Gazi Üniversitesi
Fen Bilimleri Dergisi
PART C: TASARIM VE TEKNOLOJİ

Gazi University
Journal of Science
PART C: DESIGN AND TECHNOLOGY

GU J Sci, Part C, 13(X): XX-XX (2025)

Production of D2 and 17-4 PH Bimetallic Materials and Investigation of Their Mechanical Properties in Atomic Diffusion Additive Manufacturing Method

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Article Info

Research article
Received: 21/03/2025
Revision: 22/04/2025
Accepted: 02/05/2025

Keywords

Additive manufacturing
17-4PH
D2 Tool Steel
Bimetallic

Makale Bilgisi

Araştırma makalesi
Başvuru: 21/03/2025
Düzeltme: 22/04/2025
Kabul: 02/05/2025

Anahtar Kelimeler

Eklemeli İmalat
17-4PH
D2 Takım Çeliği
Bimetalik

Graphical/Tabular Abstract (Grafik Özet)

Bimetal structures were produced from D2 and 17-4 PH steels using the Atomic Diffusion Additive Manufacturing method with the Markforged Metal X device. The mechanical and chemical properties of the transition region were analyzed in detail. / Markforged Metal X cihazı Atomik Difüzyon Eklemeli İmalat yöntemi kullanılarak D2 ve 17-4 PH çeliklerinden bimetal yapı üretilmiş, geçiş bölgesinin mekanik ve kimyasal özellikleri detaylı şekilde analiz edilmiştir.

***Figure A**: Graphical abstract /**Şekil A:** Grafiksel özet*

Highlights (Önemli noktalar)

- *D2 and 17-4 PH steels were successfully combined in a single structure with ADAM technology. D2 ve 17-4 PH çelikleri ADAM teknolojisiyle tek yapıda başarıyla birleştirildi.*
- *Mechanical and chemical continuity was achieved in the bimetal transition region. Bimetal geçiş bölgesinde mekanik ve kimyasal süreklilik sağlandı.*
- *High-quality filament-based production was achieved with a density value of 95.4%. %95,4 yoğunluk değeri ile yüksek kaliteli filament bazlı üretim gerçekleştirildi.*

Aim (Amaç): *This study aims to combine D2 tool steel and 17-4 PH stainless steel, which have different mechanical and physical properties, into a single bimetal structure using the Markforged Metal X device and examine the resulting interfacial behavior in detail. / Farklı mekanik ve fiziksel özelliklere sahip D2 takım çeliği ve 17-4 PH paslanmaz çeliğini, Markforged Metal X cihazı kullanarak tek bir bimetal yapıda birleştirmek ve ortaya çıkan arayüzey davranışlarını detaylı olarak incelemektir.*

Originality (Özgünlük): *This study reports the first successful joining of D2 and 17-4 PH steels in a single production cycle using the ADAM method, a filament-based metal additive manufacturing technology. Microhardness, microstructure, and chemical distribution analyses evaluated the transition zone at the interface holistically. / Bu çalışmada, filament bazlı metal katkı üretim teknolojisi olan ADAM yöntemi ile D2 ve 17-4 PH çeliklerinin ilk kez tek üretim döngüsünde başarılı bir şekilde birleştirilmesini raporlamaktadır. Arayüzeydeki geçiş bölgesi mikrosertlik, mikroyapı ve kimyasal dağılım analizleriyle bütünsel olarak değerlendirilmiştir.*

Results (Bulgular): *The produced bimetal samples had a density of 95.4%. Microhardness results showed that the transition region was homogeneous, and SEM/EDS/MAP analyses showed a controlled chemical transition of approximately 30 µm. In XRD analyses, ferrite was detected in D2, and martensite and austenite phases were detected in the 17-4 PH region. / Üretilen bimetal numunelerde %95,4 yoğunluk elde edilmiştir. Mikrosertlik sonuçları geçiş bölgesinin homojen olduğunu, SEM/EDS/MAP analizleri ise yaklaşık 30 µm'lik kontrollü kimyasal geçişin gerçekleştiğini göstermiştir. XRD analizlerinde D2'de ferrit, 17-4 PH bölgede ise martensit ve austenit fazları tespit edilmiştir.*

Conclusion (Sonuç): *ADAM technology has proven to be a successful method for producing functional bimetals by integrating steels with different characteristics into a single structure. / ADAM teknolojisi, farklı karakteristiklere sahip çelikleri tek yapıda bütünleştirerek işlevsel bimetal üretimi için başarılı bir yöntem olduğunu göstermiştir. Bu yaklaşım, havacılık, otomotiv ve kalıpçılık gibi sektörlerde uygulamaya yönelik yüksek potansiyel sunmaktadır.*

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DOI: 10.29109/gujsc.1662944

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Production of D2 and 17-4 PH Bimetallic Materials and Investigation of Their Mechanical Properties in Atomic Diffusion Additive Manufacturing Method

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Abstract

The study focused on producing bimetallic structures consisting of 17-4 PH stainless steel and D2 tool steel using the Markforged brand Metal X device. It was investigated whether these two metals, which have different physical and mechanical properties, could be combined through layered production with suitable filament combinations. Samples with cylindrical geometry were printed according to the extrusion-based layered production principle and then subjected to debinding and sintering processes within the scope of the ADAM (Atomic Diffusion Additive Manufacturing) methodology. During the production process, the samples were processed by positioning them vertically in order to ensure interface compatibility and prevent interlayer accumulation. Density, X-ray diffraction (XRD), hardness, and microstructure analyses (SEM/EDS/MAP) were performed on the produced bimetal samples; a density value of 95.4%, which is considered relatively high for filament-based metal additive production, was reached. The findings revealed the Metal X device's suitability for producing bimetal and hybrid structured metal materials. This study offers significant application potential for producing high-performance and functional parts in defense, aerospace, automotive, and manufacturing sectors by combining materials with different mechanical and thermal properties within a single structure.

Atomik Difüzyon Eklemeli İmalat Yönteminde, D2 ve 17-4 PH Bimetalik Malzeme Üretimi ve Mekanik Özelliklerinin İncelenmesi

Makale Bilgisi

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Öz

Yapılan çalışmada, Markforged marka Metal X cihazı kullanılarak 17-4 PH paslanmaz çelik ve D2 takım çeliğinden oluşan bimetalik yapıların üretimi üzerine odaklanılmıştır. Fiziksel ve mekanik özellikleri birbirinden farklı olan bu iki metalin, uygun filament kombinasyonlarıyla katmanlı üretim yoluyla bir araya getirilebilmesi araştırılmıştır. Silindirik geometriye sahip numuneler, ekstrüzyon temelli katmanlı üretim prensibine göre basılmış ve ardından ADAM (Atomik Difüzyon Katkı Üretimi) metodolojisi kapsamında bağlayıcı giderme ve sinterleme süreçlerine tabi tutulmuştur. Üretim sürecinde özellikle arayüzey uyumunun sağlanması ve katmanlar arası yığılmaların önlenmesi amacıyla numuneler dikey yönde konumlandırılarak işlenmiştir. Üretilen bimetal numunelere yoğunluk, X-Ray Diffraction (XRD), sertlik ve mikroyapı analizleri (SEM/EDS/MAP) gerçekleştirilmiş; filament bazlı metal katkı üretimi için oldukça yüksek kabul edilen %95,4 yoğunluk değerine ulaşılmıştır. Elde edilen bulgular, Metal X cihazının bimetal ve hibrit yapıda metal malzeme üretimine olan uygunluğunu ortaya koymuştur. Bu çalışma, farklı mekanik ve termal özelliklere sahip malzemelerin tek bir yapı içinde birleştirilmesi ile birlikte savunma, havacılık, otomotiv ve üretim endüstrisi gibi sektörlerde yüksek performanslı ve işlevsel parçaların üretimi için önemli bir uygulama potansiyeli sunmaktadır.

1. INTRODUCTION (GİRİŞ)

Additive manufacturing (AM) emerged in the mid-1980s and was initially used only for prototyping. The stereolithography (SLA) method developed by Chuck Hull laid the foundation for this field [1]. Over time, with the advances in three-dimensional printer technologies, production has become possible not only with polymer-based but also with high-performance engineering materials such as metal and ceramic [2]. According to the classification developed by ASTM International, additive manufacturing technologies are divided into categories such as powder bed fusion (PBF),

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DOI: 10.29109/gujsc.1662944

direct energy deposition (DED), material extrusion (FDM/FFF), binder injection, and vat photopolymerization [3]. These technologies have gained prominence as an alternative to conventional manufacturing in sectors including defense, aerospace, automotive, biomedical, and tooling industries [2-4].

Today, notable devices in metal-based additive manufacturing include EOS M290, Renishaw AM400, Desktop Metal Studio System, and Markforged Metal X [2, 5]. These systems operate on different sintering principles and provide cost-effective, high-precision manufacturing options tailored especially for small-scale production [4, 5]. Among them, the Markforged Metal X system stands out for its use of ADAM (Atomic Diffusion Additive Manufacturing) technology, which utilizes filament-based metal materials that are transformed into final parts through debinding and sintering [6]. With its wide material portfolio (e.g., 17-4 PH, H13, A2, D2, Cu), safe operation, and affordability, the Metal X system is increasingly preferred in small and medium-sized industrial settings [4-6]. ADAM technology stands out with its lower equipment cost, safer working environment, and simpler hardware requirements compared to traditional methods such as powder bed melting (PBF) and direct energy deposition (DED). Thanks to its filament-based production structure, it provides a more homogeneous density and excellent surface quality, creating an accessible and practical alternative in metal additive production [7]..

The development of multi-material structures offers numerous advantages, including a wide range of applications over traditional materials. Additive manufacturing enables not only monolithic but also bimetallic structures, which combine different materials to create components with enhanced mechanical and functional performance [8,9]. This approach allows for the local optimization of properties such as hardness, corrosion resistance, and wear resistance [10]. Bimetallic production offers significant advantages, especially in applications requiring mechanical properties such as strength and toughness in certain component areas. ADAM technology, on the other hand, can create a seamless metallurgical bond between dissimilar metals and overcome the limitations of traditional joining methods thanks to the layer-by-layer material deposition and controlled sintering process [11,12]. However, challenges including differences in thermal expansion coefficients, microstructural incompatibilities, and varying sintering behaviors complicate the reliable production of such multi-material components [13]. Therefore, evaluating the interfacial characteristics of these structures through microstructural examination and mechanical testing techniques—such as optical microscopy and hardness profiling—is essential, particularly when integrating dissimilar materials like D2 tool steel and 17-4 PH stainless steel [7,14].

2. MATERIALS AND METHODS (MATERYAL VE METOD)

In this study, two engineering materials with different properties were used to investigate the manufacturability of bimetallic structures by additive manufacturing methods: D2 tool steel and 17-4 PH stainless steel. Both materials were supplied in filament form compatible with the Markforged Metal X system.

Tool steel D2 has high wear resistance thanks to its alloy elements, especially its high carbon content, and is, therefore, widely used in the mold and cutting tool industry. 17-4 PH stainless steel is a frequently preferred material in the aviation, energy, and medical sectors thanks to its superior corrosion and mechanical properties, which can be improved with secondary heat treatments. The chemical compositions of the materials used are given in Table 1.

Table 1. Chemical composition of 17-4 PH and D2 Filament materials (17-4 PH ve D2 Filament Malzemelerinin Kimyasal Bileşimi)

Element	D2 Tool Steel (%)	17-4 PH SS (%)
C (Carbon)	1.40 – 1.60	0.07 – 0.10
Cr (Chromium)	11.0 – 13.0	15.0 – 17.5
Mo (Molybdenum)	0.70 – 1.20	≤ 0.60
V (Vanadium)	0.70 – 1.20	—
Mn (Manganese)	≤ 0.60	≤ 1.00
Si (Silicon)	≤ 0.60	≤ 1.00
Ni (Nickel)	—	3.0 – 5.0
Cu (Copper)	—	3.0 – 5.0
Nb/Cb (Niobium)	—	0.15 – 0.45
Fe (Iron)	Balance	Balance

This study produced samples using the Metal X device belonging to Markforged. This system is based on ADAM (Atomic Diffusion Additive Manufacturing) technology, which divides the production process into three basic steps. In the first step, filaments containing metal powder were extruded layer by layer to create a structure suitable for the specified geometry. The second step involved placing the completed green parts into a special solvent bath and removing the plastic binder. In the third and final stage, the parts were taken into a sintering furnace at high temperatures under a controlled atmosphere and combined at the atomic level, and a high-density structure was obtained. The manufacturer's recommendations carried out the sintering process in an N_2/H_2 gas mixture atmosphere at 1300 ° C for approximately 24 hours.

Printing processes were controlled by Markforged Eiger™ software and were based on standard parameters recommended by the manufacturer. However, parameters such as layer height and infill ratio were optimized to increase the interface integrity between the two different materials. The samples were designed as a structure where two different materials were combined, with 75% D2 and 25% 17-4 PH ratios. Changing the filament tank during the production process produced two materials sequentially along a vertical interface in a single printing cycle. This structure was designed to consist of 80 layers; the first 60 layers were produced using D2, and the last 20 layers were produced using 17-4 PH material. A solid infill structure was preferred, and a wall thickness of 4 mm was determined for the printing parameters to ensure optimum mechanical properties. This design was structured to increase mechanical strength and obtain a clear material transition. All processes during production were carried out with software support.

Various characterization studies were performed on the produced samples. Density measurements were applied according to the Archimedes principle. SEM (scanning electron microscopy) analyses were performed for microstructure characterization using JEOL JSM 6060 LV. EDS (Energy Dispersive X-ray spectroscopy) and MAP (element distribution) analyses to evaluate the chemical transition in the interface region were also taken with the same device and were performed with 20 kV acceleration voltage. XRD (X-ray Diffraction) studies for structural phase analyses were performed using a Bruker brand X-ray diffractometer. XRD measurements were performed by scanning in the range of 2θ = 30°-90° with a step size of 0.02°. The hardness profile was measured in different material regions using the micro-Vickers method, and the mechanical property differences in the transition region were evaluated. Figure 1 shows the design of Bimetal material production in the Eiger Program

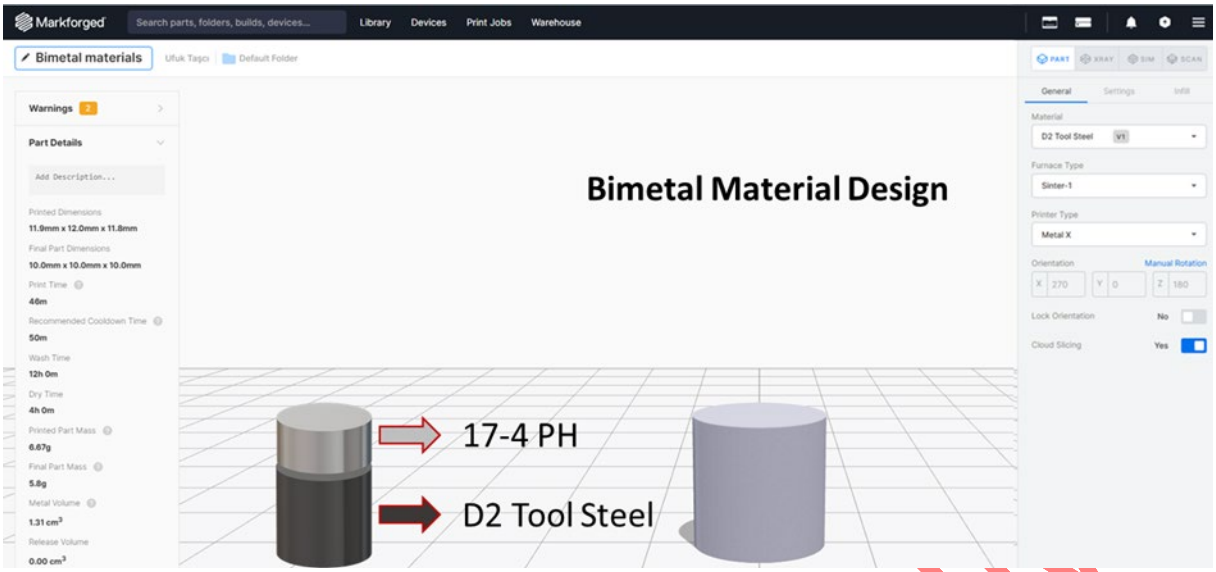

Figure 1. Design of bimetallic material production (Bimetalik malzeme üretiminin tasarımı)

The test samples were designed as cylindrical, especially with dimensions of 10x10 mm. The cylindrical geometry prevented problems such as accumulation and cracks that would occur during production steps. The produced sample was cut from the lateral section on the wire erosion machine for microstructure characterization. The transition region between the materials was positioned along the Z axis, i.e., in the vertical direction. Thanks to this configuration, microstructural differences that may occur after sintering could be observed, and the interfacial behavior could be analyzed in detail.

3. RESULTS AND DISCUSSION (SONUÇLAR VE TARTIŞMA)

D2 tool steel and 17-4 PH stainless steel used in bimetallic production can be processed in the same production cycle due to their similar sintering temperature ranges. In the sample used in this study, since the D2 material has a volume fraction of approximately 75%, the sintering process was planned according to the technical requirements of D2 and carried out in an atmosphere-controlled furnace. After sintering, classical metallography preparation processes were applied to the bimetal sample and then the microstructure of the D2/17-4 PH structure produced with the Markforged Metal X device is presented as an optical microscope image in Figure 2. In the microstructure examination, it was observed that successful sintering took place between the two different materials and continuity was provided at the interface. It is understood that the micropores detected in the sample were formed during the production process and are a natural result of the layered printing process in particular. These pores are related to the production process carried out without applying any external pressure and the removal of binders during washing and sintering at the green part stage. Therefore, porosity was considered as part of the microstructural characteristic of the material and interpreted as a property specific to the production method.

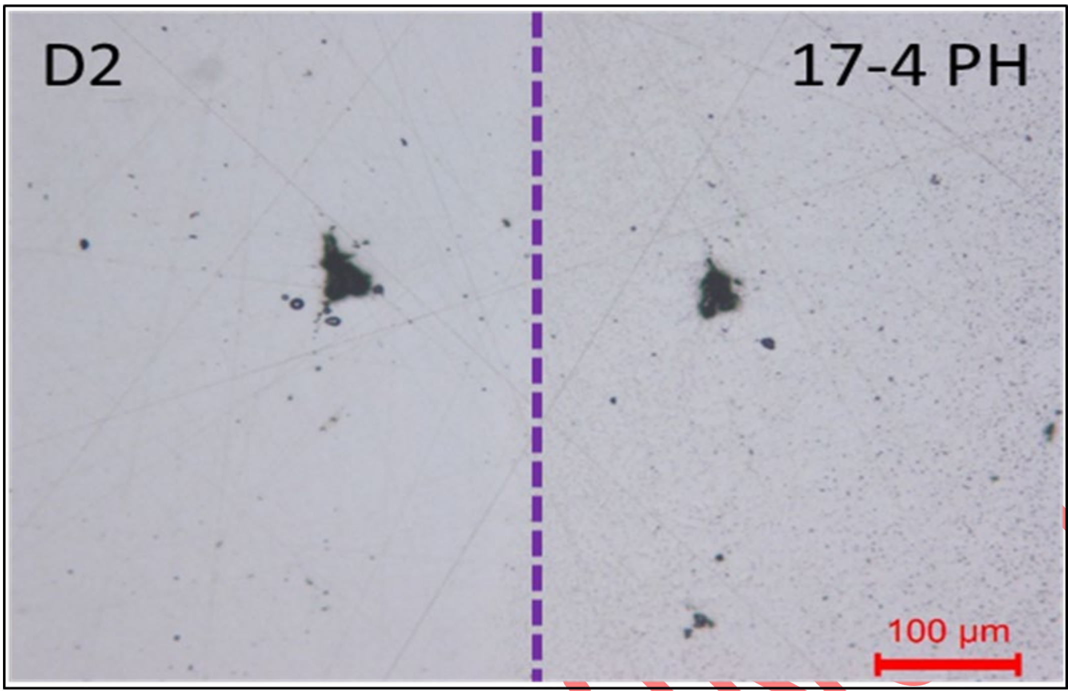

Figure 2. Optical microscope image of printed bimetallic material (Baskılı bimetalik malzemenin optik mikroskop görüntüsü)

Figure 3 shows the XRD patterns and crystal structure analysis results of the produced bimetal material. The prominent peaks of the 17-4 PH martensite phase were detected at 44.5, 65, and 82 at 2ϴ. In the same analysis, the ferrite phases of the D2 material were also determined [14,15]. As a result of XRD analysis, it was determined that there were Fe-Cr, α-Fe and austenite phases in the bimetallic structure. These phases show that both materials (D2 and 17-4 PH) maintain their unique microstructural characteristics. The main thing to notice about the Fe-Cr phases is that D2 tool steel has a lot of chromium, which makes it very hard and resistant to wear. α-Fe (ferrite) phases are another phase typically seen in D2 steel and contribute to the mechanical strength of the structure [16]. The austenite phase, one of the characteristic peaks of the 17-4 PH region, represents the ductility and toughness of the material that can be improved by heat treatment [17]. This phase distribution shows that both materials maintain separate phases and that there is no significant phase transformation at the interface. Thus, it is understood that the produced bimetallic structure can carry functional differences and offer an advantageous mechanical profile for application areas.

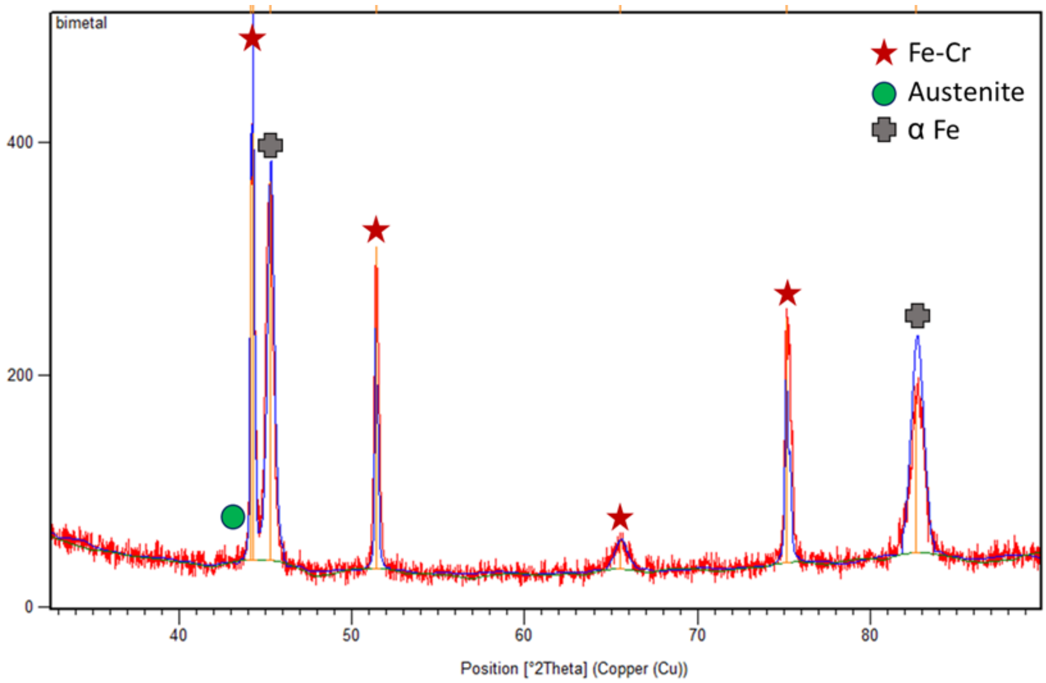

Figure 3. XRD patterns of printed bimetallic sample (Basılı bimetalik numunenin XRD desenleri)

The density value of the produced bimetallic sample was 95.4%, and the relevant measurement results are presented in Figure 4. This rate is a remarkable value when the limitations of the filament-based metal additive manufacturing technology are considered. Especially in ADAM (Atomic Diffusion Additive Manufacturing) technology, reaching densities above 90% is considered a technical success due to the gaps formed after sintering and the expansion differences between the materials. One of the highest density values obtained in the studies conducted with Markforged Metal X in the literature was reported as 92.9% [18,19]. In this context, the 95.4% density value obtained in our study is significant in showing both the suitability of the sintering parameters and the compatibility of D2 and 17-4 PH materials.

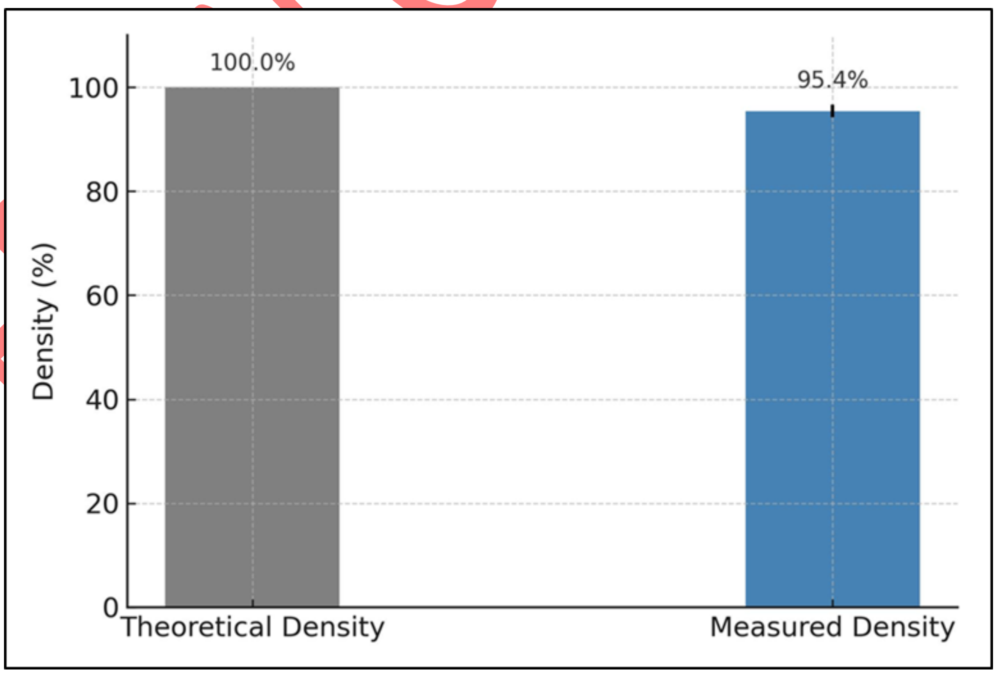

Figure 4. Density measurements for printed bimetallic samples (Baskılı bimetalik numuneler için yoğunluk ölçümleri)

Microhardness measurements provided important data for evaluating mechanical differences between D2 and 17-4 PH materials and the bimetallic transition region, and the relevant results are presented in Figure 5. According to the HV(0.5) load measurements, an average of 422.3 HV was obtained in the D2 tool steel region, 385.2 HV in the 17-4 PH stainless steel region, and 386.1 HV in the bimetallic transition region. It was observed that D2 exhibited a more complex and hard structure due to its higher carbon and alloying element content. On the other hand, 17-4 PH steel showed moderate hardness due to the precipitation hardening mechanism. The hardness value obtained in the transition region was measured very close to the 17-4 PH region and with a low deviation (±1 HV), indicating that no significant mechanical discontinuity occurred between the two materials.

In addition, the fact that no sudden fluctuations, sharp drops, or jumps were observed in the measurements in the transition region revealed that the hardness profile progressed statistically continuously and in a curvilinear character. This supports the successful material diffusion after sintering and the fact that no sudden phase or structure changes occurred in the transition region. Therefore, the transition region was evaluated as "homogeneous" regarding the average value and the smooth trend of the hardness distribution [20].

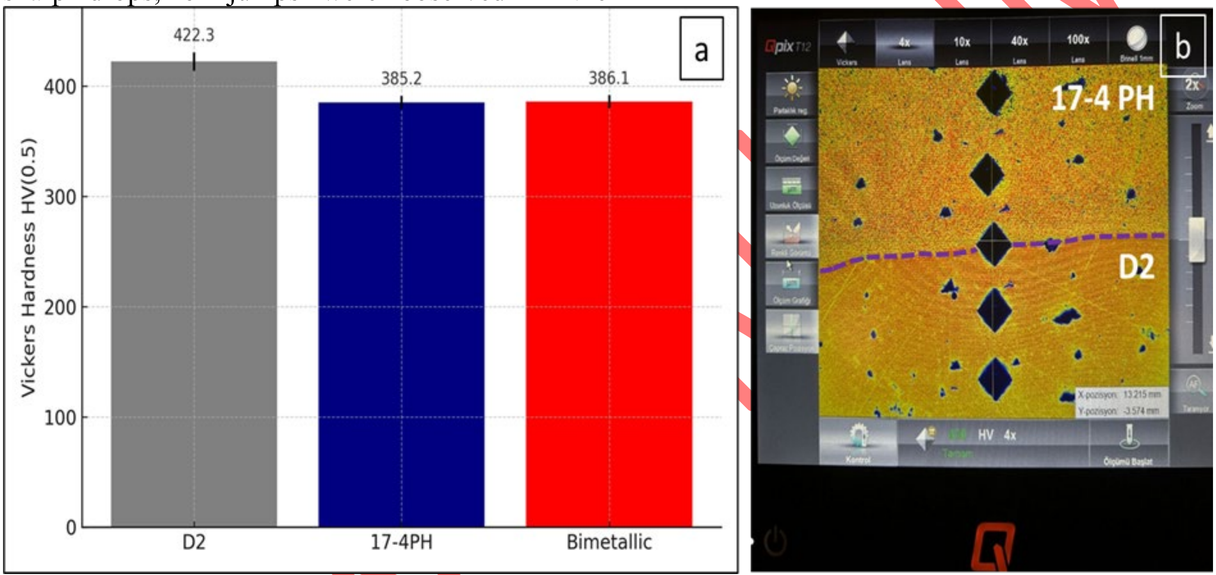

Figure 5. Hardness value of printed bimetallic material (a), analysis application image (b)(Baskılı bimetalik malzemenin sertlik değeri (a), analiz uygulama görüntüsü (b))

SEM/EDS analyses evaluated the elemental distribution and chemical transition at the interface between D2 tool steel and 17-4 PH stainless steel. The spectra taken from four different regions marked on the figure revealed the characteristic alloy elements of both materials. Regions 1 and 2 are located on the D2 side and are seen to contain high amounts of chromium (13.56–17.69%) and alloy elements such as vanadium, molybdenum and niobium associated with carbon. The fact that nickel and copper elements specific to 17-4 PH material are not found in these regions shows that the material boundaries are successfully protected. Regions 3 and 4 are located on the 17-4 PH side, and here, nickel, chromium, and copper elements contributing to precipitation hardening together with high iron content (69.90–74.99%) were also detected. Especially at point number 4, the significant increase in nickel (4.35%), chromium (24.55%), and copper (1.04%) ratios shows that the precipitation character is prominent in this region. The same point is also remarkable in representing the boundary region where the chemical transition starts, as it is close to the interface region. The EDS spectra, particularly in areas 1 and 3, show a clear but steady change in the amounts of the alloying elements Cr, Fe, and Ni. This gradual transition proves that ADAM technology successfully performs interatomic diffusion during sintering. According to the measurements made on the image, it was determined that the transition occurred with a width of approximately 30 μm. This numerical value shows that the transition region has both microstructural and chemical continuity, i.e., a diffusion-based bond is formed instead of a clear boundary between the two materials. This situation offers a significant advantage in interfacial stability and long-term mechanical strength. All these findings reveal that two different materials are combined layer by layer during the printing process and that chemical contamination remains quite limited, thus confirming that the Markforged Metal X system can successfully manage material transitions in bimetallic production and support the continuity of the interface [21,22].

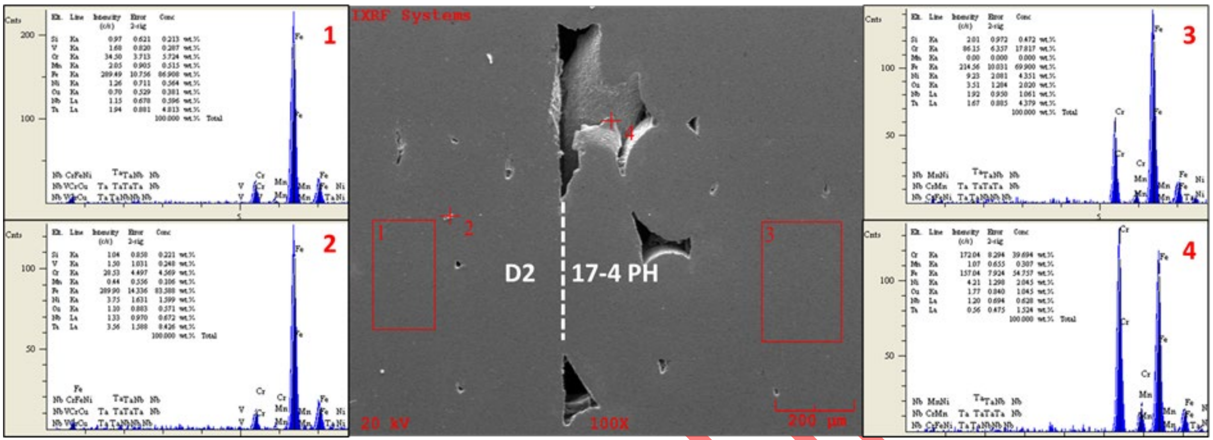

Figure 6. SEM/EDS analysis image of printed bimetallic samples (Basılı bimetalik numunelerin SEM/EDS analiz görüntüsü)

Figure 7 provides an element mapping (MAP) analysis to evaluate the distribution of main alloy elements on the surface of the bimetallic structure consisting of D2 and 17-4 PH materials. The distributions of Fe, Cr, Ni, Cu, Nb, Ta, Mn, and Si elements were mapped separately in the analyses performed in the regions determined on the SEM image. Since the iron (Fe) element constitutes the basic structure of both materials, it shows a homogeneous and dense distribution in both regions. Although the chromium (Cr) element is found in high amounts in both alloys, it has a more widespread superficial distribution, especially on the 17-4 PH side; this situation coincides with the high chromium content (15–17%) that provides the stainless property of the material. It was observed that the elements such as nickel (Ni) and copper (Cu), which play an active role in precipitation hardening, are predominantly localized in the 17-4 PH region and are more densely distributed there. Microalloying elements such as niobium (Nb) and tantalum (Ta) were found to be distributed homogeneously in both regions at low concentrations. Manganese (Mn) and silicon (Si) elements are found as additive elements in both materials but generally have a sparser distribution [23,24].

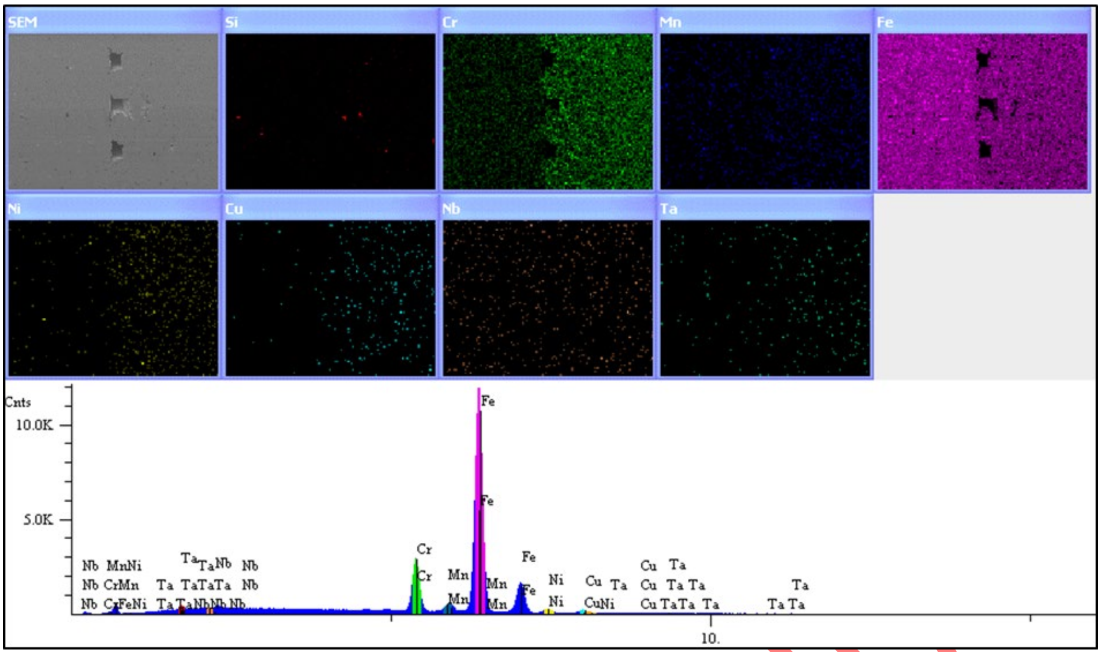

Figure 7. SEM/MAP analysis image of printed bimetallic samples (Basılı bimetalik numunelerin SEM/MAP analiz görüntüsü)

4. CONCLUSIONS (SONUÇLAR)

This study showed that D2 tool steel and 17-4 PH stainless steel could be successfully combined into a single bimetallic sample using a Markforged Metal X device. The properties of the bimetallic sample, such as density, microstructure characterization, and SEM/EDS/MAP, were investigated, and the experimental results are given below:

- D2 and 17-4 PH materials were successfully made together in the same production cycle because they have similar sintering temperature ranges, which indicated that ADAM technology is good for producing multiple materials at once.
- The 95.4% density value, which is uncommon in filament-based additive manufacturing systems, shows that the process optimization and sintering parameters are effective; this indicates that the production quality is good enough for industrial use.
- Microhardness tests indicated that there were no sudden changes in strength in the transition area, which confirms that a smooth transition was created at the interface without any breaks and kept the structure intact.
- The XRD analyses showed that the key microstructure features of both materials remained intact after sintering, and their functional properties were still preserved.
- SEM/EDS data indicate that the edge between the materials is well maintained, and there is a careful chemical change at the interface; this helps stop material separation and improves production quality.
- In MAP analyses, the typical arrangement of alloying elements like Cr, Ni, Fe, and Cu in both areas helps keep the material identifiable and maintains the separation of functions within the structure.
- The general production process and characterization results demonstrate the successful use of the Markforged Metal X system for bi-metal production and interface engineering.
- The findings show that cost-effective and functional bimetal components can be produced in applications requiring different mechanical demands within the same part, especially in mold, aviation, and automotive sectors.

ACKNOWLEDGMENTS (TEŞEKKÜR)

This study was supported by Gazi University BAP with the project number FBG-2022-7860 " Eklemeli İmalat Yöntemiyle Inconel 625 Matrisli B4C Katmanlı Fonksiyonel Derecelendirilmiş Kompozit Malzeme Üretimi Yapısal Mekanik Tribolojik ve Radyoaktivite Özelliklerinin Araştırılması". / Bu çalışma Gazi Üniversitesi BAP tarafından FBG-2022-7860 "Eklemeli İmalat Yöntemiyle Inconel 625 Matrisli B4C Katmanlı Fonksiyonel

Derecelendirilmiş Kompozit Malzeme Üretimi Yapısal Mekanik Tribolojik ve Radyoaktivite Özelliklerinin Araştırılması" proje numarası ile desteklenmiştir.

DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Ufuk TAŞCI*:** He conducted the experiments, analyzed the results and performed the writing process.

Deneyleri yapmış, sonuçlarını analiz etmiş ve maklenin yazım işlemini gerçekleştirmiştir.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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