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Mechanical and Wear Behavior of High Performance CuNiCoSi Alloy

Volkan Karakurt[1], Orçun Zığındere[1], Talip Çitrak[1], Feyzanur Öztürk[1], Feriha Birol[1]
[1]Sağlam Metal San.Tic. R&D Center
Kocaeli/Türkiye
volkan.karakurt@saglammetal.com, orcun.zigindere@saglammetal.com

Abstract **-** Cu-Ni-Si-X alloys, known as Corson alloys, are used for many applications such as connector components, high-power electronics, and welding electrodes and are very significant industrial alloys. These alloys have been the most studied copper alloy group for a long time. In recent years, studies on the CuNiCoSi alloy, which is included in the Corson alloy group, have attracted attention. This alloy has advantages such as high strength, superior load-carrying capacity, good conductivity, toughness, improved wear resistance, and thermal stability. In this study, it was aimed to determine the effects of cobalt (Co) addition to the Cu-Ni-Si alloy system on mechanical properties and wear behavior and to compare with CuNi2Si alloy. In this context, solution and aging heat treatments were applied to CuNi2Si and CuNiCoSi alloys under the optimum conditions determined in the previous study, and then they were subjected to hardness, conductivity, and wear tests. According to the test results, it was determined that the CuNiCoSi material has higher hardness and conductivity than the CuNi2Si material. In the wear test performed under 20N load, CuNiCoSi material showed higher wear resistance compared to CuNi2Si material. At the same time, in the wear test performed under 20N load, it was determined that the CuNiCoSi material had a lower coefficient of friction than the CuNi2Si material.

Keywords**:** Corson, Copper, Alloys, CuNi2Si, CuNiCoSi

1. Introduction

High-strength Corson alloys refer to a special alloy group that prioritizes strength and conductivity, are designed for use in special engineering applications. These alloys are generally copper-based and have been developed to provide particularly high strength, durability, and corrosion resistance by incorporating various additional elements [1]. High-strength Corson alloys are widely used in special applications in the metal industry and are especially preferred in areas such as the aviation industry, defense systems, and the energy sector. The unique properties of these alloys, their capacity to adapt to complex engineering needs, and their wide range of applications make high-strength Corson alloys industrially and technologically important [2]. The ever-increasing demand for materials that seamlessly combine functionality and durability has led to a focus on Corson alloys containing cobalt, as well as nickel and silicon. Conventional Cu-Ni-Si alloys are widely used in electrical applications because of their high strength, excellent electrical conductivity and good anti-stress relaxation properties [3]. Over the past few decades, the properties of the alloy have been enhanced by adjusting the ratio of Ni to Si and optimizing the heat treatment process. [4].

Cu-Ni-Si alloys with 600-800 MPa strength and 30%-45% IACS conductivity, appear to have reached the limits for ternary alloys. [5]. Thus, the addition of trace elements to ternary Cu-Ni-Si alloys has been implemented with the expectation of further improving performance. Further investigation is required due to the limitations of CuNiSi alloys under harsh load-bearing conditions, despite their impressive blend of electrical conductivity and mechanical strength. [6]. The addition of cobalt to the CuNiSi matrix creates a potential new material. Cobalt is recognized for its remarkable strength and hardness. It serves as a potent reinforcing agent that enhances an alloy's resistance to mechanical stress. The presence of cobalt in the microstructure promotes the formation of additional intermetallic compounds, including Co2Si and Ni2Si precipitates. These reinforcements act as complex barricades for dislocation movement, effectively inhibiting plastic deformation and increasing the alloy's resistance to mechanical stress. By adding Co to the Cu-Ni-Si alloy, a (Ni, Co)2Si precipitation phase is formed, which improves heat resistance stability. This phrase enhances the material's resistance to softening at high temperatures while maintaining thermal strength. [7-8].

A study was carried out to compare the properties of CuNiCoSi alloy with those of conventional CuNi2Si alloy. It is believed that this high-performance material, possessing exceptional strength, conductivity, and wear resistance, can effectively address the increasing technological demands, particularly in recent years. This study aims to investigate the effect of adding Co to the Cu-Ni-Si alloy system on its mechanical properties and wear resistance. In this study, the objective was to develop the widely used commercial CuNi2Si material and introduce the high-performance CuNiCoSi material to the industry.

2. Experimental Procedure

In this study, the production of CuNiCoSi alloy, a new generation high-performance Corson alloy, was compared to the conventional CuNi2Si material widely used in the industry. CuNi2Si and CuNiCoSi alloys were produced using the liquid melt method. Co addition was carried out into the CuNiSi alloy system using CuCo10 master alloy. The surface of the cast ingots was machined on a lathe and then subjected to the hot forging process. Hot forged CuNi2Si and CuNiCoSi materials were both deformed at a ratio of 62% and then subjected to a precipitation-hardening heat treatment. To evaluate the mechanical and wear resistance of the alloys produced, they underwent hardness and wear tests following solution, quenching, and aging heat treatments, under previously optimized conditions.

2.1. Chemical Analysis

The chemical analysis of the material produced under industrial conditions for use in casting works was carried out using a Foundry-Master Smart HITACHI brand optical emission spectrometer. For the materials to have the desired composition during the casting phase, samples were taken from the crucible before casting and spectral analysis was performed, and castings were carried out when the appropriate elemental composition was deemed appropriate.

2.2. Microstructure Analysis

Each sample to examine for microstructural analysis was sanded and polished on the QATM QPOL 250 brand automatic sanding and polishing device. 240-2000 grit SiC sandpaper was used for sanding, and 6.3 and 1 µm diamond polishing solution and appropriate polishing tools were used for polishing, respectively. Then, the alloys were etched in the solution prepared as in Table 1 to reveal the microstructural details. Etched samples were characterized with the Carl Zeiss Ultra Plus Field Emission Scanning Electron Microscopy, FESEM brand device.

Tablo 1: Composition and working status of the etchant prepared for CuNi2Si and CuNiCoSi alloys

Composition	**Conditions**
25mL HN_4OH, 25mL H_2O, 50ml %2.5 $(NH_4)_2S_2O_8$	at 27°C for 25 seconds

2.3. Hardness and Conductivity Tests

Hardness measurements of the samples were made with the Rockwell B Scale hardness test by TS EN ISO 6508-2 [9] standard. At least 5 hardness measurements were taken from each sample and the average was reported. Electrical conductivity measurements were made by the ASTM E1004 [10] standard. Electrical conductivity tests were carried out with the TANOS SIGMASCOPE SMP350 device.

2.4. Wear Test

Pin-on-disc type device, Turkyus brand POD/HT/WT model, was used for the wear tests conducted in dry conditions by ASTM G99 [11] standards. A 6 mm diameter 100Cr6 steel ball was used against the wear test samples. Test parameters were as follows: sliding speed 300 rpm, track distance 20 mm, sliding distance 1000mm, and load 20N. Weight losses were measured with a 0.001 g precision scale before and after the test. The wear rates of CuNi2Si and CuNiCoSi alloys were calculated using the weight (g) loss data obtained from a precision scale and the following formula:

$$W_a = \Delta G / d.M.S \ (\frac{\mathrm{mm3}}{\mathrm{Nm}}) \qquad (1)$$

Wa: Wear rate (mm3/Nm), ΔG: Weight loss (mg), M: Loading weight (FN) (N), S: Wear path (m), d: Density (mg/mm3) [12].

At the same time, friction coefficient data was recorded and reported with the load cell in the wear device.

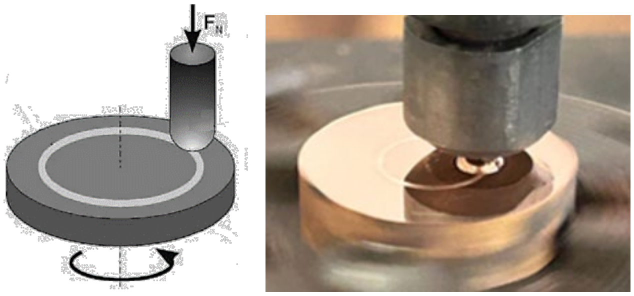


Fig. 1: Images of the wear type and trace on the sample surface.

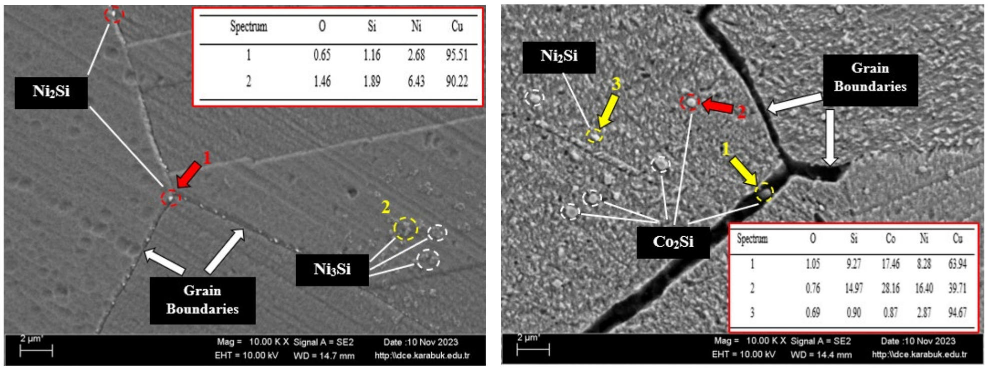
3. Experimental Results

The chemical analyses of CuNi2Si and CuNiCoSi alloys used in the experimental studies are presented in Table 2.

Table 2: Chemical compositions of the alloys used in the study

Alloys	Chemical Composition (% wt.)					
	Cu	Ni	Pb	Si	Co	Others
CuNi2Si	96,72	2,14	0,0069	0,661	0,0053	0,46
CuNiCoSi	96,59	1.45	0,0020	0.562	1.25	0,15

A solution heat treatment was applied to hot forged materials deformed 62%, followed by aging treatment. Figure 2 shows SEM images at 10 KX of CuNi2Si and CuNiCoSi alloys after heat treatment. In Figure 2, it can be seen that the CuNi2Si material contains Ni_2Si and Ni_3Si intermetallic phases. On the other hand, the CuNiCoSi material contains spherical Co_2Si intermetallic phases that have precipitated at grain boundaries and in the matrix, as well as the Ni_2Si phase.



Spectrum	O	Si	Ni	Cu
1	0.65	1.16	2.68	95.51
2	1.46	1.89	6.43	90.22

Spectrum	O	Si	Co	Ni	Cu
1	1.05	9.27	17.46	8.28	63.94
2	0.76	14.97	28.16	16.40	39.71
3	0.69	0.90	0.87	2.87	94.67

(a) (b)

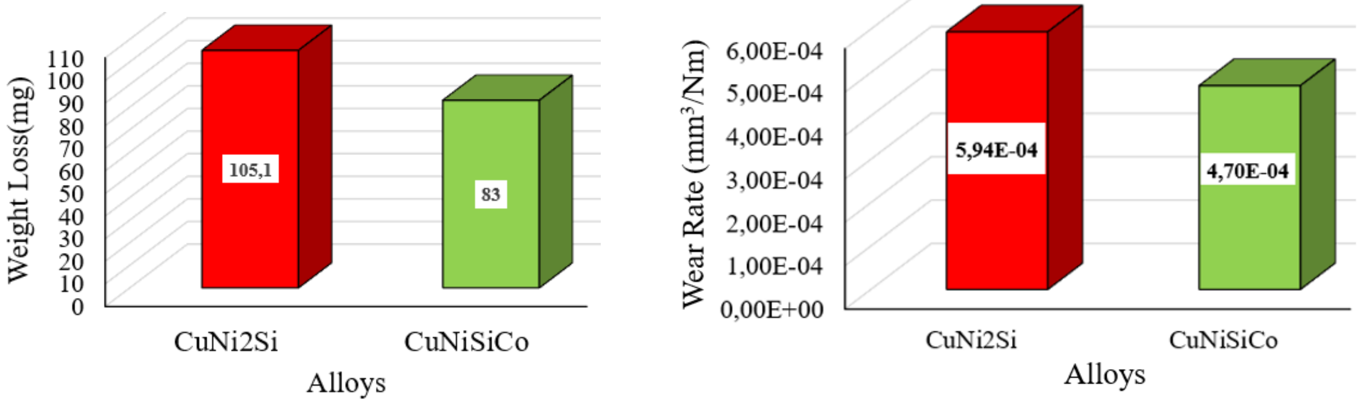
Fig 2: 10 KX scanning electron image of CuNi2Si(a) and CuNiCoSi(b) alloy

Table 3 provides the results of the hardness and conductivity tests conducted on the alloys. The hardness of the CuNi2Si material aged at the optimum temperature and time was found to be 95.1 HRB, while that of the CuNiCoSi material was measured to be 99.16 HRB. The difference in hardness between the two materials was found to be 4 HRB. It is believed that the increase in hardness of the CuNiCoSi material was due to the formation of Co2Si intermetallics as a result of the dissolved Co and Si in the matrix during the aging heat treatment. The study measured the conductivities of CuNiSi and CuNiCoSi alloys after undergoing optimal heat treatment, resulting in peak hardness. The CuNiCoSi alloy had a conductivity of 26.1 MS/m, which is 23% higher than the CuNiSi alloy's conductivity of 21.1 MS/m. Copper alloys with high conductivity are essential in the coolant and cooling systems of various machinery, including electronics and automotive engines [13]. The high conductivity of CuNiCoSi makes it a better material for efficiently removing heat from critical components and preventing overheating, ultimately resulting in longer life than CuNi2Si with lower conductivity.

Table 3: Hardness and conductivity results of the produced alloys

Alloys	Hardness HRB	Conductivity MS/m
CuNi2Si	95,10	21,1
CuNiCoSi	99,16	26,1

According to the wear test results, CuNi2Si and CuNiSiCo alloys experienced weight losses of 105.5 mg and 83 mg, respectively. This indicates that CuNiSiCo alloy had 27% less weight loss compared to CuNi2Si alloy. It can be concluded that CuNiCoSi material is less likely to experience weight loss than CuNi2Si material because of its higher hardness and strength values. The CuNiCoSi alloy has higher hardness and strength due to stronger interatomic bonds within its structure, making it more resistant to dislodgement by abrasive particles on the wear surface. [14]. The wear rates for the CuNi2Si alloy and CuNiCoSi material were 5.94 x10-4 mm^3/Nm and 4.70 x10-4 mm^3/Nm, respectively. The high wear resistance of CuNiCoSi material is attributed to the addition of Co to CuNi2Si material. Additionally, the Co element has a grain refining effect which reduces material removal area by preventing crack propagation, thereby increasing wear resistance. [15-16].



(a) (b)

Fig 3: Graphs of weight losses (a) and wear rates (b) of CuNi2Si and CuNiCoSi alloys.

The average friction coefficient values for both alloys were determined over a sliding distance of 1000 m. The value for the CuNi2Si material was found to be 0.86624µ, while for the CuNiCoSi material, it was 0.7595µ. This shows that the CuNiCoSi alloy has a 27% lower friction coefficient compared to the CuNi2Si material. It has been found that the CuNiCoSi material has a low coefficient of friction. This is due to the intermetallic phases present in the material which act as a buffer in the wear mechanism. It is believed that the Co2Si intermetallic phase in the CuNiCoSi alloy acts as a buffer between the two surfaces. This prevents particles from breaking off from the material surface and creates a flatter wear surface, resulting in a low coefficient of friction behavior. The study found CuNiCoSi alloy to be highly wear-resistant, with a low friction coefficient and high electrical conductivity, making it ideal for numerous applications.

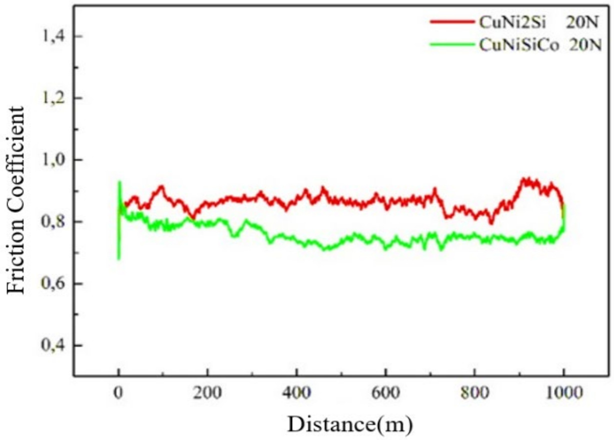


Fig 4: Friction coefficients diagrams of CuNi2Si and CuNiCoSi alloys measured at a sliding distance of 1000 m.

4. Conclusion

The study investigated the effect of adding Cobalt to the Cu-Ni-Si Corson alloy system in comparison to the typical Corson alloy, CuNi2Si alloy. The results revealed that the Co-reinforced CuNiCoSi alloy had higher hardness, greater wear resistance, and higher conductivity with a lower friction coefficient. The increase in hardness and wear resistance without compromising conductivity was attributed to the presence of Co_2Si intermetallic phase observed from SEM images.

The findings of this study suggest that the CuNiCoSi alloy holds great potential as a high-performance alloy across various industries. The alloy's superior hardness, mechanical strength, and conductivity, along with its improved wear resistance, make it a preferred choice for industrial equipment, aviation, space, nuclear energy, electrical energy production, and demanding electrical and electronic applications that prioritize optimal performance and reliability.

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