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Effects of heat input on mechanical properties, microstructures and thermal conductivity of copper alloy in gas tungsten arc welding technology

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ABSTRACT

Copper-to-copper welding presents several complex technical challenges, primarily due to the unique properties of copper as a material. One of the main issues is copper's high thermal conductivity. The purpose of this study is to determine the mechanical properties, such as tensile strength, hardness, and thermal conductivity, of welded metal products produced using the gas tungsten arc welding (GTAW) technology. The filler material used is ERCuNi 90/10 rods. The welding method involves variations in welding heat input, specifically 1.09 kJ/mm, 1.13 kJ/mm, and 1.2 kJ/mm. The results of the study show that welding heat input affects the mechanical properties and thermal conductivity of copper. The highest tensile strength of 180 MPa at 1.2 kJ/mm is due to the higher heat input, which improves weld penetration and strengthens the metallurgical bond, enhancing the load-bearing capacity of the welded joint. The highest hardness of 132.12 HV or 1295 MPa is found in the weld metal (WM) due to microstructural transformation during solidification. The use of ERCuNi 90/10 filler contributes to the formation of a harder dendritic structure compared to the heat-affected zone (HAZ) and base metal. Meanwhile, the highest thermal conductivity of 206.72 W/mK occurs at 1.09 kJ/mm because the lower heat input reduces the mixing of filler metal with pure copper, preserving copper's thermal properties better than at higher heat input. At higher heat input, increased nickel dilution from the filler reduces thermal conductivity, as nickel has lower thermal conductivity than pure copper.

Keywords: gas tungsten arc welding, copper alloys, thermal conductivity, mechanical properties, heat input.

INTRODUCTION

Welding is a fundamental material joining process that plays a crucial role in various industrial applications. Among the different welding techniques, gas tungsten arc welding (GTAW) technology or tungsten inert gas (TIG) is distinguished by its use of a non-consumable tungsten electrode and an inert gas, such as argon or helium, to shield the molten metal from oxidation, ensuring high-quality and precise welds. [1], including the manufacturing of heat pipes [2–3]. Copper is often the material of choice in this industry due to its superior properties, such as extremely high thermal conductivity, ductility, and corrosion resistance [4–5]. Copper-based heat pipes play a vital role in cooling systems, ranging from electronic devices to applications in the renewable energy and nuclear sectors. Copper's ability to efficiently transfer heat makes it a primary material for thermal management across various industries [5]. However, the fabrication process of copper-based heat pipes presents its own challenges, particularly in welding.

Copper-to-copper welding faces several complex technical obstacles, one of which is copper's high thermal conductivity. This property causes heat from the welding arc to quickly dissipate throughout the material, making it difficult to form a stable welding pool. To address this issue, a high heat input is required to ensure optimal material melting, especially for materials with a thickness of 2 mm and above, with a significant increase in heat input needed for thicknesses above 5 mm [6-7]. In addition, copper is prone to hot cracking, particularly in the fusion zone. This phenomenon often occurs due to the segregation of elements such as phosphorus, sulfur, or oxygen, which form brittle compounds during the cooling process. This issue is exacerbated by the high shrinkage during solidification, which induces internal stresses and triggers the formation of cracks. Another challenge is copper's sensitivity to contamination. The material is easily oxidized when exposed to oxygen, nitrogen, or hydrogen in the air during the welding process. Such contamination can result in porosity or other internal defects that negatively affect the mechanical and thermal quality of the welded joint [8]. Furthermore, copper has a high melting point (1.084 °C) and a low heat absorptivity coefficient. This combination can create difficulties in stabilizing the welding arc, especially if improper welding parameters or shielding gas with high purity is used. This can affect the consistency of the welding pool and the final quality of the joint. Another challenge lies in the cooling process. Due to its thermal properties, slow cooling can trigger detrimental microstructural changes, such as the formation of brittle zones that compromise joint strength. On the other hand, excessively rapid cooling can result in high residual stresses, which affect the joint's resistance to mechanical loads (9).

Although copper's melting point of 1.084 °C is not considered high compared to structural steel, the main challenge in welding copper is not its melting point but rather its extremely high thermal conductivity. This high thermal conductivity causes heat from the weld pool to dissipate rapidly into the surrounding material, making it difficult to maintain stable melting and penetration. Unlike structural steel, which retains heat longer in the weld zone, welding copper requires a higher heat input to compensate for the rapid heat loss. If the heat input is too low, incomplete fusion and insufficient penetration may occur, whereas excessive heat input can lead to excessive grain growth and increase the risk of hot cracking. Additionally, copper is susceptible to hot cracking due to the segregation of impurities such as phosphorus, sulfur, and oxygen at grain boundaries during solidification. Therefore, selecting the appropriate welding parameters, such as heat input, filler metal, and shielding gas, is crucial to achieving high-quality welded joints.

Given these complexities, welding copper requires a combination of appropriate welding methods, process parameters, and protective treatments to address these challenges and produce high-quality joints [10–11]. Welding parameters, such as heat input and the selection of filler rods, are critical aspects of the copper welding process, especially for heat pipe manufacturing applications. Heat pipes, which rely on copper's efficient heat transfer capabilities, require welded joints with high integrity to ensure optimal thermal performance and durability under operational pressures. In this process, proper heat input settings are essential to ensure sufficient heat is generated to melt the material optimally, particularly for materials with specific thicknesses [11–12]. A heat input that is too low will result in an unstable welding pool and inadequate penetration, while excessively high current can cause the evaporation of critical elements from the copper material, thereby reducing the mechanical properties and corrosion resistance of the welded joint [13]. In addition to heat input, the selection of filler rods is another critical parameter in copper welding. The chosen filler rod must maintain thermal and mechanical compatibility with the base material [14]. For instance, the use of CuNi filler rods is highly suitable for heat pipe applications due to their chemical properties, which are similar to those of pure copper. This results in joints with high thermal conductivity, a key criterion for heat pipes. Moreover, if heat pipes are designed for more corrosive environments or require additional strength, such as in renewable energy or nuclear sector applications, the choice of filler rod becomes even more critical. In heat pipe applications, the thermal conductivity of the material is a critical factor to consider [15] during the welding process. This property not only affects the efficiency of heat transfer in the final product but also determines thermal stability during the welding process itself. The rapid heat dissipation caused by copper's high thermal conductivity can hinder the formation of a stable welding pool. Therefore, precise heat input settings and the use of filler rods that can maintain or even enhance the heat transfer capability of the joint are essential to ensure optimal heat pipe performance. Errors in the selection of filler rods can affect the performance of heat pipes, such as increasing the risk of porosity or hot cracking, which can ultimately reduce heat transfer efficiency. Therefore, in addition to setting the appropriate heat input to ensure optimal material melting, the use of the correct filler rod becomes a crucial step in ensuring the quality and function of heat pipes as reliable passive cooling systems. Thus, in-depth research is needed to understand the impact of welding parameters on the properties of copper materials, particularly in the context of modern applications such as heat pipes. One commonly used welding process in the industry is GTAW welding, which is widely applied for welding copper, stainless steel, titanium, and other high-quality materials [1, 14].

Previous studies have been conducted to determine suitable welding parameters [16–19]. Mechanical property testing after the GTAW process on dissimilar CuCrZr/SS and Oxygen-Free High Conductivity Copper (OFHC)/SS joints showed different results. The experimental results indicated that the tensile strength of the post-weld dissimilar CuCrZr/SS and OFHC/SS joints reached 310 MPa and 220 MPa, respectively. The fracture surface morphology from the tensile test exhibited a dimple pattern, and microhardness showed a hardness distribution of 70~130 HV in the fusion zone. Scanning electron microscope observations revealed that Fe and Cr elements from stainless steel dissolved into the copper substrate, confirming that the dissimilar joints were successfully fused [17]. The mechanical property testing on welded joints of dissimilar materials, copper and stainless steel 304, fabricated using the GTAW process. The welded specimens were heat-treated at 650 °C for 1 hour, 2 hours, and 3 hours. Tensile strength and microhardness measurements were performed to analyze the effect of post-weld heat treatment on the mechanical properties of the dissimilar copper and stainless steel joints. The specimens heat-treated for 3 hours showed an increase in tensile strength and hardness compared to those heat-treated for 1 hour and 2 hours [17].

Although previous research has evaluated the effect of GTAW parameters on copper materials, most studies have focused on a single aspect, such as mechanical or thermal properties, without considering the interrelationship between both aspects comprehensively. Furthermore, very few studies have examined the direct relationship between welding parameters and material performance in practical applications, such as heat pipes, which require thermal conductivity data as one of the parameters to support the heat pipe's performance. This creates a knowledge gap that needs to be addressed, particularly in determining the optimal parameters to produce high-quality welded joints that meet industrial requirements. This experiment offers a more comprehensive approach by simultaneously examining the effects of GTAW heat input on the mechanical properties, thermal conductivity, and microstructure of copper materials.

The novelty of this study lies in the integrated approach that simultaneously examines the relationship between heat input parameters, mechanical properties, thermal conductivity, and microstructure in Cu-Cu welding using ERCuNi 90/10 filler metal. Unlike previous studies that primarily focused on individual aspects such as mechanical strength or microstructure, this research provides a comprehensive analysis of how welding parameters influence multiple material properties in a single investigation.

Furthermore, the thermal conductivity of welded copper has not been widely explored, particularly concerning its application in heat pipe products. Since heat pipe performance highly depends on the material's ability to conduct heat efficiently, evaluating the impact of welding on thermal conductivity is crucial. This study not only investigates the effect of different heat input (2.05 kJ/mm, 1.64 kJ/mm, and 1.55 kJ/mm) on mechanical and microstructural properties but also analyzes how microstructural changes influence thermal conductivity, providing valuable insights for applications where heat dissipation is a critical factor.

The study aims to identify microstructural changes resulting from welding heat input and their impact on welded joint quality. With this approach, the experiment is expected to provide new insights that support innovations in copper welding technology, while also improving the quality and efficiency of heat pipe manufacturing.

MATERIALS AND METHOD

The material used in this study is copper with a thickness of 2.7 mm. The properties of copper material as shown in Table 1 and the chemical composition of the material as shown in Table 2.

Table 1. Material properties

Parameter	Melting point	Tensile strength	Hardness	Elongation	Thermal conductivity
Cu	1.085 °C	210–250 MPa	40–65 HV	30–50%	385 W/m·K
Filler Rod: ERCuNi 90/10	1100–1145 °C	300 MPa	90 HV	30%	40 W/m·K

Table 2. Chemical properties

Parameter	Cu	Ni	Fe	Mn Max.	Zn Max.	C Max.	Pb Max.	S Max.	P Max.	Other Max.
Cu	99.9%	0.002%	0.095%	-	-			0.002%	-	-
Filler Rod: ERCuNi 90/10	> 86.5	9-11	1-1.8	1.0	0.5	0.05	0.02	0.02	0.02	0.5

The dimensions of the welded material are 250 × 100 mm, with two sheets. The welding was performed using the GTAW process with ultra-high purity argon (UHP) as the shielding gas. UHP refers to ultra-high purity argon or argon 5.0 with 99.999% purity. In this study, the root side was also shielded with UHP argon through purging welding to prevent oxidation and enhance weld quality. A shielding gas flow rate of 10 liters per minute (lpm) and DCEN current polarity. The tungsten used is 2% Lanthanated tungsten, and the filler rod used is ERCuNi 90/10. The tungsten electrode was positioned 2 mm from the workpiece during welding. Once the electrode-to-workpiece distance and gas flow rate were set, variations in heat input were achieved by adjusting the heat input and travel speed shown in Table 3, The welding power source used is a certified welder.

ERCuNi 90/10 is a copper-nickel-based welding wire containing 90% copper and 10% nickel with filler rod properties as shown in Tables 1 and the chemical composition of the filler rod as shown in Table 2, designed for applications that require a combination of high corrosion resistance, good mechanical strength, and adequate thermal conductivity. This filler is commonly used in the welding of copper-nickel alloys or pure copper, particularly in aggressive environments such as marine applications, heat exchangers, and heat pipes [20]. The addition of nickel enhances corrosion resistance, especially against seawater or corrosive fluids, and increases the strength of the welded joint, making it a reliable choice for high-pressure and high-temperature conditions. In GTAW or MIG welding, ERCuNi 90/10 is paired with argon shielding gas to prevent oxidation and ensure high-quality welds, although its thermal conductivity is lower than that of pure copper.

The selection of the ERCuNi 90/10 filler rod is suitable for welding copper to copper using TIG, as it provides a combination of mechanical and chemical properties that support successful welding of materials with high thermal conductivity. The success of welding with this filler is attributed to several key factors, including the 10% nickel content, which enhances the mechanical strength of the weld, enabling it to withstand both mechanical and thermal pressures. The chemical compatibility between the ERCuNi 90/10 filler and the base copper material ensures minimal segregation of elements during solidification, contributing to the formation of a uniform microstructure free from defects like hot cracks or porosity. This filler also has good welding fluid characteristics, allowing for the formation of a stable welding pool, even though copper has the tendency to spread heat rapidly. Moreover, ERCuNi 90/10 is resistant to oxidation during welding, as it is used with argon shielding gas, ensuring the weld surface quality is high.

The experiment method began with the preparation of the copper material for the welding process, where the material's surface on the welding side was cleaned using acetone to ensure no

Table 3. Welding parameters

Sample	Current (A)	Voltage (V)	Travel speed (TS) (mm/min)	Heat input (HI) (kJ/mm)
HI1#	120	12	79	1.09
HI2#	135	12	86	1.13
HI3#	150	12	90	1.20

contaminants were present on the material. Next, welding was carried out using the GTAW process with heat input of 1.09 kJ/mm (HI1#), 1.13 kJ/mm (HI2#), and 1.20 kJ/mm (HI3#) shown in Table 3. After the welding process, a visual testing and penetrant test was performed to assess the potential for surface weld defects. The penetrant test used the solvent removal method, in accordance with ASME Section V, Article 6, as the tested material was a welded joint. which provides the standard guidelines for liquid penetrant examination. The solvent removal method is one of the techniques in non-destructive testing (NDT) used to detect surface defects such as cracks, porosity, or scratches on the material. This method involves the use of a solvent to clean excess penetrant from the material surface [21].

After the penetrant test, where no weld defects were found, macro testing was conducted to evaluate the quality and geometric characteristics of the weld. Macrographic testing uses a metallographic cutting machine to section the sample, followed by grinding and polishing to smooth the surface. The sample is then etched with a solution to reveal the macrostructure. The final results are observed using a digital camera to evaluate fusion. Then, mechanical property testing, including tensile strength and hardness tests, was performed. The tensile test specimens followed the ASTM E8/E8M standard, as shown in Figure 1. The tensile testing equipment used is the Galda Bini Universal Testing Machine™, with a maximum load of 100 kN. The total number of tensile test samples was 9, with 3 specimens for the HI1# sample, 3 specimens for the HI2# sample, and 3 specimens for the HI3# sample. Vickers hardness test using a FutureTech Corp tool, Model FM-800™, by applying an indentation load of 1 kgf with a delay time of 15 seconds, in accordance with ASTM E384. The tested material was welded copper. Prior to testing, the specimen surface underwent surface preparation, including abrasion and polishing, to achieve a low surface roughness, ensuring precise indentation measurements. Hardness evaluations were conducted across distinct regions, namely the FZ, HAZ, and BM. The measurements followed a linear sequence: BM → HAZ → FZ → HAZ → BM to assess hardness variations across the weldment. For the hardness test, a total of 3 specimens were used, corresponding to the three heat input variations, with three test points for each variation

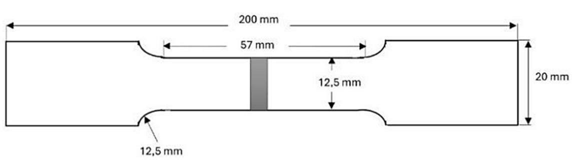


Figure 1. Tensile test specimen (22)

Next, thermal conductivity testing was carried out using the hot plate method. The hot plate method for measuring thermal conductivity is a technique used to determine a material's ability to conduct heat. The principle of this method involves placing the sample between two plates with different temperatures. One plate is heated, while the other plate is kept cold, as shown in Figure 2. Thermal conductivity is calculated from the temperature difference between the two plates and the heat flux flowing through the sample [23]. The total number of thermal conductivity test specimens was 3, corresponding to the three heat input variations, with each specimen undergoing three measurements.

Furthermore, microstructural testing was conducted to understand the microscopic characteristics of the material produced by the welding process. The microstructural testing was performed on the areas of the WM, HAZ, and base metal [24]. Weld metal is the portion that melts and solidifies during welding, with its microstructure changing due to solidification. The heat-affected zone surrounds it, does not melt but undergoes microstructural changes due to high heat, which

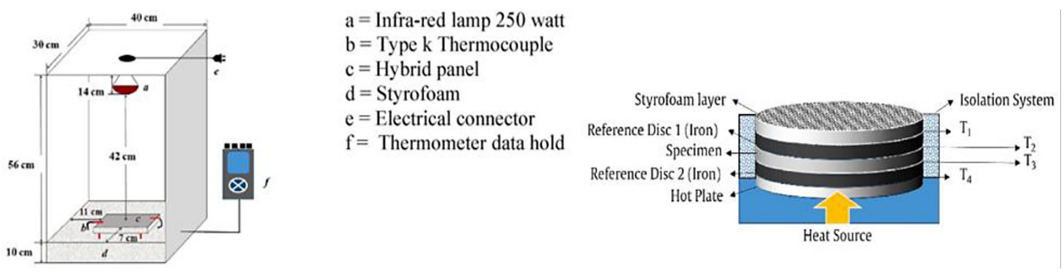


Figure 2. Schematic of thermal conductivity measurement (23)

can affect mechanical properties. Beyond the HAZ is the base metal, which generally remains stable except in areas closest to the HAZ. Selecting the appropriate base metal is crucial to ensuring compatibility and preventing joint failure.

RESULTS AND DISCUSSION

The results of welding copper with copper using the GTAW process are shown in Figure 3. It presents the face side of the welded specimen between copper and copper using GTAW. This image illustrates the sample after the welding process, providing a general overview of the weldment. The labeled zones, including the base metal, weld metal, and HAZ, follow standard welding terminology and serve as a reference for identifying different regions within the welded joint. In this process, copper, being a material with very high thermal conductivity, requires precise heat input control to achieve good fusion without causing defects. The welding result in the image appears neat, indicating that the heat input and welding technique were managed effectively. The weld is free from visual defects such as cracks or porosity, suggesting that the microstructure in the weld metal region is relatively uniform without significant segregation. The HAZ around the weld shows adequate thermal impact, but not excessive, preserving the mechanical properties of the base copper material.

Subsequently, the results from the penetrant test indicated no surface defects such as microcracks or inclusions that could affect the joint's strength. This also suggests that welding parameters such as current, welding speed, and the use of UHP argon gas inert protection were appropriate to prevent oxidation or other defects during the welding process. Overall, the neat visual appearance of the weld and the favorable penetrant test results reflect optimal welding process control as shown in Figure 4. This also indicates that the heat interaction provided successfully created a strong metallurgical bond without causing excessive thermal damage to the base material or the weld zone.

Tensile testing was conducted to identify the location of failure, whether it occurs in the weld metal, heat-affected zone (HAZ), or base metal. The failure location provides insight into the homogeneity of the microstructure and the metallurgical quality of the weld. The tensile test results show failure occurring in the HAZ for all specimens as shown in Figure 5., with varying tensile strength values as shown in Figure 6. This indicates that the HAZ is the weakest region in the welded joint. Due to the high thermal conductivity of copper, heat dissipation during the GTAW process leads to significant microstructural changes in this area. The heating and cooling cycles can induce recrystallization and grain growth, resulting in a reduction in mechanical strength.

The use of ERCuNi 90/10 filler rod with varying heat input affects the size and characteristics of the HAZ. Higher heat input result in a larger HAZ and increased grain growth, further contributing to mechanical weakening. Consequently, during the tensile test, specimens fail in the HAZ

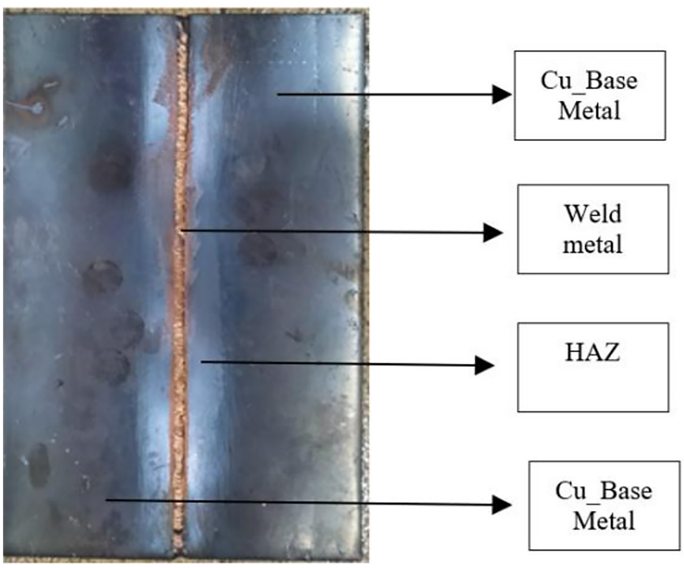


Figure 3. Welded joint of copper material

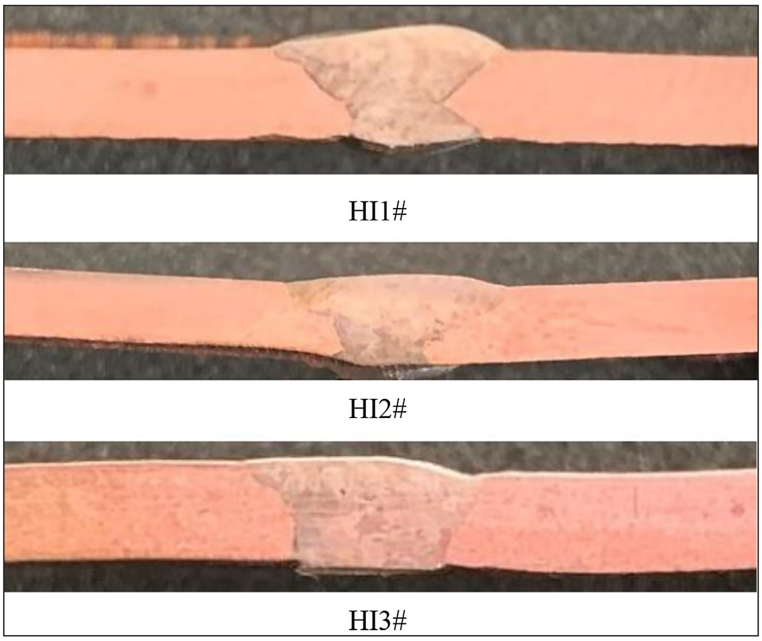


Figure 4. Macro view of three heat input variations

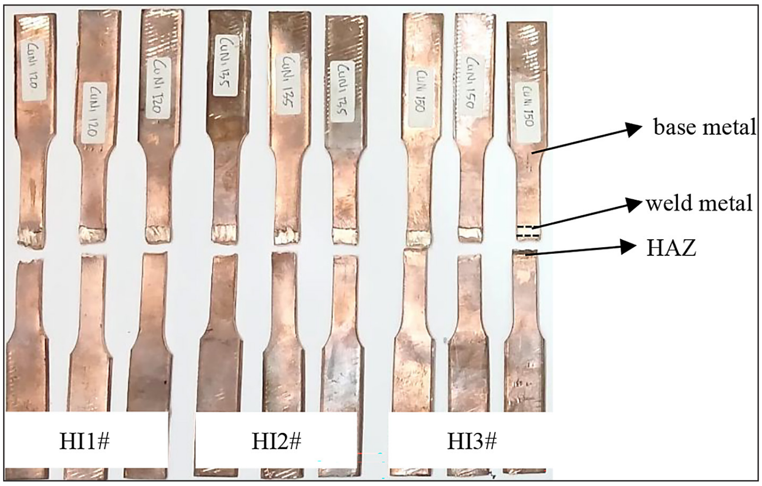


Figure 5. Tensile fracture on the welded specimen

due to its lower mechanical properties compared to the fusion zone and base metal. The variation in tensile strength among the specimens is attributed to different levels of softening in the HAZ, depending on the heat input during welding.

Fig. 6 shows the relationship between heat input and tensile strength in the weld result of copper to copper using the ERCuNi 90/10 filler rod and GTAW method. It can be observed that tensile strength increases gradually with higher heat input. At 1.09 kJ/mm (HI1#), the tensile strength is recorded at 172 MPa, increasing slightly to 173 MPa at heat input of 1.13 kJ/mm (HI2#), and then rising significantly to 180 MPa at heat input of 1.2 kJ/mm (HI3#). This result aligns with the findings of Chang et al. (2017) [17], who also reported that increasing heat input or heat input in dissimilar metal welding led to better mechanical strength due to enhanced fusion between materials. However, unlike their study, which focused on Cu-Stainless Steel welding, this study emphasizes the effect of heat input variations on pure Cu-Cu joints using ERCuNi 90/10 filler, highlighting the role of nickel in strengthening the weld metal through solid solution hardening. The values presented in Figure 6 are also the average results of three samples for each heat input variation. Specifically, three samples were tested for heat input of HI1#, three samples for heat input of HI2#, and three samples for heat input of HI3#, resulting in a total of nine samples. This approach ensures that the data reflect a representative average

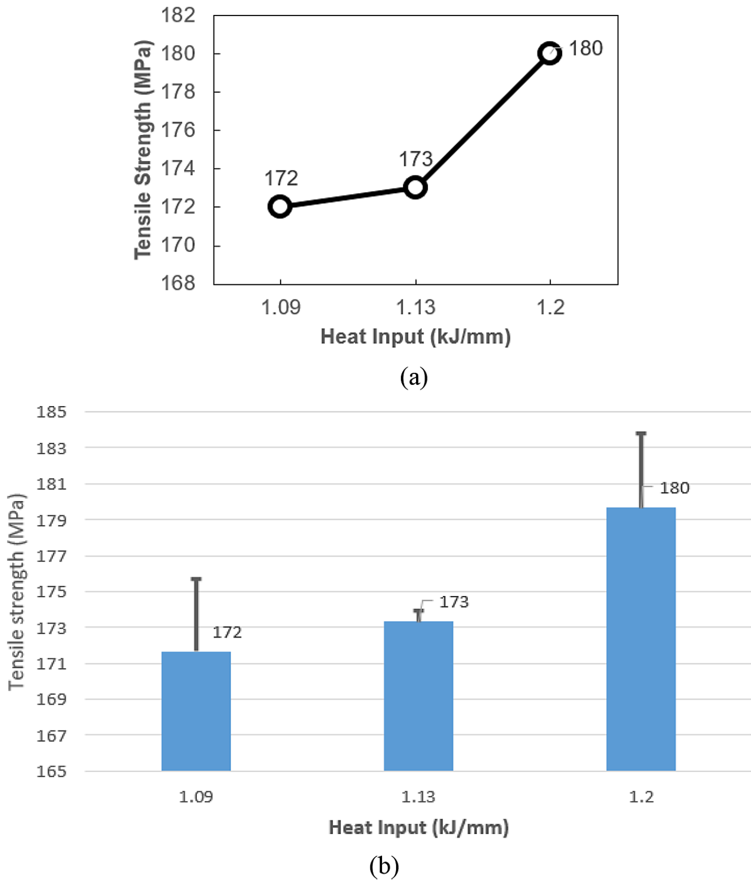


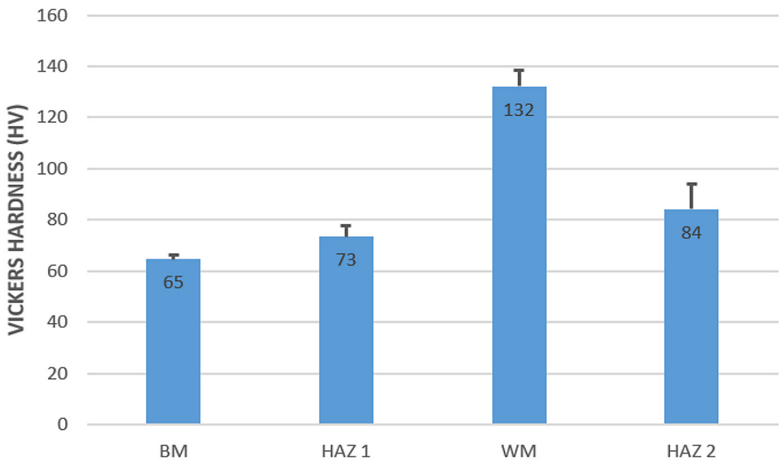
Figure 6. (a) Tensile strength, (b) standard deviation

for each welding parameter. While the deviation variation indicates consistency in the mechanical properties of the weld.

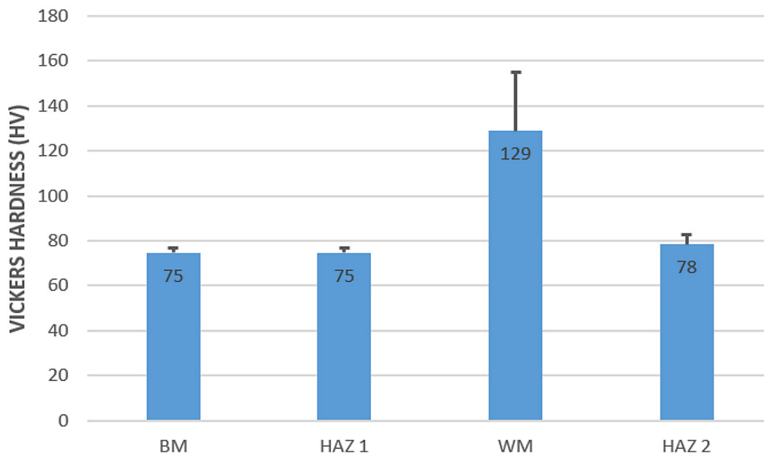
Subsequently, hardness testing was performed using a maximum load of 1000 gf. A total of 5 indents were made in each welding zone, including BM, HAZ 1, WM, and HAZ 2, resulting in a total of 20 indents (Fig. 7) on one specimen from each of the three specimens tested for the HI1#, HI2#, and HI3# heat input variations. This number of measurements was carried out to ensure an accurate assessment across different zones of the weld joint. The test was conducted in accordance with ASTM E384, which establishes the standard procedure for microhardness testing of materials. Vickers hardness data was then collected using a Vickers hardness tester, as shown in Figure 7. It shown the vickers hardness profile of copper-to-copper welding using the GTAW process with ERCuNi 90/10 filler rod. The hardness test was conducted on BM, HAZ 1, WM, and HAZ 2 under different heat input of HI1#, HI2#, and HI3#. The results indicate that the highest hardness values are consistently found in the WM, averaging 133 HV, while the BM has the lowest values at approximately 65 HV. HAZ 1 and HAZ 2 exhibit higher hardness than BM but lower than WM, with average values of 73 HV and 72 HV, respectively. The increase in hardness in the WM is due to solidification and rapid cooling, while microstructural changes in the HAZ result in a slight increase in hardness compared to the BM. While the deviation variation indicates consistency in the mechanical properties of the weld.

Table 4 shows the average Vickers hardness values measured at several locations on the weld specimen, namely the first heat-affected zone (HAZ 1), WM, and second heat-affected zone (HAZ 2), based on three heat input parameters: HI1#, HI2#, and HI3#. HAZ 1 is located on the left side of the WM, and HAZ 2 is on the right side of the WM as shown in Figure 8.

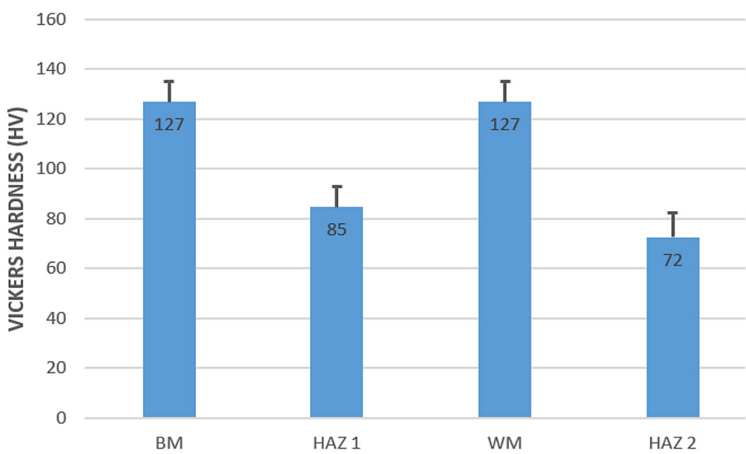
At HI1#, the highest hardness value was found in the weld metal (WM) with a value of 132 HV. The hardness in HAZ 1 was 73 HV, while HAZ 2 had a value of 84 HV. The high hardness in WM indicates the formation of a harder microstructure due to rapid cooling at lower heat input. The lower hardness values in the HAZ suggest that heat affects the zone without significant transformations



(a) HI1#



(b) HI2#



(c) HI3#

Figure 7. Vickers hardness and standart deviation

to increase hardness. These results are consistent with Ramachandran & Lakshminarayanan (2020) [18], who found that the WM exhibited the highest hardness in Cu-Stainless Steel laser welding due to microstructural refinement. However, in the heat input study, the use of ERCuNi 90/10 filler introduced additional strengthening effects through the incorporation of nickel, which was not considered in previous research.

At HI2#, a similar pattern was observed. The highest hardness value remained in the WM at 129 HV, slightly lower than at 1.09 kJ/mm. HAZ

Table 4. Vickers hardness with five times at various locations

Location	BM	HAZ 1	WM	HAZ 2	HAZ 1	WM	HAZ 2	HAZ 1	WM	HAZ 2
		HI1#			HI2#			HI3#		
Test 1	64	72	124	96	71	112	79	90	118	67
Test 2	63	69	141	92	77	122	77	96	119	89
Test 3	66	78	133	71	75	175	72	78	127	67
Test 4	64	70	128	80	76	121	83	83	137	67
Test 5	67	78	136	83	74	113	81	77	133	73
Average	65	73	132	84	75	129	78	85	127	72

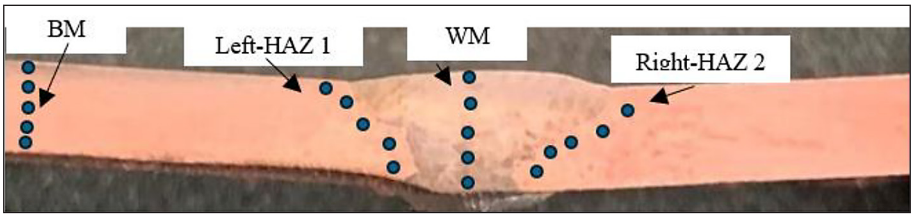


Figure 8. Location of material hardness data collection

At HI3#, the highest hardness in WM dropped to 127 HV, slightly lower than the previous two heat input. Hardness in HAZ 1 increased to 85 HV, while in HAZ 2, it decreased to 72 HV. The more even heat distribution at this heat input produced a more stable hardness pattern across the various zones, although the peak hardness in the WM slightly decreased, likely due to a slower cooling rate.

From these results, it can be concluded that the highest hardness value was always found in the WM for all heat input parameters, indicating that this area underwent hardening due to microstructure transformation, such as the formation of harder copper-nickel compounds. The lower hardness in the HAZ indicates that this zone was subjected to reheating without additional alloying elements from the filler rod, leading to a softer microstructure. At higher heat input, the more uniform heat distribution resulted in more uniform hardness values, although the peak hardness in the WM slightly decreased.

In addition to heat input, the ERCuNi 90/10 filler also influenced the hardness values due to its alloy composition, which consists of 90% copper and 10% nickel. The addition of nickel increases the hardness of the WM through solid solution strengthening, where nickel atoms hinder the movement of dislocations in the microstructure. Additionally, nickel enhances the strength and resistance to deformation in the WM. The highest hardness values recorded in the WM at each heat input setting directly reflect the contribution of this filler to the mechanical properties of the weld metal.

Thermal conductivity is the ability of a material to transfer heat through its structure. In thermodynamics, thermal conductivity is measured as the amount of heat flowing through a material per unit of time, per unit area, and per unit temperature gradient. This value is typically expressed in W/m·K (watts per meter kelvin). Testing the thermal conductivity of welded copper-to-copper joints aims to evaluate the heat transfer capability of the weld compared to the base material. This is crucial because copper is known for its very high thermal conductivity, and the welding process can impact this property. The test ensures that the welded joint does not experience a significant decrease in heat transfer capability, which could affect the performance of components requiring high thermal conduction, such as heat pipes, radiators, or heat exchangers. Based on the results obtained using the hot plate method, the thermal conductivity values are presented in Figure 9.

The Figure 8 illustrates a decrease in thermal conductivity as the heat input increases from base metal to HI3#. At HI1#, the thermal conductivity reached the highest value of 206.72 W/m·K, which then significantly decreased to 144.02 W/m·K at HI2#, and further dropped to 123.65 W/m·K at HI3#. This decline can be attributed to changes in the microstructure and material distribution in the weld zone due to variations in heat input parameters. While the deviation variation indicates consistency in the mechanical properties of the weld.

The ERCuNi 90/10 filler rod directly influences thermal conductivity due to its relatively high nickel content. Pure copper exhibits exceptionally high thermal conductivity, but the addition of nickel tends to reduce it, as nickel diminishes the ability of electrons to move freely within the crystal structure, the primary mechanism for heat transfer in metals. At higher heat input, the slower cooling rate allows for the formation of a more homogeneous microstructure, but it can also result in precipitates or phases that further reduce thermal conductivity.

The decline in thermal conductivity values shown in the Figure 9 indicates that as the heat input increases, the presence and distribution of nickel alloy in the weld metal have a more significant effect on the thermal properties. This also confirms that while the ERCuNi 90/10 filler rod enhances the mechanical strength of the weld metal, it contributes to a reduction in thermal conductivity compared to pure copper. Similar trends have been reported in heat pipe applications, as demonstrated by Mahdavi et al. (2018) [15], who highlighted that thermal performance is directly affected by material composition and heat input. However, this study extends those findings by directly linking heat input variations to thermal conductivity changes, emphasizing its importance in welding applications for heat pipe manufacturing.

Microstructure analysis for evaluating welded joint quality, microstructure analysis is employed to evaluate the quality of welded joints, determining whether the joints have formed properly and identifying micro-defects such as porosity, microcracks, or inclusions that may reduce the strength of the joint [25]. Additionally, microstructure testing is useful for studying the HAZ. The welding process generates heat that impacts the microstructure around the weld area, which is also influenced by heat input [26]. In the HAZ, changes in grain size, phase, or material texture often occur, which affect mechanical properties such as hardness, ductility, and corrosion resistance. The results of the microstructure analysis using ERCuNi 90/10 filler rods for welding copper to copper are shown in Figure 10. The microstructure examination was conducted using Carl Zeiss™ optical equipment.

Figure 10a presents the microstructure of the welded joint at HI1# using ERCuNi 90/10 filler metal. The main zones observed include HAZ 1, WM, and HAZ 2, each undergoing microstructural changes due to thermal effects during the welding process. In HAZ 1, heat exposure leads to recrystallization and grain growth, but no melting occurs in this zone. WM undergoes complete melting during welding and solidifies with a characteristic dendritic pattern, where the distribution of nickel from the filler metal contributes to solid solution strengthening. HAZ 2, located on the opposite side of WM, exhibits grain growth similar to HAZ 1, although differences arise due to the non-uniform heat distribution during welding. Overall, at HI1#, heat control is stable enough to prevent excessive microstructural changes in HAZ, which helps reduce the risk of thermal defects in the welded joint.

Figure 10(b) illustrates the welded microstructure at HI2#, where the increased heat input results in larger grain growth in HAZ compared to HI1#. The WM exhibits a more uniform dendritic solidification pattern than HI1#, indicating improved homogeneity due to a

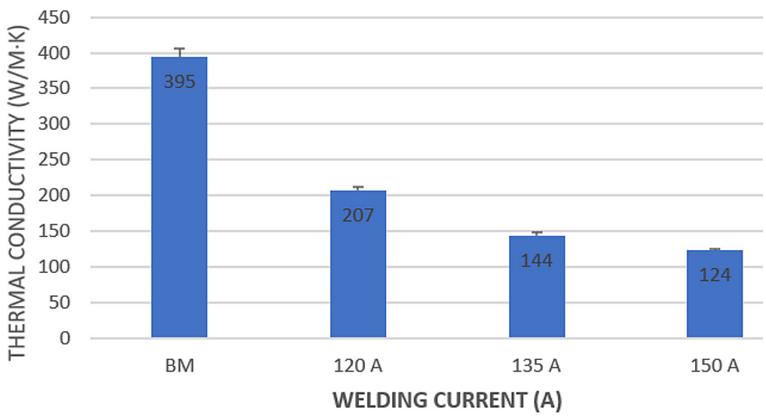
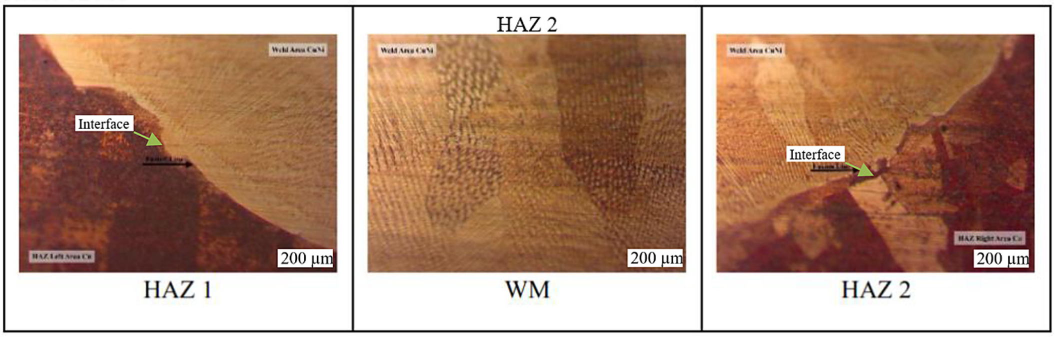
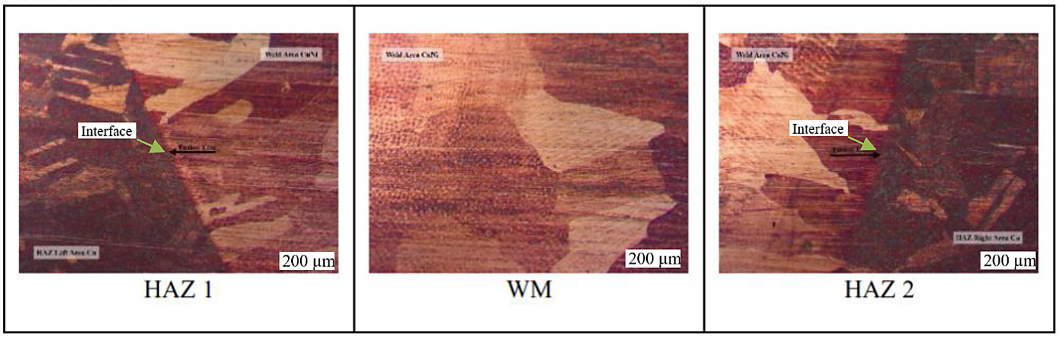


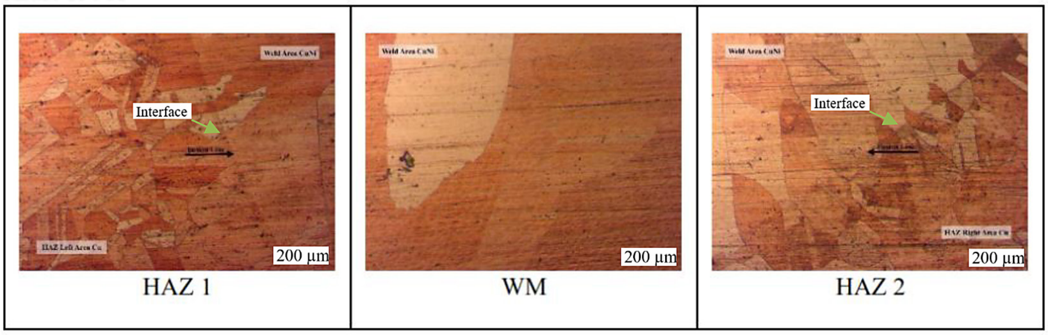
Figure 9. Thermal conductivity values of welded copper joints and standard deviation



(a) HI1#



(b) HI2#



(c) HI3#

Figure 10. Microstructure test results for different heat input

slightly slower cooling rate. The distribution of nickel within the WM becomes more uniform, contributing to enhanced mechanical properties and corrosion resistance of the welded joint. Fig. 10c depicts the microstructure at HI3#, where the higher heat input produces the most significant grain growth in HAZ. This is due to a longer thermal cycle, allowing grains to grow larger before cooling. In WM, the dendritic pattern appears more uniform compared to lower heat input, suggesting better fusion between the base metal and filler metal. The slower cooling rate also allows for more effective diffusion of alloying elements, which improves both microstructural homogeneity and mechanical properties. The impact of heat input on grain size is consistent with the findings of Shen et al. (2010) [6], who reported that higher welding heat input leads to coarser grains in copper welding. However, unlike their study, which investigated friction stir welding, the present study provides insights into GTAW with ERCu-Ni 90/10 filler, demonstrating how filler composition influences the final microstructure.

Overall, the observed microstructural changes indicate that variations in heat input directly influence grain size, solidification patterns, and the final mechanical properties of the welded joint. Higher heat input lead to greater grain growth in HAZ and improved homogeneity in WM, ultimately determining the mechanical characteristics of the weld.

CONCLUSIONS

The effect of GTAW heat input on the tensile properties, hardness, and thermal conductivity of copper material, which are critical factors in the performance of heat pipes, has been evaluated in this experiment. Microstructural changes resulting from the variations in heat input and their impact on the welded joint quality have also been assessed, leading to several conclusions being drawn. The heat input significantly influences the mechanical properties and thermal conductivity of copper materials. The tensile strength results show that the highest value is achieved at a heat input of 1.2 kJ/mm, with a tensile strength of 18.31 kgf/mm², while the lowest value is observed at 1.09 kJ/mm. This indicates that higher heat input lead to an increase in tensile strength, which is also influenced by the chemical composition of the filler rod. Meanwhile, the highest hardness values are consistently found in the WM for all heat input parameters, demonstrating that this region undergoes hardening due to microstructural transformations, although hardness decreases in the heat-affected zone (HAZ). Thermal conductivity values increase with higher heat input, from 1.09 kJ/mm to 1.2 kJ/mm, with the highest thermal conductivity observed at 1.09 kJ/mm, reaching 206.72 W/mK.

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