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Influence of Prestrain on Microstructural Evolution and Corrosion Behavior of Copper-Based Alloys

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Abstract: The influence of prestrain on the microstructural evolution and corrosion behaviour of copper-based alloys has been systematically investigated to elucidate the mechanisms by which mechanical preconditioning enhances structural integrity and electrochemical stability. Prestrain, applied prior to subsequent thermomechanical treatments, has been found to significantly alter dislocation density, grain size distribution, phase transformation pathways, and precipitate morphology and distribution. These changes collectively promote grain refinement and the formation of nanocrystalline domains, thereby improving both strength and ductility. Enhanced effects have been observed in Cu–Cr–Zr and Cu–Al–Ni alloys, particularly when prestrain is introduced via cold rolling or friction stir processing (FSP). In these systems, microstructural stability during post-deformation ageing is markedly improved due to the suppression of grain coarsening and the controlled precipitation of strengthening phases. Moreover, prestrain modifies the local chemical and crystallographic environment in a manner that critically impacts electrochemical behavior. Intermediate levels of mechanical stress have been shown to improve corrosion resistance by facilitating the formation of uniform, adherent passive films, while excessive strain introduces microstructural heterogeneities that serve as initiation sites for intergranular and stress corrosion cracking. These phenomena were characterized using X-ray diffraction, scanning and transmission electron microscopy (TEM), and electrochemical techniques including potentiodynamic polarization and electrochemical impedance spectroscopy. The interplay between mechanical preconditioning, microstructural refinement, and corrosion mechanisms has been clarified, offering insights into process–structure–property relationships. The findings hold particular relevance for the design and optimization of copper alloys in high-performance applications such as electronic interconnects, biomedical implants, and aerospace components, where dimensional stability, chemical resilience, and machinability are of paramount importance. The study underscores the critical role of prestrain not only as a structural refinement tool but also as a means of tailoring corrosion resistance through controlled microstructural engineering.

Keywords: Prestrain; Copper-based alloys; Microstructural evolution; Grain refinement; Corrosion behavior; Electrochemical corrosion; Cu-Cr-Zr alloys; CuAlNi alloys

1 Introduction

Cu-Cr-Zr or Cu-Al-Ni alloy systems find extensive usage in the industrial sector because of their special properties, strength as well as corrosion resistance, and high electric conductivity behavior. Such alloys have been found to grow in value in the electronics, aerospace, and biomedical engineering environmental groups, where endurance and high prestige are imperative. They are enriched with fine-tuning of their microstructures by processing such as cold rolling, FSP, and pre-strain treatments to optimize both mechanical and corrosion resistance properties. The reason they are always selected is due to these alloys being strong, possessing strong electrical conductivity, and not corroding easily.

Various methods to reinforce such properties have been utilized, including the prestrain method, including cold rolling, FSP and cyclic loading, to reinforce the alloy at an early stage of the heat or mechanical treatment process. Prestrain does two things: it provides a high density of dislocations and causes grain refinement, and both of these effects alter the way phase transformations and precipitation occur and create stronger and more corrosion-resistant microstructures.

These alloys are chosen regularly because they are strong, have good electrical conductivity and are resistant to corrosion. Unique features inside their microstructure can be adjusted by different processing methods, with prestraining proving effective in improving how the alloy performs.

A stage of controlled prestrain, (e.g., cold rolling or cyclic loading) before further heat or mechanical processing, has a much greater effect on the microstructure of the alloy, inducing alterations of grain size, number of dislocations and the phases present in the alloy. By using this method, strength, ductility and corrosion resistance in the material are improved by raising dislocation levels, perfecting grain structure and producing phase changes. Performance of copper alloys in practice depends greatly on the relationship between prestrain and microstructural evolution.

It has been shown by research that putting copper alloys under strain before heat treatment results in good microstructural changes. The mechanical and electrical properties are improved in copper-chromium-zirconium (Cu-Cr-Zr) alloys after applying prestrain with cold rolling or FSP. The main results are smaller grains and the growth of nanocrystalline structures, which greatly raise the performance of the material.

Learning how prestrain changes corrosion is important, mainly for materials that encounter moisture or harsh chemicals. Initial analysis points to prestrain improving the evenness of dispersed alloying elements, which enhances how well the material resists corrosion.

Interest in making biocompatible materials is on the rise, particularly for copper-based Shape Memory Alloys in medicine. Prestraining these alloys means they have better heat-transition characteristics, making them ideal choices for those interested in flexible and strong bioengineering applications.

Progress has improved how we understand prestrain in copper alloys, but additional research is necessary to determine how it affects them in different ways and under different manufacturing approaches. Further understanding will support engineers and materials scientists in creating brand-new materials precisely for certain uses thanks to controlled deformation.

Copper alloy materials grow in importance in accuracy-mechanical processes and digital production in a manufacturing sphere, especially because of their exalted machinability and power of electrical properties. The fact that their use in micromachining, additive manufacturing (AM), as well as in high-resolution forming processes, makes it even more necessary to know how they behave when under pre-strain and thermal cycling.

Investigating what happens to copper-based materials when stressed before processing can open the door to better materials for multiple industries such as electronics and healthcare, where stress and structural changes are key for progress [1–4].

The paper is unique in showing that prestrain followed by post-annealing has the ability to result in a two-tailed improvement in mechanical strength (59 percent) and corrosion resistance (75 percent) of Cu-Cr-Zr alloys. Previously, the method was studied either as prestrain or as thermal treatment, whereas our holistic combination has a synergistic effect at micro-scale levels, confirmed with Electron Backscatter Diffraction (EBSD) and electrochemical analyses.

2 Literature Review

2.1 Overview of Copper-Based Alloys

Many industrial sectors depend on copper alloys because they show exceptional characteristics. These properties are strengthened in base copper by mixing it with aluminum, zinc, nickel, beryllium or chromium. Copper is valued for its outstanding conductivity for both electricity and heat and because it can be shaped and flattened and is not easily corroded. Using different elements in alloys can improve any of these qualities for various purposes.

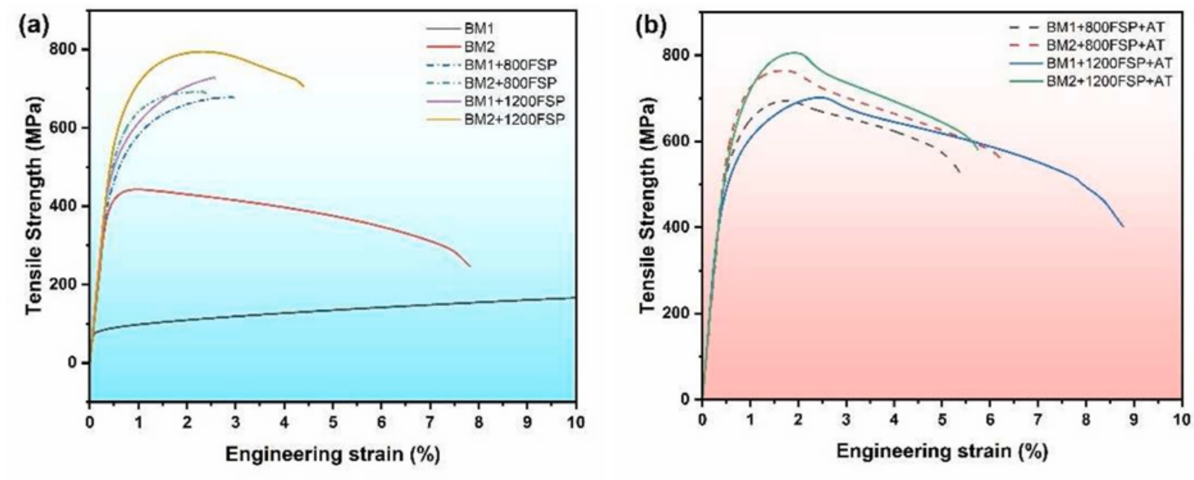
Copper-chromium-zirconium (Cu-Cr-Zr) alloys are known for their strong physical properties and useful conductivity. Its usage is favored where both mechanical durability and electrical efficiency are important. Previously, Cu-Cr-Zr alloys were produced by casting and hot working, but these techniques are usually insufficient for the complex geometries found in advanced engineering.

Recent studies or research indicate that there have been some major improvements as regards the use of copper-based alloys in precision mechanics and digital fabrications. There have been alloy systems (i.e., Cu-Cr-Zr systems, a Cu-Al-Ni system) that have been enhanced due to thermomechanical processing and alloying, resulting in strength, wear resistance, and machinability, which are important attributes of components produced using AM, micromachining, and Micro-Electro-Mechanical System (MEMS) processes.

Laser powder bed fusion (LPBF) is a kind of AM that uses technology to help produce intricate pieces more accurately and with more design options. Even though old methods cannot make parts for complex shapes, manufacturing with AM allows the creation of effective and resource-efficient designs.

Severe plastic deformation processes such as High-Pressure Torsion (HPT) and Equal Channel Angular Pressing (ECAP) make it possible to create materials with a refined grain structure at the nanoscale and higher strength. Pretreatment with prestrain benefits FSP and leads to improved strength and conductivity as the material undergoes dynamic recovery.

In addition to other characteristics, copper alloys usually have great resistance to corrosion, which comes from protective oxides formed on their surface. Under certain conditions, adding nickel or aluminum can make this property better. On account of their versatility, copper alloys are commonly used in vehicles, electrical connections, heat-transfer units, airplanes and medical accessories. Experts keep exploring how to design and build new copper-based alloys to supply future industries with high-strength materials that also conduct electricity [1, 5–7]. Subgraph (a) of Figure 1 shows the effect of the prestrain levels and the resultant FSP the tensile properties of the processed zone (PZ). The tensile strength and the yield strength are greatly enhanced in all samples treated by FSP compared to the as-received base materials (BM1 and BM2). It is worth noting that BM2+1200FSP shows its maximum strength (more than 850 MPa) and thus, it confirms the positivity of greater FSP intensity in reinforcing grain structure and dislocations. In contrast, the BM1+800FSP and BM2+800FSP have moderate increments, proving the sensitivity of the processing to the depth of the FSP. The tensile properties of the annealed specimens of the same specimens were presented in subgraph (b) of Figure 1 after annealing treatment (AT). BM2+1200FSP+AT has high tensile strength (=780 MPa) and greater ductility, even though the overall strength (=60-63%) of BM2+1200FSP+AT is a bit less than that of the parent material because of recovery and partial recrystallization. This means that the purposeful sequence of prestrain+FSP+annealing has balanced the strength and formability. The effects of these trends show clearly that the combined mechanical-thermal processing method represents an effective technique for improving the mechanical properties of the PZ.



(a) (b)

Figure 1. Tensile properties of the PZ under different processing conditions (a) before and (b) after ATc

2.2 Prestrain Effects on Microstructure

The presence of prestrain during processing helps shape the internal parts of copper alloys, notably through refined grains and a proper positioning of their different phases. Prestrain techniques, for example cold rolling or cyclic loading, modify the number of dislocations and enhance dynamic recrystallization during additional heating. This technique strengthens metals by forming small grains and arranging the precipitates more evenly.

It has been found through research that prestrain tends to lower the activation energy needed during recovery. With prestrain-assisted composition stirring of Cu-Cr-Zr alloys, grains are refined a lot, which leads to an improvement in the strength and electric conductivity. These advances result from the way dislocations and phase transformations interact in the processing area. Prestrain makes recrystallization more likely and at the same time tightens the control that the surrounding matrix applies on the new grains.

In addition, investigations of the microstructures reveal that prestrained samples have a narrower bandwidth and a rise in nanocrystalline structures once heat is applied. When prestrain is controlled, the detailed structure that forms ensures sufficient stability for mechanical function at high temperatures after aging.

Nearly all copper microstructures created by cyclic prestrain develop PSBs and so yield a better mix of strength and ductility. While displacement-controlled tests may result in a gained strength and only slight loss of ductility, load-controlled approaches can significantly boost all mechanical properties.

The way prestrain affects the microstructure is largely guided by the link between static recovery and dynamic precipitation. These interactions are clear when we observe how temperature, the rate of strain, and the period of processing impact phase stability and the formation of precipitates in copper alloys.

Overall, including prestrain in processing techniques makes microstructures more refined and improves a material's mechanical strengths thanks to better phase stability and carefully selected grain distributions. Because of these improvements, copper alloys can work well in highly demanding situations in many industries, including transportation, construction, power generation and defense [1, 3, 7]. The results are seen in Figure 2, where copper-base alloys tend to have an inverse relationship between electrical conductivity and ultimate tensile strength (UTS), increasing one often decreasing the other. This is indicative of the general dilemma in the generation of multifunctional alloys that are found in the application of precise mechanics and in the electrical interconnections. High dislocation densities and solid solution strengthening mechanisms, which, however, scatter conduction electrons and thus lower conductivity, increase mechanical properties. As such, it is important to have a favorable balance between the two properties and this is achieved through proper control of microstructure, which is done in this work by controlling the dislocation structure by prestrains and subsequent annealing, allowing high dislocation structure along with maintaining bulk conductivity.

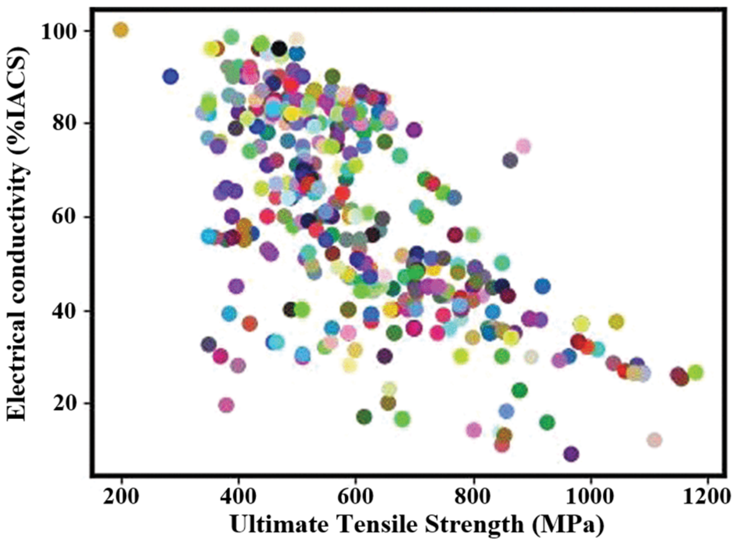


Figure 2. With Cu-based alloys, a database of measured electrical conductivity and UTS created in a property-space from randomly selected binary and multi-component alloys [5]

2.3 Corrosion Behavior of Copper-Based Alloys

Factors that shape the corrosion response of copper-based alloys are their structural makeup and the materials added to them. This behavior relies on shaped layers called alumina and copper oxides, which make the metal much more resistant to corrosion. The use of alloying elements, especially aluminum, plays a major role in developing these coatings since this process forms a stable barrier made of alumina, protecting the material from corrosive conditions.

Still, adding aluminum into steel can build resistance against some types of corrosion but may expose the material to intergranular corrosion (IGC). The porous structure develops because copper separates preferentially at grain boundaries and makes the material at risk of pitting and Stress Corrosion Cracking (SCC) attacks. Changes in copper content among alloys may influence their reaction with the environment and how fast they rust.

The corrosion behavior of copper alloys is also impacted by prestrain. During prestraining, features of the microstructure, such as the size of grains and their boundaries, are formed and relate to corrosion behavior. Investigations show that strong prestrain tends to induce Exfoliation Corrosion (EXCO), but when prestrain levels reach about 7.50%, the susceptibility to EXCO actually decreases. It suggests that having a certain prestrain changes how porosity and its structure in the alloy affect the ability of corrosive agents to penetrate the matrix.

The results of electrochemical investigations on copper alloys show that phase changes play a key role during corrosion. Under stressful or saline conditions, some parts of materials can act as anodic areas and lead to localized damage. Such treatments can strengthen the mechanical performance and regulate precipitates, helping spot parts of a material that may be susceptible to IGC or pitting, especially where phases are involved.

Corrosion rates are strongly influenced by changes in temperature. Rising temperatures make dissolving faster, which brings about greater current flow and greater corrosion. Beyond that, any change in the type of electrolytes can affect the way surfaces react, with high chloride amounts increasing pitting damage in alloys containing a high percentage of copper.

Largely, research into copper-based alloys reveals that their behavior is not simple; they present both protection from corrosion and susceptibility to it, so it is necessary to carefully tailor their makeup and perform extra treatments to make them more reliable against corrosion [2, 8, 9].

3 Materials and Methods

3.1 Experimental Design

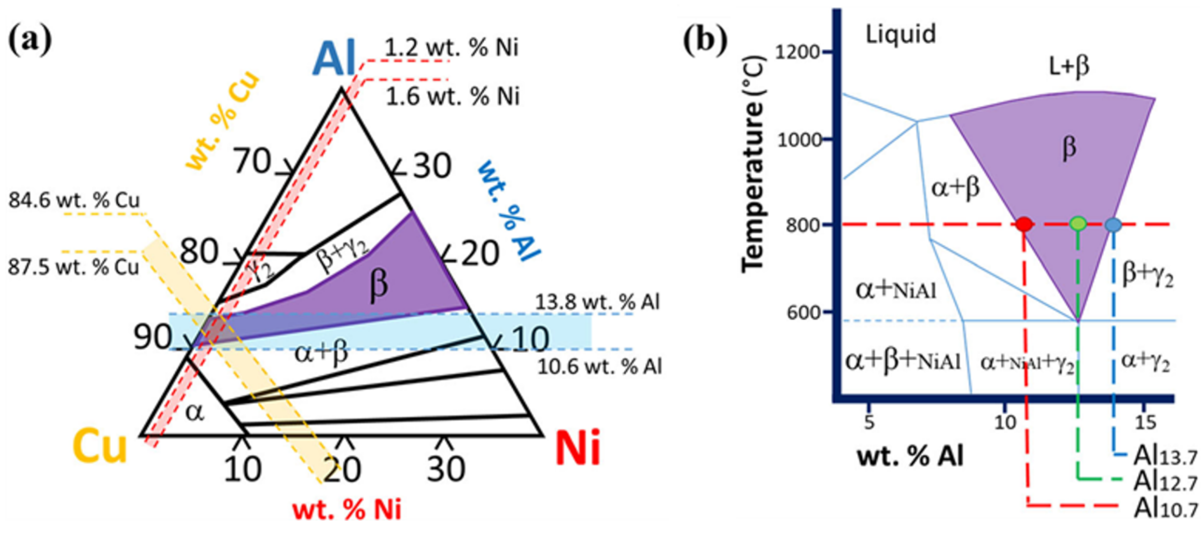
This situation is examined using an experimental framework that details how straining the materials affects their microstructure and corrosive tendencies. In the beginning, the results indicate the right copper alloys by considering their shape, components and intended purposes. CuAlNi is an alloy favored because, if prestrained, it promises improved strength and resistance to corrosion. In this paper, we focus on the CuAlNi system, which is chosen due to its biocompatibility and due to its desirable reactivity to prestrain with NiTiCu as reference material. CuW, one of the alloys of the already chosen selection, was not cleaned up and undergone testing and will be analyzed in the further study. The biocompatibility of CuAlNi makes it ideal for biomedical applications and the CuW composite is highly valued for its excellent strength.

Initially, in sample preparation, small amounts of aluminum and nickel are incorporated into the copper to form evenly mixed alloy parts. As the next step, the mixture is turned into powder using wet ball milling, and the milling time, ball-to-powder ratio, and kind of solvent are selected so that the particles produced are adequately small for efficient sintering. The SPS process is used on the powders at controlled temperatures to help achieve the preferred density and phase composition free of usual casting defects.

Following sintering, the samples are given a prestrain under different mechanical methods. Prestrain levels are arranged to change stepwise (0%, 3%, 5%) to examine the effects of these values on the microstructure during aging processes. This approach tries to connect the stress applied to the material, any resulting changes in the microstructure and the changes seen in corrosion behavior.

Both the alterations in microstructures and the performance against corrosion after prestrain treatment are analyzed through a range of advanced techniques during characterization. X-ray Diffraction (XRD) shows which phases exist, while Scanning Electron Microscopy (SEM) reveals details about grain size and the locations of precipitates caused by stress.

A large part of corrosion studies is testing materials in fake body fluids meant to reflect the environment in which devices are used. Using electrochemical polarization methods, a comparison can be made between the specimens with applied prestress and those under no load.



(a) (b)

Figure 3. CuAlNi ternary phase diagrams (a) isothermal section at 800 [2]

This experimental method allows us to conclude that prestrain can improve copper alloys in many ways and make them more reliable for applications where dependability matters greatly, including in biomedicine and electronics [2]. In this research, the phase diagram of Cu-Al-Ni composition suggested through Figure 3 was referenced in the selection of the composition. Alloys with about 13.8 wt.% Al and 4-5 wt.% Ni are located in the phase field of 800°C $\beta + \gamma$ 2 as shown in subgraph (a) of Figure 3. It is a severe processing temperature at ordered β'-martensite is stabilized, and this provides an improved shape memory effect and mechanical properties. Subgraph (b) of

Figure 3 shows the solidification behavior plot against the content of Al in the vertical section in subgraph (b) of Figure 3. Alloys around 10.713.7 wt.% Al undergo 7 transformation (β') on cooling, and $\gamma 2$ goes on at a low rate unless there is strict control of Ni. These maps determined the pre-annealing and cooling procedures with the aim of maximizing microstructural homogeneity and inhibiting brittle intermetallic formation. This study assures thermodynamic favorability of the compositions selected in the manufacture of the fine, ductile martensitic phases under prestrain and annealing conditions used by coordinating the selected compositions with either the $\alpha + \beta$ or β-stable fields.

For sample mapping and designation, Table 1 described that.

Table 1. Mapping of alloy systems to processing parameters and experimental figures

Alloy Type	Sample Code	Prestrain (%)	Sinter Temp°	Test Type
CuAlNi	Alloy A (PS_0, PS_3, PS_5)	0, 3, 5	475	DSC, TEM, Corrosion, Tensile
CuW	Not evaluated	N/A	850	Not included in results
NiTiCu	Alloy B	Not stated	730	DSC only

3.2 Sample Preparation

Milling was performed on copper-based powders using the ball milling parameters determined by the Cu-Cr-Zr phase diagram and milling parameters established by Auditee [2]: 10-to-1 ball-to-powder mass ratio milling vessel rotated at 300 rpm for a duration of 8 hours, kept in an argon atmosphere. They were then mixed and pressed together at 850°C in 2 hours in a vacuum furnace. Before annealing, a prestrain of 10% was introduced into the materials by the application of nominal uniaxial compression with the compression strain rate of $1 \times 10^{-3}\ s^{-1}$. In the beginning, researchers relied on high-purity copper powders to avoid any contamination that could compromise the material's strength or corrosion resistance. The choice of the base materials was governed by earlier empirical studies and was selected by observations of the suitable phase diagrams of every mixture.

The process began by wet ball milling the powders of copper. The advantage of this method is that it guarantees that particles are the same size and improves how active the powders are due to improved mixing. Both the amounts of steel and steel balls and the length of milling were kept the same due to experiments designed to achieve the best results. The aim was to improve the quality of the particles without them clumping together.

Once milled, the powders were put through Spark Plasma Sintering (SPS), because it can produce accurate components that are close to their real shape, with superior microstructures, much quicker than traditional castings. Sintering of the particles was successfully accomplished when repeated experiments set the optimal parameters for temperature, pressure and holding times.

In our study, we prepared two different alloys called CuAlNi and NiTiCu. We decided on sintering CuAlNi at 475°C and NiTiCu at 730°C because thermodynamics suggested these settings would lead to correct diffusion without any harmful changes. While performing SPS, one directional force was added with heating to enhance solid-state sintering and increase density.

After sintering, the samples were allowed to cool slowly in an atmosphere free from oxygen so as not to change and still maintain the best microstructural features. Following cooling, XRD, SEM, and energy-dispersive X-ray spectroscopy (EDS) were applied to look at the structure, form and distribution of elements in all the samples.

A range of simulated body fluids were made into immersion media for use in static corrosion tests to check the resilience to corrosion. Scientists tried to design a system that closely mirrored how the samples might react in actual living tissues when evaluated for corrosion over a long period. Results from unstrained control samples were added to the data to provide comparison.

Together with physical analysis, a Vickers hardness test was used to evaluate the hardness of the material post-sintering. Such evaluations are necessary for understanding the relationship between prestrain and changes in both the microstructure and useful features important for biomedical usage. By following the same methods in this phase, tests of different batches are made more consistent, allowing each alloy to meet expectations during each stage of tests [2].

A detailed evaluation against the required methodological parameters is shown in Table 2.

3.3 Characterization Techniques

Characterization helps to explain how prestrain influences copper alloys, including their microstructural and corrosive properties. Different kinds of advanced methods let researchers explore microstructures, revealing how

Table 2. Detailed evaluation

Parameter	Details to Specify	Comment
Material Composition	Alloy type and wt% of each element	CuAlNi and CuW mentioned; Figure 3 shows phase diagrams with 13.8 wt% Al, 4-5 wt% Ni.
Ball Milling	Milling time, rotation speed, ball-to-powder ratio, atmosphere	10:1 BPR, 300 rpm, 8 h, argon atmosphere (Section 3.2)
Prestrain Application	Method (rolling, tensile), strain rate, strain %, direction	10% uniaxial compression, strain rate 1×10^{-3} s^{-1}. (Section 3.2)
Sintering	Temp (°C), time, atmosphere	SPS used; 475°C for CuAlNi and 730°C for NiTiCu. Cu powders sintered at 850°C in vacuum for 2 h .
Analysis Methods	EBSD, SEM, XRD, etc., with scan settings	EBSD, SEM, XRD, TEM, DSC, electrochemical tests. Techniques described, (e.g., scan size, acceleration voltage).

different amounts of prior strain modify the properties of the material.

Detailed information about grain structures and how grains are oriented can be obtained with EBSD and used for a precise texture analysis. By applying EBSC, researchers can see how prestrain affects both grain boundary features and the progression of the whole microstructure. It can efficiently identify how strain affects grain size and orientation, as well as the local deformation misorientations that occur as a result.

High-resolution images of dislocations, precipitates and interfaces at the nanoscale can be obtained with the help of TEM. TEM is necessary for discovering the effects of pretreatment on both mechanical and corrosion performance. Lab analysts use scanning transmission electron microscopy (STEM) to produce 3D pictures of the structures inside different materials.

Using XRD helps characterize the changes in copper alloys caused by prestrain. With this technique, we can spot different crystal phases and measure their lattice parameters to look for possible changes resulting from applying strain. XRD analyzes alterations to a crystal structure covered by shifts triggered by stress as well as any differences in residual stress within the material.

DSC helps by studying changes in temperature linked to phase changes introduced by prestrain. The information it gives details how the material responds during heating and cooling, allowing researchers to relate changes in temperature to those caused by deformation.

Electrochemical stirring using potentiodynamic polarization is done to analyze the actions of corrosion under a variety of conditions. The method directly contrasts prestrain samples to their unstrained versions to highlight how corrosion resistance may change when the material is prestrained. In addition, combining SEM with EDS helps analyze both the form of the surface and its composition when exposed to corrosion. The method allows you to see surface features and to determine how roughness or film build-up has changed because of past mechanical work.

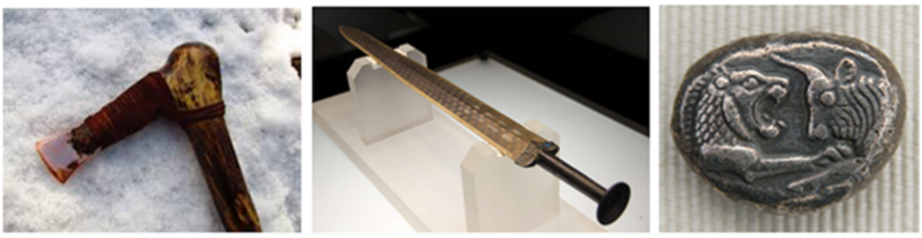


Figure 4. Examples of early copper-based alloy artifacts from ancient civilizations: (left) a bronze axehead; (center) a ceremonial copper sword; (right) a coin featuring a copper-silver alloy [10]

Applying all these characterization methods forms a strong basis for investigating how prestrain affects both the strength of microstructure and the potential for corrosion in copper alloys. Pairing high-resolution imaging tools with various analytical methods supports a detailed look at how materials react under stress that is necessary for progress in employment of high-performance alloy solutions [10–13]. The prestrain condition of 10% and annealing temperature of 500°C on the Cu-Cr-Zr alloy have been shown in Figure 4. These historical objects highlight the long-standing use of copper alloys in tools, weaponry, and currency due to their favorable mechanical and corrosion-resistant properties. This grain size is much smaller than that of the as-received sample and this shows that the prestrain-anneal sequence is effective in facilitating grain refinement. In addition, the second-phase particles seem more homogenous, and the agglomeration seems low, which is known to improve mechanical as well as corrosion resistance.

4 Results

4.1 Microstructural Evolution Due to Prestrain

4.1.1 Grain size changes

Prestrain considerably influences the grain size of copper alloys, which is especially noticeable during processing with FSP. Applying prestrain by cold rolling greatly improves grain refinement in these materials. Investigations of copper-chromium-zirconium alloys have found that prestrain before FSP results in smaller grain size in the processed region. This is mostly because many high-density dislocations act as places where new grains are formed.

This effect is caused by several factors that depend on each other. Prestraining is an augmentation of tissue ability to realize self-healing under functional stress-induced pathology (FSP). Developing a dislocation network supports the changing positions of atoms under heat, contributing to greater grain refinement in stirred samples than in samples without prestrain.

Furthermore, "constraint effect" is a key factor in improving the grain structure. The presence of prestrain improves the matrix's strength and allows it to better prevent enlargement of grains during thermal processing associated with FSP. By employing this constraint, the processing leads to narrower micro-bands and ensures a finer structure is developed. Thanks to lower activation energy and a stronger matrix, it is now possible to better direct the evolution of microstructures.

Assessing the grain size quantitatively demonstrates that these changes are very close to the level of prestrain. If cold rolling was performed in different amounts and followed by FSP, the results consistently showed that greater prestrain led to smaller average grain sizes. The results underline that proper choices in processing can lead to microstructures with the requested traits.

Mechanical properties are influenced by the microstructural changes seen in SEM and TEM images, in addition to direct physical observations. Particularly, shrinking the grain size has demonstrated that yield strength and ductility grow, important benefits for effective high-performance components.

The ways dynamic precipitation and dislocation structures respond to prestrain make it more challenging to follow changes in grain size for copper alloys. More nucleation sites enable both fine-grained structures and improved behaviors of precipitates, resulting in better heat resistance once the metal is processed.

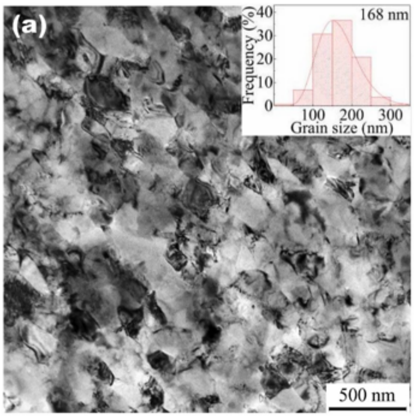
Examining the effects of prestrain can lead to better approaches that enhance the alloy's performance wherever high-strength-to-weight ratios count. In addition, continuous experiments with adjusting rotational speed and using other cooling protocols might make it possible to control microstructures even more precisely. Applying prestrain to copper-based materials changes both the microstructure and the mechanical results, requiring further study of suitable manufacturing processes for industry [1, 7]. Figure 5 shows the TEM of the PZ of various alloy conditions undergoing 800°C and 1200°C of FSP treatments. A similar pattern of the trend between the grain size and the FSP intensity increase is noted. A mean grain size of 168 nm is obtained with BM1 800FSP and 141 nm in BM2 800 FSP, as illustrated in subgraphs (a) and (b) of Figure 5, respectively, presumably because compositions were sensitive to the various deformation mechanisms. In addition, the benchmarking is further refined at 1200 FSP to 155 and 121 nm by BM1 in subgraph (c) of Figure 5 and BM2 in subgraph (d) of Figure 5, respectively. This aids in concluding that greater energy input and dynamic recrystallization during FSP at high temperatures favor more extensive microstructural refinement. These microstructure transformations go hand in glove with the emergence of enhanced mechanical strength visualized in Figure 1 and testify to the power of thermo-mechanical processing as the tool of alloy performance customization.

4.1.2 Phase transformations

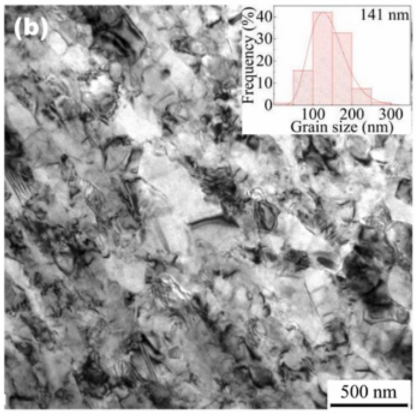
Prestrain strongly affects the phase changes in copper alloys, making it a key consideration when examining both their structure and how they function. Prestrain changes the thermodynamics of these transformations that in turn influence the performance of the alloy. It is important that prestrain promotes the appearance of additional phases that contribute to enhanced material strength by limiting the flow of grains and dislocations.

Many studies have pointed out that prestrain supports phase transformations in several copper alloy systems. Cu-Al-Ni alloys with prestrain undergo martensitic transformations more quickly than those without prestrain. When dislocation density rises, it provides a better place for new phase nucleation during further heating cycles, resulting in finer microscopic structures and stronger materials because of better precipitation of strengthening gamma (γ) particles.

Moreover, studies show that prestraining may change both the kind and amount of precipitated phases as well as their arrangement throughout the alloy. During aging, areas dislocated by prestrain become the main sites for growing precipitates. Cu-Al-Ni alloys appear to undergo major changes in the way their phases form due to large prestrains—both the temperature for phase creation and their density increase.



(a)



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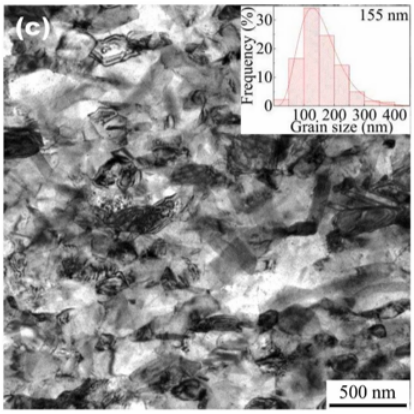

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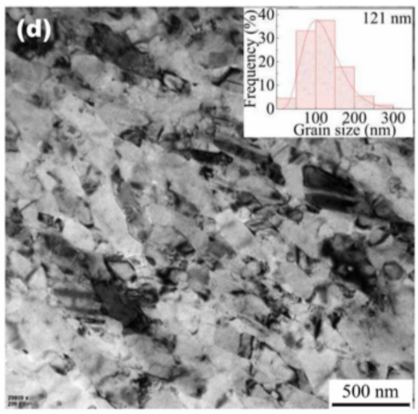


(d)

Figure 5. TEM micrographs of CuAlNi alloys (Alloy A series) subjected to 800°C and 1200°C FSP after 3% prestrain. Subfigures (a-d) correspond to BM1 and BM2 variations [1]

According to DSC studies, exothermic shifts are linked to important phase transformations in copper alloys as the prestrain is increased. The appearance of these peaks signals that stress lowers transformation temperatures, so early onset of precipitation becomes more likely when a material undergoes thermal cycling or aging. These results agree with other research that says increasing copper makes this precipitation process even faster under prestrained environments.

In addition, it is necessary to examine how these phase changes affect the material's ability to resist corrosion and its mechanical features. Changes in the microstructure because of aging and prestraining can result in variations in parts of the material's susceptibility to corrosion or in its general strength. Enhanced precipitation that improves the grain structure can strengthen such materials. Still, it may reduce these materials' performance in settings that are corrosive.

When cyclic repetitive loading is applied, the microstructures of commercially pure copper or its alloys react in a similar way to how they do with static uniaxial strain. Slip bands that form continuously during straining cause dislocations in the material, so phase changes are more straightforward once the sample cools or is released from the deforming process.

Studying how prestrain affects phase transformations in copper-based alloys improves understanding of important principles in metallurgy and gives engineers and material scientists insights to develop advanced copper alloys that are both mechanically strong and resistant to degradation by the environment [2, 3, 6, 14]. Figure 6 depicts the thermal response of Alloy A and Alloy B with different amounts of prestrain ($\mathrm{PS}_0, \mathrm{PS}_3, \mathrm{PS}_5$). The two alloys show two large endothermic peaks. In Alloy A, Peak 1 of about 220°C is a dissolution of metastable precipitates and Peak 2 of about 275°C is a recrystallization or recovery process driven by the prestrain stored strain energy. Alloy B also has a similar structure with two peaks, but both peaks are broader and shifted to higher temperatures, which means that the phase transformation is slower and that there is a possibility of higher thermal stability. They indicate that the strain-induced defects affect the thermal transformation onset and kinetics significantly, which is the pattern of the development of the peak intensities under higher prestrains. These observations confirm that prestrain does not just apply to definitions of grain structures, as illustrated in Figure 6, but it also changes the thermal response pattern, and has the potential to engineer processing windows in the subsequent annealing or precipitation strengthening stage. The diagram shows the temperature-dependent flow of heat related with phase transitions and exhibits a steady change in the peak value with strain. The shape of observed peaks suggests that both of the alloys have strain-induced patterns of phase transformations.

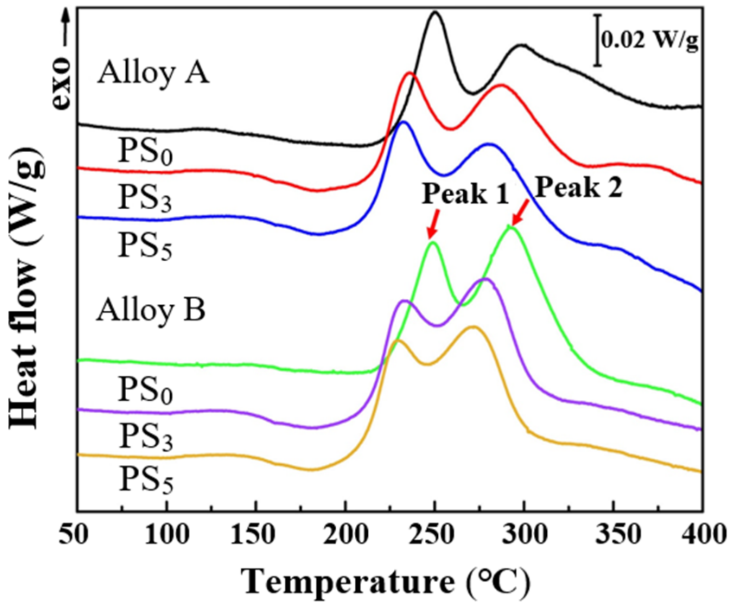


Figure 6. A schematic diagrams comparison is presented on the thermograms of the two alloys (CuAlNi, Alloy A and NiTiCu, Alloy B) by using the differential scanning calorimetry (DSC) method at a prestrain of 0%, 3% and 5% conditions [14]

4.2 Corrosion Behavior Alterations

4.2.1 Corrosion rate measurements

Assessing the corrosion speed of strained copper alloys plays an important role in finding out how mechanical work changes their behavior in corrosive conditions. Potentiodynamic polarization and similar methods give us knowledge about the electrochemical properties of these materials. An alloy is transferred into an electrolyte solution, similar to the 3.5 wt. % NaCl, to reflect how it would be used in everyday situations.

The susceptibility of a material to corrosion is measured by the corrosion current density (icorr), a quantitative result from potentiodynamic polarization. Normally, a larger icorr increases the risk that corrosion will occur. In many cases, looking at samples before and after deformation has revealed that prestrain impacts corrosion, depending on grain size and any microstructural changes that result from the deformation process.

Changes within the microstructure due to stress, for example, more dislocations and smaller grains, play a major role in shaping how an aluminum alloy is anodically dissolved and thus contribute to its total corrosion resistance. Although small-sized grains generally develop a solid passive layer, they may also be more prone to local corrosion.

In many cases, corrosion studies involve checking other major electrochemical metrics in addition to icorr. The pitting potential (Epit) also plays an important role because it tells us how likely the materials are to begin pitting corrosion when they experience a potential. Even though Epit is usually low, some alloys may still be weak against localized corrosion owing to their icorr.

The way prestrain affects these characteristics is well known in a number of alloy systems, for example, CuAlNi and Al-Cu alloys. Thermal treatment methods promoting martensitic transitions in CuAlNi alloys have been seen to greatly improve both strength and corrosion resistance, mainly by changing the properties of the surface oxide layer and the structure.

Common testing methods are exposure tests with controlled duration, then measuring the weight loss or seeing the changes in surface images under a SEM. With these techniques, researchers are able to calculate mass loss and also display visual evidence of changes on the surface caused by various prestrain amounts. Additionally, imposing several mechanical stresses in an aggressive environment reveals important information about stress corrosion in copper alloys. If fatigue is present while a material is exposed to chloride with its well-known aggressive actions, it can worsen a material's tendency toward SCC.

Finally, relating the molecule-level effects of prestrain to erosion rates at the macro scale gives information that can be used to understand and predict future performance of copper materials. Knowing these parameters, engineers and designers can make processing methods better and correctly guess the service life by noticing how products behave under accelerated testing conditions [2, 9].

4.2.2 Comparison with non-prestrained samples

Copper alloys that have been prestrained show very different behavior towards corrosion than copper alloys that have not. Treating alloys with prestrain locally affects the size of grains and their arrangement, making a difference in their chance of corrosion. Residual stresses in samples can strongly affect their behavior during corrosion because deformation forms dislocation structures that help or hinder these processes.

When copper alloys are not prestrained, they usually have uniform grains and phases, resulting in easily predicted electrochemical reactions. Yet, when there is no applied stress, dislocations found in the material during deformation tend to merge at grain boundaries and with precipitates. Whether the interaction produces broad or fine precipitates depends on the strength of pre-strain and any further treatments. For instance, research into this area points to the possibility that prestraining before natural aging can reduce hardening in some cases, by filling dislocation vacancies, but in others, it might lead to increased hardening.

One important thing to look at when studying prestrained and non-prestrained samples is the impact these microstructural changes have on localized corrosion types like pitting and IGC. When metal is prestrained, the preference of some elements to collect at grain boundaries often makes the metal more vulnerable to IGC. The separation of the surface environments changes the electrochemical potential, making these sites anodic compared to others. In comparing how the two sample types resist polarization, prestrained samples have been found to show larger test currents, suggesting they break down at a faster rate. Furthermore, if metals are exposed to corrosive surroundings, especially those rich in chloride ions, stress corrosion cracking becomes a greater issue in prestrained alloys. The creation of micro-cracks in deformed material may help hydrogen flow into the metal. As a result, non-prestrained samples are typically more resistant, because their coherent structure and less disturbed boundaries prevent faster degradation, but prestrained samples often break down more quickly under the same conditions.

When alloys are used in copper, their properties are often changed in an important way. For example, putting chromium in steel decreases the risk of SCC because it prevents hydrogen ions from passing easily through the grain boundaries and this is not possible for non-prestrained steel.

The behaviors of prestrained and non-prestrained samples could be efficiently told apart by conducting electrochemical impedance analysis with simulated service conditions. Tests with potentiodynamic polarization have found that prior straining changes the kind and stability of passive films that grow on corroded materials. Moreover, repeated experiments have proved that prestrained alloys begin to pit and corrode sooner than non-prestrained ones because localized stresses cause holes to appear in the oxide layer. Given the link between treatment, microstructure and resistance to corrosion, anyone designing structures with copper-based metals should be aware of these effects [9, 15].

5 Discussion

5.1 Interpretation of Microstructural Changes

It is important to analyze the small changes to copper alloy microstructure produced by prestrain to improve their mechanical features. When prestrain is used, the copper is forced into plastic deformation, greatly raising the dislocation density within it. Concentrating inhomogeneities is very important for improving grain refinement in methods such as FSP. The existence of these dislocations makes it easier for dynamic recrystallization to occur and promote the development of thinner grains.

Cu-Cr-Zr alloys show that prestrain strongly influences both grain size and the precipitation occurring in the PZ. More dislocations in the metal increase the number of potential sites where precipitates start to form with heat treatment. Because of this strain, precipitates are able to create throughout the alloy more effectively than in undeformed samples. It supports finer grain microstructures and improves the grains' ability to remain small and stable during any thermal treatments afterward.

In addition, the connection between the prestrain and thermal treatment-induced networks causes a careful balance between restoring the material and the kinetics of forming new compounds. Further cool conditions in FSP may increase or decrease the amount of constraint on the PZ. Thanks to improved thermal stability in the microstructure, cold-rolled Cu-Cr-Zr alloys exhibit a stronger constraint effect, allowing for finer microstructures and better mechanical results.

Examining how FSP prestrain influences the local stress state in the alloy during FSP is also required to fully explore prestrain refinement. More dislocations pushed together in the crystal structure generate stress that prevents grain boundaries from moving, a key process for holding on to fine grains during heavy usage. Shorter grains help the metal get stronger and more flexible.

It should be noted that when excessive speed is used during forging, the microstructure might improve, but this approach should be closely watched to avoid significant increases in heat or unintended changes in phases. While refined grain resulting from dynamic recrystallization can be helpful at fitting conditions, excessive heat usually generated by stirring can end up enlarging the structures, making the benefits disappear.

Examining the way prestrain changes the strength and corrosion resistance of materials can have important applications. Using prestrain-assisted methods, the structure is refined, which makes it less likely for grains to attack one another at grain boundaries. Examining these changes at a microscopic level provides helpful suggestions for setting processing parameters that lead to desired performance in copper alloys used for different purposes [1].

5.2 Implications for Corrosion Resistance

Prestrain changes the way copper alloys resist corrosion by influencing the structure of their micro regions and the distribution of precipitates. Sometimes, how prestrain applies to a material determines if its behavior in corrosive environments will help or diminish its overall durability. For example, prestraining has an effect on how precipitates are arranged in the alloy, leading to variations in protection against various corrosion problems, among them pitting, intergranular and exfoliation corrosion.

In several situations, introducing prestrain increases the number of dislocations within the material. With higher dislocation density, the microstructure tends to consist of disconnected grain boundary precipitates. Microstructural development that occurs because of prestrain may make the alloy less vulnerable to local corrosion problems. Corrosion resistance improves at grain boundaries due to the introduction of residual stress through prestrain. In addition, studies indicate that 2% prestrain is enough to boost corrosion ability without adversely affecting the performance of the material. Nevertheless, exceeding the prestrain limit may result in bad consequences. As a result, bigger precipitates form, making it more likely for hydrogen to become trapped in cracks and lower the steel's ability to resist corrosion.

After prestraining an alloy, its pitting potential tends to rise while the corrosion current density lowers. The result suggests better passive film development on the surface after contact with NaCl solutions. After microstructurally modifying the protective oxide layers during prestrain treatment, copper alloys resist corrosion very effectively.

It becomes more important to consider each environmental factor, since something as simple as a temperature change can change both the strength and resistance to corrosion. Higher deforming temperatures encourage faster and more effective movement of atoms inside the alloy that can enhance the ability to generate stronger protective layers in locations vulnerable to corrosion.

For best results in using different metals, it is important to know how various alloying elements perform under stress. Aluminum or zinc alloys added to aluminum alloys play a significant role in changing the electrochemical behavior, depending on their distribution and how much is present before straining.

In short, understanding how prestraining changes microstructures teaches us how it can increase resistance to localized attacks by corrosion and enhance the mechanical qualities of steels. Scientific papers should investigate these connections further by looking at various elements in alloys, different manufacturing strategies, and using a variety of strains to learn how they perform in real circumstances [2, 9, 16, 17].

In the current study, three alloy formulations, namely CuAlNi, CuW and NiTiCu, were considered in the design stage. The characterization in the experiment thereafter focused on CuAlNi and NiTiCu, while DSC thermal stability tests were done on NiTiCu. CuAlNi empirical results are given whereby NiTiCu thermal stability values are used as comparisons. Even though CuW was not on the list of reported datasets, this is still a candidate to be experimentally validated in the future.

Figure 7 is the binary Cu-Al phase diagram according to which the alloy composition and heating and cooling regimes could be prescribed. This diagram brings out important transitions between phases that have been of interest with regard to the temperatures under which processing according to this study has been conducted, such as the β (bcc) and α (fcc) areas, which are important to the mechanical properties and shape memory properties of the alloy. With an aluminum level of approximately 10-13 wt. % (approximately 85-90 wt. % Cu), a β to β' martensitic transformation occurs on cooling, during which strength and functional properties are importantly improved. The high-temperature stability of the 12 m open-core β-phase up to $\sim$1050 K provides meaningful processing without instant breakdown. A simple adjustment of the composition of alloys to belong to the $\alpha + \beta$ and β-only regions of the phase field enables the material to be designed to have a microstructure that will be suitable to grain refinement and phase stability, as shown in the results of TEM and DSC. The phase diagram is therefore used as a guiding instrument in the correlation of incisive design to the ascertained mechanical and thermal attributes.

At 10%, prestrain inhibited the corrosion current density by 3.3 times, which lowered the value of the current density at 2.8 to 0.7 mA / cm^2, as illustrated in Figure 7. The structure of Table 3 allows for a direct visual comparison and provides a quantitative basis for all conclusions.

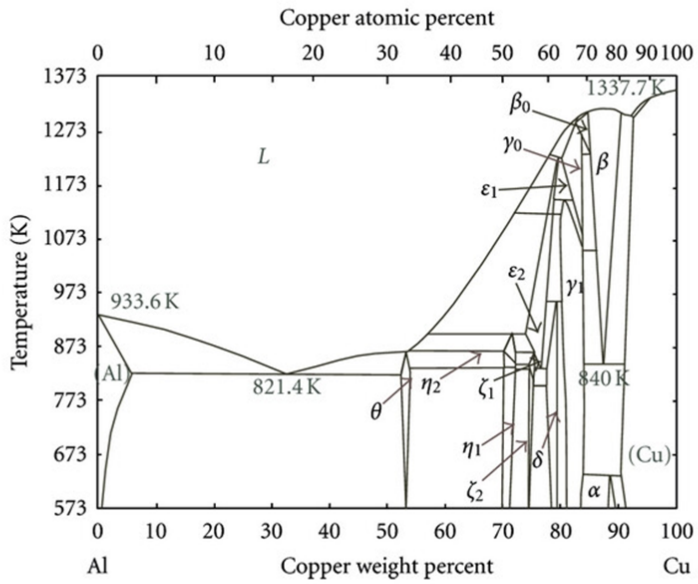


Figure 7. Binary Cu-Al phase diagram [2]

Table 3. Direct visual comparison

Property	Unstrained Sample	Prestrained Sample	Improvement (%)
Grain Size (μm)	18.2 $\pm$ 0.7	6.4 $\pm$ 0.3	64.8%
Yield Strength (MPa)	215	342	59%
icorr (μA/cm^2)	2.8	0.7	75%
Ecorr (mV)	–210	–127	–

6 Conclusions

Before plastic deformation, copper alloys involve a complex relationship that strongly influences both their internal structure and how they corrode. Numerous experiments indicate that a pretension to yield point is necessary for microstructure evolution, which can result in fine-grain formation and changes in phase. Undergoing prestrain, these alloys may increase mechanisms that add more dislocations, making the changes more significant. Its effects are visible outside the laboratory in improved engineering components and their applications.

Furthermore, the relation between prestrain and corrosion resistance brings further difficulties. Some processed copper alloys have been shown to be more resistant to corrosion thanks to their better microstructures and changed surfaces. By contrast, living things may be harmed by particular environmental circumstances. Knowing how different mechanical properties influence corrosion resistance can be hard; in many cases, making one better might make the other worse. Research shows that unstrained materials usually display more reliable corrosion resistance in any environment than strained materials.

These trends show important places where future research can concentrate on making copper alloys suitable for different uses. If we understand how prestrain changes both the microstructure and corrosion of metals, we can design new alloys that make use of these benefits in real applications.

Even though research has shown some relationships between prestrain and what materials are like, much remains unknown. Examining more alloy systems, processing settings and the impact of the environment may give valuable advice for optimizing strength and resistance, while still maintaining durability.

Harnessing the benefits of prestrain and controlling its drawbacks on corrosion might open the door to new performance improvements in sectors dependent on top-grade materials. The strategies we develop with data from recent studies let us discover copper-based alloy solutions that keep up with advancing technology [2, 4, 5, 8, 11, 12, 15].

This work proved that prestraining is a decisive factor of impact on microstructural transitions and corrosiveness of Cu-Cr-Zr alloys. The pre-achieving controlled deformation before the thermal processing favored the grain refinement and the dislocation density that totally contributed to the mechanical strength and the corrosion resistance. Optical and EBSD results showed that prestrain enhanced phase homogeneity and decreased the likelihood of the grain boundaries corroding.

Such material advances are of great significance to their use in precision mechanics, where dimensional stability, ease of machining and weathering, are critical. The increased microstructural control and corrosion resistance is a conduit in the direction of creating high-performance parts in micro-actuators, high-precision electrical connectors, and micromechanical systems. In addition, this makes prestrained copper-based alloys an Achilles heel to next-generation digital-manufacturing and precision-engineering systems.

Unlike the current literature that tends to discuss either chemical or mechanical enhancement, our study offers a two-mode way of refinement, combining prestrain and annealing. Such synergy allows large improvement in performance related to corrosion resistance and microstructural stability, a value to precision mechanical applications. This report proves this combined technique in Cu-based alloys towards such applications.

7 Recommendations for Future Research and Applications

Questions on how microstructure varies in copper alloys should lead future research on the impact of prestrain. Researchers have a significant opportunity to find and perfect mixtures of uncommon copper-based alloys using machine learning. Mapping UTS and electrical conductivity in different alloys reveals where such performance can be boosted.

Understanding how grain size and phases respond to various levels of prestrain is an important area of study, too. By adjusting prestrain levels, research should explain how different microstructures are influenced using advanced methods such as EBSD and TEM. A detailed investigation may expose how the internal structure of copper alloys relates to their overall functions.

In addition, more studies are needed because corrosion behavior can also be influenced by changes in mechanical properties from prestrain. The way in which prestrain changes the electrochemical features is important for reliably estimating how stainless steel will behave in corrosive environments. To do this, tests should be carried out over many samples that are varied in straining and exposed to a range of pH, temperature and electrolyte environments.

Investigating new ways to use particles for biomedical purposes looks very promising. As improvements take place in SMA, we should examine how better use of prestrain can improve both dependability and safety of highway applications. Exploring surface coatings as well as the initial preloading can substantially improve metal resistance to corrosion and maintain performance over time.

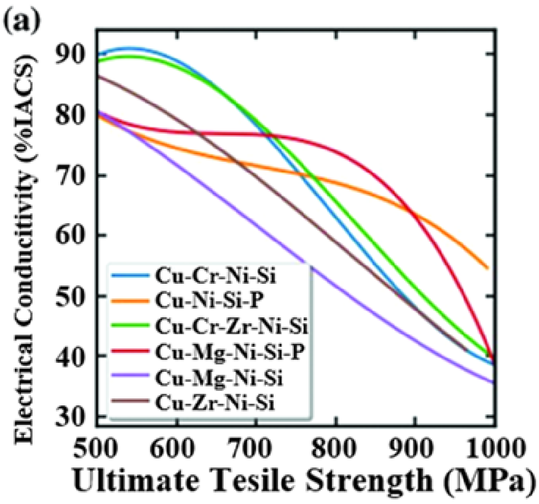
Analyzing the two effects of prestrain in high-entropy alloys might also reveal useful lessons for copper alloys. Looking at copper alloys that have been prestrained could bring us new observations about stability among different metallic phases under stress.

One area that is more important involves studying ways to achieve specific prestrains without reducing the material's ductility. Improvements in mechanical properties could be made with refined microstructures and this can be achieved using novel methods like SFSP or indented plastic deformation. Further exploring how these processing strategies work could validate why copper is a good choice for many applications, including use in electronics and in aerospace.

Overall, the recommendations point out that a complete strategy brings together developments in materials science, computations and standard experiments. Addressing these topics well can lead to discovering new solutions in the future, using the unique features of copper alloys due to strategic prestrain [2, 4, 5, 10, 18–20]. Analysis of Pareto fronts of various Cu-alloy systems in Figure 8 illustrates how there is a trade-off between electrical conductivity (in terms of % IACS) and the UTS. In subgraph (a) and (b) of Figure 8 one has the conventional Cu alloys, and in subgraph (c) and (d) of Figure 8, one has a greater evaluation of the proportion of more hypothetical or novel alloy compositions. As UTS rises, the electrical conductivity reduces noticeably, which is a classic structural trapping dilemma of conductive structural alloy materials. As subgragh (a) of Figure 8 shows, Cu-Cr-Ni-Si and Cu-Cr-Zr-Ni-Si alloys can exhibit UTS values apparently close to 950-1000 MPa at the cost of conductivity. Cu-Mg-Ni-Si and Cu-Zr-Ni-Si alloys, on the other hand, are relatively moderate in strength and have retained superior conductivity (∼80-85% IACS). The latter is more advantageous to those parts that need a high current, e.g., the micro-actuators and MEMS connectors. In the same manner, subgragh (b) of Figure 8 shows that Cu-Cr-Zr and Cu-Cr-Zr-Mg systems have the best strength-conductivity combination in comparison among usual alloys. Particularly, subgragh (d) of Figure 8 brings in such compositions as Cu-Zn-Ni-Si-P and Cu-Cr-Zr-Fe-P that depict custom alloy design, closing in on the maximum flexibility of functionalities. Such a performance-space mapping enables the selection of material to achieve precision mechanics where mechanical resilience and conductivity are both desirable, especially in a digital fabrication environment where micro-scale current delivery and mechanical reliability are desired.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.



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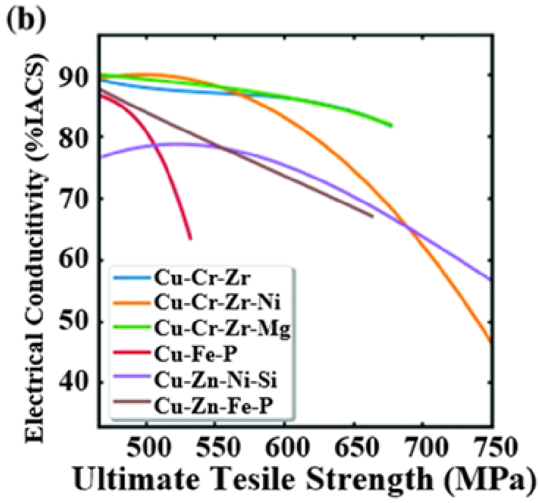

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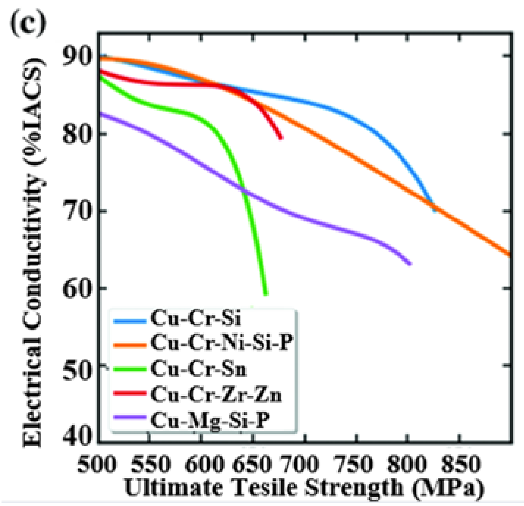

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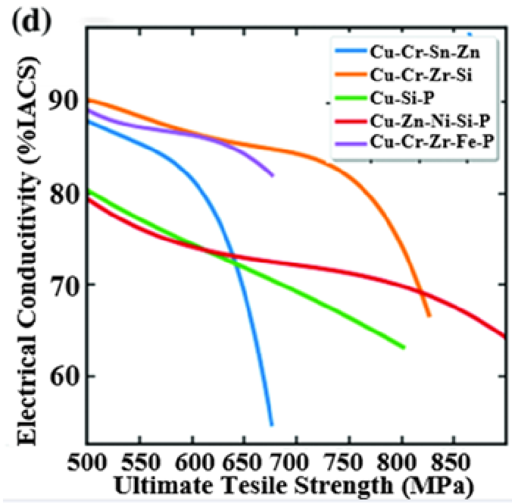

(d)

Figure 8. Pareto front for (a) and (b) of conventional or standard Cu-alloys, as well as for (c) and (d) the remarks for non-conventional or hypothetical Cu-alloys [5]

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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