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Analysis of the Interface Evolution in 304 Stainless Steel/Copper Dissimilar Welding

KELLAI Ahmed [#1], KABA Liamine[#2], DEHIMI Said[#3], KAHLA Sami[#4], MEBARKI Besma[*5]

[#]*Research Center in Industrial Technologies, P.O. Box 64, 16014 Chéraga, Algiers, Algeria*

[1]a.kellai@crti.dz , kellai.a.a@gmail.com

[2]l.kaba@crti.dz

[3]s.dehimi@crti.dz

[4]s.kahla@crti.dz

[*]*Department of Mechanical Engineering, Faculty of Technology, University of Batna 2, 05000, Algeria*

[5]besma.mebarki@univ-batna2.dz

Abstract— **Dissimilar welding between austenitic stainless steel (ASS) and copper (Cu) is crucial for industrial applications requiring both high corrosion resistance and superior thermal/electrical conductivity, notably in heat exchangers and high-vacuum systems. However, this process presents a significant metallurgical challenge, primarily due to the marked divergence in thermophysical properties and phase incompatibility under melting conditions. This study aimed to characterize the interface of the joint produced by tungsten inert gas welding process (TIG) between austenitic 304 stainless steel and copper Cu-ETP. Microstructural characterization was performed using Optical Microscopy (OM), Scanning Electron Microscopy (SEM), and Energy Dispersive Spectroscopy (EDS), while mechanical properties were assessed via microhardness testing. Results showed a weld bead with a satisfactory appearance and confirmed excellent interfacial adhesion. This success is primarily attributed to the diffusion of copper into the steel's fusion zone, suggesting good atomic integration of the constituent materials. Furthermore, the average microhardness of 103 HV measured in the fusion zone quantitatively confirms the acceptable mechanical properties of the dissimilar joint.**

Keywords— **TIG welding process, austenitic stainless steel, copper, microstructure, mechanical properties**

I. INTRODUCTION

Welding dissimilar materials offers engineers greater design flexibility and significant economic advantages by leveraging the specific characteristics of each material [1]. Among the current areas of research in this field is the welding of copper and stainless steel due to the complementary properties of these materials: the excellent thermal and electrical conductivity of copper and the mechanical strength of stainless steel [2], [3], [4]. These assemblies are essential in various industrial applications, including heat exchangers, fusion reactors, electronics, and chemical processing. However, welding these dissimilar metals presents significant challenges due to their different physical and metallurgical properties [5], [6], [7], such as dissimilar melting points, different thermal expansion coefficients, and the risk of forming a brittle interface at the weld interface, which requires a thorough understanding and continuous development of welding techniques. Recent research aims to overcome these obstacles, with the goal of improving the quality of welded joints and ensuring their long-term reliability under harsh operating conditions [6], [8], [9].

Laser welding is a powerful technique despite the risk of liquid phase separation and micro-cracking that it can induce [10], [11], [12]. However, studies have shown that shifting the beam toward stainless steel can generate joints without defects and with good properties [4], [6]. Similarly, electron beam welding (EBW) is known for its deep penetration and reduced heat-affected zone (HAZ), although it can cause heterogeneous microstructures and porosity [13]. Beam displacement has proven to be a flexible parameter, essential for improving joint characteristics [14]. Among the processes also used, friction stir welding (FSW) stands out as a techno-economic method that completely avoids fusion defects. However, the choice of tool material and spindle offset are crucial for the success of the process [15]. In addition, gas tungsten arc welding (GTAW/TIG) has been the subject of extensive research using different filler metals to create defect-free joints, although tensile strength can sometimes be lower [16]. The objective of this work is to study the interface between 304 austenitic stainless steel and copper during dissimilar TIG welding.

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II. MATERIALS AND METHODS

The experimental setup is shown in Figure 1. It consists of a Miller Dynasty 350 TIG generator equipped with an AC/DC power control system, connected to an inert gas cylinder (99.95% pure argon) to protect the weld fusion zone, as well as another inert gas cylinder (industrial argon) for reverse protection. The materials used in this study are Cu-ETP copper sheets and 304 austenitic stainless steel. The dimensions of these samples are 150 x 150 x 2 mm. The filler metals used were ER309 austenitic stainless steel. The chemical composition of these materials is shown in Table I.

Before welding, the edges of the sheets to be joined are mechanically prepared. This involves thorough cleaning with a stainless steel wire brush to remove any surface contamination (oxides, grease, impurities, etc.) that could affect the quality of the weld. The sheets are then positioned end to end and spot welded to ensure precise alignment and maintain the desired gap. The welding parameters are shown in Table II. After welding, a representative sample is taken for detailed micrographic analysis. Preparing this sample involves rigorous mechanical polishing until a mirror-like surface is obtained. The sample is then subjected to a controlled chemical etching using a Glyceregia solution, composed of 10 ml of nitric acid ($HNO3$), 20 to 50 ml of hydrochloric acid (HCl), and 30 ml of glycerol. This selective etching highlights the different phases and microstructural constituents for microscopic observation.

The welded joint was analyzed using a Nikon optical microscope and a scanning electron microscope. The distribution of chemical elements in the interface was determined using EDS techniques. To study the mechanical properties, we used a BUEHLER LTD microhardness tester with a pitch of 0.5 µm and a load of 500 g.

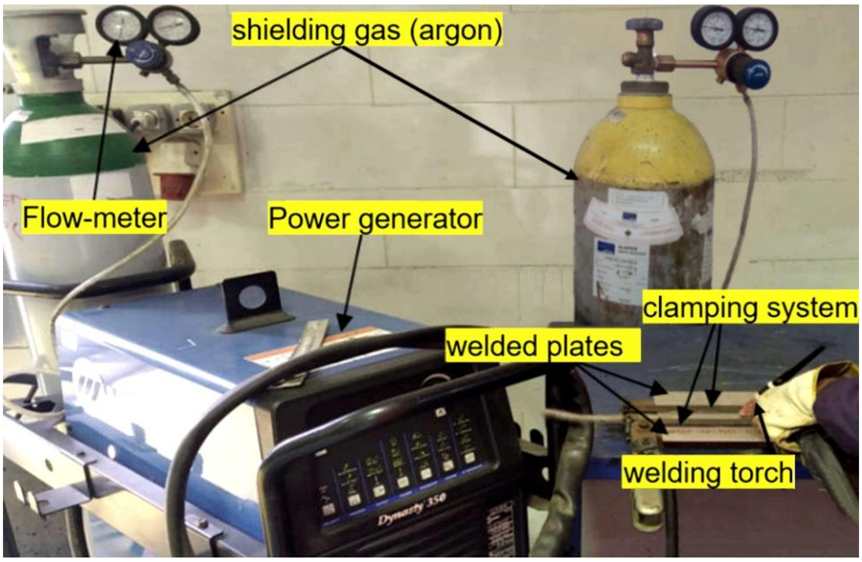

Fig. 1 Experimental set-up

TABLE I
CHEMICAL COMPOSITION OF BASE METALS AND FILLER METAL

Material		**Al**	**Si**	**Cu**	**Cr**	**Mn**	**Co**	**O**	**Ni**	**P**	**C**	**Fe**
Base metal	**304**	0.18	0.37	--	16.43	2.97	0.71	--	9.49	0.04	0.004	Bal.
	Cu-ETP	--	--	99.95	--	--	--	0.004	--	--	--	--

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Filler metal	**ER309**	--	0.46	--	22.25	1.89	--	--	14.15	--	0.19	Bal.

TABLE III

THE WELDING PARAMETERS

Gas flow rate Q_{up} (l/min)	**Gas flow rate Q_{down}(l/min)**	**Current I(A)**	**Voltage U(V)**	**Speed S(mm/s)**	**Energy H(J/mm)**
10	10	110	12	2.47	534.42

III. RESULTS AND DISCUSSION

Figure 2 illustrates the visual appearance of the weld bead on the top and bottom surfaces of the joint. The bead has a uniform, high-quality appearance, with an average width of approximately 10 mm.

(a) top face (b)) bottom face

Fig. 2 Visual appearance of the weld joint

Figure 3 illustrates the microstructure of the different weld zones. The fusion zone (FZ) exhibits a microstructure produced by liquid-solid solidification, characterized by equiaxed dendritic grains. In contrast, the heat-affected zone (HAZ) undergoes a solid-state transformation, resulting in a microstructure characterized by large grains with twins [2], [9], [10].

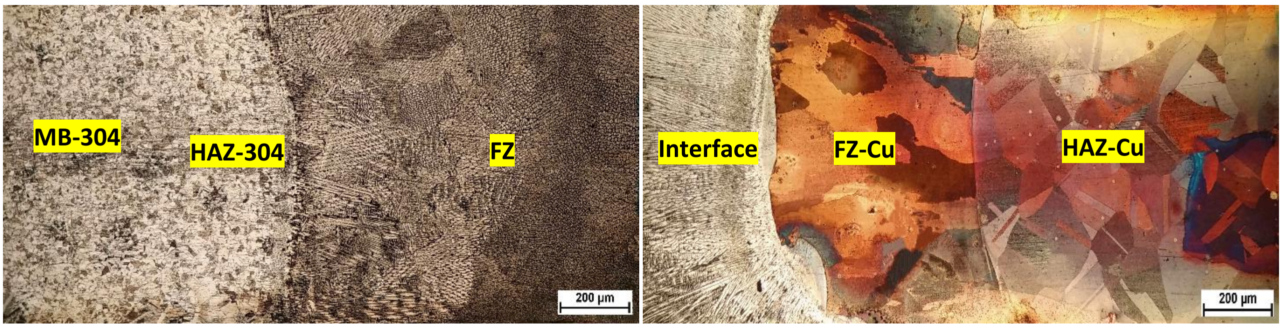

Fig. 3 Optical micrograph of the different areas of the weld joint

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Fig. 4 shows an SEM micrograph and EDS analysis of the distribution of chemical elements at the interface between copper and stainless steel. The SEM micrographs and EDS analysis show a map of the distribution of chemical elements at the interface, with copper-rich grain boundaries. For the base metal BM, the figure shows a structure characterized by coarse polyhedral grains with twins.

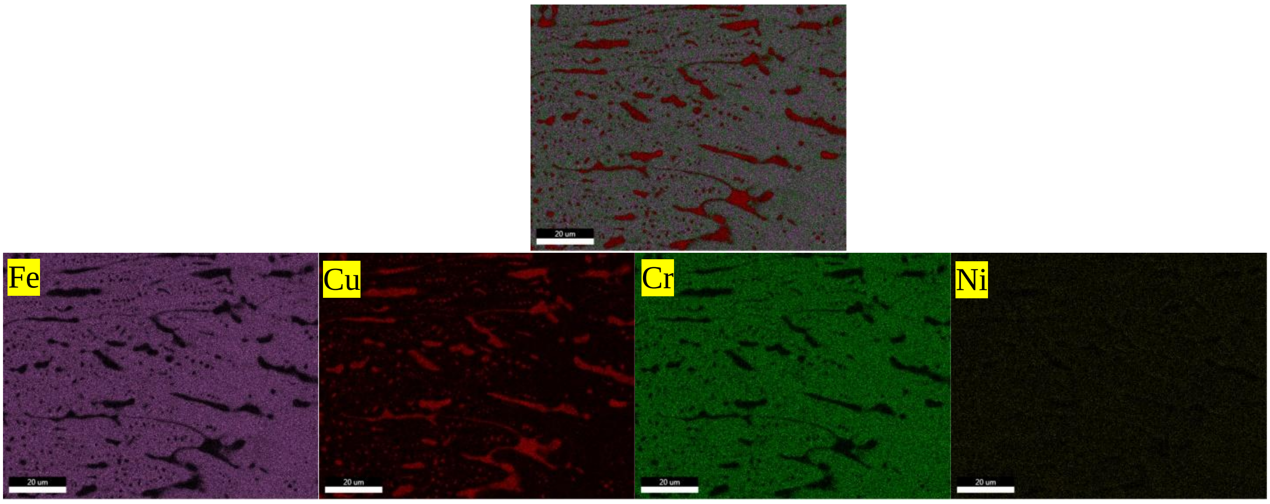

Fig. 4 SEM micrograph and EDS analysis of the copper-stainless steel interface

Fig. 5 illustrates the microhardness profile across the different zones of the dissimilar Cu-304 weld. The fusion zone exhibits a higher average microhardness of 165.9 HV compared to both the copper base metal (47.76 HV) and the 304 stainless steel base metal (156.92 HV). This elevated hardness is attributed to two primary factors: microstructural refinement and the formation of a composite structure. The efficient intermixing of the two base materials during welding promotes the growth of a fine-grained microstructure, which consequently increases hardness. Furthermore, the development of a composite structure characterized by cellular and columnar dendrites within the weld zone also contributes significantly to this observed increase in hardness [15], [16], 17].

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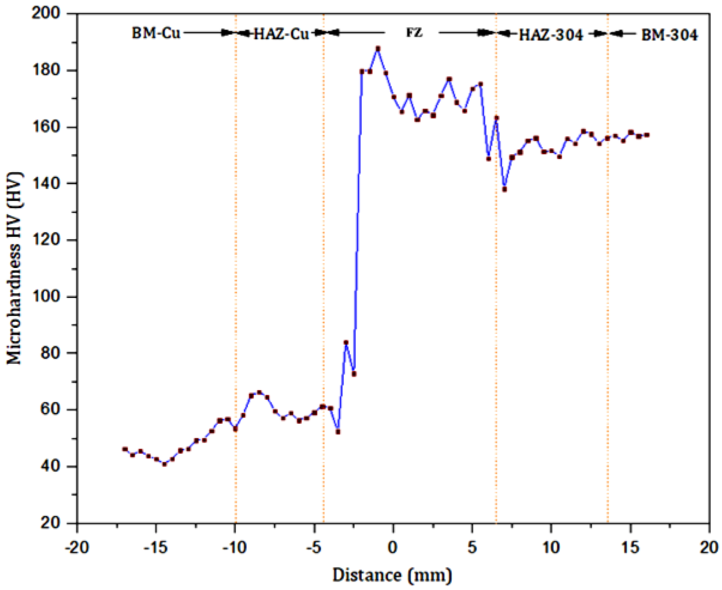

Fig. 5 Microhardness profile

IV. Conclusions

Based on the findings of this work, the following conclusions can be drawn:

1. The chosen welding parameters produced a high-quality weld, characterized by a good appearance and satisfactory penetration.
2. Metallurgical analysis, using SEM micrographs and EDS, revealed a distinct interface between the stainless steel and copper, where grain boundaries were enriched with copper.
3. The homogeneous intermixing of the base metals facilitates grain refinement in the fusion zone, which is the primary factor leading to the increased mechanical hardness.

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