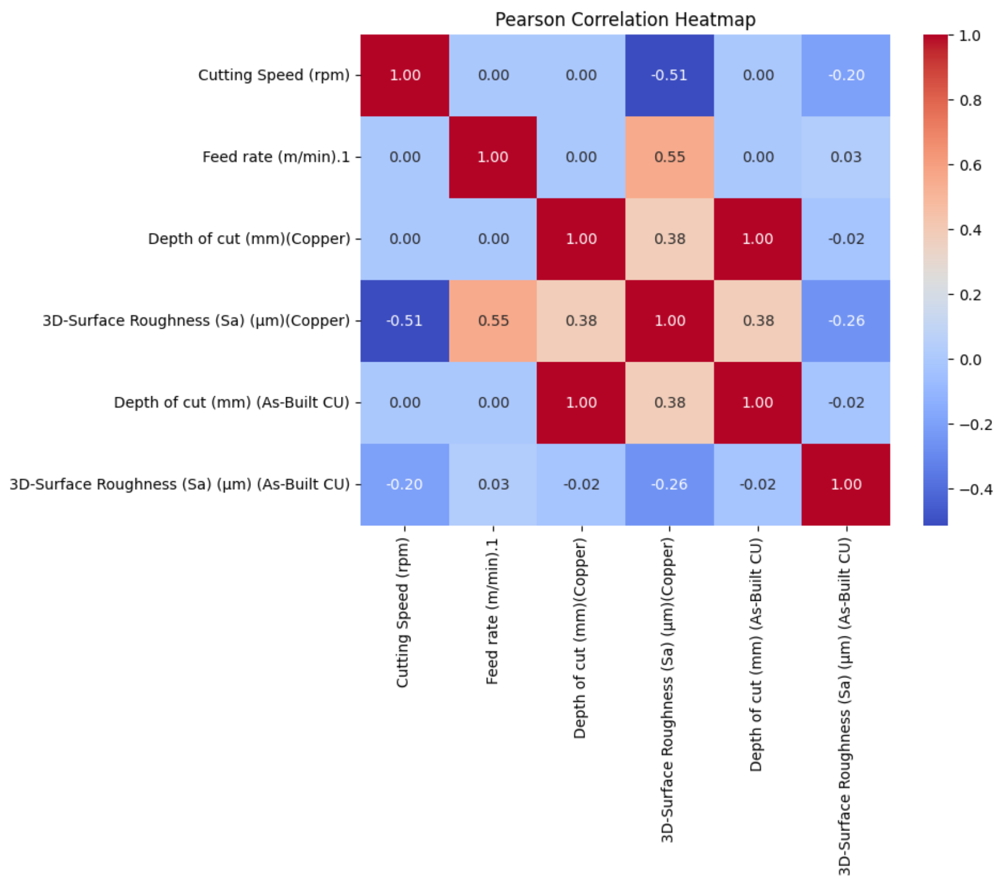

Fig. 17. Pearson correlation heat map

3. Dependency of surface roughness on FR for copper (Cu): surface roughness is observed to be directly proportional to FR. With higher FR, the tool makes rough excisions, resulting in deeper tool marks and a higher surface roughness. Reducing the FR allows for finer in deeper tool marks and a higher surface roughness. Reducing the FR allows for finer cuts, as the tool has more time for precise shaping of the material.
4. Dependency of surface roughness on FR for CuCrZr: owing to the high strength and hardness of CuCrZr, higher FR results in increased surface roughness due to higher cutting forces and less effective material removal, resulting in increased surface roughness. Optimum value of FR is needed for the tool to cut through the material, as lower range of FR can increase wear or even cause tool breakage at sub optimum rates [28,29]. Table 6 shows the parametric correlation of CS and FR vs DoC and surface roughness respectively for Cu and as-built CuCrZr. Based on the correlation coefficients, the heat map is generated. Figure 17 shows the Pearson's correlation heat map.

Table 6. Parametric comparison of milling for Cu and as-built CuCrZr

	DoC, mm		**3D-S_a, µm**	
	As-built	Copper	As-built	Copper
CS	0	0	-0.2	-0.51
Feeding rate	0	0	0.03	0.55

Conclusions

The experimental observations and the comparative study between copper and alloyed CuCrZr offer valuable insights into the interdependencies between material properties and the process parameters of DoC, CS, and product surface quality in copper machining. Additively manufactured CuCrZr differs significantly in properties with respect to commercial copper and requires optimal balance of the process parameters. It is observed that in both materials, optimal cutting parameters of CS, FR control the surface quality while balancing material removal rate and tool wear. However, CuCrZr generally requires more precise control of these parameters to ensure better surface quality obtained with the milling operations. This makes the machining process more challenging for CuCrZr as compared to commercial copper. This analysis has enabled establishment of dependencies and correlations between parameters involved in machining processes of Cu and its alloyed form CuCrZr, contributing to enhanced precision and efficiency in manufacturing. Future investigations can be focussed on the analysis of additional variables like tool material, geometry, coolant utilization, and other machining techniques for ensuring quality of the final product. As-built CuCrZr is used in high-performance applications like heat exchangers, rocket engine parts, and electrical contacts due to its strength, good thermal conductivity, and suitability for additive manufacturing.

CRediT authorship contribution statement

Subba Reddy Mundla: experimentation, sample preparation, testing and characterization, parametric analysis; **Arungalai S. Vendan**: experimentation, ML based parametric analysis, paper writing, technical interpretations; **C. P. Paul**: ideation, experimentation, testing and analysis; **Arun K. Shettigar**: idea for experimentation, technical inputs, technical interpretation of results, guiding in paper writing; **Sudhakar C. Jambagi**: idea for experimentation, technical inputs, technical interpretation of results, guiding in paper writing.

Conflict of interest

The authors declare that they have no conflict of interest.

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