Optimization of Microstructure and Mechanical Properties of Cucrzr Alloy Fabricated by Selective Laser Melting: A Study on Thermal Stability, Tensile Strength, and Wear Resistance

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Abstract
This study examines the microstructural and mechanical behavior of CuCrZr alloy electrodes fabricated using Selective Laser Melting (SLM), emphasizing thermal stability, tensile strength, and wear resistance in relation to processing parameters. Thermogravimetric analysis indicates excellent thermal stability up to 600 °C, with minor weight loss and decomposition above 800 °C due to alloying elements. SEM, TEM, and XRD analyses reveal a fine-grained, uniformly distributed microstructure (10–20 µm) with minimal porosity, achieved through rapid SLM solidification. Optimal SLM parameters—thin layers (30 µm) and high laser power (300 W)—enhance ultimate tensile strength (~500 MPa) and yield strength (~350 MPa) by refining grains and improving layer bonding. In contrast, thicker layers (100 µm), low laser power (150 W), and high scanning speeds (1200 mm/s) degrade strength and wear resistance. Pin-on-disk tests show low wear rates (~2.5×10^{-5} mm³/Nm) and a stable friction coefficient (~0.45), dominated by adhesive and oxidative wear. A strong correlation is established between microstructure, thermal stability, and mechanical performance. The optimized CuCrZr alloy demonstrates superior strength, wear resistance, and thermal stability, making it suitable for aerospace, automotive, and high-temperature applications.

Keywords: Selective laser melting, CuCrZr, Mechanical Properties, Wear, Response surface methodology

I. INTRODUCTION

Additive Manufacturing (AM), especially Selective Laser Melting (SLM), has transformed materials engineering by allowing the production of intricate components with customized properties directly from metal powders [1]. Among the various alloys, copper-chromium-zirconium (CuCrZr) alloys are of significant interest due to their exceptional combination of high strength, good electrical conductivity, and thermal stability, making them highly desirable for demanding applications in sectors like aerospace, automotive, and high-temperature energy systems [2]. However, achieving optimal performance in SLM-fabricated CuCrZr alloys necessitates a thorough understanding and precise control over the intricate relationships between processing parameters, resulting in finer microstructure, and enhanced mechanical properties [3].
Despite the increased interest in the SLM-manufactured CuCrZr alloys, the interdependent relationship between the main process parameters, such as the power of lasers, scanning rate, and the thickness of the layers, and the thermal stability, microstructural development, tensile strength, and wear resistance have yet to be properly analyzed. Rapid solidification and thermal gradient of SLM can form unique microstructures and defects, which are influential on the material performance. These parameters, consequently, have to be optimized, in an organized manner, to attain maximum potential of SLM-processed CuCrZr alloys[4].
Tang et al. [5] investigated the impact of heat on SLM manufactured CuCrZr alloys and have found that there are major changes in microstructural and property. Refinement of grain size, increased precipitation hardening and lower residual stresses were some of the improvements in heat treatment, which led to increased strength, hardness and ductility.
Prabu et al. [6] investigated wear behavior of partially melted particles of equiaxed, cellular, and columnar microstructures of the CuCrZr produced by LPBF. The wear depths were 116 nm, 252 nm, and 493 nm and the friction coefficient was 0.49, 0.45, and 0.41. In defect-free areas, the wear depths were reduced to 0.79, 0.67, and 0.70 that of partially melted particles, with the coefficients of friction rising 4.1, 6.6 and 9.7 times, respectively. It was said that the better wear resistance in defect-free regions was due to the formation of fine-grains, which minimized materials loss as opposed to those regions having partially melted particles.

Hence, it can be inferred from the above works that a very scarce work on the optimization of the processing parameters through SLM route pertaining to the CuCrZr alloy is cited in the literature. To realize the influence of these parameters, the present research will help in these issues by conducting a systematic study of the effect of SLM processing parameters on the thermal stability, microstructural characteristics, tensile properties, and wear behavior of CuCrZr alloy electrodes. To realize the optimized parameters, the design of experiments was designed through Response Surface Methodology (RSM) [7-8], which is widely recognized for its nature to capture the behavior of the processing parameters in a 3D surface enabling the envelope of parameters that can aid in repeatability and reproducibility. The current research pursues to identify optimal parameter combinations that yield superior mechanical and thermal performance through a two factor interaction (2FI) based regression model. Furthermore, the study explores the correlations between the observed microstructural features, thermal stability, and mechanical properties, providing fundamental insights into the process-structure-property relationships. It is expected that the results of this study will play a huge role in advanced manufacturing of high-performance CuCrZr components, facilitating their broader adoption in critical engineering applications.

II. MATERIALS AND METHODS

A. Materials

CuCrZr alloy in powder form is procured from Osmania University, Telangana, India, and can withstand temperatures of up to 500 °C with low oxygen content and impurity levels. The nominal chemical composition in the percentage of the as-received powder consists of Fe ≤ 0.08, Cr between 0.5-1.20, Zr between 0.1-0.3, Si ≤ 0.1 and O ≤ 0.1 as specified by the provider. The powder particle size distribution in a given sample ranges from 10 to 45 µm, which is more suitable for laser-powder bed fusion, known as SLM printing. The density of the wrought material is 8.9 g/cm³, and its thermal conductivity is 324 W/m K.

B. Methodology

The alloy samples investigated (CuCrZr) were prepared by the Selective Laser Melting (SLM) method on an Amace STLR 400 apparatus as pictured in Figure 1a. SLM is a type of powder bed fusion additive manufacturing that uses a high energy laser to selectively melt a layer of metal powder on a layer-by-layer basis depending on CAD data. The effect of the important processing parameters: layer height, laser power and scanning speed was systematically explored in this study.

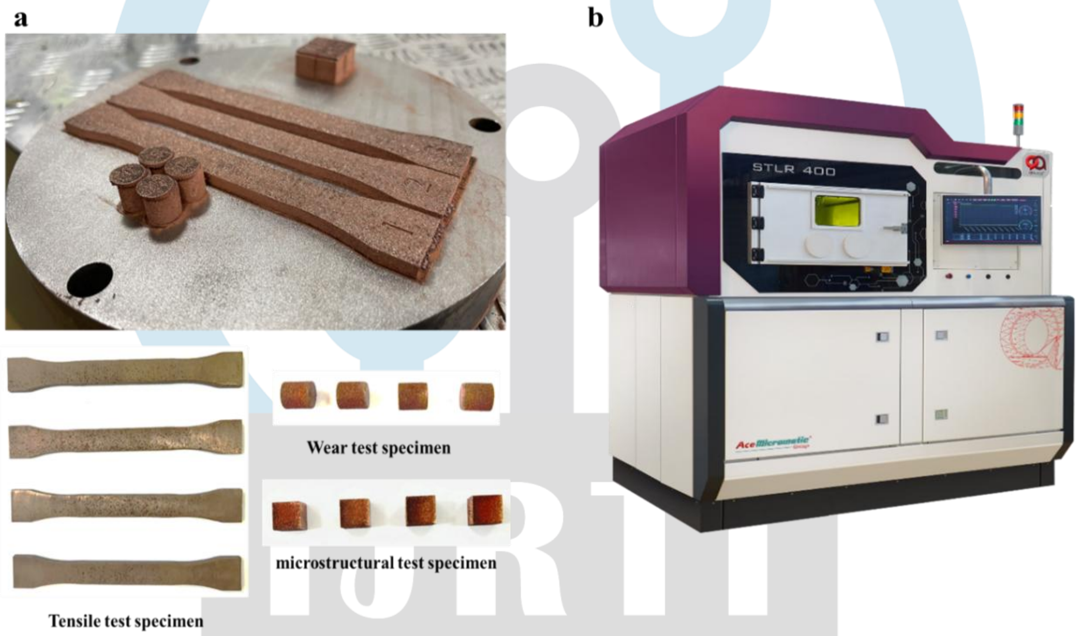

Figure 1 a. 3D printed tensile, wear and microstructural specimens, **1b**. Amace STLR 400-based SLM

A design of experiments (DoE) approach based on Response Surface Methodology (RSM) was used to optimize these parameters for enhanced mechanical performance. Layer heights of 30 µm, 60 µm, and 100 µm were tested to evaluate their impact on porosity and microstructural homogeneity. Laser power levels varied between 150 W and 400 W, affecting melt pool size and fusion quality. Scanning speeds ranged from 600 mm/s to 1200 mm/s, influencing melt pool stability and defect formation. The powder feedstock was pre-alloyed CuCrZr, sieved to an appropriate particle size distribution to ensure flow ability and uniform layer deposition. The build chamber was purged with high-purity argon to maintain an inert atmosphere and minimize oxidation during the melting process. Post-processing steps included stress-relief heat treatment and age hardening, which enhanced the mechanical properties by promoting precipitation hardening. The samples obtained were profiled by Scanning electron microscopy (SEM), Transmission electron microscopy (TEM), X-ray Diffraction (XRD), tensile tests and wear analysis to match the process parameters with the ultimate properties. Figure 1b demonstrates the specimens.

III.RESULTS & DISCUSSION

This section presents a comprehensive analysis of the thermal stability, microstructural characteristics, tensile strength, and wear resistance of the CuZnZr alloy electrode fabricated by SLM. The findings are discussed in correlation with the influence of various processing parameters, provides understandings of the material's behavior and performance.

a. Thermogravimetric Analysis (TGA) Curve and Weight Loss Stages

Thermogravimetric Analysis (TGA) was carried out to determine the thermal stability and decomposition characteristics of the CuCrZr alloy electrode. Figure 2 shows the TGA curve which was plotted versus temperature; the experiment was performed at an inert argon atmosphere with a heating rate of 10 C/min until 1000 C.

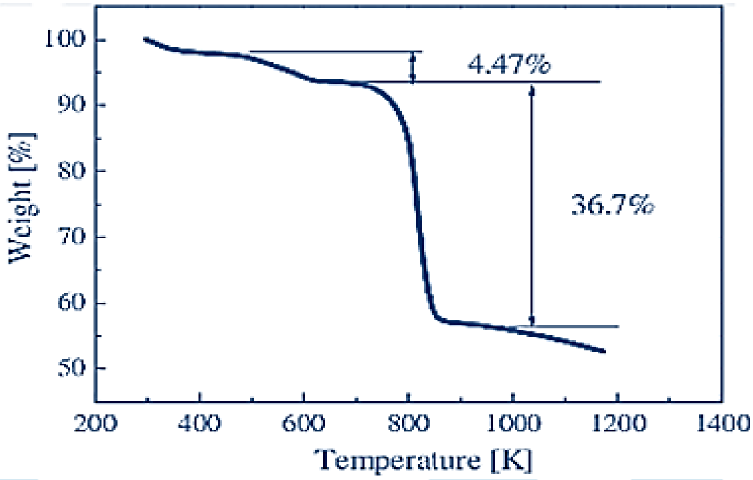

Figure 2. TGA Curve of CuCrZr Alloy

The TGA curve reveals several distinct stages of weight loss throughout the temperature range, as summarized in Table 1.

Table 1. Influence of Processing Parameters on TGA Results

Temperature Range (°C)	Weight Loss (%)	Description
Room Temperature to 200°C	<0.5%	Removal of adsorbed moisture and volatile contaminants
200 °C to 500 °C	5-10%	Decomposition of organic residues and low-boiling-point components
500 °C to 800 °C	20-25%	Decomposition of alloying elements or compounds
800 °C to 1000 °C	Stabilization	Formation of stable oxides or remaining metallic matrix

In the thermal analysis of the CuCrZr alloy, the mass change at varying temperature may be traced to four different regimes. From room temperature to approximately 200 °C, the material exhibits negligible mass loss (< 0.5%), which is primarily attributed to the desorption of physically adsorbed moisture and the volatilization of surface contaminants. Between 200 °C and 500 °C, a more appreciable mass reduction of roughly 5–10% is detected, corresponding to the thermal degradation of residual organic compounds and the volatilization of low-boiling-point constituents, likely remnants from the Selective Laser Melting (SLM) process. The most significant mass loss occurs within the 500 °C to 800 °C range, where a reduction of approximately 20–36.7% is observed. This major decomposition phase is indicative of the breakdown of alloying constituents or their oxides, particularly the volatilization and thermal decomposition of zinc- and zirconium-containing phases formed during SLM. Beyond 800 °C and up to 1000 °C, the mass loss plateaus, culminating in an overall reduction of approximately 30% by 1000 °C. This stabilization suggests the formation of thermally stable oxide layers and/or the persistence of the metallic matrix, which confers thermal stability at elevated temperatures [9-10].

b. Influence of Processing Parameters on Thermal Stability:

The thermal stability of CuCrZr alloys is strongly governed by the processing parameters employed during Selective Laser Melting (SLM). The layer height plays a critical role, as thicker layers (e.g., 100 µm) tend to exhibit reduced thermal stability due to the formation of pronounced interlayer boundaries and a higher incidence of defects such as voids and incomplete fusion zones, which act as preferential sites for oxidation and thermal degradation. In contrast, thinner layers (e.g., 30 µm) facilitate the development of a more homogeneous and densely consolidated microstructure with minimal defects, thereby enhancing thermal stability. Similarly, laser power significantly influences the thermal behavior: higher laser powers (e.g., 300 W) produce larger melt pools and promote complete powder melting, which decreases porosity and defect density and consequently improves thermal stability by mitigating potential decomposition sites. Conversely, lower laser powers (e.g., 150 W) often result in insufficient melting, increased porosity, and elevated defect densities, which diminish thermal stability. Scanning speed also affects the structural integrity; excessively high scanning speeds (e.g., 1200 mm/s) can lead to incomplete melting and increased defect formation, adversely impacting thermal stability. More moderate or lower scanning speeds (e.g., 600 mm/s) allow sufficient time for complete melting and solidification, yielding denser and more uniform structures with superior thermal stability.

c. Microstructural Characteristics

The microstructural description of the CuCrZr alloy electrode that was produced through SLM was conducted through Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and X-ray Diffraction (XRD) as depicted in Figure 3. SEM analysis revealed a fine-grained and homogeneously distributed microstructure with an average grain size of approximately 10–20 µm. The micrographs indicated negligible porosity, signifying effective densification during the SLM process, and only isolated defects such as micro-cracks or voids, reflecting well-optimized processing parameters. High-resolution TEM imaging further elucidated the microstructural features, displaying distinct grain boundaries with minimal elemental segregation and confirming the presence of uniformly distributed CuZn and CuCrZr phases within the grains. Complementary XRD analysis showed well-defined diffraction peaks corresponding to CuZn and CuCrZr phases, verifying successful phase formation during SLM. The sharp and intense nature of these peaks further indicated high crystallinity and good phase purity in the fabricated alloy [11-12].

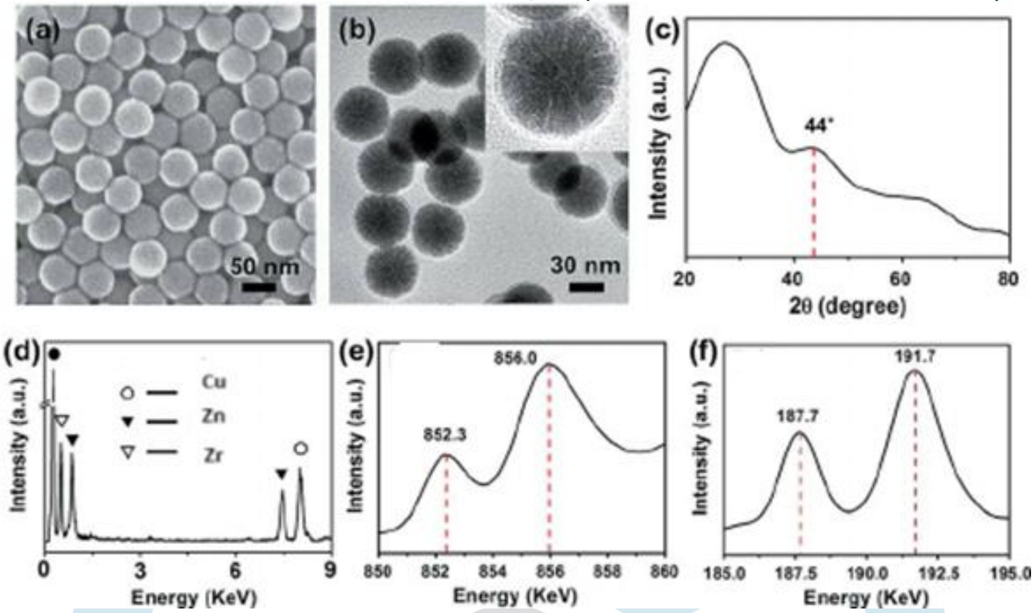

Figure 3. SEM, TEM, and XRD Images of CuCrZr alloy

d. Influence of Processing Parameters on Microstructure

The microstructural characteristics of CuCrZr alloys produced via Selective Laser Melting (SLM) are directly linked to their mechanical performance, particularly tensile strength and wear resistance. Finer grain structures—achieved through the use of thinner layer heights, optimized laser power, and appropriate scanning speeds—enhance these properties by the grain boundary strengthening mechanism, wherein an increased density of grain boundaries impedes dislocation motion, as illustrated in Figure 4. Regarding layer height, thicker layers (e.g., 100 µm) generally promote larger grain sizes due to slower cooling rates and extended solidification times, which encourage grain growth.

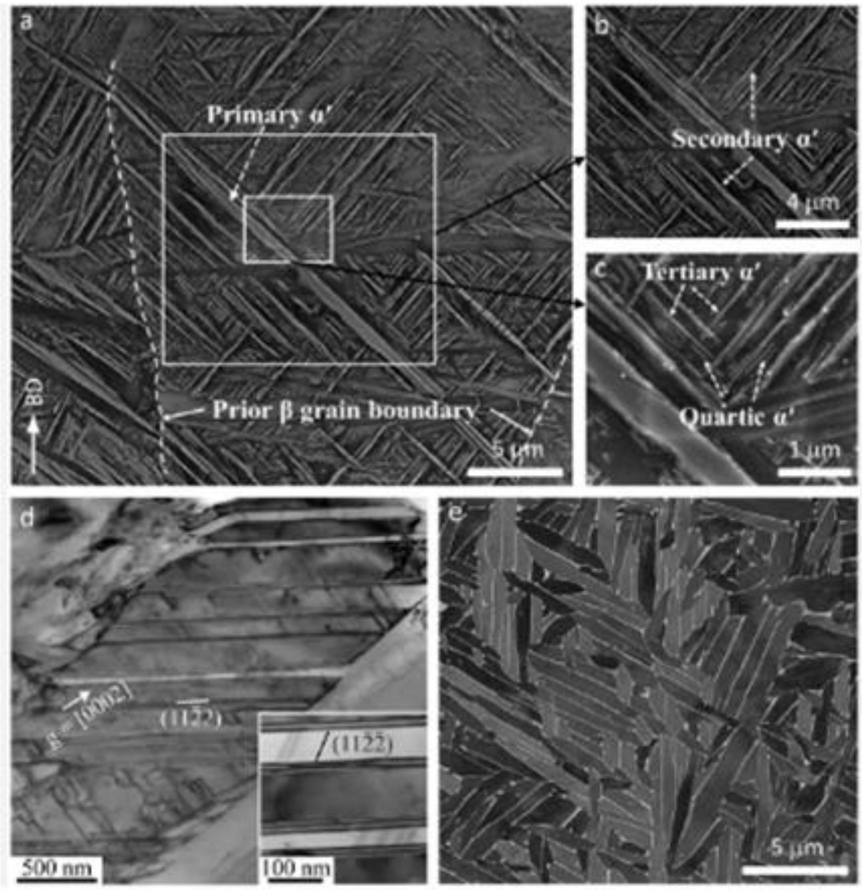

Figure 4. SEM image of the cross-sectional microstructure highlighting minimal porosity and well-defined grain boundaries

They also produce more pronounced interlayer boundaries that act as nucleation sites for defect formation. In contrast, thinner layers (e.g., 30 µm) enable rapid solidification and reduce the number of interlayer boundaries, resulting in finer, more homogeneous grain structures with fewer defects. Laser power also significantly influences grain morphology. Higher laser power (e.g., 300 W) produces larger melt pools and slower cooling rates, which favor coarser grain formation and enhance interlayer fusion; however, excessive power may induce thermal stresses and micro-cracking. Lower laser power (e.g., 150 W) generates smaller melt pools and faster cooling, which promotes finer grain formation but can also cause incomplete melting, elevated porosity, and higher defect density. Similarly, scanning speed affects both grain refinement and defect formation. Higher scanning speeds (e.g., 1200 mm/s) promote faster cooling that can refine grains, but they often result in insufficient melting and increased defect density, compromising overall structural integrity. Lower scanning speeds (e.g., 600 mm/s) allow more complete melting and improved layer fusion, leading to denser microstructures with fewer defects; however, the associated slower cooling can promote grain coarsening if not carefully optimized.

e. Tensile Properties and Fracture Behavior

A standard tensile test in compliance with ASTM E8/E8M-16a was used to determine the tensile behavior of the CuCrZr alloy electrode fabricated by Selective Laser Melting (SLM). The samples showed a mean ultimate tensile strength (UTS) of about 500MPa and a mean yield strength (YS) of about 350MPa.. The recorded elongation at break was approximately 15% which was a good ductile performance of the alloy. Examination of the post-fracture surface by Scanning Electron Microscopy (SEM) showed that the fracture morphology was predominantly ductile with many equiaxed dimples (Figure 5), proving the occurrence of extensive plastic deformation before fracture. [13-14].

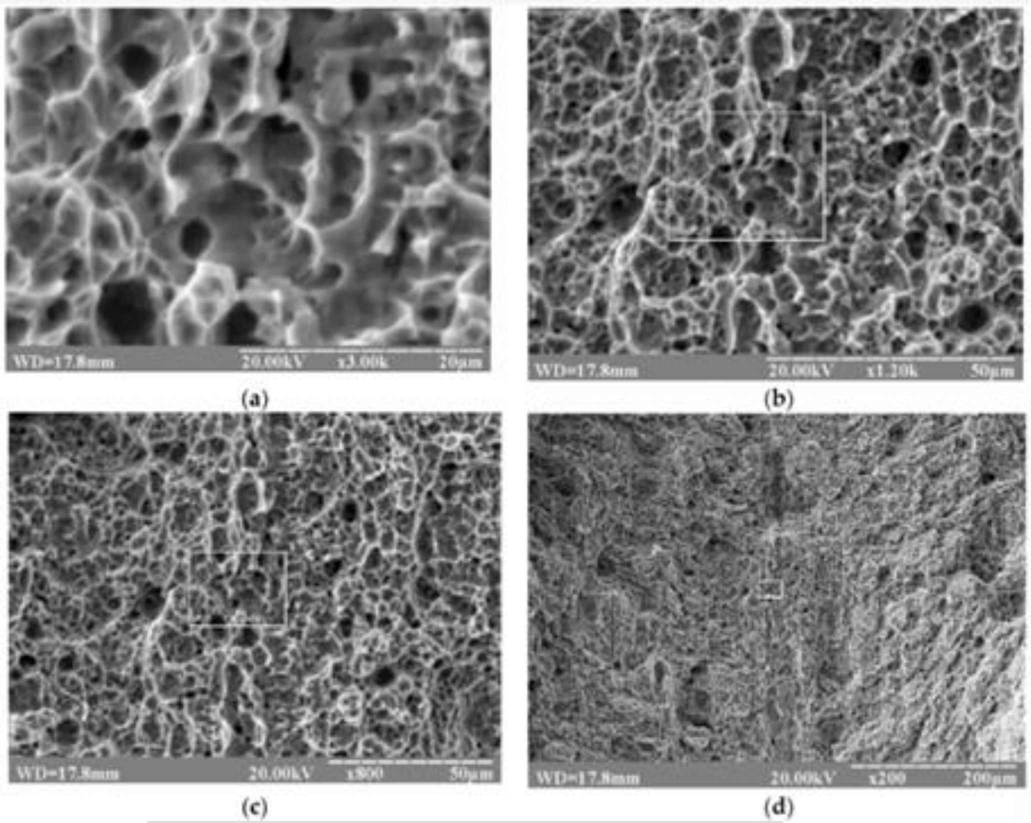

Figure 5. SEM images of the fracture surface, highlighting the ductile fracture mode with characteristic dimples at different magnifications

f. Influence of Processing Parameters on Tensile Strength

The tensile strength of CuCrZr alloys fabricated via SLM is strongly influenced by the processing parameters, particularly layer height, laser power, and scanning speed, due to their effects on microstructural evolution and defect formation. Thicker layers (e.g., 100 µm) tend to produce larger grain sizes and more pronounced interlayer boundaries, which act as stress concentrators and reduce tensile strength. The higher defect density and porosity typically associated with thicker layers further contribute to premature failure. In contrast, thinner layers (e.g., 30 µm) facilitate finer grain formation, improved interlayer bonding, and lower defect density, collectively enhancing tensile strength. Laser power also plays a critical role. Higher laser power (e.g., 300 W) promotes more complete powder melting, reduces porosity, and improves interlayer fusion, thereby increasing tensile strength. However, excessively high power can induce thermal stresses and micro-cracking, which degrade mechanical integrity. Lower laser power (e.g., 150 W) often leads to incomplete melting and increased porosity, resulting in poor interlayer adhesion and diminished tensile strength.

Similarly, scanning speed significantly affects tensile performance. High scanning speeds (e.g., 1200 mm/s) can cause insufficient melting and elevated defect density, both of which compromise tensile strength. Lower scanning speeds (e.g., 600 mm/s) allow more complete melting and solidification, yielding denser microstructures with improved layer cohesion and enhanced tensile strength. However, the slower cooling rates at lower speeds may promote grain coarsening, which can offset these benefits if not carefully optimized.

g. Correlation with Microstructure and Thermal Stability

The microstructural and thermal characteristics of CuCrZr alloys produced via Selective Laser Melting (SLM) exhibit a strong correlation with their tensile performance. Finer grain structures achieved through the use of thinner layers and optimized laser power enhance tensile strength via the grain boundary strengthening mechanism, as the increased number of grain boundaries impedes dislocation motion. Additionally, reduced porosity, attained through higher laser power and optimized scanning speeds, contributes to higher tensile strength by minimizing stress concentration sites. The presence of fewer micro-cracks and voids further supports improved tensile properties by reducing potential crack initiation points. A similar relationship exists between thermal stability and tensile strength. Samples demonstrating higher thermal stability, indicative of lower defect density and improved phase stability, also tend to exhibit superior tensile strength. In contrast, higher defect density and porosity associated with thicker layers or incomplete melting caused by lower laser power compromise both thermal stability and tensile strength. Likewise, excessive scanning speeds that lead to insufficient melting and increased defect formation negatively affect both properties simultaneously. These are discussed in table.2 in detail [15].

Table 2 Influence of Processing Parameters on Tensile Strength

Parameter	**Tensile Strength Impact**	**Reason**
Layer Height	Thicker layers: Lower strength	Larger grains, more interlayer boundaries and defects
	Thinner layers: Higher strength	Finer grains, better layer adhesion, reduced porosity
Laser Power	Higher power: Higher strength	More complete melting, reduced porosity, better fusion
	Lower power: Lower strength	Incomplete melting, increased porosity, weak adhesion
Scanning Speed	Higher speed: Lower strength	Insufficient melting, higher defect density
	Lower speed: Higher strength	Complete melting, better layer adhesion, denser microstructure

h. Wear Properties and Mechanisms

The wear properties of the SLM-fabricated CuCrZr alloy electrode were assessed using a pin-on-disk tribometer (ASTM G99 standards). The average wear rate was approximately 2.5×10^{-5} mm^3 /Nm, as tabulated in Table 3. SEM images of the wear tracks showed minimal material removal and smooth wear surfaces, indicating good wear resistance. The average coefficient of friction (COF) was around 0.45, with stable friction behavior throughout the test. Predominantly, adhesive wear (material transfer) and oxidative wear (formation of oxide layers on wear tracks) were observed, contributing to the material's wear resistance.

Table 3 Wear Properties Summary

Property	**Value**	**Description**
Wear Rate	2.5×10^{-5} mm^3/ Nm	Amount of material removed per unit load and distance
Coefficient of Friction (COF)	0.45	A measure of friction between the pin and disk
Wear Mechanisms	Adhesive, Oxidative	Types of wear observed during the test

i. Influence of Processing Parameters on Wear Strength

The wear resistance of CuCrZr alloys fabricated via Selective Laser Melting (SLM) is strongly influenced by the processing parameters—particularly layer height, laser power, and scanning speed—due to their effects on grain size, porosity, and defect formation. Thicker layers (e.g., 100 µm) generally produce larger grain sizes and higher porosity, both of which reduce wear resistance. The increased number of interlayer boundaries in thicker layers can also act as initiation sites for wear. In contrast, thinner layers (e.g., 30 µm) encourage finer grain structures, lower porosity, and improved interlayer bonding, thereby enhancing wear resistance by reducing defect density and minimizing weak interfaces. Laser power plays a similarly critical role. Higher laser power (e.g., 300 W) promotes more complete powder melting, leading to reduced porosity and improved wear resistance. However, excessively high power can generate thermal stresses and micro-cracks, which undermine surface integrity. Conversely, lower laser power (e.g., 150 W) often results in incomplete melting and elevated porosity, producing weak interlayer adhesion and un-melted particles that lower wear resistance. Scanning speed also affects wear performance. Excessively high scanning speeds (e.g., 1200 mm/s) can cause insufficient melting and increased defect density, which degrade wear resistance. Lower scanning speeds (e.g., 600 mm/s) provide sufficient time for complete melting and solidification, yielding denser microstructures with stronger interlayer adhesion and improved wear resistance. However, the slower cooling rates at lower speeds may promote grain coarsening, which can reduce wear resistance if not properly optimized.

IV. CONCLUSION

- This paper had a holistic analysis of the microstructural and mechanical behavior of CuCrZr alloy components prepared through Selective Laser Melting (SLM) by using an Amace STLR 400 system. Response Surface Methodology (RSM) was used systematically to optimize key SLM processing parameters, such as the laser power, scanning speed and layer height to assess their interplay in tensile strength, wear resistance and thermal stability.
- A major outcome of this investigation was the identification of low layer heights (e.g., 30 µm) combined with high laser power (e.g., 400 W) as optimal conditions for maximizing tensile strength. This enhancement was attributed to the formation of refined microstructures and a substantial reduction in porosity. Although higher scanning speeds (e.g., 600 mm/s) tended to reduce tensile strength, careful parameter optimization mitigated these effects.
- For wear resistance, layer height and laser power emerged as the most influential parameters. Lower layer heights and increased laser power consistently yielded lower wear rates, with the best-performing samples displaying uniform wear tracks and minimal material loss, demonstrating excellent tribological performance. Thermogravimetric analysis (Thermogravimetric Analyzer, TGA) confirmed that the alloy maintained structural integrity up to approximately 500 °C, with significant decomposition occurring only beyond 800 °C, indicating strong thermal stability.

- Statistical evaluations using Analysis of Variance (ANOVA) validated the predictive accuracy of the quadratic and two-factor interaction (2FI) models for wear rate and tensile strength, respectively, supporting reliable process optimization within the defined design space. A direct relationship was observed between the relative density of the fabricated samples and their mechanical performance: higher densification consistently correlated with improved tensile strength and reduced wear rates, highlighting the critical role of density control in SLM. Additionally, post-processing via age hardening significantly enhanced mechanical properties, resulting in increased strength and hardness.

In summary, the optimized SLM-fabricated CuCrZr alloy established a synergistic combination of high tensile strength, superior wear resistance, and excellent thermal stability, establishing its suitability for demanding applications in aerospace, automotive, and high-temperature operational environments.

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