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CuAlFe ve CuAlFeNi alaşımlarının yapısal ve manyetik özelliklerinin incelenmesi

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Öz: Bu çalışmada CuAlFe ve CuAlFeNi (% ağırlık) alaşımları kullanılmıştır. Çalışmada; iki alaşım için faz yapısı, kristalografisi ve manyetik karakterizasyonu Ni elementine bağlı olarak incelenmiştir. Nikel elementinin eklenmesinden sonra mikroyapıdaki değişimleri gözlemlemek için Taramalı Elektron Mikroskobu (SEM) ve X-ışını Difraktometrisi (XRD) kullanılmıştır. Alaşımların manyetik davranışları, Fiziksel Özellik Ölçüm Sistemi (PPMS) cihazı ile karakterize edilmiştir. SEM sonuçları, her iki alaşımda da Kappa fazlarının oluştuğunu ortaya koymuştur. CuAlFe ve CuAlFeNi' nin doygunluk mıknatıslanması 300 K' de ~ 8.6 ve ~ 6.1 emu/g iken, CuAlFe ve CuAlFeNi' nin zorlayıcı alan değerleri sırasıyla ~ 3262.67 ve ~ 1750.70 A/m olarak bulunmuştur. Dolayısıyla manyetik sonuçlar, Ni elementinin manyetik parametrelerde bir farka neden olduğunu göstermiştir. Ayrıca, her iki alaşımda yumuşak ferromanyetik özellikler sergilemiştir. Elde edilen sonuçlar, çalışılan alaşımların yumuşak ferromanyetik uygulamalarda kullanılabileceğini göstermektedir.

Anahtar kelimeler: Cu Bazlı Alaşımlar, mikroyapı, alaşım elementleri, kappa.

Investigation of structural and magnetic properties of CuAlFe and CuAlFeNi alloys

Abstract: In this work, the CuAlFe and CuAlFeNi (wt. %) alloys were used. This study, the phase structure, crystallography and magnetic characterization of the two alloys are investigated depending on the Ni element. The Scanning Electron Microscope (SEM) and X-ray Diffractometry (XRD) were used to observe the changes in the microstructure after the addition of element Ni. The magnetic behavior of the alloys was characterized by Physical Properties Measurement System (PPMS) instrument. SEM results revealed that Kappa phases were formed in both alloys. While the saturation magnetization of CuAlFe and CuAlFeNi is ~ 8.6 and ~ 6.1 emu/g at 300 K, the coercivity field values of CuAlFe and CuAlFeNi are approximately 3262.67 and 1750.70 A/m, respectively. Thus magnetic results showed that the element Ni caused a difference in the magnetic parameters. Furthermore, both alloys exhibited soft ferromagnetic properties. The results indicate that the worked alloys could be used in soft ferromagnetic applications.

Keywords: Cu-based alloys, microstructure, Alloying Elements, kappa.

1. Introduction

In the last times, Copper-based shape memory alloys (SMAs) are of interest in practical applications due to their excellent properties and low cost [1, 2]. Cu-based alloys can be categorized into three types: CuZn, CuAl and CuSn alloys. Recent studies have focused on CuAl alloys [3-7]. Three high temperature equilibrium phases appear in the phase diagram of CuAl alloys. These phases: the disordered body-centered-cubic (β-phase), the face-centered-cubic solid solution (α-phase), and the β_1 phase which is an ordered form of β with a DO_3 structure [3-7]. CuAl alloys have interesting properties such as thermal conductivity, corrosion resistance, and wear. Therefore, these alloys are widely used in bearings, gears, and bushings among Cu-based alloys [8, 9]. The CuAl alloys have some disadvantages. For example, they are very brittle; however, this property can be cured by adding different element [3, 4]. Fe added to CuAl alloys causes the formation of intermetallic phases. The presence of these high-hardness phases improves the alloy's increases the alloys wear resistance. Moreover, the addition of Fe to CuAl alloy refines the grain size, which improves the toughness of the alloy and minimizes the formation of the γ phase. The addition of Ni to CuAl and CuAlFe alloys reduces the transformation temperatures [4-9].

For centuries, magnetic alloys have been designed and studied by researchers [3, 7, 10]. Magnetic materials are studied in two categories as hard and soft. The soft magnetic materials should have good mechanical characteristics, low coercivity, high magnetization and structural stability at high-temperature. These materials are used in applications such as transmission, generation, electric motors and electromagnets [10, 11]. Hard

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magnetic materials have extensive hysteresis, coercivity, low initial permeability and saturation flux density and high hysteresis energy. The hard magnetic materials are used in telecommunication, data processing and consumer electronics [10, 11]. Moreover, it is well established that the magnetic properties of materials are highly sensitive to their composition and the resulting phase structure. In addition, the composition of material might change the phase of a material, resulting in a change in magnetic properties [12, 13].

Several studies in the literature have investigated the structural properties of Cu-based alloys [14–20]. Wang et al. [15], comprehensively have investigated the microstructural properties and heat treatment processes of CuAlFe alloys. They found that the microstructures of these alloys varied depending on the Al content. The α, γ_2, and martensitic phases (α′, β_1') were determined depends on the depends on the Al content. Another study, [16] reported that the microstructure of the CuAlFe alloy changed with increasing Fe content. They observed the formation of copper-rich α, γ_2, and Fe-rich κ phases. Additionally, they found that the grain size and morphology varied depending on the amount of iron added. Nam et al. [17], investigated the phase transformations by adding 9% Al and 4% Fe to the shape memory alloy CuAl. This study analyzed and explained the shape memory mechanism of the alloy based on the transformation of the martensite phase. After heat treatment, a martensitic microstructure formed in the alloy, but when it was heated again, the martensitic structure decomposed into β' and vitmantet forms. Finally, it was found that the material returned to its initial state, consisting of α and γ_2 phases. In another study, Gao et al. [18] systematically investigated the optimum composition ratio for commercial applications by varying the Al content. The study revealed different phase structures at varying Al concentrations, specifically the β′ and γ′ martensitic phases.

However, there are very few studies on the magnetic properties of CuAlFe and CuAlFeNi alloys [19, 21]. Studies on these alloys have found that they exhibit soft magnetic behavior with very low coercivity and narrow hysteresis. Furthermore, it has been shown that the addition of Ni to CuAlFe alloys contributes to the improvement of soft magnetic properties. Our previous studies have provided information on these properties of Cu-based alloys. However, this study examines the structural, crystallographic, and magnetic behaviors under different heat treatments and composition. The structural analysis of these alloys was carried out using characterization techniques such as SEM, XRD, and PPMS. With these analyses, the effects of the Ni element and different heat treatments were discussed.

2. Materials and Methods

The Cu-based alloys: CuAlFe (alloy 1) and CuAlFeNi (alloy 2) were produced in this study. The obtained results from the Energy Dispersive X-ray (EDX) technique were given in Table 1. The alloys were fabricated by an arc-melting system under an argon atmosphere. The produced alloys were used as the cylindrical samples with a 1 cm diameter of and a 10 cm of length. After samples obtained from the alloys were homogenized for 1 h at 800 °C and subsequently cooled in the furnace (slowly cooling). The structure of the alloys were analyzed using SEM (FEI/Quanta 450 FEG type). Also, crystallographic parameters of the alloys have been performed by Shimadzu model XRD-6000 analysis. Magnetic measurements of the alloys were conducted at room temperature using Quantum Design PPMS 9T (PPMS) device, in a magnetic field range between -10 and +10 Tesla.

Table 1. Chemical composition (wt. %) of the alloys.

Alloy	**Cu (wt. %)**	**Al (wt. %)**	**Fe (wt. %)**	**Ni (wt. %)**
CuAlFe	86.37	10.45	3.19	-
CuAlFeNi	75.42	13.84	5.43	5.32

3. Results and Discussion

Figure 1 indicates the XRD results. In the alloys, γ_2, α, β and κ phases were found from XRD observations. In Figure 2, α (111), α (200), α (220), and α (311); κ, β (220), κ, β (400), κ, β (311), and κ, β (422); the γ_2 (330), γ_2 (332), γ_2 (631), and γ_2 (651) planes were determined. In our previous study, α, γ_2, β, and kappa (I, II, III, IV) phases were formed, whereas in this study, α, γ_2, β, and kappa (II, III, and IV) phases occurred [19]. It is believed that these differences arise from the composition and thermal processing.

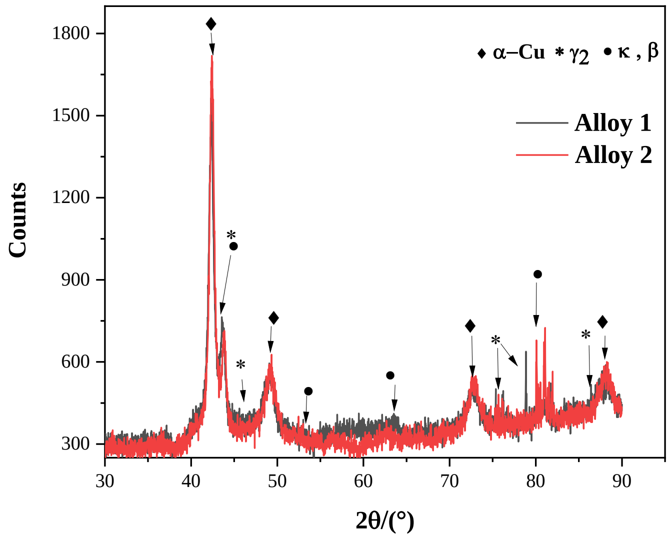
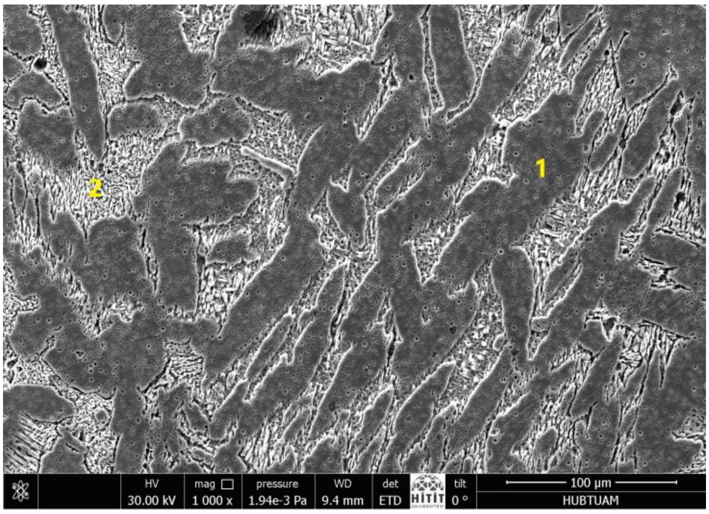


Figure 1. XRD patterns of the alloys.

For worked alloys SEM images are given in Figure 2. When the SEM images of alloy 1 were examined, it was observed that α+κ phases were formed. The α-phase is a copper-rich face-centered cubic (f.c.c.) solid structure [14-20]. The κ-phases can be classified into κ_I, κ_{II}, κ_{III} and κ_{IV}. κ_I, κ_{II}, κ_{III} and κ_{IV} phases are characterized by dendrite-shaped, smaller globular, plate-like, and fine precipitates, respectively [15]. In Figure 2.a, the κ precipitates were formed as κ_2, κ_3, and κ_4 and perlite ($\alpha+\gamma_2$) phases consisting of small white areas [19]. The κ_2 precipitates occurred as globular-like, κ_3 lamellar-like, and κ_4 as small precipitate-like structures. Figure 2.b shows the SEM images of alloy 2. When Figure 2.b is examined, Kappa precipitates are formed in the forms of κ_2, κ_3, and κ_4. The κ_2 precipitates are observed as globular, κ_3 precipitates are observed lamellar, and κ_4 are observed as small precipitates. In addition to these, it is determined in Figure 2.a.b that Cu-rich-α precipitates are formed [14-20]. It was found that Ni leads to the formation of intermetallic κ phases in the CuAlFe alloy. Formation of the κ phases can be explained by considering the reaction between Fe and Al, as well as the solubility of Fe in phases of alloy. In Cu-based alloys, the solubility of alloying elements in the copper matrix varies for each element. As a result, depending on the solubility of the elements, intermetallic compounds and solid solutions are formed in the matrix [22, 23].

In a similar study, Aldırmaz et al. [19], the Cu-based alloys were melted in a vacuum induction furnace under an argon atmosphere and cast. The samples of alloy were homogenized at 800 °C for 30 min, then step quenched in an ice-water medium (rapidly cooling). The microstructural analysis of the CuAlFe and CuAlFeNi alloys showed the presence of eutectoid and kappa phases in the microstructure. They observed that the dendrite structures in the CuAlFeNi alloy disappeared when Ni was added. This study observed the effect of cooling rate on kappa phase. For the CuAlFe alloy, it was observed that the dendrite-shaped κ_I precipitates disappeared upon slowly cooling and the grains became more distinct. However, in the CuAlFeNi alloy, the grain structures were observed to be less distinct.



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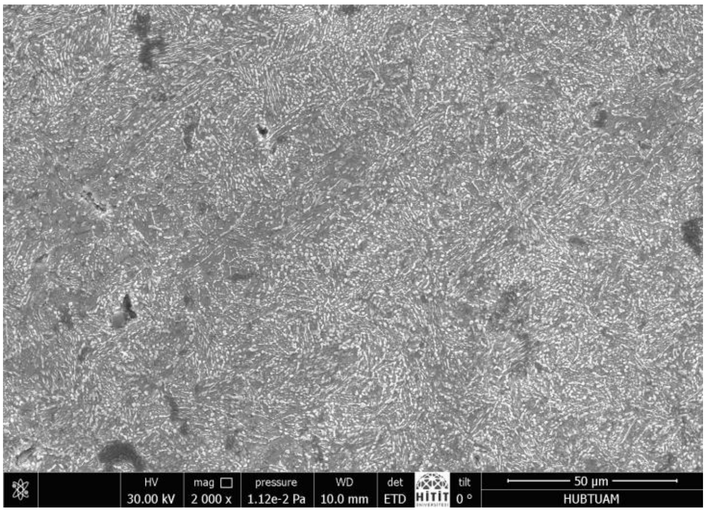


b)

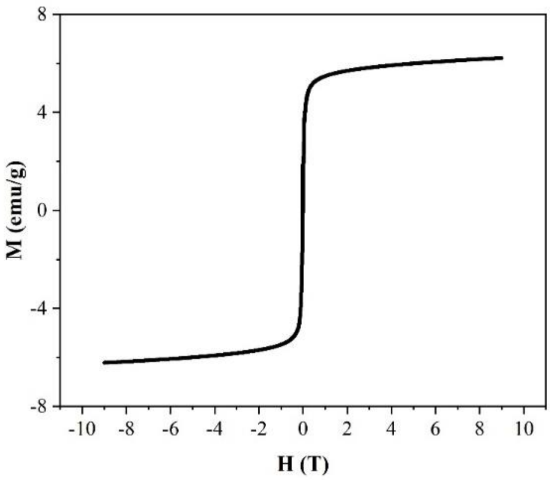
Figure 2. SEM microstructure of the (a) CuAlFe alloy, and (b) CuAlFeNi alloy.

To research the magnetic properties of the alloys, the magnetization analyses were performed, and the results are given in Figure 3. The M-H graphs of the alloys showed typical ferromagnetic behavior and the magnetization values increased with the applied magnetic field. The saturation magnetization *(M_s)* and coercivity (H_c) values were found from the obtained graphics. The M_s of the CuAlFe and CuAlFeNi alloys was determined to be approximately 8.6 and 6.1 emu/g, respectively. In addition, the H_c values for the alloys were found to be approximately 3262.67 and 1750.70 A/m, respectively. In this study, when the M_s and H_c values were compared with our previous investigation [19], an increase in these values was observed (Table 2). The differences in magnetic parameters are due to the heat treatment and composition. However, the M_s and H_c values are higher in alloy 1 than in alloy 2. This result is due to the ferromagnetic behavior of Fe. Because, the magnetic moment of Fe is thought to be more easily moved in the phases formed in the alloy, it impacts the material’s magnetic properties. There are very few studies on the magnetic properties of CuAlFe and CuAlFeNi alloys [19, 21]. Therefore, this study, compared to previous studies [19, 21], provides information about the effect of heat treatments on the magnetic properties. The results showed that both alloys exhibit soft magnetic behavior. Therefore, the alloys can be used in soft magnetic applications [7, 19, 24, 25].

Table 2. The magnetic analysis results of the alloys.

Alloy	M_s (emu/g)	H_c (A/m)	Reference
CuAlFe	8.6	3262.67	This study
CuAlFeNi	6.1	1750.70	This study
CuAl	0.03306	8753.52	[7]
CuAlFe	8.7	4376.76	[19]
CuAlFeNi	4.3	2785.21	[19]

In this study, values of M_s and H_c, when are compared to our previous work [19], the H_c values are found to be higher (Table 3). However, while the M_s values were high in alloy 2, a slight decrease was shown in alloy 1. The differences in these values can be explained by heat treatments, and composition.



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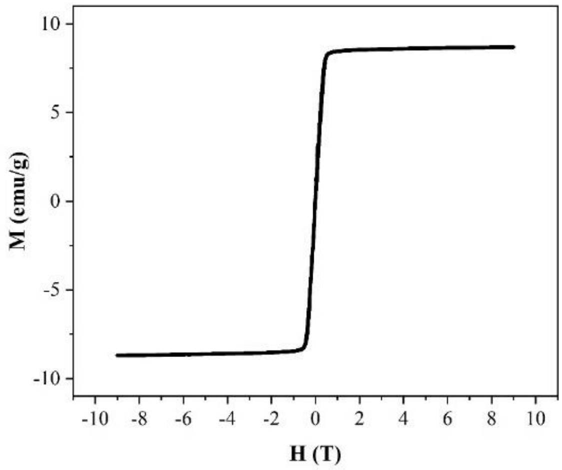


(b)

Figure 3. Magnetization behavior of (a) CuAlFe, and (b) CuAlFeNi alloys.

In Figure 4, the alloys were coded as CA (CuAl) [7], CAF (CuAlFe) and CAFNi (CuAlFeNi). According to these codes, the change in the M_s and H_c values of the alloys is shown in Figure 4. In addition, while the H_c value showed a linear decrease [7], the M_s value increased when passing from CA to CAF, and decreased when transitioning to CAFNi. The difference in composition of the materials could be the reason for the differences in values of M_s. In literature, it has been observed that M_s is dominated by the chemical composition and crystal structure, whereas coercivity can be significantly affected by grain size, secondary phase, dislocations, precipitates, and impurities [25-28]. In the study conducted by Aldırmaz et. al [7], the M_s value for the CuAl alloy was found to be 0.03306 emu/g. According to this result, Fe increased the M_s values more than Ni [7]. The M_s increases due to the ferromagnetic behavior of Fe. The magnetic moment of the alloying elements plays an important role in M_s and coercivity. Thus, the increase in M_s can be show that the magnetic moments of Fe move easily, thereby and increasing the M_s [19, 25]. Additionally, Fe-rich precipitates may also have contributed to the M_s value.

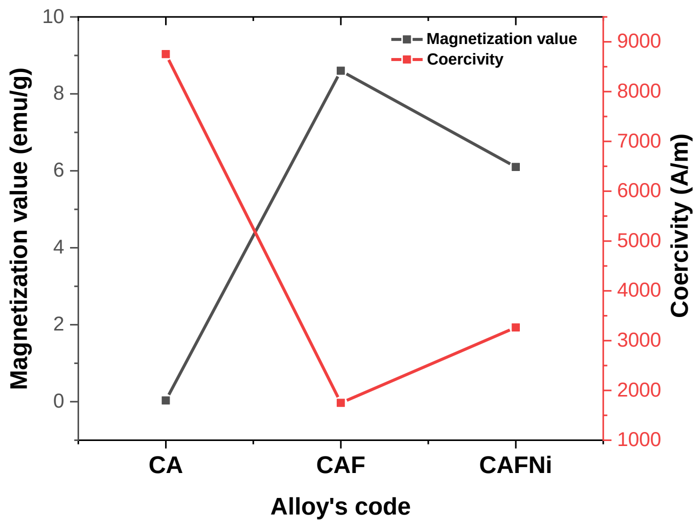
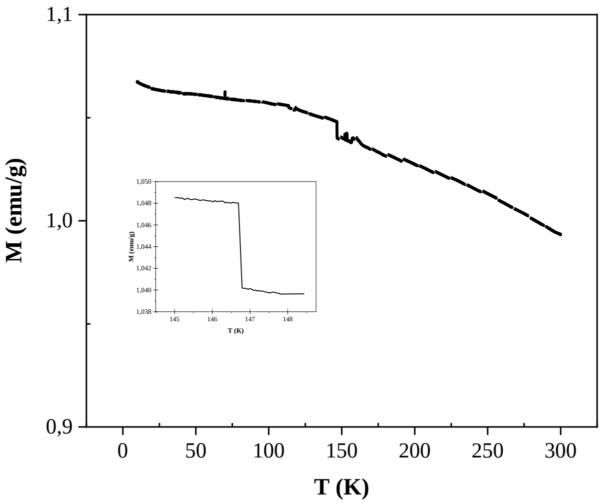


Figure 4. Magnetization and Coercivity values the alloys [7].

The magnetization curves of alloys 1 and 2 were plotted as a function of temperature in Fig. 5.When Figure 5 was examined, the Curie temperatures for alloys 1 and 2 were found above 100 K. These temperatures were found to be approximately 148 and 110 K for alloys 1 and 2, respectively. In fact, the addition of Ni to the CuAlFe alloy has reduced the Curie temperature. Curie temperatures could not be determined in our previous study (alloys 1 and 2) [19]. However, in this study, Curie temperatures were determined as they are affected by the composition and different heat treatments.



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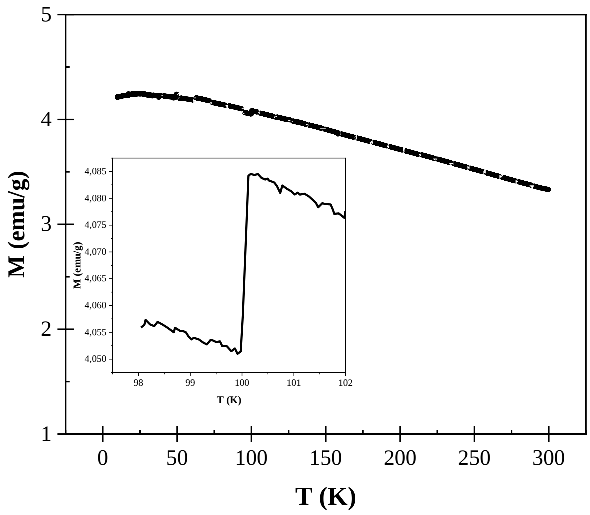

(b)

Figure 5. M-T behavior of (a) CuAlFe, and (b) CuAlFeNi alloys.

All magnetic results showed that the alloys exhibited soft magnetic behaviors due to their low hysteresis and coercivity [19, 29, 30]. It was also found that Fe and Ni improved the soft magnetic properties of the CuAl alloy [7]. Another result obtained from the study is that different cooling rates cause changes in the magnetic parameters of the alloys.

4. Conclusions

In this article, the effects of Fe and Ni elements on the microstructures and magnetic properties of CuAlFe and CuAlFeNi alloys have been compared. It was found through the analyses that the microstructures and magnetic parameters of the alloys are influenced by the alloying elements and phase structures.

From SEM results: it was found that kappa phases are affected by the cooling rate. In addition, dendrite structures were disappeared with slowly cooling. While the grain boundaries were more distinct in the CuAlFe alloy, the grain boundaries disappeared in the CuAlFeNi alloy. Magnetic observations revealed that the added Ni element caused differences in saturation magnetization and coercivity field values. When comparing Fe and Ni, it was observed that Fe increased magnetic saturation more than Ni.

Finally, the CuAlFe and CuAlFeNi alloys exhibited soft ferromagnetic behavior. We can also express that CuAlFe and CuAlFeNi alloys are suitable for soft magnetic applications such as electrical power generation and transmission systems, electric motors, and electromagnetic devices. In addition, since the kappa phases have high hardness that can improve wear resistance. Therefore the CuAlFe and CuAlFeNi alloys can be used in these areas.

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