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Research Article

The Investigation of the Weldability of Ti6Al4V Alloy with Different Stainless Steel Series Using Copper Interlayer via Friction Welding

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ABSTRACT

Friction welding is a solid-state welding method used for joining metals with different properties, providing minimal thermal deformation in welded joints. Based on this advantageous feature of friction welding, this study investigates the weldability of Ti6Al4V alloy with 316L, 316Ti, 310, 430, and 304 series stainless steels using a Cu powder interlayer. Following the experimental procedures, the microstructures of the materials were analyzed using SEM-EDX, their macrostructures were visually inspected for physical changes, microhardness measurements were taken, and tensile tests were performed. It was observed that the Cu powder interlayer significantly influenced the reactions and bonding between the materials, playing a crucial role in both microstructure and mechanical properties. In this study, successful joining results were achieved using the friction welding method, and the microstructural characteristics and mechanical performance of the welded joints were thoroughly evaluated. Upon examining the microhardness results, no significant variations in hardness values were observed on the Ti6Al4V side.

1. INTRODUCTION

Welding is a technique that permanently joins metallic and plastic materials, typically performed using heat, pressure, or a combination of both. Ideally, the materials should have similar melting points, and the surfaces should be clean. However, achieving these conditions can be challenging, which has led to the development of various welding methods. Welding techniques are classified into two main categories: fusion welding and solid-state welding. In fusion welding, the materials are melted using heat, while in solid-state welding, the materials are joined below their melting points [1]. Friction welding is an important solid-state welding technique that enables the joining of cylindrical parts by generating heat through friction. This method does not require filler materials or shielding gases and offers advantages such as low energy consumption, fast processing times, and the ability to join dissimilar materials [2-5].

Titanium and its alloys remain among the most widely used materials in biomedical applications due to their exceptional strength and biocompatibility [6,7]. Among titanium alloys, Ti6Al4V is a commonly preferred alloy belonging to the $\alpha+\beta$ alloy group, offering balanced properties through its aluminum and vanadium content [8]. This alloy is widely used in numerous industrial applications due to its advantages such as low density, high thermal stability, excellent mechanical properties, effective corrosion resistance, and biocompatibility [9-11]. Ti6Al4V is frequently employed in fields such as jet engines, spacecraft, the automotive industry, and medical implants. However, the welding processes of titanium alloys carry risks of distortion and contamination due to high heat input. Specifically, the absorption of harmful gases in the weld seam of Ti6Al4V can lead to a reduction in mechanical properties. Friction welding offers an effective solution to mitigate these challenges, as its low heat input and controlled process can enhance weld quality and prevent gas absorption. Therefore, the potential advantages provided by friction welding in joining Ti6Al4V alloy play a noteworthy role [12].

Stainless steels offer a wide range of properties and applications, making them essential in industrial and engineering fields. 316L and 316Ti belong to the austenitic stainless steel category; 316L, with its low carbon content, provides superior performance in corrosive environments such as seawater, while 316Ti, with titanium addition, enhances stability and corrosion resistance at high temperatures [13]. 310 stainless steel is an austenitic alloy designed for high-temperature applications, known for its excellent heat resistance and oxidation resistance [14]. Ferritic 430 stainless steel is favored in less corrosive environments and decorative applications, while 304 stainless steel, the most common type in the austenitic group, offers good general corrosion resistance and workability [15]. Each of these steel types serves a broad range of industrial applications by offering properties tailored to specific requirements.

In this context, Ünal et al. investigated the friction welding of AISI 430, AISI 440, and AISI 304 stainless steels with AISI 4340 steel and examined the fatigue strength of the materials after welding. The experiments were conducted using a continuous drive friction welding machine at different rotational speeds; the weld zones were examined using optical and scanning electron microscopes, while EDAX analyses and Vickers hardness measurements were performed. Fatigue tests were carried out on a rotating bending fatigue machine, and fracture surfaces were analyzed with SEM [16]. Ting et al. joined 304 stainless steel with Ti-15-3 titanium alloy using electron beam welding with a copper interlayer. The microstructures of the welded region were examined by optical microscopy, scanning electron microscopy, and X-ray diffractometry, and the mechanical properties were evaluated through tensile testing. The formation of $TiFe_2$ intermetallic phases on the stainless steel side and Ti-Cu and Ti-Fe-Cu layers on the titanium side was observed [17]. Turner and colleagues explored the weldability of titanium alloys using the linear friction welding method. They conducted experiments on Ti6Al4V alloy and evaluated heat transfer effects using thermocouples [18]. The experimental results were consistent with the modeling outcomes. Kumar and Balasubramanian studied the friction welding of SUS 304 HCU austenitic stainless steel pipes. In the welding process, using friction welding parameters, it was observed that the potential for eutectic formation of Cu at low temperatures was minimized [19].

In this study, the joining of Ti6Al4V alloy with 316L, 316Ti, 310, 430, and 304 stainless steels was performed. A precise direct-drive friction welding machine, where all welding parameters could be controlled via a PLC automation system, was utilized. In preliminary trials, several attempts without using an interlayer resulted in failure, prompting the re-evaluation of Ti6Al4V alloy's weldability with the use of an interlayer. The method employed involved filling 4 mm diameter holes drilled into the surface of the material to be welded with powdered Cu, which served as the interlayer. This approach led to successful joining results. Copper powder was used as the interlayer, and the powder was compressed into the hole created in the material with a specialized punch. Since the powder was secured to the stationary side of the welding machine, no material loss occurred. The welded joints were evaluated through microstructural characterization, tensile tests, microhardness measurements, and SEM-EDS analyses.

2. MATERIAL AND METHOD

The samples used in the experiments were commercially procured. The device utilized for the welding process was specifically designed for this purpose. All welding parameters could be controlled through a touchscreen interface on the PLC unit. The mechanical structure of the friction welding device is divided into three main sections: the drive area, the movable area, and the pressure area. These sections are bolted onto a single piece made of St52 material, which is 50 mm thick, to prevent vibrations. The welded samples and the welding process parameters are presented in Table 1.

TABLE I
WELDED SAMPLES AND WELDING PROCESS PARAMETERS

Welded Pairsdönm	Interlayer Materials	Friction Time (sn)	Forging Time (sn)	Friction Pressure (MPa)	Forging Pressure (MPa)	Rotational Speed (dev/dk)
Ti6Al4V-316L	Cu	5	15	100	250	2850
Ti6Al4V-316Ti	Cu	5	15	100	250	2850
Ti6Al4V-310	Cu	7	15	75	175	1800
Ti6Al4V-430	Cu	7	15	75	175	1800
Ti6Al4V-304	Cu	11	15	75	175	1800

Commercially obtained rods with a diameter of 8 mm and a length of 3 meters were cut to a length of 30 mm using a precision sample cutting device and subjected to turning operations on a lathe to achieve a smooth joint. Holes with a diameter of 4 mm and a depth of 2 mm were drilled into the samples to be joined with the Ti6Al4V alloy on the lathe. Copper powder was placed in these holes as an interlayer using a special pressing apparatus, and a drop of alcohol was applied to each powder to prevent scattering. During welding, the Ti6Al4V sample was placed in the rotating section, while the other material was positioned in the fixed section. Figure 1 shows the friction welding machine used in the experiment. European Journal of Technique, European Journal of Technique. European Journal of Technique, European Journal of Technique, European Journal of Technique, European Journal of Technique, European Journal of Technique, European Journal of Technique [2-6].

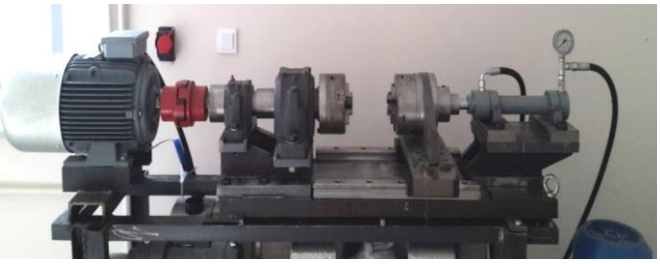


Figure 1. Friction Welding Machine Used in the Experiment

After the samples were placed, the welding process was carried out, and they were reduced to suitable sizes for metallographic analysis. Subsequently, the samples were subjected to cold mounting and prepared for microstructure and microhardness examinations. The samples were polished sequentially with water sandpapers numbered 180 to 2000 and then polished with 1 µm and 3 µm paste. After polishing, the surfaces were cleaned with ethyl alcohol. Chemical etching was performed for 30 seconds using different etchants on the Ti6Al4V and stainless steel samples. The welded samples were prepared for scanning electron microscopy and energy-dispersive X-ray spectroscopy (EDX), and microhardness measurements were conducted using the Vickers method. Hardness values were measured at ten different points horizontally with 0.5 mm spacing, focusing on the center of the weld zone. Tensile specimens were prepared according to ASTM E 8M-04 standards, and tensile tests were performed using a "AG-IC SHIMADZU" device with a capacity of 100 kN. Tensile strength, percentage elongation, and stress values were measured using the TRAPEZIUM-X software.

3. RESULTS AND DISCUSSION

The Ti6Al4V alloy has been successfully joined with 316L, 316Ti, 310, 430, and 304 materials. The macrostructure, microhardness, tensile tests, as well as SEM and EDX analyses of the obtained welded samples have been thoroughly examined. The results of these analyses are presented below.

3.1. Macrostructure Investigations

Macrostructure images of the welded samples are presented in Figure 2. The macro and cross-sectional images of the samples welded using a copper interlayer for AISI 316L-Ti6Al4V alloys have also been analyzed. In these samples, the neck region was observed in the Ti6Al4V alloy, resulting in a length reduction of 5.08% after welding. The cross-sectional images clearly show that the welding process was successfully carried out and that the deformation of the weld interzone was evident. The macrostructure images of the samples welded with AISI 316Ti and Ti6Al4V alloys reveal that the neck region is located within the Ti6Al4V alloy, with a length reduction of 6.1%. This situation reflects the influence of the physical properties of the Ti6Al4V alloy and the applied welding parameters. In the macrostructure images obtained from the friction welding of AISI 310 and Ti6Al4V alloys, it can be seen that the joining process was successfully executed, with the neck region forming on the Ti6Al4V alloy side. The length reduction resulting from the welding process was measured to be approximately 2.5%. Upon examining the cross-sectional images, it was observed that the deformed area was limited and that the copper interlayer diffused throughout the weld zone. Similarly, the welded samples of AISI 430 and Ti6Al4V alloys using a copper interlayer were also investigated. A successful welding operation was observed in these samples, and the macrostructure analysis indicated that the neck region was on the AISI 430 side, with a length reduction of 3% occurring after welding. The cross-sectional image clearly illustrates the deformation of the weld zone and the diffusion of the copper interlayer throughout the weld section. Finally, macro and cross-sectional photographs of the friction welding processes of AISI 304 and Ti6Al4V alloys using a copper interlayer have been examined. In cases where the friction time was 5 seconds, the welding process was unsuccessful; however, at 11 seconds and a rotational speed of 1800 RPM, the welding operation successfully facilitated the joining of the materials. The neck region formed in the Ti6Al4V alloys after welding, with a length reduction measured at 0.89%. The cross-sectional images indicate that the structure of the spot hole was preserved due to minimal deformation observed on the AISI 304 side, resulting in a robust joint region.

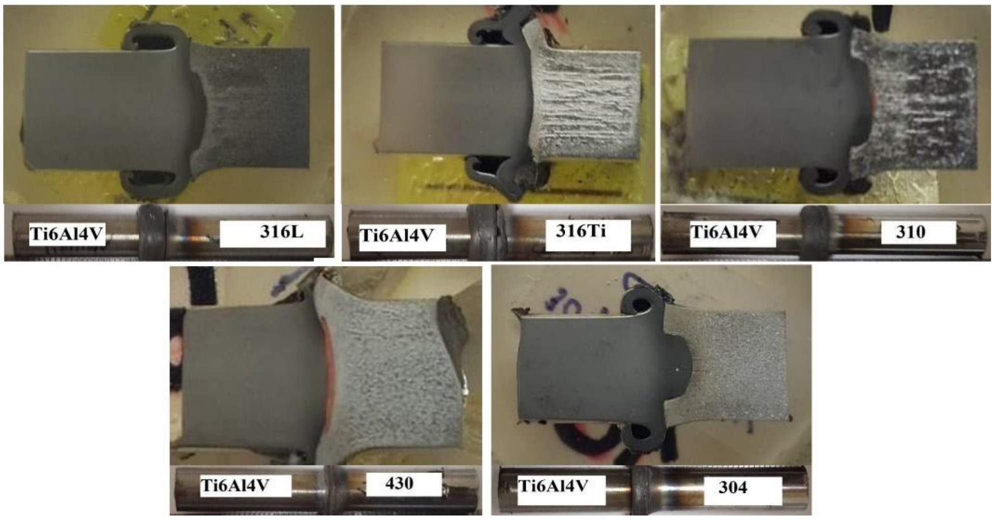


Figure 2. Macrostructure Images of Welded Samples

3.2. Microhardness Measurement Results

Figure 3 presents the microhardness profiles of weld samples using a Cu interlayer. In the Ti6Al4V-316L weld, it is observed that while there is no significant change in the hardness values on the Ti6Al4V side, a notable decrease is observed on the 316L side towards the weld interface. This reduction in hardness is attributed to the elevated temperatures in the weld region, which relieve internal stresses within the material [20,21]. Conversely, in the microhardness graph of the weld process using a Cu interlayer for the 316Ti and Ti6Al4V alloys, the hardness on the Ti6Al4V side remains relatively stable up to the fusion zone, with an average value of approximately 310 HV. However, the 316Ti side exhibits an increase in hardness values up to a distance of 3 mm from the fusion zone, rising from 212.2 HV to 266.8 HV. This increase is linked to the reduction of internal stresses facilitated by the heat in the weld zone, which enhances hardness. Despite these differing trends in hardness, the underlying cause appears to be similar—both phenomena are related to the thermal influence on internal stresses within the material. Therefore, a more nuanced reinterpretation is required to accurately reflect the relationship between thermal effects and hardness variations in the weld region.In the welding process between the 430 and Ti6Al4V alloys, no significant change in hardness values was observed, which is attributed to the low heat input in the fusion zone. The highest hardness value measured on the AISI 430 side was 238 HV, while on the Ti6Al4V side, it was 324 HV. The microhardness values in the welding process between AISI 304 and Ti6Al4V alloys did not exhibit a significant change. The interlayer hardness could not be measured due to the thin section thickness at the weld interface. The highest hardness value measured on the AISI 304 side was 330 HV, and 358 HV on the Ti6Al4V side.

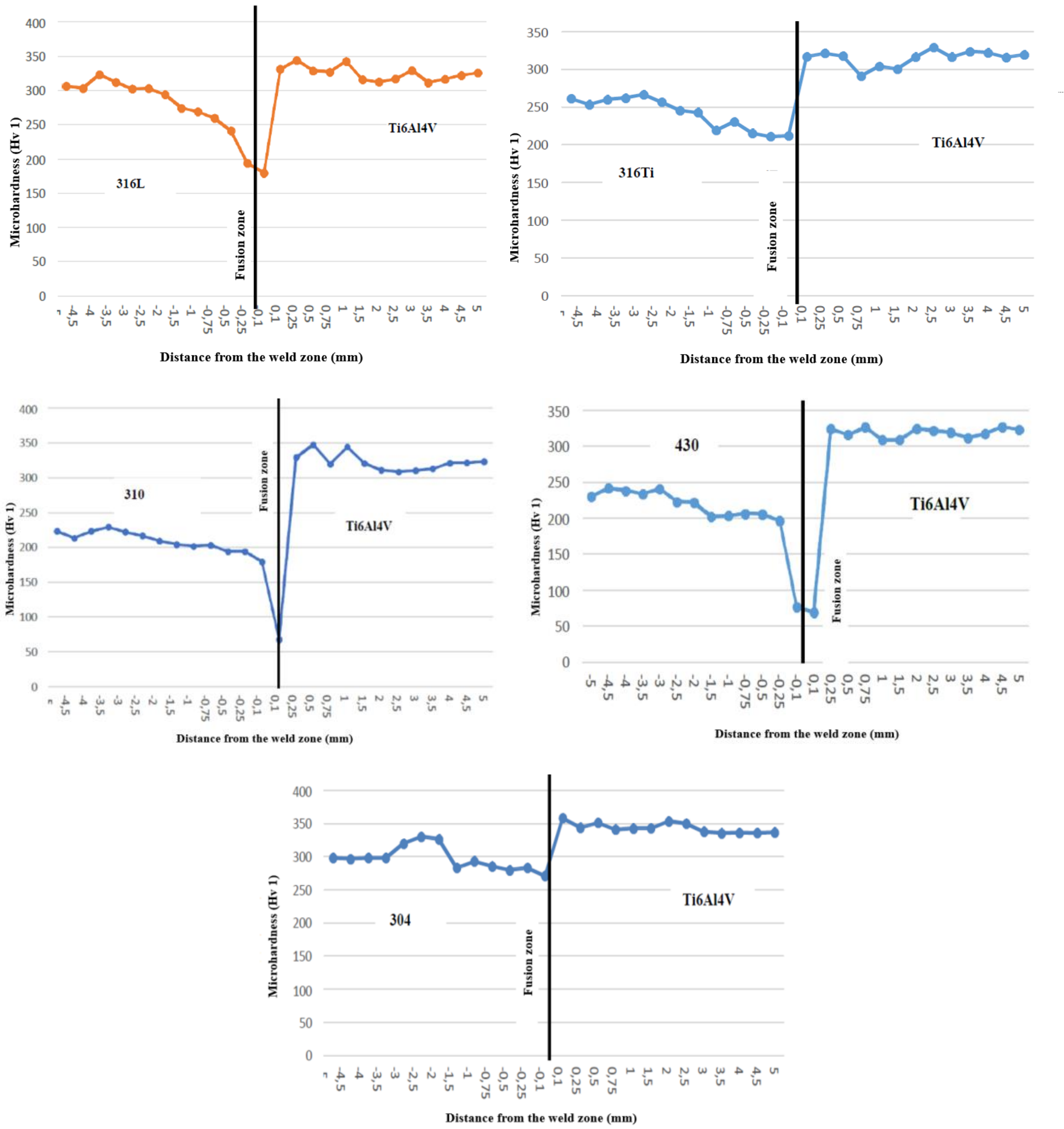


Figure 3. Microhardness Measurement Graphs of Welded Samples

3.3. Tensile Test Analysis

Figure 4 presents the tensile strength of samples welded using a copper interlayer. It has been observed that the elastic deformation of the 316L-Ti6Al4V materials is approximately 42 MPa, followed by a fracture occurring at 291 MPa, with a material elongation of 3.5%. The tensile strength exceeds that of the copper interlayer, which has a tensile strength of 200 MPa. This phenomenon is primarily associated with the low heat input during the welding process. Low heat input reduces the material's overall thermal exposure. It facilitates rapid cooling, promoting the formation of a finer microstructure and enhancing tensile strength. Therefore, although both rapid cooling and low heat input contribute to the outcome, the main factor responsible for the increase in tensile strength is the low heat input, which controls the cooling rate and improves material properties. [21-22]. According to the tensile graph of samples welded with Cu interlayer using 316Ti and Ti6Al4V alloys, the material exhibits an elastic strain value of 45 MPa, and the fracture strength is measured to be approximately 320 MPa, with an elongation of 4.6%. The tensile strength surpasses the tensile strength of copper, which is 200 MPa. In the average tensile strength graph of the Ti6Al4V alloy with a value of 310, the material exhibits elastic behavior up to approximately 45 MPa, followed by fracture at 440 MPa in the interfacial region, with a 5.5% elongation. This value exceeds the tensile strength of copper, which is 220 MPa, due to the interlayer thickness of approximately 200 μm and the substantial cross-sectional thickness. The friction welding process has enhanced the tensile strength, primarily due to the effects of friction time and consolidation pressure. Friction time allows for more heat generation and material softening, promoting better interfacial bonding, while consolidation pressure ensures proper contact and densification of the material, further improving the mechanical properties. In the tensile graph of the 430 and Ti6Al4V alloy, the material exhibits elastic properties up to approximately 40 MPa, followed by a fracture occurring around 230 MPa, with an elongation of 3.1%. The tensile strength exceeds the tensile strength of the copper interlayer, which is 200 MPa; this is attributed to the significant interlayer thickness and the uniform distribution of the interlayer across the cross-section. The average tensile graph of the Ti6Al4V alloy with 304 shows elastic properties up to approximately 40 MPa, after which a fracture occurs at 187 MPa, resulting in an elongation of 2.8%. This value is below the tensile strength of copper, which is 220 MPa, due to the interlayer thickness being approximately 20 µm. European Journal of Technique, European Journal of Technique, European Journal of Technique.

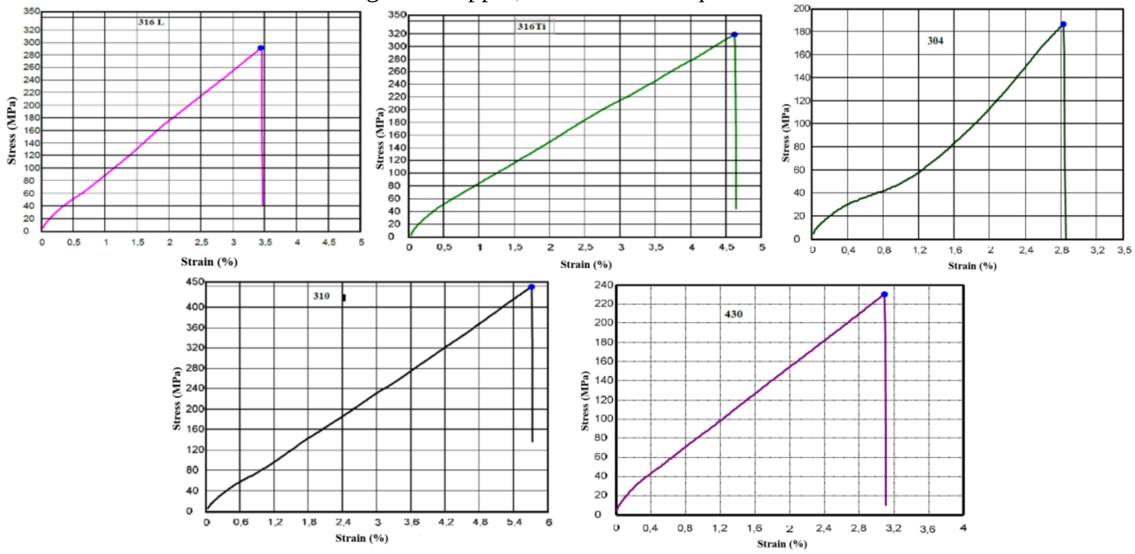
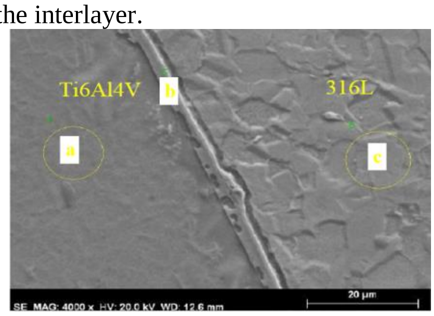


Figure 4. Tensile Test Graphs of Samples Joined Using Cu Interlayer

3.4. Microstructural Analyses

Figure 5 presents the SEM images and EDX analyses of the welded materials. Upon examining the SEM images of the 316L and Ti6Al4V samples, it was observed that the weld zone exhibited a smooth and homogeneous distribution along a consistent line. Furthermore, it was determined that a thin layer, approximately 5 µm thick, was formed in the weld interfacial region. The EDX results of the samples indicated that the highest proportions of elements in the weld interfacial region were 28.64% Ti, 40.04% Fe, and 13.45% Cu (Figure 5). This indicates that solid-state diffusion of atoms occurred from the weld pairs towards the interlayer.



Element	a region (%wt.)	b region (% wt.)	c region (% wt.)
Ti	90.15	28.64	-
Al	5.97	1.16	-
V	3.88	-	-
C	-	0.02	0.03
Si	-	0.53	0.77
Cr	-	8.09	17.44
Fe	-	40.04	69.42
Ni	-	5.72	10.07
Mn	-	1.54	2.27
Cu	-	13.45	-

Figure 5. SEM Images and EDX Results of 316L-Ti6Al4V Welded Samples

In the SEM analyses conducted on the joining of 316Ti and Ti6Al4V alloys using a copper interlayer, it was observed that the bonding region was distinctly visible across the entire surface. The interfacial thickness in this region was measured to be 15 microns (Figure 6).

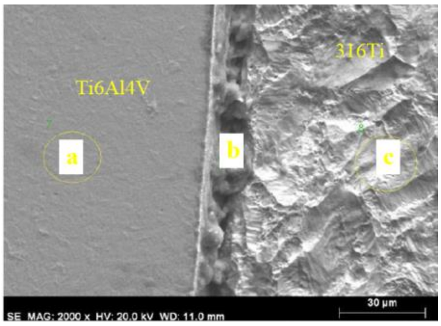
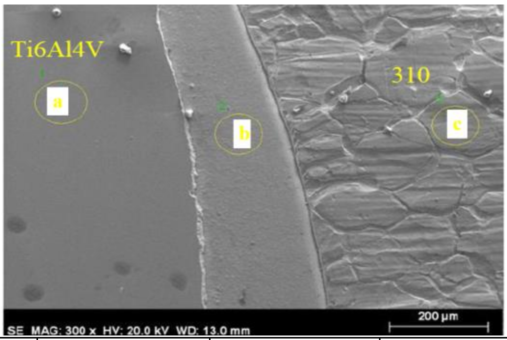


Figure 6. SEM Image of 316Ti-Ti6Al4V Welded Samples

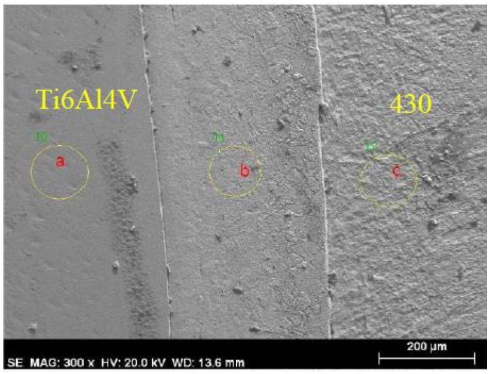
The SEM images of the samples welded with a copper interlayer using the 310 and Ti6Al4V alloys demonstrate that the welding process was successful and that the copper interlayer formed uniformly and homogeneously (Figure 7). Additionally, the SEM photograph indicates that the thickness of the interfacial layer is approximately 200 µm. Upon examining the EDX analyses, it was concluded that due to the width of the weld interfacial thickness, only 100% Cu atoms are present, suggesting that diffusion may occur at the contact areas.



Element	a region (% wt.)	b region(% wt.)	c region (% wt.)
Ti	90.15	-	-
Al	5.97	-	-
V	3.88	-	-
C	-	-	0.24
Si	-	-	0.63
Cr	-	-	21.87
Fe	-	-	57.50
Ni	-	-	17.82
Mn	-	-	1.94
Cu	-	100	-

Figure 7. SEM Images and EDX Results of 310-Ti6Al4V Welded Samples

Upon examining the SEM images of the samples welded using a copper interlayer with the 430 and Ti6Al4V alloys, it was observed that the welding process was successful and that the weld region exhibited a smooth and homogeneous distribution along its length (Figure 8). The SEM images clearly demonstrate that the thickness of the weld interfacial region occupies a broad area with a thickness of 350 µm at the bonding region. Furthermore, EDX analyses revealed that due to the considerable thickness of the weld interfacial region, only the copper phase was present in the area.



Element	a region (% wt.)	b region (% wt.)	c region (% wt.)
Ti	90.15	-	-
Al	5.97	-	-
V	3.88	-	-
C	-	-	0.11
Si	-	-	0.57
Cr	-	-	15.82
Fe	-	-	82.53
Ni	-	-	0.97
Mn	-	-	-
Cu	-	100	-

Figure 8. SEM Images and EDX Results of 430-Ti6Al4V Welded Samples

Upon examining the SEM images of the 304 and Ti6Al4V alloys, it was observed that the weld region formed around the drilled pin hole. The welding process was carried out uniformly across the cross-section, and the interfacial thickness was measured to be approximately 30 microns (Figure 9).

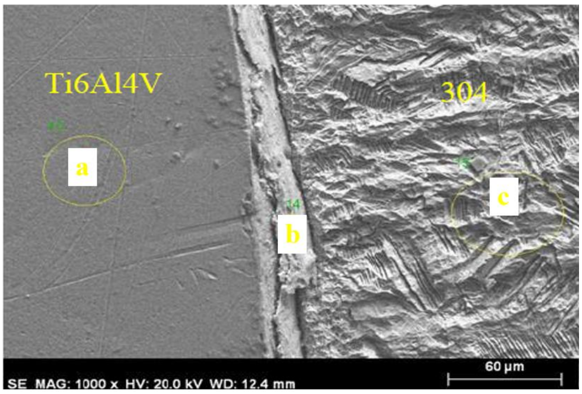


Figure 9. SEM Images of 304-Ti6Al4V Welded Samples

4. CONCLUSION

The results obtained from friction welding processes conducted using a Cu interlayer in various metal alloys have been examined in detail. The findings of the research are summarized below:

- In both macro and microstructural evaluations, it was observed that the interlayer formed uniformly across the weld surface in all joining operations without any discontinuities.
- The interlayer thicknesses of the welded samples were determined to be 5 µm for 316L, 15 µm for 316Ti, 200 µm for 310, 350 µm for 430, and 30 µm for 304.
- It was found that the tensile strengths of the materials were consistent with the tensile strength of the interlayer used. The highest elongation and tensile strength were measured at 5.5% elongation and 440 MPa for the 310 stainless steel-Ti6Al4V alloy pair.
- In the microhardness analyses, no significant change in hardness values was observed in the Ti6Al4V portion. This can be attributed to the limited heat input into the material due to the neck formation occurring on the titanium side, which prevented a temperature-dependent reduction in hardness values. Additionally, microstructural changes in the heat-affected zone and the stability of the material's crystal structure may have contributed to the preservation of hardness by limiting the effects of high temperatures. These mechanisms play a crucial role in explaining the relationship between heat input and hardness.

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