UDC 621.791:669.295:669.14
DOI: 10.15587/1729-4061.2025.320930

DEVELOPMENT OF DISSIMILAR METAL JOINING METHOD FOR CP-TI AND SS-316L USING GTAW WITH TIN BABBITT FILLER ROD

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Dissimilar metal joining between commercial pure titanium (CP-Ti) and stainless steel 316L (SS-316L) poses challenges due to thermal property differences and brittle intermetallic compound formation. This study examines weldability and joint characteristics under varying welding currents (185A, 195A, 205A) and backing plate conditions. The main challenge is ensuring weld integrity while minimizing intermetallic compounds and defects that degrade mechanical properties. Non-destructive testing, metallography, SEM-EDS, and hardness testing were conducted. Results indicate that without a backing plate, hardness in the heat-affected zone (HAZ) of SS-316L increased with welding current, from 160.7 HV at 185 A to 167.5 HV at 205 A. In CP-Ti, hardness rose from 148 HV at 185 A to 160.7 HV at 205 A. With a backing plate, SS-316L HAZ hardness peaked at 185 A (182.7 HV) but decreased to 167.5 HV at 205 A. Similarly, CP-Ti hardness was lower with a backing plate (154 HV at 205 A BP). Sensitization in SS-316L was detected but remained mild. The tin babbitt filler rod suppressed brittle Fe-Ti intermetallic compounds due to its high thermal conductivity and low melting point, ensuring better heat distribution. This reduced cracking risks at the fusion line and improved bonding. However, porosity remained an issue, particularly in SS-316L joints, increasing at higher currents and potentially leading to microcracks. Controlling welding parameters and shielding conditions was crucial to minimizing porosity and enhancing joint quality. These findings confirm that optimizing welding parameters and environmental control reduces intermetallic compounds and porosity, improving GTAW feasibility for on-field welding in applications such as heat exchangers, piping, and pressure vessels

Keywords: dissimilar metal joining, CP-Ti, SS-316L, Tin Babbitt, GTAW

Received 11.12.2024
Received in revised form 30.01.2025
Accepted 18.02.2025
Published

How to Cite: *Anugra, B. A., Ramdan, R. D., Wahyudiono (2025). Development of dissimilar metal joining method for CP-Ti and SS-316L using GTAW with Tin Babbitt filler rod. Eastern-European Journal of Enterprise Technologies, 1 (12 (133)), 27–35. https://doi.org/10.15587/1729-4061.2025.320930*

1. Introduction

Dissimilar metal joining, such as between CP-Ti and SS-316L, poses significant challenges in materials engineering due to the complexity of their differing metallurgical and thermal properties. CP-Ti is renowned for its lightweight, high strength, and excellent corrosion resistance [1–3], whereas SS-316L excels in chemical and corrosion resistance [4, 5]. The combination of these two materials holds great potential for applications in the petrochemical, aerospace, medical, and automotive industries, which demand strong and reliable joints.

However, joining CP-Ti and SS-316L faces several key challenges. One major issue is the formation of brittle intermetallic compounds that can compromise joint quality [6–8]. Additionally, the mismatch in thermal properties can lead to cracking at high temperatures during welding [9]. Titanium is also highly susceptible to contamination during welding, which can cause porosity, while SS-316L is prone to sensitization, reducing its corrosion resistance. Therefore, joining these materials requires methods that minimize the negative effects of their property differences and optimize joint quality.

Welding techniques must not only meet high-quality standards in workshop fabrication environments but also be applicable to field fabrication conditions. In field scenarios, urgent needs often arise, particularly when welding is required for spare components that were not initially designed to be joined by welding. Frequently, welding is carried out directly in production areas as an emergency solution to prevent significant losses caused by reduced production rates or complete shutdowns. In such situations, welding solutions must consider techniques, parameters, and methods that ensure safe, effective, and efficient joints.

Therefore, further research on dissimilar metal welding methods remains highly relevant, both scientifically and practically. Studies on these techniques not only support the development of more effective joining solutions but also strengthen their application in the ever-evolving modern industrial sectors. Research on CP-Ti and SS-316L welding is thus critical to addressing current technological challenges and enhancing joint quality in industrial applications.

2. Literature review and problem statement

In a study examining dissimilar welding between titanium alloys and steel, which are widely used in industries such as aerospace, nuclear, and power generation due to their high strength and corrosion resistance, it was found that the formation of brittle intermetallic compounds (IMC) like FeTi and Fe_2Ti must be minimized to achieve strong joints. However, the main unresolved issue is the difficulty in forming a good metallurgical bond due to differences in thermal properties and mismatch in base materials during conventional fusion welding. As a solution, solid-state joining processes like diffusion bonding and friction welding can be applied, along with the addition of interlayer materials such as Cu, Nb, or V. Nevertheless, a major challenge that arises is the precise control of parameters and the long process time, which makes this approach impractical for industrial applications. Therefore, further research is needed to test the feasibility of conventional welding processes like TIG and MIG for Ti-steel combinations, with or without an interlayer [6]. A review suggests that conventional techniques are not effective enough for joining titanium and stainless steel due to suboptimal parameter control.

In another study, dissimilar metal welding between titanium (Ti) and stainless steel (SS) was explored, with broad applications in industries such as nuclear and aerospace. While fusion welding is promising, a significant challenge lies in the formation of brittle IMC compounds that can weaken the mechanical properties of the joints. The main difficulty is related to thermal property differences and material mismatch, causing challenges in melting both metals simultaneously. As a solution, interlayers such as Cu, Nb, or V are used to reduce IMC formation and enhance joint strength. Advanced processes like laser beam welding (LBW) and cold metal transfer (CMT) have been applied, but challenges remain regarding material thickness and precise parameter control. This underscores the need for further research on conventional welding techniques like TIG and MIG, which could potentially provide a more sustainable and cost-effective approach [10]. A review also highlights that the proper selection of filler materials can minimize IMC formation, although no definitive solution has been found to overcome this with various techniques.

Another study focused on welding between stainless steel 304 (SS304) and titanium alloy TC4 using the AgCuTi filler rod. The study showed that direct fusion welding of SS/Ti failed due to the formation of brittle Ti-Fe IMC. However, issues related to element diffusion and thermal stresses at the interface remain as potential causes of local weak zones in the joint. As a solution, the filler rod that prevents direct contact between SS and Ti, such as AgCuTi, was used to avoid the formation of Ti-Fe IMC. This approach proved effective, but there are concerns about local element segregation and stress concentration at the interface, which require further research to optimize laser welding parameters and filler rod composition to enhance joint integrity [11]. While AgCuTi can prevent IMC formation, the main challenge remains element segregation and stress concentration.

Next, a study on the liquid-solid phase reaction at the Ti-6Al-4V-brass and brass-AISI304L stainless steel interfaces, with diffusion welding carried out at temperatures of 875–925 °C, pressures of 4–12 MPa, and welding times of 20 and 40 minutes, showed Cu and Zn diffusion from the interlayer into the base metals, along with diffusion of other elements such as Ti, Fe, Cr, Al, V, Ni, Mn, Si, and C. The maximum hardness values were recorded at 595.2 VHN on the AISI304L side and 612.4 VHN on the Ti-6Al-4V side. However, the main issue faced was excessive heat input at the interface during laser welding, leading to element segregation and significant thermal stress, potentially causing joint failure. The solution is the use of AgCuTi filler metal, which improves wetting and spreading at the interface, enhancing metallurgical bonding between SS and Ti. Although improvements were noted, local IMC formation at the interface zone remains a challenge. Therefore, further research is needed to optimize laser welding parameters and filler rod composition to reduce IMC formation and enhance the mechanical properties of SS/Ti joints [9]. In this variation of the study, AgCuTi successfully improved bonding, though the primary challenge remained related to local IMC formation in certain zones.

Unlike previous welding methods, this study investigates friction welding as a solid-state joining method between titanium grade 2 (Ti Gr 2) and stainless steel 304L (SS 304L) using copper as an interlayer in two forms: rod (Method 1) and coin (Method 2). The results show that the use of oxygen-free copper as an interlayer facilitates bonding between Ti Gr 2 and SS 304L, preventing the formation of hard intermetallic phases. Method 1 with copper rods achieved a maximum tensile strength of 303 MPa, while Method 2 with copper coins reached 270 MPa, both resulting in defect-free joints with a narrow heat-affected zone (HAZ). However, the main issues that arose were the processing time and operational complexity, particularly in placing the interlayer and maintaining consistent bonding conditions. A solution could be the development of custom fixtures for placing the copper layer and further research on welding parameters and alternative materials to improve joint properties [12]. While copper successfully prevented IMC formation, precise placement of the layer and uniform pressure distribution remain major challenges in enhancing bonding quality.

Another study presents results on an innovative GTAW process to join TC4 titanium alloy and 304 stainless steel using Cu foil as an interlayer and Ni-based alloy as filler metal. The innovative welding design achieved a tensile strength of 485 MPa and successfully prevented transverse cracking in the weld, a common issue with Cu-based filler metals. However, unresolved issues related to residual stress distribution and the formation of brittle intermetallic compounds at the Ti side interface were identified. The reason for this may be related to the high residual stress in Cu-based joints, which causes transverse cracks, as well as challenges in controlling the dissolution of the Ti alloy and formation of brittle Ti-based phases. To address these difficulties, Ni-based filler metal is recommended, which reduces residual stress and minimizes the formation of brittle phases. This approach was used in the study, but increased Cu foil thickness and welding current caused additional Ti-based intermetallic formation. All these findings suggest that further research is needed to optimize Cu foil thickness and welding parameters to achieve better welding performance on dissimilar Ti alloy/stainless steel joints [13]. This research, using conventional

GTAW techniques, successfully maintained joint integrity without transverse cracks, but further optimization is needed to reduce intermetallic formation and residual stress in Ti joints.

Next, a study on DMW between austenitic stainless steel 304L (ASS) and titanium-stabilized ferritic stainless steel 439 (FSS) using 309L ASS filler rod showed that the ferrite phase fraction in the weld zone (WZ) decreased with increasing heat input (HI), from 37.2 % at low HI to 32.39 % at high HI. However, unresolved issues remain concerning the effects of microstructure and mechanical properties in the WZ produced with high HI compared to low HI, as well as differences in corrosion behavior between the two conditions. The cause of these issues may be related to technical difficulties in controlling welding process parameters at high HI, the impossibility of selecting the right filler material, or the high cost of laboratory testing that limits further research, making such studies impractical. To overcome these difficulties, more efficient welding technology should be explored, or more precise techniques for controlling HI during welding should be adopted. This approach has been used in previous research, but significant differences in corrosion results and mechanical characteristics are still observed [14]. All of this indicates the need for further research to optimize welding conditions. This study provides important insights into the impact of heat input on microstructure and mechanical properties in DMW between 304L ASS and 439 FSS steel, but further exploration is needed to optimize welding conditions and joint quality.

Although various welding techniques have been explored, including the use of different filler rods and interlayers to reduce the formation of brittle IMCs and improve joint quality, the main challenges remain unresolved. Various studies indicate that factors such as differences in thermal properties, difficulties in controlling process parameters, as well as the effects of residual stress and element segregation at the interface zone, continue to hinder the achievement of optimal joint quality. Additionally, limitations in heat control during welding and operational challenges in applying certain techniques, whether in controlled industrial environments or in field settings with restricted conditions, further complicate the process of joining dissimilar metals. Therefore, further research is needed to develop more effective and efficient methods to address these issues, particularly in optimizing welding parameters and selecting additional materials that can minimize IMC formation and enhance the mechanical strength of the joint.

3. The aim and objectives of the study

The aim of this study is development of dissimilar metal joining method using a conventional method (GTAW) between CP-Ti and SS 316L, enabling its effective application for field repairs under specific welding parameters.

To achieve this aim, the following objectives are accomplished:

– to qualify the weld joint results by evaluating the joint quality using non-destructive testing (NDT) methods, such as visual inspection and Dye Penetrant Testing;

– to analyze the characteristics of the welded joints, including visualizing the weld structure through metallographic testing, identifying elemental diffusion in the weld zone using SEM-EDS, and assessing embrittlement through hardness testing;

– to investigate the presence of sensitization and porosity in the joints by analyzing the elements in areas of discontinuities using SEM-EDS.

4. Materials and methods

This study investigates the joining of CP-Ti and SS-316L using GTAW with Tin Babbitt as the filler rod. The object of this study is the weld quality and metallurgical characteristics of the joint under various welding conditions. The main hypothesis is that Tin Babbitt can facilitate bonding between CP-Ti and SS-316L while minimizing intermetallic compound formation due to its thermal properties. This study assumes a uniform heat distribution during welding and the absence of contamination due to shielding gas leakage. The simplifications adopted include macro- and microstructural observations as well as mechanical testing in the form of hardness testing.

Specimens were prepared using CP-Ti and SS-316L as substrates, each with a thickness of 6 mm, while Tin Babbitt was employed as the filler rod. The chemical composition of the materials was analyzed using a Portable XRF Analyzer (Niton Mobile Analyzer), and the results are presented in Table 1. The welding currents applied were 185 A, 195 A, and 205 A, with each welding current condition tested both with and without the use of a 1 mm thick SS-316L backing plate.

Table 1

Chemical composition of the materials

Material used	Ti (%wt)	Fe (%wt)	Cr (%wt)	Ni (%wt)	Cu (%wt)	Mo (%wt)	Mn (%wt)	Cu (%wt)	Sn (%wt)	Sb (%wt)	Other (%wt)
CP-Ti	99.08	0.92	–	–	–	–	–	–	–	–	–
SS-316L	–	66.94	16.42	12.16	0.39	2.13	1.42	0.39	–	–	–
Tin Babbitt	–	–	–	–	–	–	–	3.5	Bal.	7.5	0.25

The first step, after each substrate was welded using a Tin Babbitt filler rod with a Kobelco welding machine and a Tin Babbitt wire feeder, was cutting the central section of the specimen using a wire-cutting machine (Sodick AG-600) to minimize the thermal impact on the specimen. This technique allows for improved weld profiling, which is critical for analyzing the welding properties and performance. Following the cutting process, metallographic preparation was conducted for analysis using an optical light microscope (Nikon Eclipse MA200), providing insights into the bonding interface between the substrate and weld metal, as well as identifying sensitization in the HAZ of SS-316L. Vickers hardness testing (ZWICK 3202) was subsequently performed on each zone to evaluate hardness distribution. Additional samples, sized 20×20 mm, were prepared for SEM-EDS analysis to investigate sensitization within the joint, the presence of discontinuities, and intermetallic compounds in the fracture area. SEM-EDS evaluation was carried out using a JEOL SEM+EDS JCM 7000 instrument. All test results were systematically compiled and comprehensively evaluated, correlating them with the thermal properties of each substrate.

5. Results of research on dissimilar metals joining CP-Ti and SS-316L

5. 1. Qualification of weld joints using Tin Babbitt filler rod

Based on observations, the use of a backing plate during welding demonstrated a significant reduction in porosity within the weld cross-section compared to specimens welded without a backing plate, regardless of the welding current variation. The results of the Dye Penetrant Test, as presented in Fig. 1, revealed surface discontinuities such as porosity and undercut in several specimens. These defects were most prominent in specimens welded at 185 A with a backing plate and at 205 A without a backing plate, with welding inconsistencies being a dominant contributing.

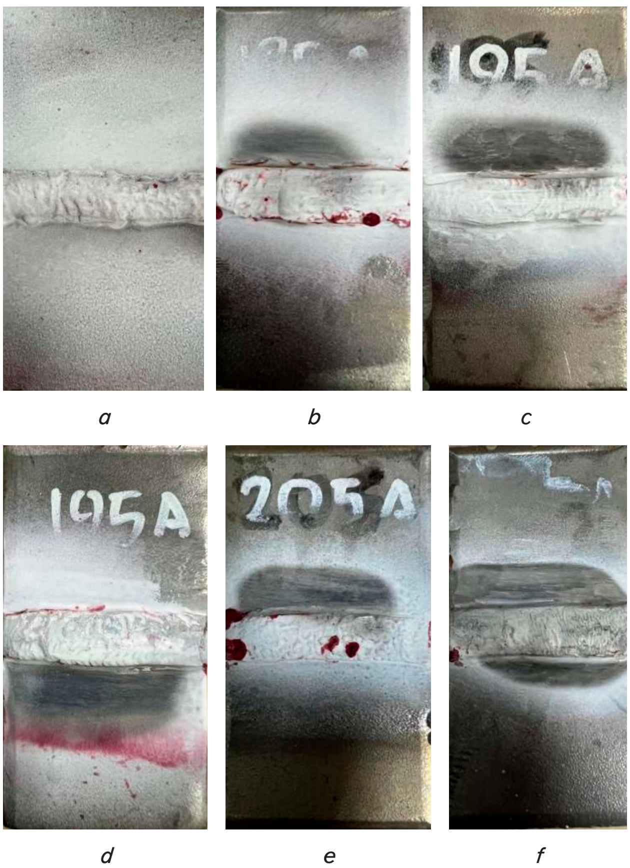


Fig. 1. The results of the dye penetrant test:
a – welding current 185 A without backing plate;
b – welding current 185 A with backing plate;
c – welding current 195 A without backing plate;
d – welding current 195 A with backing plate;
e – welding current 205 A without backing plate;
f – welding current 205 A with backing plate

Discontinuities reaching the surface, such as porosity, can occur due to gas entrapment during the welding process. During rapid cooling in air, gas bubbles become trapped and solidify, resulting in porosity that extends to the surface. This phenomenon is often associated with the high welding current required in this method. The higher the welding current, the greater the welding temperature produced, which increases the risk of discontinuities. This indicates that higher welding currents can elevate the likelihood of discontinuities by increasing the chances of gas entrapment and the formation of porosity.

5. 2. Analyzing the characteristics of welded joints

The metallographic data shown in Fig. 2 presents the findings for each variable used in this study. In general, porosity tends to be more prevalent and larger in size as the welding current increases. This phenomenon is more dominant in the welds involving SS-316L. This is due to the high tendency of SS-316L to react with oxygen through C-Cr bonding at elevated temperatures. On the other hand, while titanium is also known to be highly reactive and susceptible to contamination at high temperatures, each substrate influences the formation of porosity in the weld metal, particularly at the fusion line of each substrate. In the GTAW process, contamination can occur if the welding environment is not properly controlled or does not meet the required standards. If the inert gas shielding is suboptimal, reactions between the molten metal and atmospheric gases can occur, leading to an increase in porosity formation. Additionally, the cleanliness of the substrate surface and the welding electrode are also important factors that affect the level of contamination during the welding process.

The porosity formed in this process has the potential to manifest as metallurgical porosity or keyhole porosity. Metallurgical porosity is caused by gases trapped during the solidification of the molten metal, while keyhole porosity is typically generated by gases evaporating due to the very high welding temperatures in the GTAW process and the low melting point of the filler rod. The rapid cooling process also contributes to the formation of porosity because the gases do not have enough time to escape from the molten metal before solidification occurs, resulting in them being trapped inside the metal structure.

To gain deeper insight, SEM-EDS testing was conducted to analyze element diffusion in the joint between the two dissimilar metals. This test provides information about the atomic interactions at the material interfaces and how the elements from both metals migrate and mix in the joint area. The analysis focuses on the area around the fusion line, including the base metal (HAZ) and weld metal, with a comparison of the chemical composition based on the reference in Table 2. The purpose of this test is to determine whether element diffusion occurs from the base metal to the weld metal and vice versa, while also predicting the type of bond formed.

Table 2

Elements in % mass of the heat affected zone and weld metal area

Element	Line	205 A Welding current			
		SS-316L		CP-Ti	
		HAZ	WM	HAZ	WM
C	K	14.60 %	2.72 %	–	2.90 %
O	K	–	5.98 %	–	5.98 %
Ti	K	–	1.24 %	99.76 %	1.98 %
Cr	K	14.97 %	0.50 %	–	–
Fe	K	59.39 %	2.27 %	–	1.51 %
Ni	K	9.49 %	0.31 %	–	–
Cu	K	–	2.71 %	–	3.63 %
Sn	L	0.87 %	68.01 %	0.24 %	68.17 %
Sb	L	0.68 %	16.26 %	–	15.83 %

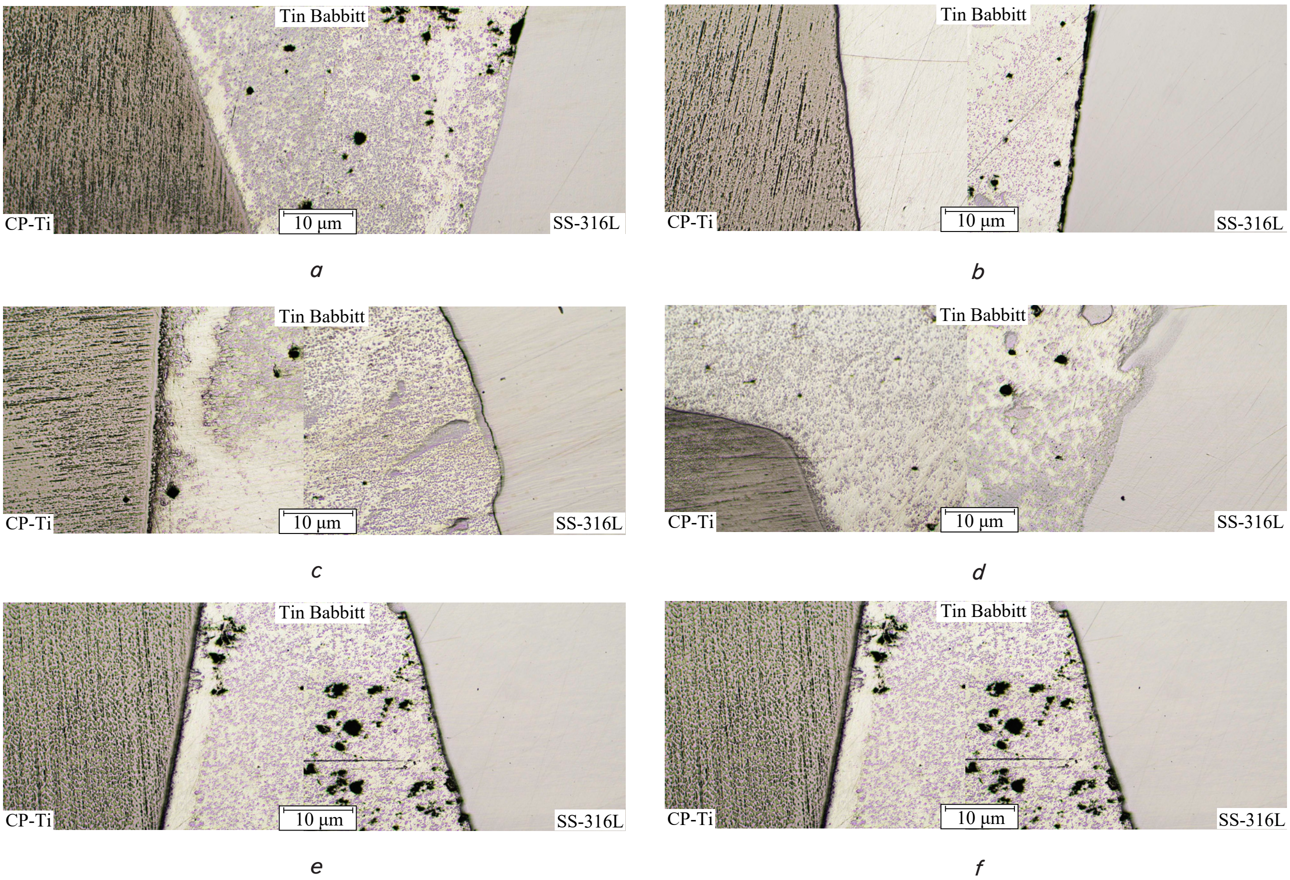


Fig. 2. The results of metallography: *a* — welding current 185 A without backing plate; *b* — welding current 185 A with backing plate; *c* — welding current 195 A without backing plate; *d* — welding current 195 A with backing plate; *e* — welding current 205 A without backing plate; *f* — welding current 205 A with backing plate

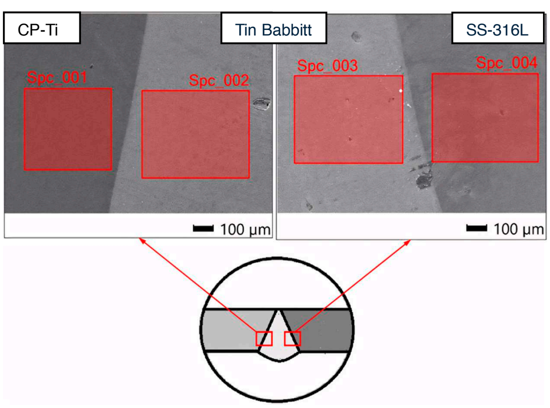


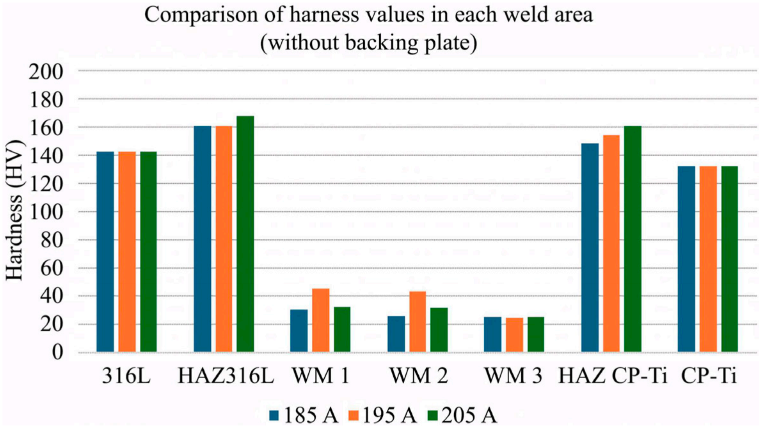
Fig. 3. The % mass comparison of chemical elements in the heat affected zone and weld metal adjacent to the fusion line of each substrate

The results in Table 2 indicate that element diffusion occurs during the welding process, which is consistent with the data collection locations illustrated in Fig. 3. Overall, the element diffusion in the three welding current variables tested tends to increase with the rise in welding current. This leads to compositional inhomogeneity, which negatively impacts the mechanical properties and corrosion resistance of the joint. At welding currents of 195A and 205A, the oxygen content and other elements such as C, Cr, Fe, and Ti indicate the potential formation of oxide compounds (Ti-O, Cr-O, Fe-O) and carbide compounds (Fe-Cr, Ti-Cr), which can weaken the joint. As the welding current increases, so does the porosity form. Additionally, the decrease in Cr content becomes more pronounced as the current increases, although still at small levels. This suggests slight sensitization and indicates that the bonding is likely metallurgical bonding with low strength.

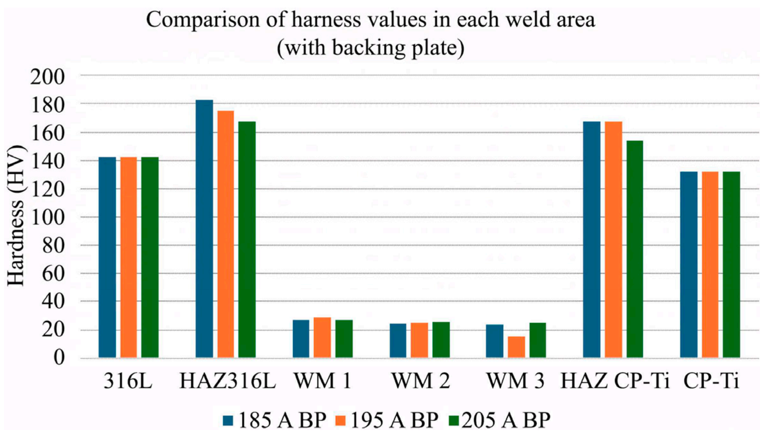
A hardness test was also conducted to evaluate the mechanical properties of the welded material. This test covers three areas: the substrate, weld metal, and heat-affected zone (HAZ), as shown in Fig. 4.

In the welding process without a backing plate, the hardness of the heat-affected zone (HAZ) in both SS-316L and CP-Ti increases with the rise in welding current. Conversely, with the use of a backing plate, the hardness of the HAZ decreases. The hardness of the HAZ in SS-316L tends to be higher compared to the CP-Ti area at the same welding current. The hardness of the weld metal is higher near SS-316L than near CP-Ti, as the diffusion of elements from SS-316L into the weld metal is more significant than from CP-Ti.

The increase in hardness in the HAZ is due to the formation of oxide and carbide compounds during welding, which are hard in nature. The use of a backing plate helps to lower the hardness in the HAZ by absorbing heat, slowing down the cooling process, and promoting a more homogeneous microstructure. The phase transformation in CP-Ti (from α/HCP to β/BCC) leads to a relatively insignificant increase in hardness compared to carbide formation in SS-316L. At higher welding currents, the faster cooling rate increases the hardness due to the large temperature gradient compared to the surrounding environment.



a



b

Fig. 4. The results of Hardness Test: *a* – without backing plate; *b* – with backing plate

5. 3. Investigating the presence of sensitization and porosity

The observation in Fig. 5 shows a slight thickening at the grain boundaries in the HAZ zone of SS-316L, although the thickening is relatively small and not widespread. This phenomenon indicates the occurrence of sensitization, but at a very low level. The extent of this sensitization can be further confirmed by a decrease in Cr content based on the SEM-EDS analysis.

In addition to sensitization, this study also aims to identify changes in the chemical composition in the discontinuity areas, such as porosity, which is produced during the welding process. These changes in composition can indicate the formation of new compounds that cause discontinuities in the weld joint. Fig. 6 shows the SEM test results on the porosity formed under various welding current variables without a backing plate. From this result, it can be confirmed that as the welding current increases, the formed porosity tends to have larger dimensions.

Table 3 displays the differences in chemical composition between the discontinuity area and the reference area, corresponding to the data collection areas shown in Fig. 7. In the discontinuity area, there is an increase in the levels of Fe and Cu compared to the reference area. Conversely, the levels of Sn and Sb decrease, which is indicated as a result of the formation of new compounds due to chemical reactions during the welding process.

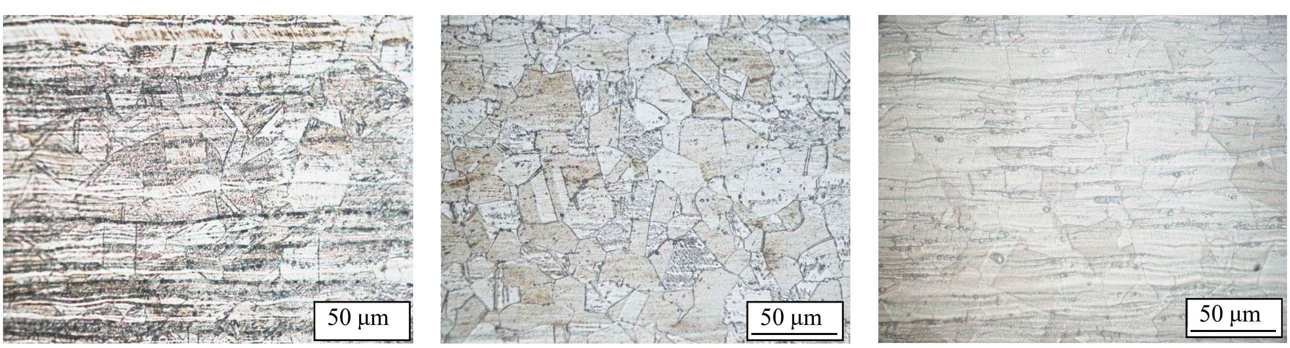
In the welding process with higher currents, the dimensions of the formed porosity tend to increase. The increased levels of Fe and Ti in the porosity area compared to the reference area suggest the possible formation of Fe-Ti intermetallic compounds. This porosity is primarily caused by gas trapped during the welding process, which is related to the decrease in Sn levels. The decrease in Sn can be explained by its low melting point, making it prone to phase change into gas and getting trapped during rapid cooling.

The area near the welding arc in the GTAW process reaches high temperatures, allowing certain elements to reach their boiling points, producing gas that then forms porosity. Sn, with its low melting point, can also interact with Fe and Ti to form small amounts of intermetallic compounds. Although Sn's small atomic size allows it to easily dissolve in the metal matrix, Sb tends to form stronger bonds with Fe.

Table 3

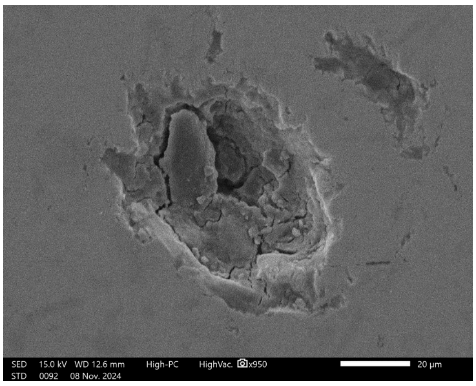
Elements in % mass of the discontinuity area and reference

Element	Line	Weldingc 195 A	
		Reference	Discontinuity
Ti	K	0.77 %	5.42 %
Fe	K	1.36 %	51.01 %
Cu	K	4.64 %	12.83 %
Sn	L	83.61 %	23.44 %
Sb	L	9.62 %	7.3 %



a *b* *c*

Fig. 5. Sensitization of SS-316L without a backing plate: *a* – welding currents 185A; *b* – welding currents 195A; *c* – welding currents 205A



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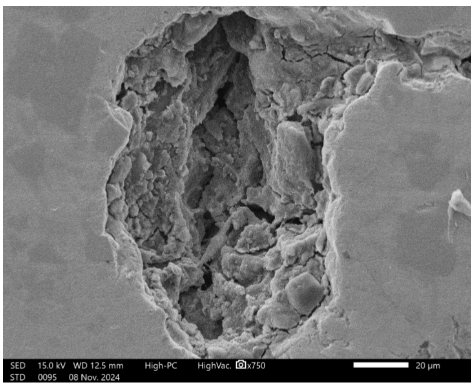

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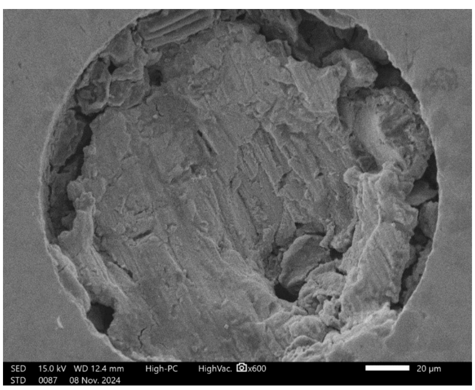

c

Fig. 6. Scanning electron microscopy test results in the welding discontinuity area: *a* — welding current 185 A; *b* — welding current 195 A; *c* — welding current 205 A

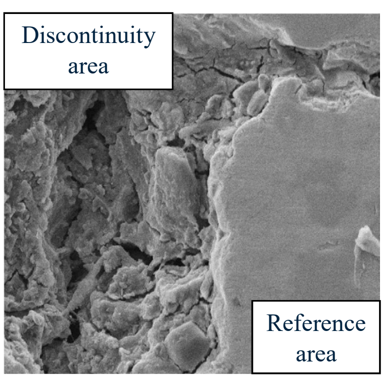

Fig. 7. The chemical composition of the discontinuity area and the reference area

Although the intermetallic compounds formed are not overly detrimental, Sn's low melting point significantly hinders the diffusion of Fe and Ti. This prevents the formation of brittle compounds that could reduce the strength of the weld joint. This phenomenon explains the low level of Fe and Ti diffusion in the weld metal, despite the formation of intermetallic compounds during the welding process.

6. Discussion of the results of the dissimilar metal joining study between CP-Ti and SS-316L

The aim of this study is to explore the use of Tin Babbitt as a filler wire in welding two materials, SS-316L and CP-Ti, with the hope of producing a joint with integrity while minimizing the formation of brittle intermetallic compounds, which are often difficult to avoid in the welding process. Tin Babbitt is commonly used as bearing lining material and has a unique microstructure, consisting of a soft matrix (solid solution) and hard intermetallic compounds such as Cu6Sn5 and SbSn. This combination provides a balance between wetting ability, conformability, and wear resistance [15]. Additionally, Tin Babbitt is known for its good corrosion resistance, particularly in lubricated environments, as well as its high chemical stability [16].

In this study, Tin Babbitt is introduced as a filler wire for joining SS-316L and CP-Ti, which is an approach that has not been widely explored before. The results show that Tin Babbitt successfully reduces the formation of brittle intermetallic compounds and improves the structural stability of the joint. Additionally, the study varies the welding current to observe the effect of heat input on joint quality. The findings indicate that joints using Tin Babbitt as a filler wire exhibit good bonding with each substrate.

The heat generated during welding causes rounding of the precipitate corners, especially on SbSn, which is cuboid in shape, potentially reducing stress concentrations and improving fatigue resistance. However, prolonged heating or high temperatures can risk increasing the size of the precipitate, which can negatively affect the mechanical properties of the material [15]. The increase in deposition current in the TIG welding process also affects the size and distribution of phases, which can alter the thermal and mechanical properties of the Tin Babbitt layer [17]. Due to its high thermal conductivity and low melting point, Tin Babbitt effectively fills and spreads between the substrate surfaces, accommodating the thermal property differences between SS-316L and CP-Ti.

Visual inspection and dye penetrant testing (Fig. 1) show that the resulting joints are free from surface cracks, indicating that Tin Babbitt provides a good joint. However, further analysis (Fig. 2) confirms that no internal cracks are found, while also showing that the metallurgical bond formed is relatively low, as evidenced by element diffusion between the substrate and weld metal, as shown in Table 2. This diffusion primarily occurs near the fusion line, where elements such as Ti, Fe, Cr, O, and C are detected in the weld metal. The presence of these elements suggests the potential formation of oxide (Ti-O, Cr-O, Fe-O) and carbide (Fe-Cr, Fe-C), as well as brittle intermetallic phases like Fe-Ti or Ti-Cr. However, the presence of Sn-rich Tin Babbitt helps minimize the formation of these brittle compounds by maintaining joint integrity.

The bond between Tin Babbitt and the base material occurs through a combination of chemical bonds (formation of intermetallic compounds) and mechanical bonds (adhesion to the substrate surface) [15, 16]. The effect of GTAW on bond quality is influenced by temperature control, cooling rate, and surface cleanliness. The success of good joint integrity is crucial to ensure strong adhesion, uniform phase distribution, and mechanical durability of the Tin Babbitt layer [17]. Additionally, hardness testing shows an increase in hardness in the heat-affected zone (HAZ) (Fig. 4), especially in the HAZ of SS-316L, due to carbide and oxide formation during welding.

Porosity is a major issue observed in the welding results (Fig. 6). Some porosity reaches the surface, while others are trapped within the weld metal. This porosity can damage the mechanical integrity of the joint, as it acts as a weak point that may initiate cracks under load. SEM-EDS analysis shows that an increase in welding current causes more and larger porosity, particularly near the fusion line. This porosity is also associated with the formation of microcracks that are very brittle and prone to residual stress during cooling.

From a practical application perspective, this method can be applied in industries requiring the joining of SS-316L and CP-Ti while minimizing the formation of intermetallic compounds. Potential applications include the petrochemical industry, such as in sampling points valve and heat exchangers, as well as other industries, including manufacturing, marine, and others. The ideal conditions for applying this method include optimal heat control during welding and the use of inert gas shielding to reduce external contamination. The use of Tin Babbitt as a filler can be an effective alternative for welding CP-Ti and SS-316L.

A major limitation of this study is the reliance on specific welding parameters. Tin Babbitt has a much lower melting point than its substrates, which, according to the ASM Handbook, places it in the category of Brazing and soldering. Furthermore, porosity trapped in the weld metal is unavoidable, although its presence is within acceptable limits as it has very small dimensions, around 20 microns. However, in high-load applications, porosity can become a significant weak point. This study only identifies the elements forming intermetallic compounds, and the actual intermetallic phases have not been determined. Further research should focus on optimizing welding parameters, assessing joint performance under various conditions, and exploring alternative fillers or hybrid techniques. XRD analysis is needed to identify intermetallic compounds, while tensile, fatigue, and compression tests should evaluate weld performance.

This study demonstrates that Tin Babbitt filler rod is an effective material for joining SS-316L and CP-Ti, forming a stable bond while reducing the risk of cracking and brittle intermetallic compounds. By optimizing welding parameters, particularly welding current, and maintaining a controlled environment, porosity can be minimized, leading to better joint quality and performance. More importantly, this research provides a welding solution using GTAW, which has not been previously reported for joining SS-316L and CP-Ti with different techniques and materials [11, 14, 17–23].

7. Conclusions

1. The use of Tin Babbitt filler rod in welding SS-316L and CP-Ti results in a joint with no cracks observed at the fusion line, as confirmed NDT, including visual inspection and Dye Penetrant Testing. The use of Tin Babbitt significantly reduces the risk of cracking and ensures a strong bond between the materials. Controlling heat input and using a backing plate are crucial for achieving high-quality welding.

2. The diffusion of elements from the substrate to the weld metal occurs in small amounts, potentially forming brittle intermetallic compounds. Tin Babbitt, rich in Sn, plays a role in suppressing the formation of these compounds, although it cannot completely prevent it. The increase in hardness, particularly in the HAZ of SS-316L, indicates the mechanical stability of the joint, despite some embrittlement, which does not lead to cracking during cooling.

3. One of the main challenges observed is porosity, especially in joints involving SS-316L. Porosity trapped in the weld metal can weaken the joint and cause microcracks due to residual stress. This porosity is associated with elements that form brittle intermetallic compounds, such as Fe-Ti-Cr. Strict control over welding parameters, such as adjusting welding current and optimizing the welding environment, is crucial to minimize porosity and improve the overall quality and stability of the joint.

Conflict of interest

The authors declare that they have no conflicts of interest related to this research, whether personal, publication-related, or otherwise, that could influence the research and the results presented in this paper.

Financing

All financing for this research was provided by PT Pupuk Kujang, by sending their employee to pursue a master's degree.

Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors have used artificial intelligence technology within acceptable limits, solely to refine word choices in this manuscript, and it was not used as a tool for analyzing or interpreting test results.

Acknowledgments

The authors would like to express their deepest gratitude to PT Pupuk Kujang Cikampek for their full financial support, as well as for providing the materials and certified welding to complete this research. Without the substantial support from this company, this research would not have been possible.

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