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The effect of TIG welding technology parameters on the weld quality of copper material joints for heat pipe applications

Azwinur[1*], M. Hadi Kusuma[2], Usman[1], Surya Dharma[3]

[1]Department of Mechanical Engineering, Politeknik Negeri Lhokseumawe, Lhokseumawe, 24301, Indonesia
[2]Pusat Riset Teknologi Reaktor Nuklir, Badan Riset dan Inovasi Nasional, Tangerang Selatan, 15314, Indonesia
[3]Department of Mechanical Engineering, Politeknik Negeri Medan, Medan, 20155, Indonesia
*Corresponding author: azwinur@pnl.ac.id

Abstract

Copper is a commonly used material for heat pipe fabrication using the welding process. However, welding copper to copper presents significant challenges due to its inherent material properties. Its exceptionally high thermal conductivity facilitates rapid heat dispersion, complicating the maintenance of a stable melting zone. Furthermore, copper is prone to oxidation, which generates brittle oxides that can adversely affect weld quality. This research paper examines the relationship between TIG welding parameters—specifically current, voltage, shielding gas flow rate, and filler rods—and the mechanical properties of the resulting heat pipe material. The study involves varying the welding current at levels of 120 A, 135 A, and 150 A, along with different types of filler rods. The results indicate that both the selection of welding current and the type of filler rod significantly influence the tensile strength of copper welded joints. Notably, the use of higher currents in ERCuSi-A welding tends to decrease hardness in the Heat-Affected Zone (HAZ), while producing more complex variations in hardness within the Weld Metal (WM), dependent on the interplay between heat and the chemical composition of the filler rod. Additionally, nickel in the ERCuNi filler rod contributes to an increase in weld hardness.

Keywords:
Copper, heat pipe, nuclear systems, hardness, TIG.

1 Introduction

Copper is an essential material in heat pipe fabrication, prized for its exceptional thermal conductivity. Heat pipe technology has become a highly efficient and versatile method for heat transfer, finding extensive applications across various industries [1]. The selection of materials and welding parameters significantly influence the mechanical properties of heat pipe materials, which are crucial for ensuring the reliability and performance of these systems [2]. As noted by Cooper, lightweight materials with high thermal conductivities are particularly important for heat pipe applications, especially with the increasing demand for portable electronics. Heat pipe-based heat exchangers are used in diverse applications, including space technology, electronic cooling, HVAC systems, solar energy, water desalination, and nuclear power, with temperatures ranging from sub-zero to as high as 950°C [1] [3].

The operation of a heat pipe relies on the temperature gradient between its two ends, where the working fluid undergoes a phase change to transfer heat from the evaporator to the condenser [4].

A heat pipe is an efficient, passive heat transfer device that is widely used in various applications such as electronic cooling, heating, ventilation, and air generation. Its working principle relies on heat transfer through a liquid-gas phase change, allowing heat flow without the need for an external energy source. A typical heat pipe comprises three main components [5][1][6]. In the evaporator section, heat causes the working fluid (typically water, alcohol, or other specialized fluids) to evaporate into gas. This phase change absorbs a substantial amount of latent heat, facilitating efficient heat transfer from the heat source to the other parts of the system. In the Adiabatic section, heat transfer occurred without any exchange of energy with the surrounding environment. And in the condenser section, the vapor condenses back into a liquid, releasing latent heat to the surrounding environment. This liquid then returns to the evaporator section, often through a capillary wick in the heat pipe, thus facilitating return flow without the need for a pump [7].

Heat pipe operation involves a continuous cycle of evaporation and condensation, making it highly efficient because of the phase-change process that absorbs and releases substantial energy [7][8].

Heat pipes have the advantages of high heat transfer efficiency, ability to operate over a wide temperature range, and the fact that they do not require an external power source to transfer heat [4][9]. Owing to these characteristics, heat pipes are utilized across various industries, such as heat pipes, which are commonly used to cool components in computers, laptops, and other electronic devices. Heat pipes are employed in passive cooling systems for nuclear reactors and nuclear fuel storage [10][11].

Selecting appropriate materials for a heat pipe is essential for achieving optimal performance, durability, and reliability. This choice depends on factors such as the thermal conductivity, corrosion resistance, mechanical strength, and compatibility with the working fluid [12][13]. Each part of the heat pipe, from the container to the wick structure, plays a crucial role in ensuring efficient heat transfer, making material selection a critical aspect of heat pipe design.

For a container or outer shell, a material with high thermal conductivity and durability is ideal because it requires repeated cycles of heating and cooling. Copper is commonly used because of its excellent thermal conductivity and compatibility with water [14], and is a frequent choice for working fluids in heat pipes used in electronics cooling. However, the weight of copper can be a limiting factor, especially in applications where minimizing weight is crucial, like aerospace. In these cases, aluminum, which is lightweight and has relatively good thermal conductivity, is often preferred. Aluminum is suitable for applications that prioritize weight reduction, although it may require surface treatments to enhance its resistance to corrosion. Stainless steel, known for its high corrosion resistance and ability to withstand higher temperatures, is often used in heat pipes in harsh environments, such as nuclear reactors. While stainless steel has a lower thermal conductivity than copper and aluminum, its durability makes it suitable for long-term applications. Titanium is another option, especially in extreme environments requiring high chemical compatibility and corrosion resistance, but its high cost and lower thermal conductivity make it less common [15].

Inside the heat pipe, the wick structure is equally important, as it enables the capillary action that returns the condensed liquid to the evaporator section. A copper wick is frequently used in conjunction with copper heat pipes, providing good capillary action and compatibility with water, which makes it a popular choice in general cooling applications [16]. For high-temperature or chemically demanding environments, stainless steel wicks are advantageous, because they are compatible with various working fluids, such as ammonia or acetone. Sintered metal powders, often made of copper or stainless steel, are also used to create high-porosity wicks, which offer precise capillary control and are ideal for miniature or micro heat pipes where efficient liquid return is critical.

The compatibility between the container and wick materials with the working fluid is crucial for preventing chemical reactions that could compromise the performance of the heat pipe. For instance, copper and water form reliable pairings for moderate to high temperatures, which are commonly used in electronic cooling applications. Ammonia with aluminum or stainless steel is preferred in low-temperature applications, such as refrigeration or aerospace, where ammonia functions effectively at sub-zero temperatures. Meanwhile, acetone or methanol, which is compatible with stainless steel, is suitable for high-temperature applications that require fluids with a high boiling point.

In summary, the material selection for a heat pipe involves careful consideration of the thermal conductivity, corrosion resistance, mechanical strength, and compatibility with the working fluid. By selecting the appropriate materials, the efficiency of the heat pipe can be maximized, ensuring that it operates safely and effectively across a wide range of environmental and temperature conditions.

However, the manufacturing and fabrication of heat pipes often involve welding processes, which can significantly impact the mechanical properties of the materials used.

Welding is essential in the fabrication of heat pipes, as it directly influences the structural integrity and performance of the final product. The Tungsten Inert Gas (TIG) welding process is commonly used for heat pipe welding due to its capacity to produce high-quality, defect-free welds [17]. However, the influence of TIG welding parameters on the mechanical properties of heat pipe materials is an important area of investigation to ensure the reliability and durability of these devices.

Previously, several studies have been conducted on copper with various welding processes [18-20]. Jau-Wen Lin, in his article on comparison of mechanical properties of pure copper welded using friction stir welding and tungsten inert gas welding. The purpose of this study was to investigate the mechanical properties including bonding, tensile strength, and impact resistance of pure copper welded using Friction Stir Welding (FSW) method and compare them with Tungsten Inert Gas (TIG) welding. The results showed that the notch tensile strength and notch strength ratio for FSW (212 MPa, 1.10) were significantly higher than those for TIG welding (190 MPa, 1.02). For the impact test, the energy absorption values of the weld zone and heat affected zone for FSW (2.87 J, 2.25 J) were higher than those for TIG welding (1.32 J, 0 J) [21].

Sooriyamoorthy Elangovan, in his article on the optimization of ultrasonic welding parameters for copper-to-copper joints, utilizes design of experiments. This study considers various welding parameters, including welding pressure, welding time, and vibration amplitude, while producing ultrasonically welded copper joints with a thickness of 0.2 mm. The use of alternative joining methods may damage the weld due to the small size of the joint. An appropriate design of experiments, based on Taguchi's robust design methodology, was developed and implemented to conduct the trials. Analysis of Variance (ANOVA) and signal-to-noise ratio analysis were employed to examine the effects of different welding parameters on weld strength and to identify the optimal parameters [22].

In this research paper, we investigate the influence of various TIG welding parameters—namely welding current, travel speed, shielding gas flow rate, and filler rod—on the mechanical properties of heat pipe materials. The objective of this study is to explore the relationship between these TIG welding parameters and the mechanical properties of the resulting heat pipe materials.

2 Research Methods

The data analysis technique used in this study is analysis with a comparative descriptive method. The data obtained in this study are in the form of tensile strength and hardness data and from observations then analyzed descriptively.

This study is an experimental study conducted in a laboratory by controlling the welding current variables and the type of filler rod to see its effect on the weld quality variables, especially mechanical properties. The material used is copper with dimensions of 300×100×2.7 mm with variations of ERCuSi-A, ERCuNi, ERBCuP and ERCu fillers.

The welding process used is GTAW with a tungsten lanthanum diameter of 2 mm. The welding currents varied were 120 A, 135 A, and 150 A. The gas used is UHP grade argon or ultra high purity.

Specimen testing involves tensile and hardness assessments. Tensile tests can determine whether the welded joint can support the load according to application standards and whether its strength is comparable to, or at least consistent with, that of the base material. Copper, while possessing high thermal and electrical conductivity, has relatively lower mechanical strength compared to metals such as steel. Therefore, tensile testing of copper welded joints is essential to ascertain whether the welding process diminishes the original strength of the material or introduces weak points that may lead to failure during use. An example of a tensile test specimen is depicted in Fig. 1.

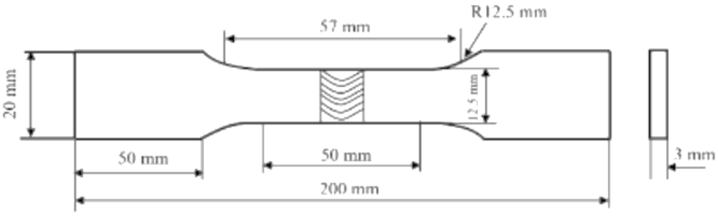

Fig. 1. Tensile test specimens.

The welding process can change the hardness of copper, especially in the HAZ. Too much or too little hardness in this area can cause problems. Measure the hardness of the weld joint, especially in the weld and Heat-Affected Zone (HAZ). Hardness provides an indication of the material's resistance to plastic deformation and wear. The location of the hardness test is shown in Fig. 2.

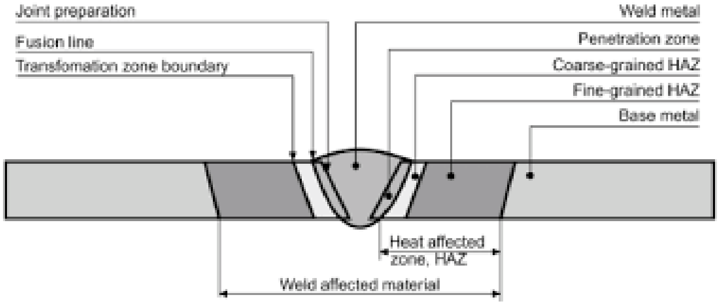

Fig. 2. Location of hardness test points.

3 Results and Discussion

The results of welding between copper to copper welding are shown in Fig. 3.

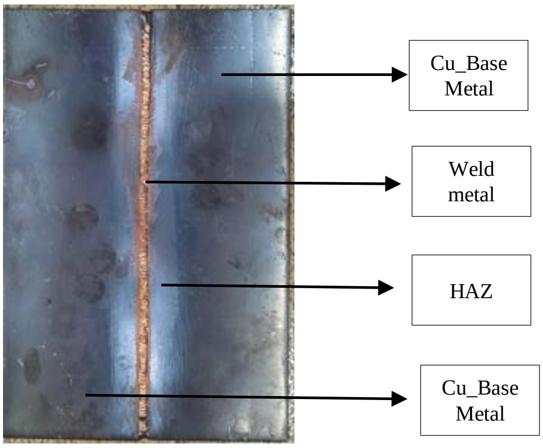

Fig. 3. Welding specimen.

Fig. 3 illustrates the welding process, where copper (Cu) is welded with various filler rods under different current settings. The results show that good fusion has occurred visually, with no surface defects observed.

To assess the material strength, tensile and strain tests were conducted, and the results are presented in Fig. 4 and Fig. 5.

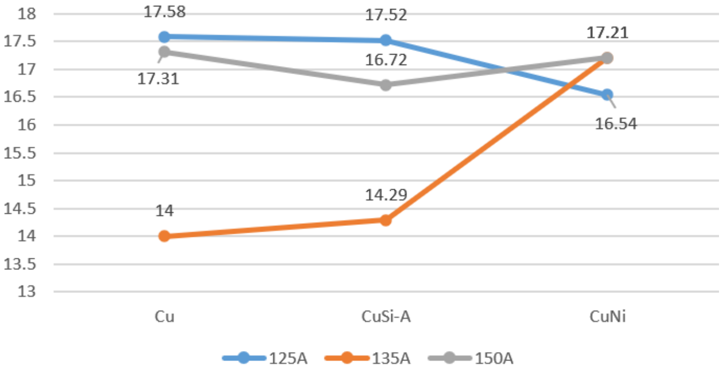

Fig. 4. Tensile test results.

The tensile test graph in Fig. 4 illustrates how variations in welding current and filler rod type influence the tensile strength of welded joints. When using a pure copper filler rod, a current of 125A yields the highest tensile strength at 17.58. However, increasing the current to 135 A results in a significant drop in tensile strength to 14. This decrease may be attributed to excessive heat affecting the microstructure, leading to increased brittleness or grain growth that diminishes material strength. At 150 A, the tensile strength slightly increases to 17.31, suggesting that pure copper exhibits greater resistance to heat at higher currents compared to medium currents.

Using the CuSi-A filler rod, a current of 125 A yields an initial tensile strength of 16.72. Notably, increasing the current to 135 A raises the tensile strength to 14.29, suggesting that this current range may enhance the structural integrity of the weld. However, when the current is further increased to 150 A, the tensile strength declines again to 16.72. This phenomenon indicates that the CuSi-A filler rod may possess an optimal current range at medium levels, where the silicon composition in the filler rod contributes to enhanced stability, thereby supporting tensile strength.

Meanwhile, the CuNi filler rod demonstrated relatively stable performance at low to medium currents. At a current of 125 A, the tensile strength measured 17.52, which is slightly lower than that of pure copper but still considerable. However, at 135 A, the tensile strength decreased to 14.29, before experiencing a slight increase to 16.54 at 150 A. These results suggest that CuNi may be more susceptible to overheating at higher currents, leading to a performance that is somewhat inferior to that of pure copper.

Overall, this graph shows that the selection of welding current and type of filler rod play an important role in determining the tensile strength of copper welded joints. Each type of filler rod has a different response to current variations, where pure copper shows the best tensile strength at low and high currents, CuSi-A has an optimum point at medium currents, and CuNi is more stable at low currents but tends to decrease at high currents.

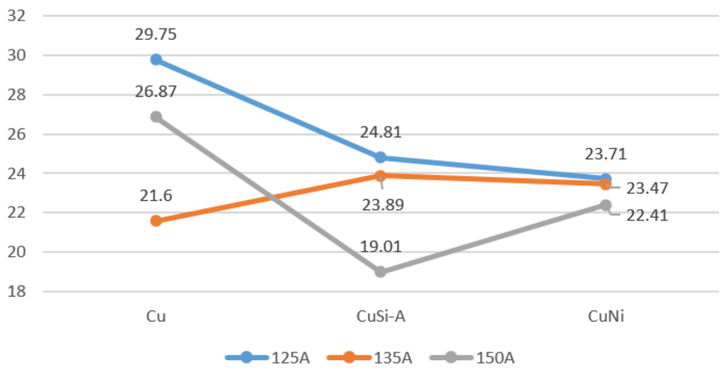

Fig. 5. Strain test.

Fig. 5 presents the strain results for welding with current variations of 125 A, 135 A, and 150 A using three types of filler rods: Cu, CuSi-A, and CuNi. At a current of 125 A, the Cu filler rod exhibits the highest strain value of 29.75, indicating that, at this current, the welded joint with pure copper demonstrates excellent strain capability. However, when the current is increased to 135 A, the strain decreases to 26.87, and it further declines to 24.81 at a current of 150 A. This reduction in strain may be attributed to increased heat, which induces microstructural changes and subsequently diminishes the elasticity of the welded joint.

For the CuSi-A filler rod, the strain value at a current of 125 A is 21.6, lower than that of pure copper. However, as the current increases to 135 A, the strain increases to 23.89, indicating that at this current, the CuSi-A filler rod has a better strain rate. When the current is increased to 150 A, the strain actually drops drastically to 19.01, indicating that the high current makes the CuSi-A filler rod less elastic, possibly due to the influence of heat that triggers changes in the microstructure.

Meanwhile, the CuNi filler rod has an initial strain value at a current of 125 A of 23.71. At a current of 135 A, the strain value only decreases slightly to 23.47. However, when the current is increased to 150 A, the strain value also decreases slightly to 22.41. The relatively stable decrease in strain value in CuNi indicates that the CuNi filler rod has a fairly stable strain capability even though the current increases, although it still experiences a slight decrease at the highest current.

The results indicate that variations in current and the type of filler rod significantly affect the strain of the welded joint. Copper (Cu) filler rods exhibit the highest strain capability at low currents, whereas CuSi-A filler rods achieve optimal strain at medium currents but experience a sharp decline at high currents. In contrast, CuNi filler rods demonstrate a relatively stable strain level in response to changes in current, although their performance is lower than that of Cu at low currents.

The strain value significantly influences welding outcomes as it indicates the extent to which a welded joint can deform or stretch before failure. A high strain capacity in a welded joint signifies that the material can endure greater deformation without cracking or breaking, which is crucial for applications requiring flexibility and resistance to dynamic or cyclic loads.

In the context of resistance to dynamic loads, welded joints with high strain have a better ability to withstand repeated loads, such as vibration and impact. This is very much needed in equipment that works continuously. In contrast, joints with low strain tend to be stiffer and are prone to cracking or failure when exposed to repeated loads.

The strain value significantly influences the resistance of a joint to temperature fluctuations. In high-temperature applications, such as heat pipes in the energy sector or welded joints in nuclear reactors, elevated strain enables the joint to accommodate thermal expansion without the risk of cracking. Conversely, low-strain joints are prone to high residual stresses, making them more vulnerable to cracking as a result of thermal expansion.

Furthermore, high strain in a welded joint allows the material to adapt to its shape under load while maintaining its strength, which is essential in applications that require the joint to remain rigid despite varying mechanical forces. Joints that are overly stiff and exhibit low strain are more likely to crack or undergo permanent deformation when subjected to uneven mechanical loads.

High strain also plays a crucial role in preventing cracking or fracture in welded joints. Joints subjected to high strain tend to exhibit greater resistance to cracking due to their increased deformation capacity. In contrast, low-strain joints are more susceptible to cracking, particularly when residual stresses from the welding process are present or when the joint experiences sudden loading. This consideration is especially pertinent in applications involving high stresses, such as in the oil and gas industry, where fracture resistance is paramount.

Consequently, high strain values are generally preferred in welds for applications that demand flexibility and resistance to dynamic loads, temperature fluctuations, or pressure variations.

Conversely, low strain values can render the joint stiffer and more prone to cracking or breaking under dynamic loading conditions or temperature changes. Therefore, it is essential to select materials and welding methods that facilitate the desired strain levels to ensure the reliability and long-term durability of the welded joint.

The hardness test results are shown in Fig. 6-Fig.8.

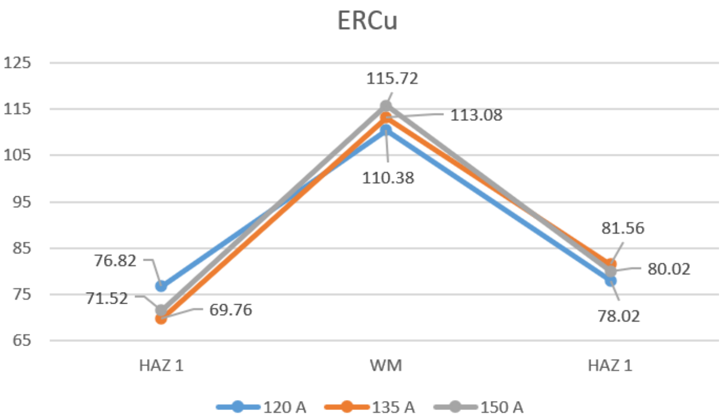

Fig. 6. Hardness value of ERCu filler rod.

Fig. 6 shows the variation of Vickers hardness value in the Heat Affected Zone (HAZ) and Weld Metal (WM) areas of the weld joint using ERCu filler rod with TIG welding method. Three variations of current used were 120 A, 135 A, and 150 A.

Increasing the welding current increased the hardness in the WM and HAZ areas, with the highest hardness value in the WM at a current of 150 A. This shows that the use of higher currents produces greater heat that affects the microstructure of the material, especially in the WM, thereby increasing the hardness.

In HAZ 1, which is around the base metal, the Vickers hardness value tends to be lower than the WM for each current variation. The Vickers hardness in HAZ 1 appears to increase with increasing current: 120 A shows a hardness of 71.52 HV, 135 A is 69.76 HV, and 150 A is 76.82 HV. Increasing the current causes an increase in heat, which can affect the microstructure in the HAZ, thus increasing the hardness at higher currents.

In the WM, which is the main weld joint area, the Vickers hardness reaches a peak value for each applied current. The highest hardness was recorded at a current of 150 A at 115.72 HV, followed by 135 A at 113.08 HV, and 120 A at 110.38 HV. The WM area has a higher hardness due to the combination of filler material and base metal, which creates a denser structure due to rapid cooling.

In HAZ 1 after WM, the Vickers hardness decreases again, but remains higher than HAZ 1 before WM. This indicates the effect of welding heat on the surrounding area which causes changes in the microstructure.

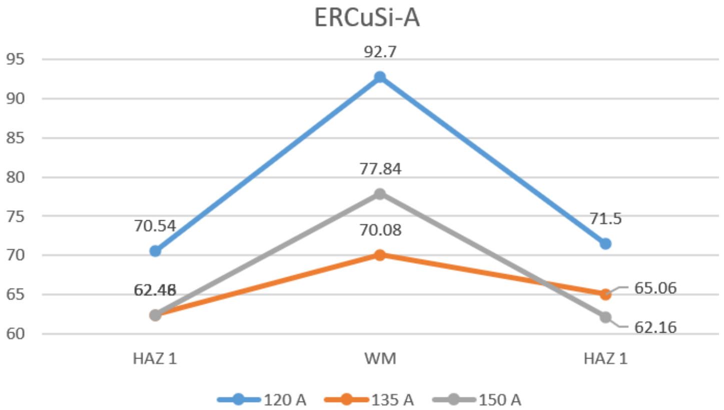

Fig. 7. Hardness value of ERCuSi-A filler rod.

Fig. 7 shows the change in Vickers hardness value in the Heat Affected Zone (HAZ) and Weld Metal (WM) areas of the welded joint using ERCuSi-A filler rod with TIG welding method at three current variations, namely 120 A, 135 A, and 150 A.

The graph shows that the chemical composition of ERCuSi-A, especially the silicon content, contributes to higher hardness in the WM area, especially at low current (120 A). However, increasing the current can change the distribution of silicon in the WM microstructure and affect the hardness in that area. In conclusion, the use of higher current in ERCuSi-A welding tends to decrease the hardness in the HAZ area, but produces more complex hardness changes in the WM, depending on the interaction between heat and the chemical composition of the filler rod.

At a current of 120 A, the Vickers hardness value in the Weld Metal (WM) area reached its peak at 92.7 HV before decreasing dramatically to 70.08 HV at 135 A. However, at 150 A, the hardness in the WM increased to 77.84 HV. This pattern indicates a significant fluctuation in hardness within the WM area, likely influenced by the chemical composition of the ERCuSi-A filler material and the thermal characteristics of the welding process. The ERCuSi-A filler rod, which contains copper and silicon, enhances the hardness properties in the WM due to the formation of specific phases resulting from the combination of these two elements. Silicon, in particular, plays a crucial role in improving the fluidity of the molten metal, contributing to a denser weld joint and increased hardness in the WM area. Nevertheless, the elevated temperatures associated with higher currents (135 A and 150 A) may lead to greater dissolution of silicon in the copper matrix, altering the microstructure of the WM and resulting in a decrease in hardness at 135 A. The subsequent increase in hardness at 150 A may be attributed to microstructural adjustments occurring during the rapid cooling of the metal.

In the Heat-Affected Zone (HAZ) 1, both before and after the WM, hardness values tend to be lower and decrease with increasing current. At 120 A, the hardness in HAZ 1 is 70.54 HV, which drops to 65.06 HV at 135 A, and further declines to approximately 62.48 HV at 150 A. This reduction in hardness is primarily due to the greater impact of heat on HAZ 1, which leads to softening of the microstructure in this region. Given that copper generally exhibits low resistance to heat, it experiences a decrease in hardness when subjected to elevated temperatures repeatedly.

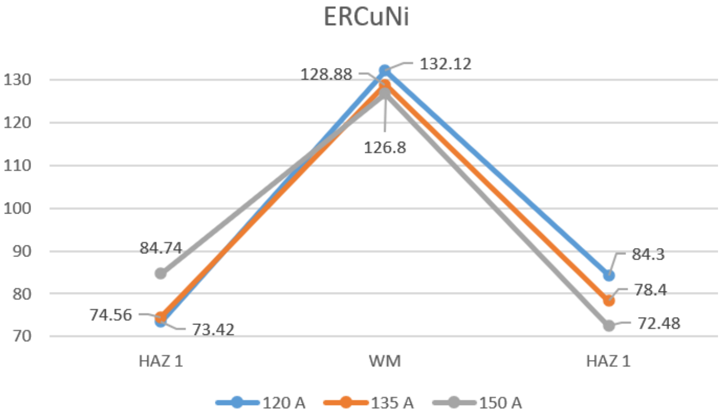

Fig. 8. Hardness values of ERCuNi filler rod.

Fig. 8 shows the change in Vickers hardness value in the Heat Affected Zone (HAZ) and Weld Metal (WM) areas of the weld joint using ERCuNi filler rod with TIG welding method on copper-based materials (Cu with Cu). The current variations used were 120 A, 135 A, and 150 A. This graph shows that the hardness in the WM area is higher than the HAZ for all currents used.

In the WM area, the hardness value peaked at a current of 120 A, which was 128.88 HV. This value decreased slightly at a current of 135 A to 126.8 HV, and then increased again at a current of 150 A to 132.12 HV. The high hardness in the WM is mainly due to the influence of the chemical composition of the ERCuNi filler rod containing Copper (Cu) and Nickel (Ni). Nickel has a significant effect on the hardness of the weld result because it can increase the strength and hardness of the material by forming a more stable and wear-resistant structure under hot conditions. Copper in the filler rod provides support for thermal conductivity properties, but does not contribute significantly to hardness like nickel. The combination of Cu-Ni in WM produces a material with high hardness because nickel acts as a reinforcing element in the copper matrix.

In the HAZ area, both before and after WM, the hardness tends to be lower. At a current of 120 A, the hardness in HAZ 1 is 74.56 HV, which then decreases to 73.42 HV at 135 A, and decreases again at 150 A to 72.48 HV. The lower hardness in this HAZ indicates that the area is softened due to the effects of welding heat, resulting in a more homogeneous microstructure but with lower hardness. On the other hand, nickel in the filler does not affect the HAZ much because most of it is in the WM, so the HAZ is dominated by the original properties of copper, which is generally softer than WM.

Overall, this graph demonstrates that the chemical composition of ERCuNi, which includes Copper (Cu) and Nickel (Ni), significantly affects the hardness of the Weld Metal (WM). This effect is primarily attributed to the presence of nickel, which enhances the material's hardness. While higher welding currents may cause slight fluctuations in WM hardness, they still result in higher values compared to the Heat-Affected Zone (HAZ). In conclusion, nickel in the ERCuNi filler rod plays a crucial role in increasing the hardness of the weld, whereas the heat generated during welding primarily reduces the hardness in the HAZ due to its softening effect on the copper structure.

4 Conclusion

Tensile testing indicates that the selection of welding current and filler rod type plays a crucial role in determining the tensile strength of copper welded joints. Each type of filler rod responds differently to variations in current. Pure copper exhibits the highest tensile strength at both low and high currents, while the CuSi-A filler rod achieves its optimal tensile strength at medium currents. In contrast, the CuNi filler rod performs more consistently at low currents but demonstrates a decrease in strength at higher currents. Both welding current and filler rod type significantly influence the strain of the welded joints. The Cu filler rod shows the best strain at low currents, while the CuSi-A filler rod reaches its optimal strain at medium currents but experiences a sharp decline at high currents. Conversely, the CuNi filler rod maintains relatively stable strain across varying currents, although its strain values are lower than those of Cu at low currents. The use of higher currents with ERCuSi-A filler rod leads to decreased hardness in the Heat Affected Zone (HAZ), but results in more complex hardness changes in the Weld Metal (WM), which depend on the interaction between heat and the chemical composition of the filler rod. The presence of nickel in the ERCuNi filler rod increases the hardness of the weld.

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References

[1] Y. Liu *et al.*, "A lightweight and high thermal performance graphene heat pipe," *Nano Sel.*, vol. 2, no. 2, pp. 364–372, 2021.

[2] A. Bryszewska-Mazurek and W. Mazurek, "Experimental investigation of a heat pipe heat exchanger for heat recovery," in *E3S Web of Conferences*, EDP Sciences, 2018, p. 12.

[3] H. Mroue, J. B. Ramos, L. C. Wrobel, and H. Jouhara, "Experimental and numerical investigation of an air-to-water heat pipe-based heat exchanger," *Appl. Therm. Eng.*, vol. 78, pp. 339–350, 2015.

[4] A. Faghri, "Heat pipes: review, opportunities and challenges," *Front. Heat Pipes*, vol. 5, no. 1, 2014.

[5] M. Mahdavi, S. Tiari, S. De Schampheleire, and S. Qiu, "Experimental study of the thermal characteristics of a heat pipe," *Exp. Therm. Fluid Sci.*, vol. 93, pp. 292–304, 2018.

[6] A. Bar-Cohen, K. Matin, N. Jankowski, and D. Sharar, "Two-phase thermal ground planes: technology development and parametric results," *J. Electron. Packag.*, vol. 137, no. 1, p. 10801, 2015.

[7] C. W. Chan, E. Siqueiros, J. Ling-Chin, M. Royapoor, and A. P. Roskilly, "Heat utilisation technologies: A critical review of heat pipes," *Renew. Sustain. Energy Rev.*, vol. 50, pp. 615–627, 2015.

[8] H. Jouhara, A. Chauhan, T. Nannou, S. Almahmoud, B. Delpech, and L. C. Wrobel, "Heat pipe based systems-Advances and applications," *Energy*, vol. 128, pp. 729–754, 2017.

[9] A. Faghri, "Review and advances in heat pipe science and technology," *J. Heat Transfer*, vol. 134, no. 12, p. 123001, 2012.

[10] K. M. Kim, Y. S. Jeong, I. G. Kim, and I. C. Bang, "Development of passive in-core cooling system for nuclear safety using hybrid heat pipe," *Nucl. Technol.*, vol. 196, no. 3, pp. 598–613, 2016.

[11] J. Choi, C. Lim, and H. Kim, "Fork-end heat pipe for passive air cooling of spent nuclear fuel pool," *Nucl. Eng. Des.*, vol. 374, p. 111081, 2021.

[12] M. S. Najiha, M. M. Rahman, and A. R. Yusoff, "Environmental impacts and hazards associated with metal working fluids and recent advances in the sustainable systems: A review," *Renew. Sustain. Energy Rev.*, vol. 60, pp. 1008–1031, 2016.

[13] J. Bao and L. Zhao, "A review of working fluid and expander selections for organic Rankine cycle," *Renew. Sustain. energy Rev.*, vol. 24, pp. 325–342, 2013.

[14] N. N. Babu and H. C. Kamath, "Materials used in heat pipe," *Mater. Today Proc.*, vol. 2, no. 4–5, pp. 1469–1478, 2015.

[15] D. B. Sarraf and W. G. Anderson, "Heat pipes for high temperature thermal management," in *International Electronic Packaging Technical Conference and Exhibition*, 2007, pp. 707–714.

[16] Y. Li, H. He, and Z. Zeng, "Evaporation and condensation heat transfer in a heat pipe with a sintered-grooved composite wick," *Appl. Therm. Eng.*, vol. 50, no. 1, pp. 342–351, 2013.

[17] M. Samiuddin, J. Li, M. Taimoor, M. N. Siddiqui, S. U. Siddiqui, and J. Xiong, "Investigation on the process parameters of TIG-welded aluminum alloy through mechanical and microstructural characterization," *Def. Technol.*, vol. 17, no. 4, pp. 1234–1248, 2021.

[18] S. T. Auwal, S. Ramesh, F. Yusof, and S. M. Manladan, "A review on laser beam welding of copper alloys," *Int. J. Adv. Manuf. Technol.*, vol. 96, pp. 475–490, 2018.

[19] W.-B. Lee and S.-B. Jung, "The joint properties of copper by friction stir welding," *Mater. Lett.*, vol. 58, no. 6, pp. 1041–1046, 2004.

[20] H.-C. Chen, G. Bi, M. L. S. Nai, and J. Wei, "Enhanced welding efficiency in laser welding of highly reflective pure copper," *J. Mater. Process. Technol.*, vol. 216, pp. 287–293, 2015

[21] J.-W. Lin, H.-C. Chang, and M.-H. Wu, "Comparison of mechanical properties of pure copper welded using friction

stir welding and tungsten inert gas welding,” *J. Manuf. Process.*, vol. 16, no. 2, pp. 296–304, 2014.

[22] S. Elangovan, K. Prakasan, and V. Jaiganesh, “Optimization of ultrasonic welding parameters for copper to copper joints using design of experiments,” *Int. J. Adv. Manuf. Technol.*, vol. 51, pp. 163–171, 2010.