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Microstructural aspects in Al-Cu dissimilar joining by FSW

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Abstract:	Sound AA2024-T3 - Cu10100 dissimilar joints were obtained by friction stir welding offsetting the tool pin towards the aluminum sheet and employing selected processing parameters. Joint microstructure was analyzed by means of conventional optic microscopy as well as scanning electron microscopy. The weld bead exhibited welding zones and some features typically encountered in similar FSW. The nugget zone consisted of a mixture of recrystallized aluminum matrix and deformed and twinned copper particles. Onion rings and particles-rich zones, made of Cu particles dispersed in the Al matrix, were also observed. EDS analysis revealed that several Al-Cu intermetallic compounds, such as Al2Cu, AlCu, and Al3Cu4, chemically different w.r.t. compounds precipitated during the T3 aging treatment (Al3Cu), were formed during the process. Microstructure variation significantly affects the microhardness distribution in the cross section of the joint.
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Cover Letter
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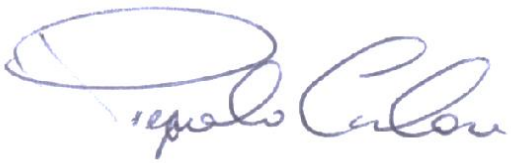
Dear Editor,

Please find enclosed our manuscript, "Microstructural aspects in Al–Cu dissimilar joining by FSW" by Pierpaolo Carlone, Antonello Astarita, Gaetano S. Palazzo, Valentino Paradiso, Antonino Squillace, which we would like to submit for publication as an original research paper in International Journal of Advanced Manufacturing Technology.

Although the Friction Stir Welding process has been/is the subject of very intensive researches and several reports, mostly dealing with similar aluminum joining, are already available in the literature, very few investigations are focused on the dissimilar joining of aluminum alloy to copper by FSW. To our best knowledge, this is the first work detailing the application of the process to join AA2024-T3, which is widely used for aeronautical applications, to Cu10100. In particular, attention was focused on some microstructural aspects inherent the welding zone. Taking into account the novelty of the work and the interest in the considered materials, we are confident that the paper would appeal to the industrial as well as academic readership of International Journal of Advanced Manufacturing Technology.

We confirm that this manuscript has not been published, accepted, or submitted for publication elsewhere. No earlier version of this paper has been presented elsewhere. No other paper has been published using the same data set.

Best Regards,



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Microstructural aspects in Al–Cu dissimilar joining by FSW

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Abstract.

Sound AA2024-T3 – Cu10100 dissimilar joints were obtained by friction stir welding offsetting the tool pin towards the aluminum sheet and employing selected processing parameters. Joint microstructure was analyzed by means of conventional optic microscopy as well as scanning electron microscopy. The weld bead exhibited welding zones and some features typically encountered in similar FSW. The nugget zone consisted of a mixture of recrystallized aluminum matrix and deformed and twinned copper particles. Onion rings and particles-rich zones, made of Cu particles dispersed in the Al matrix, were also observed. EDS analysis revealed that several Al-Cu intermetallic compounds, such as Al_2Cu, AlCu, and Al_3Cu_4, chemically different w.r.t. compounds precipitated during the T3 aging treatment (Al_3Cu), were formed during the process. Microstructure variation significantly affects the microhardness distribution in the cross section of the joint.

Keywords: friction stir welding, dissimilar joint, AA2024-T3, Cu10100, microstructure, EDS

1. Introduction

Dissimilar joining of aluminum to copper is gaining a great deal of attention in several applicative sectors. The intriguing advantages achievable in terms of weight saving and cost reduction make this combination of materials very appealing for the chemical, aerospace, transportation, and electronics industries [1-3]. Due to the difficulties in making an electrically stable bolted hybrid joint, much effort has been focused on welding aluminum to copper in the last decades [4].

Previous literature [5] pointed out that the joining of such dissimilar materials by fusion welding processes is quite challenging due to their different chemical, mechanical, thermal properties. The melting points of aluminum and copper differ of about nearly 400 °C. This may result in remarkable non-homogeneities in the microstructure of the adjoined materials, negatively affecting the overall joint performance. Indeed, aluminum is easily oxidized at elevated temperatures, and welding cracks are commonly detected in brazed or fusion welded Cu joints [6]. What is more, during fusion welding or pressure welding (brazing, diffusion bonding, etc) of Cu/Al some issues concerning the formation of hard and brittle intermetallic compounds (IMCs) in large scale at weld interface were pointed out by the experimental analysis reported by Liu et al. [7]. These IMCs could lead to a decreasing of the mechanical properties of the entire joint [8].

In recent years, solid-state joining techniques, such as friction welding, roll welding, and explosive welding have received much interest for such applications [9-11]. Among others, a great deal of attention is directed towards the friction stir welding process (FSW). Some researchers studied the FSW of Al-Cu dissimilar joints, focusing on pure aluminum and cast aluminum alloys [12]. The literature converges on two general aspects: i. sound dissimilar FSW Al–Cu joints are difficult to achieve and ii. a key role is played by the brittle IMCs formed in the nugget zone (NZ). According to the experimental analysis performed by Murr et al. [3], Al–Cu joints generally fail at the NZ or along the interface between the two materials during the mechanical tests [13]. Ouyang et al. [1] attributed the poor weldability to various brittle IMCs formed in the NZ. Lee and Jung [14] suggested that the formation of Al_2O_3 and CuO layers resulted in lower tensile strength attributable

to the presence of brittle IMCs. In a previous study [15], sound FSW Al–Cu joints were obtained by offsetting the tool to the aluminum side under a lower heat input condition. The formation of a thin, continuous and uniform IMCs layer created an excellent metallurgical bonding at Al–Cu interface, and no oxide layer was found. It is well documented that several parameters, such as tool offsetting, rotation rate and traverse speed, influenced the weld properties of the dissimilar FSW joints [16–19]. Despite the number of articles available on this topic there are very few papers dealing with the dissimilar welding between copper and the high strength aluminum alloys, such as 2XXX (Al-Cu) series. In particular the AA2024 Al-Cu alloy is widely used for structural application in aeronautics [20,21]. Due to the presence of copper precipitates at the grain boundaries, this alloy is expected to easily form IMCs with the copper during the FSW process. Moreover its hardening mechanism is based on the formation of Al-Cu precipitates (in particular Al_3Cu) in the Al lattice, preventing the dislocations migration and enhancing the mechanical properties [22]. This paper studies the dissimilar joining by FSW between pure copper (Cu10100) and the high strength aluminum alloy AA2024-T3. Due to the aforementioned reasons, the AA2024 – Cu10100 joining by FSW is expected to produce a weld bead with a very complex metallurgy. The aims of this paper are to prove the capability of the FSW process to provide sound joints and to study the microstructure and the metallurgy of the joint.

2. Experimental

AA2024-T3 rolled sheet and pure Cu10100 rolled and cold drawn sheet were used as base material. The chemical composition and the main mechanical properties of the two alloys are fully available elsewhere [23,24] and are not reported here in the interest of brevity. The in plane dimensions of the adjoined sheets were 120 mm x 30 mm, while thickness was 2 mm. AA2024 sheet was fixed in the advancing side of the joint and the tool was displaced towards the aluminium side (i.e. the harder material) of a predefined offset. A scheme of the welding configuration, including also a detail of the tool, is provided in figure 1.

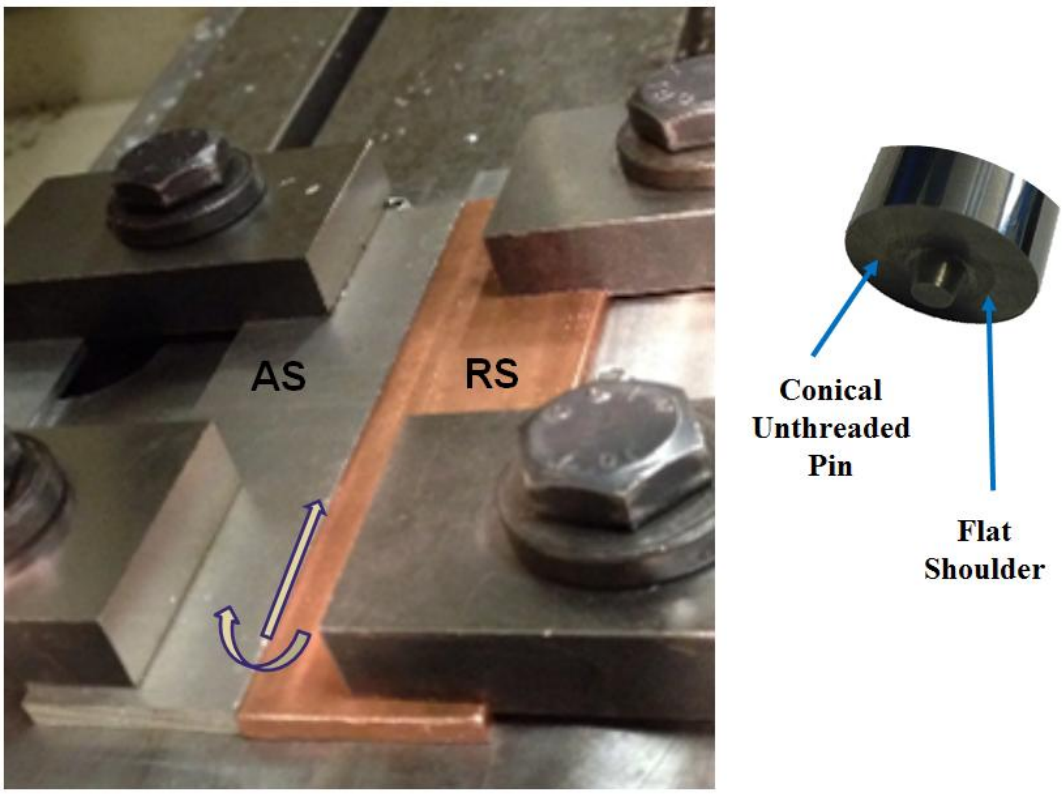

Fig. 1 FSW process setup and tool.

Non-consumable tools, made of Cr-Mo steel, were used to fabricate the joints. Tool geometry is characterised by a shoulder diameter of 20 mm and by an unthreaded conical pin with 5.2 mm major diameter, 15° cone angle and 1.8 mm length. The forging action of the tool shoulder was enhanced imposing a tilt angle of 2°. The plates were welded using a machining centre MCX 600 ECO. Process parameters were chosen on the basis of the available literature and comparing the process windows obtained welding singularly AA2024-T3 and Cu10100 [25,26]. Furthermore, a preliminary test campaign was performed by trial and error before the achievement of material continuity. The employed parameters are given in table 1.

Table 1 – FSW process parameters.

Rotational speed (rpm)	Welding speed (mm/min)	Tilt angle (°)	Tool offset (mm)
1000	80	2	1.3

The welding process was carried out following plunging, dwelling, and welding phases. The feed rate of the tool along the vertical axis during the plunging phase was set as 5 mm/min, while the duration of dwell was set as 10 seconds. Three different joints were carried out in order to ensure the repeatability of the process. The microstructure of the joint was studied through metallographic observations by means of both light optical microscope and scanning electron microscope (SEM). Moreover, chemical composition measurements were carried out through an EDS probe to study the IMCs generated by the welding process. In more details, each specimen was cold mounted in a proper thermoset resin and polished with grinding discs (P320, P600, P1200, P2000) and polycrystalline diamond suspension (3μm) on tissue disc until the surface exhibited a mirror like finish. Afterward, the samples were etched by a modified Keller's reagent (150 ml H_2O, 2 ml HNO_3, 6 ml HCl, 6 ml HF) to unveil the significant features of the aluminium metallurgical microstructures. The same procedure has been repeated to investigate the copper microstructures using a solution of 30 ml HCl, 40 ml HNO_3, 2.5 ml HF, 12 g C_2O_2 and 42.5 ml H_2O. Optical observations were performed using a metallurgical microscope equipped with a Nikon digital camera to evaluate the weld bead morphology. SEM observations and EDS measurements were carried out through an Hitachi TM3000 table top SEM equipped with a National Instruments EDS probe. Vickers micro hardness was measured in the cross section of the joint by means of a LEICA VMHT AUTO machine in order to assess the influence of the microstructure on the mechanical properties of the joint itself. Three linear patterns, orthogonal to the weld line, were programmed, respectively at the mid-thickness of the joint cross section and at a distance equal to 0.5 mm toward the top and bottom surfaces. The following parameters were adopted: distance between two consecutive indentations 1 mm, indentation load 50 gf (0.49N), loading time 15 sec, and indentation speed 60 μm/sec.

3. Results and discussion

The surface morphology of the joint is shown in Figure 2. Sound weld surfaces were achieved

adopting the aforementioned welding configuration and parameters. In this regard, it is worth to point out that in preliminary FSW tests, tunnel defects, as well as surface defects (i.e. groove, flash, instability of the welding path), were observed reverting the position of the two sheets even reducing the welding speed. Figure 2 shows also the cross-sectional macrograph obtained after etching. Satisfactory material continuity was exhibited in the weld bead. The stirring experienced by the material during the process is well appreciable in the same figure. As can be seen, copper experienced a higher deformation than aluminum. Indeed, the softened copper, stirred by the pin action, penetrates into the aluminum sheet. The plastic flow of the copper is clearly evident looking at the remixed copper hook in Figure 2, creating a sort of mechanical bond between the two materials. This allows affirming that fixing the harder plate (AA 2024 in this study) in the advancing side of the joint during dissimilar FSW is one of the key factors providing sound weld quality.

The following explanation is provided. During FSW process, adjoining material is transferred from the retreating side to the advancing side behind the pin, where the weld bead is formed [27,28]. When the softer material is fixed at the retreating side, it is easily forced towards the advancing side. Being the hardness of the AA2024 higher than that of the Cu10100, an enhanced material flow in the soft copper base is reasonably expected [29]. What is more, previous studies indicated that the weld quality in dissimilar FSW joints is strongly influenced by the offsetting of the pin [30]. Similar considerations apply to other materials pairs. For instance, Watanabe et al. [17] reported that long crack line was observed on the crown of FSW Al-Fe joints when the Fe (i.e. the harder material) was fixed in the retreating side, and sound weld surface could be obtained in reversed fixing conditions.

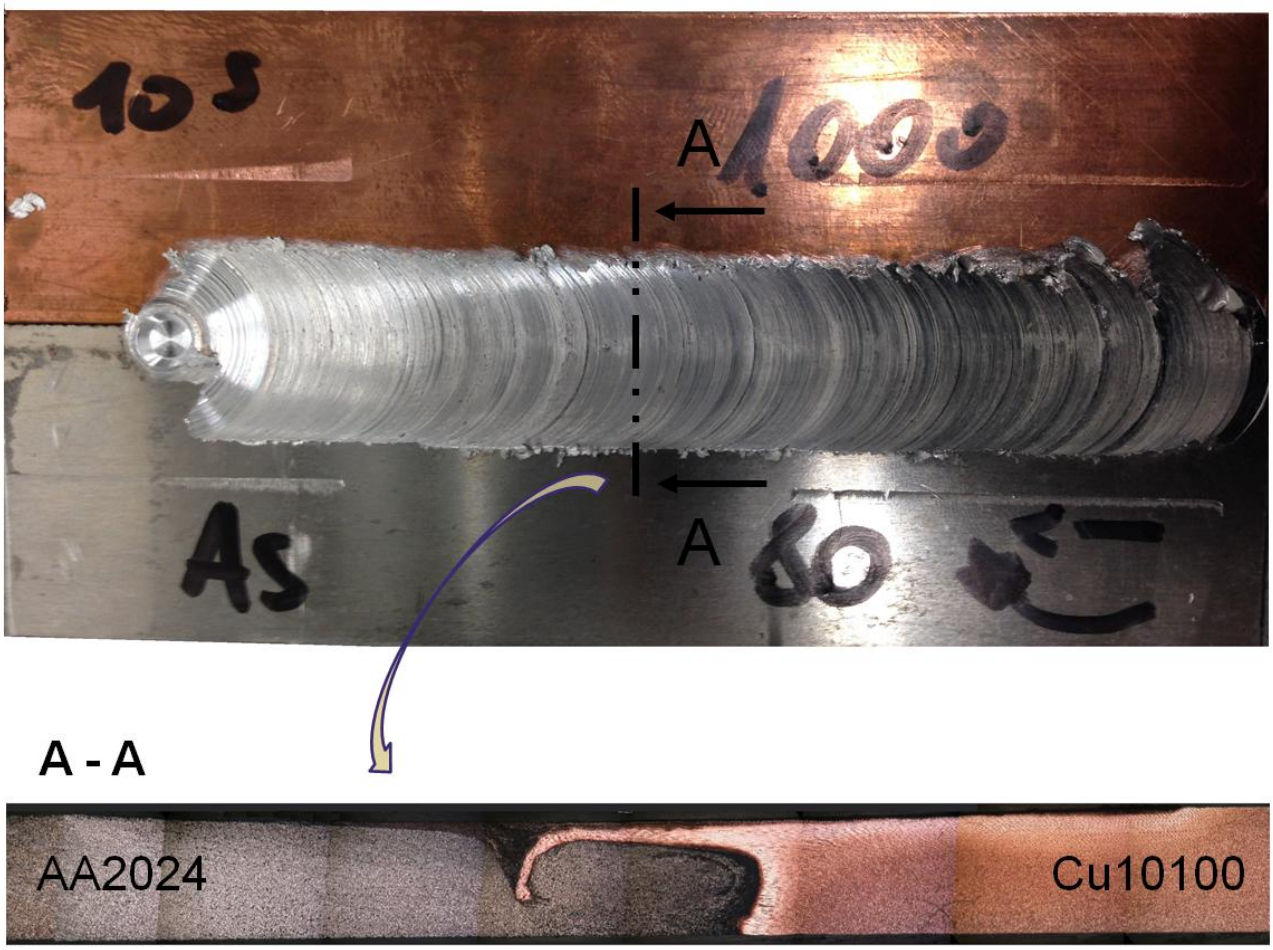

Fig. 2 Surface morphology of the joint (top) and cross section macrograph of the joint (bottom).

Figure 3 shows the SEM macroscopic appearance and microstructures of the Al–Cu joint. The NZ consists of a mixture of aluminum matrix and Cu particles. Many fine particles with various sizes and irregular shapes were dispersed in the Al matrix; large particles were also observed. The distribution of Cu particles appeared inhomogeneous in the NZ and a particles-rich zone (PRZ) was also detected near the bottom. Thus, the NZ can be considered an aluminum matrix composite with both Cu particles and Al-Cu intermetallic dispersed within. The presence of this structure is attributable to the stirring action of the tool pin, which scraped Cu pieces from the bulk copper, breaking up and dispersing them during FSW process. Typical onion rings, made of Cu particles dispersed in the Al matrix, were also detected. Intriguingly, a remixing zone (RZ) resembling the typical thermo-mechanically affected zone (TMAZ) zone observed in similar FSW butt joints was

individuated (Figure 3) and related to diffusion phenomena induced by thermo-mechanical loads experienced by the adjoining materials.

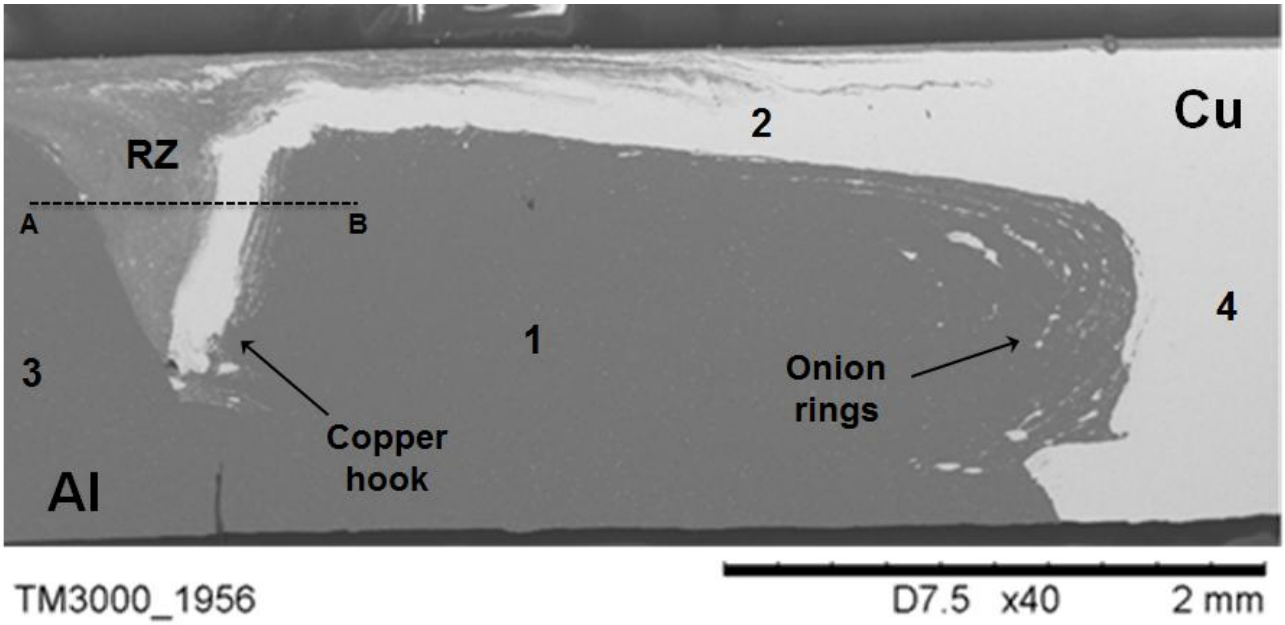

Fig. 3 SEM macrograph of the cross section of the weld bead.

In Figure 4, microstructures observed in the stirred materials (points 1 and 2, as indicated in Figure 3) as well as in the undeformed base materials (point 3 and 4, as indicated in Figure 3) are reported. Figure 4.1 depicts the microstructure in the NZ. In this zone, due to the thermo-mechanical action of the tool, the microstructure was fully recrystallized resulting in the fine equiaxial grains with average grain diameter equal to 30 μm. In figure 4.2 the microstructure observed in the point 2 of figure 3 is reported. In these zone copper experienced a severe plastic flow but the heat input was too low to achieve a fully recrystallization. As a consequence, the mean grain dimension was similar to the one of the parent material, with an average diameter of approximately 50 μm. However, the stirring effect induced very deformed and twinned grains, characterized by low defined borders. Concerning the Al in the zone external to the weld bead (Figure 4.3), it is appreciable the typical microstructure of the rolled AA2024 after the T3 aging treatment. Pancake elongated grains were exhibited, with the presence of the Al_3Cu precipitates. Moreover second phase black particles were also visible, exhibiting typical composition encountered in 2XXX aluminum alloys (that is rich in

Fe, Cu, Mg, and Mn). The microstructure of the Cu10100, externally to the stirred zone, showed the typical features induced by the cold drawing process, with the presence of some deformed grains (Figure 4.4).

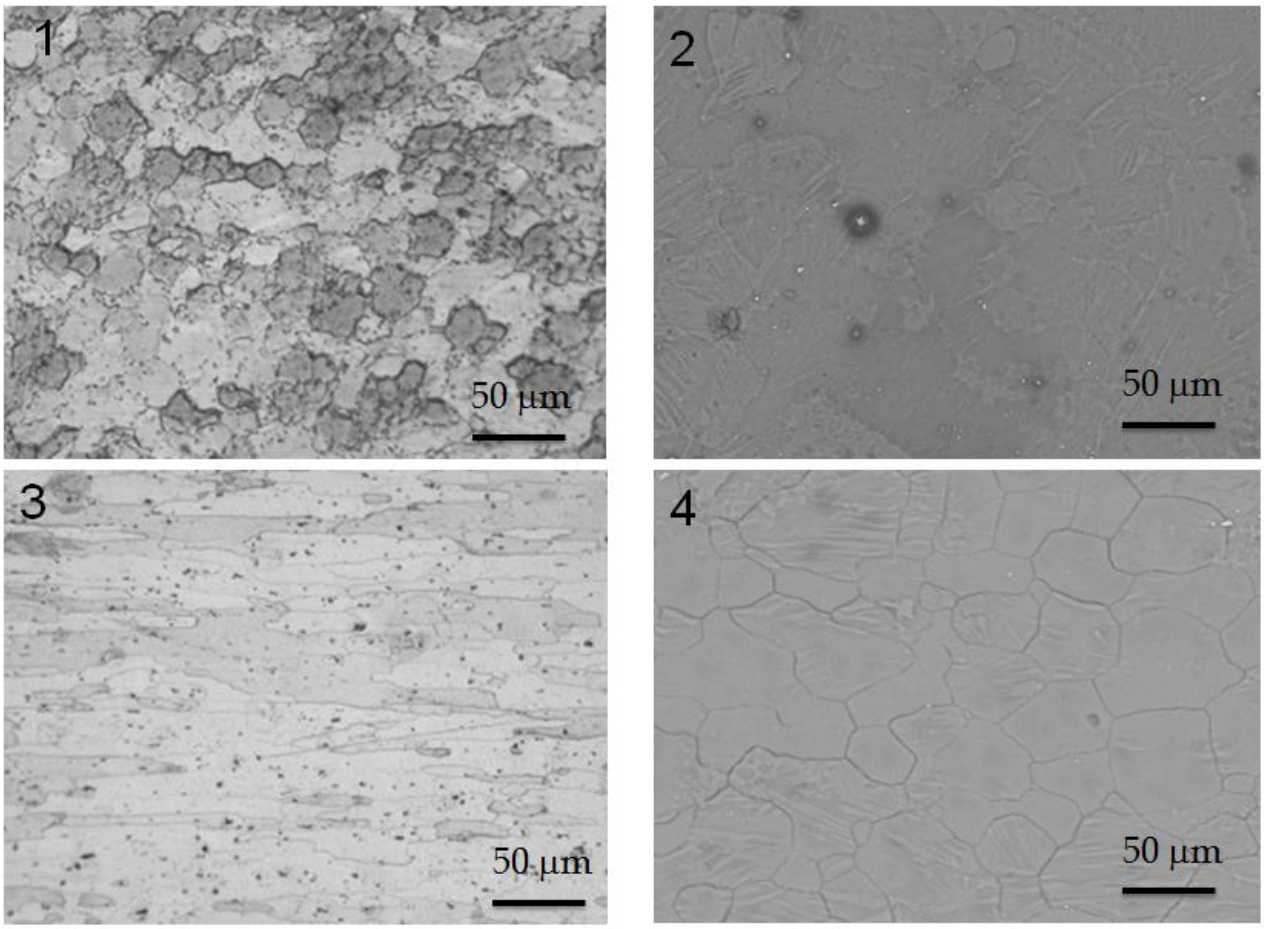

Fig. 4 Microstructure of joint: NZ (1); deformed Cu (2); undeformed AA2024-T3 (3); undeformed Cu10100 (4).

As far the IMCs precipitation is regarded, according to the Al–Cu binary equilibrium phase diagram [31], several Al–Cu particles, including Al_2Cu, AlCu, Al_3Cu_4, may be developed during the Al/Cu process induced reaction. Some studies indicated that Al-rich phase Al_2Cu and Cu-rich phase Al_4Cu_9 were the first two IMCs formed adjacent to Al side and Cu side, respectively [32-34]. However, it should be borne in mind that the AA2024 base material used in this work was rich of Al_3Cu precipitates due to the T3 heat treatment, so it is important to distinguish these particles from IMCs

developed during the welding process. The presence of the above cited IMCs in the NZ was clearly highlighted by EDS measurements. As aforementioned, these particles affect the mechanical behavior of the joint [35,36]. The EDS analysis also confirmed that these particles differ from the ones precipitated during the heat treatment. In Figure 5 a magnification of the PRZ zone is reported, showing several Cu particles dispersed in the aluminum matrix. The chemical composition of these particles (Al_2Cu, AlCu, Al_3Cu_4), given in table 2, evidently differs from the one exhibited by Al_3Cu particles precipitated during the ageing phase of the heat treatment.

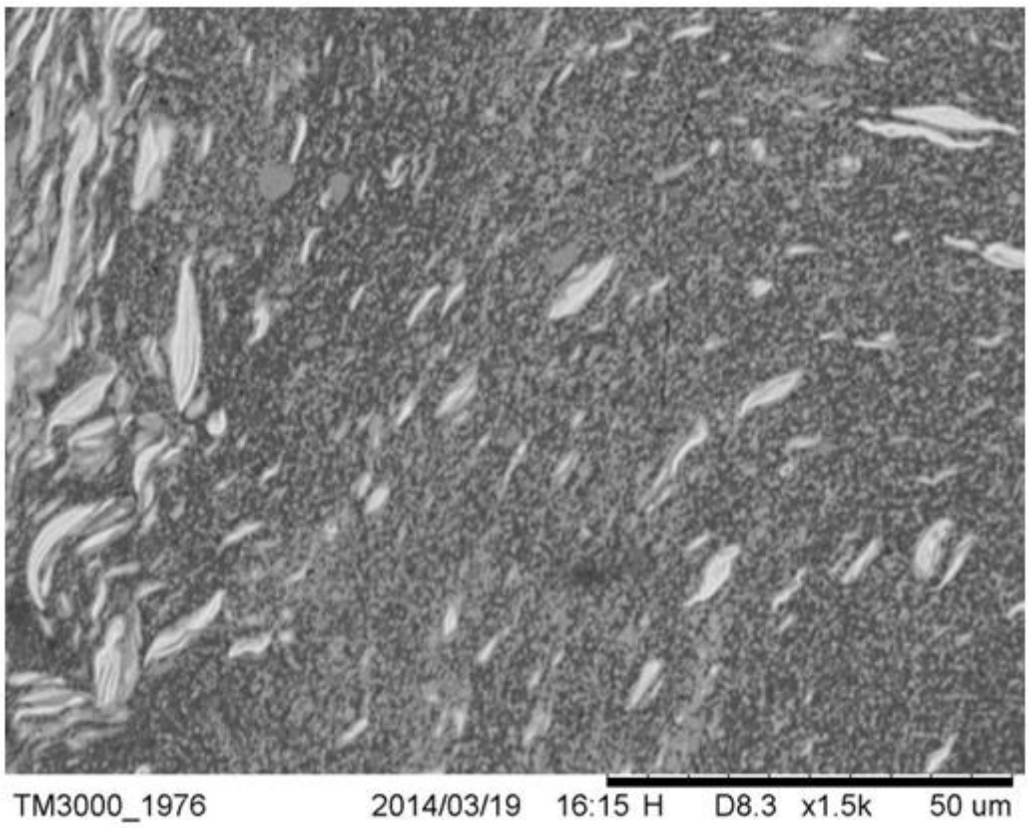

Fig. 5 Magnification of the PRZ zone (Cu particles are brighter than the Al matrix).

Table 2 – Chemical composition of IMCs precipitated during FSW process and detected in the NZ

IMC	Al (%)	Cu (%)
AlCu	52	48
Al_2Cu	65	35
Al_3Cu_4	42	58
Al_3Cu	76	24

Figure 6 shows aluminum and copper intensity, as measured through EDS analysis, along the scan line AB, as depicted in Figure 4. Please note that intensity values were normalized for both elements with respect to the maximum peak intensity in order to improve the readability of the plot. The variability of the presence of aluminum and copper can be well appreciated, confirming that in this zone the stirring action induced an intimately remixing between the two materials and a quite non-homogeneous microstructure. More specifically, at the beginning of the scan line, in correspondence of the undeformed aluminum, the chemical composition reflects the typical AA2024 one. Al percentage gradually drops with a contemporary increase of the Cu percentage approaching the RZ. Some abnormal peaks in the copper profile evidence the presence of large copper particles or lamellae dispersed in the aluminum. Then, a segment characterized by the predominant presence of copper is encountered, corresponding to the copper hook. As shown, the aluminum content completely vanishes, confirming that this hook was roughly created by the copper stirred and deposed on the advancing side of the weld. Beyond this formation, Al content increases and Cu content decreases following a marked oscillating behavior, resembling sort of a layered Al-Cu deposition. Finally, in the NZ, aluminum content results minor with respect to the parent material, due to the copper particles dispersed therein.

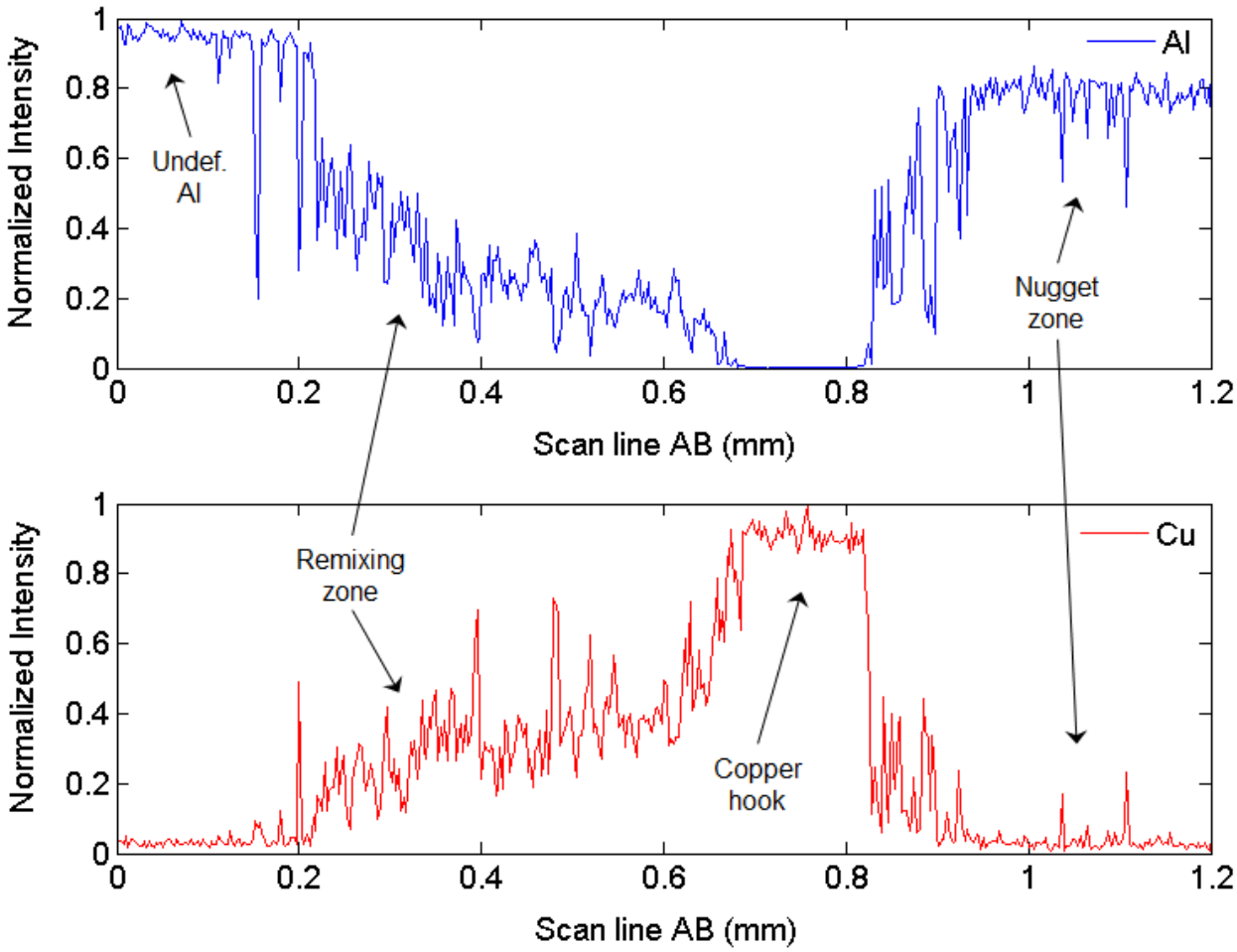

Fig. 6 Al and Cu intensity, as measured along the line AB depicted in Figure 4

In figure 7 a micrograph of transition zone in the retreating (copper) side is reported. Some cracks due to the stirring and scratching action of the pin are appreciable. As generally accepted, the presence of these cracks reduces the mechanical properties of the joint, however it is generally considered a peculiar feature of this kind of dissimilar joints [16].

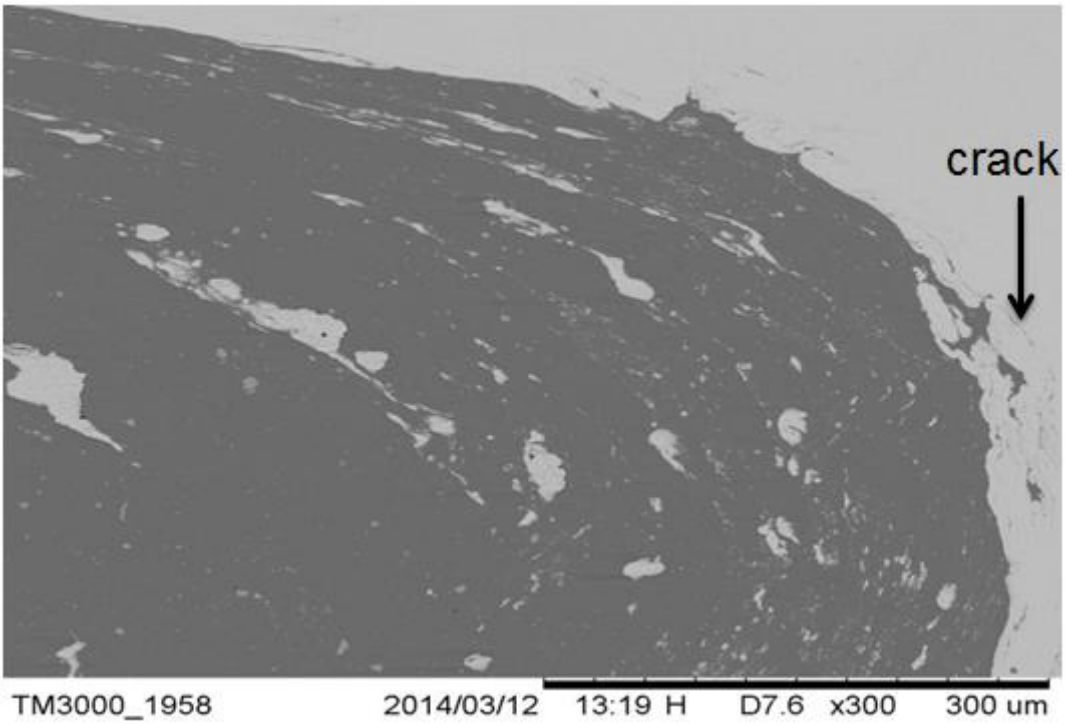

Fig. 7 Interface between AA2024 and Cu10100 (copper is the brighter)

The micro hardness distribution mapped in Figure 8 highlights the influence of the process induced microstructure on the local mechanical properties of the joint. The transition between the AA2024 base material and the Cu10100 base material is clearly visible in correspondence of the weld line. A sharp micro hardness increase was evaluated in the NZ. Despite of the grain refinement, micro hardness values minor than the base material were exhibited, due to the copper particles dispersed within. Some peaks were also measured, attributable to the intermetallic particles observed in the joint.

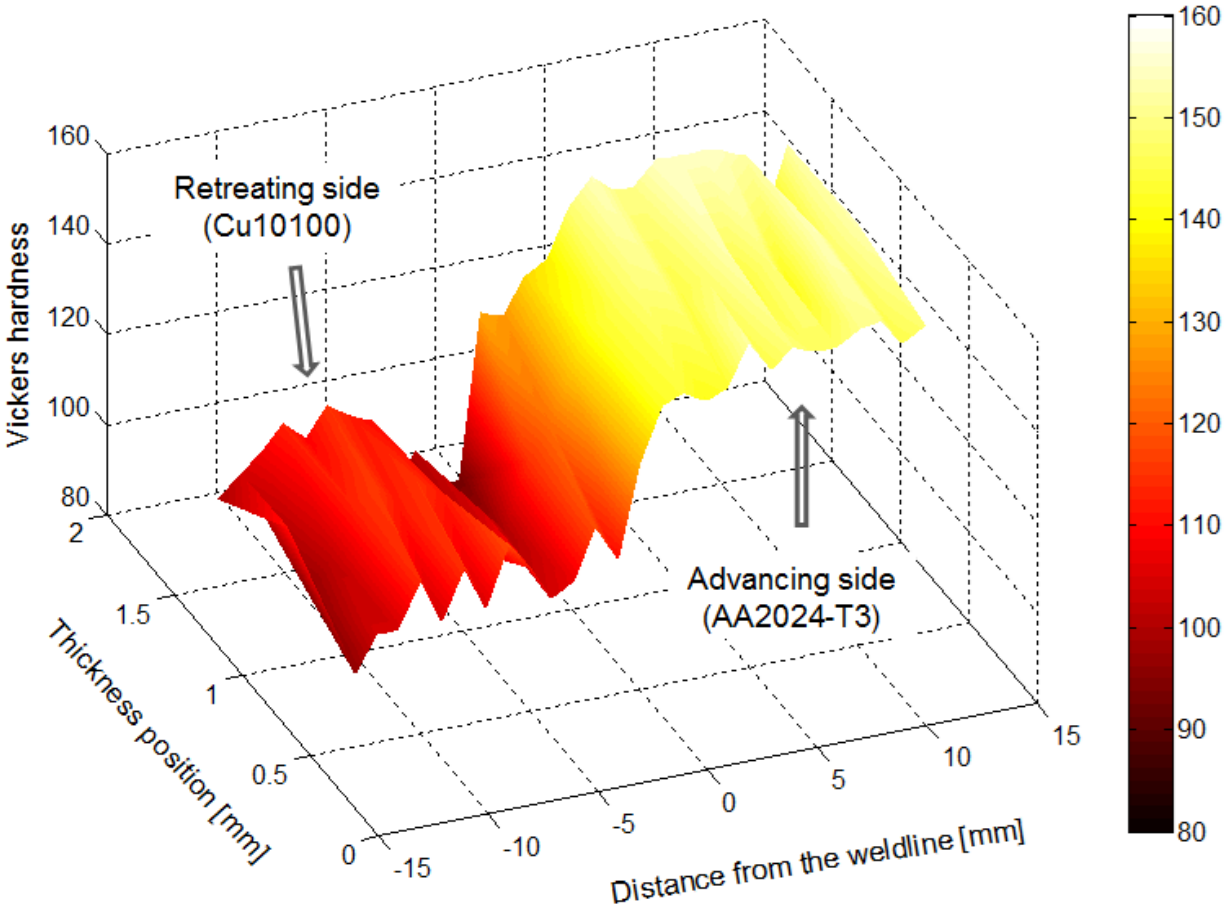

Fig. 8 Microhardness map in the weld bead.

4. Conclusions

On the basis of the experimental campaign carried out the following consideration could be drawn:

– sound AA2024-Cu10100 joints can be obtained by FSW offsetting the pin towards the aluminum side and fixing the copper in the retreating zone;

– the final microstructure exhibits typical FSW features. The NZ consists of a mixture of recrystallized aluminum matrix and deformed/twinned copper particles, resembling an aluminum matrix composite. The distribution of Cu particles with irregular shapes and various sizes appeared inhomogeneous in the NZ, with the formation of a particles-rich zone near the bottom. Onion rings, made of Cu particles dispersed in the Al matrix, were also observed.

– Al–Cu IMCs, namely Al_2Cu, AlCu, and Al_3Cu_4, were developed during the welding process, in accordance with the Al–Cu binary equilibrium phase diagram.

– a sharp microhardness increase was measured in the NZ, consistently with the observed microstructure.

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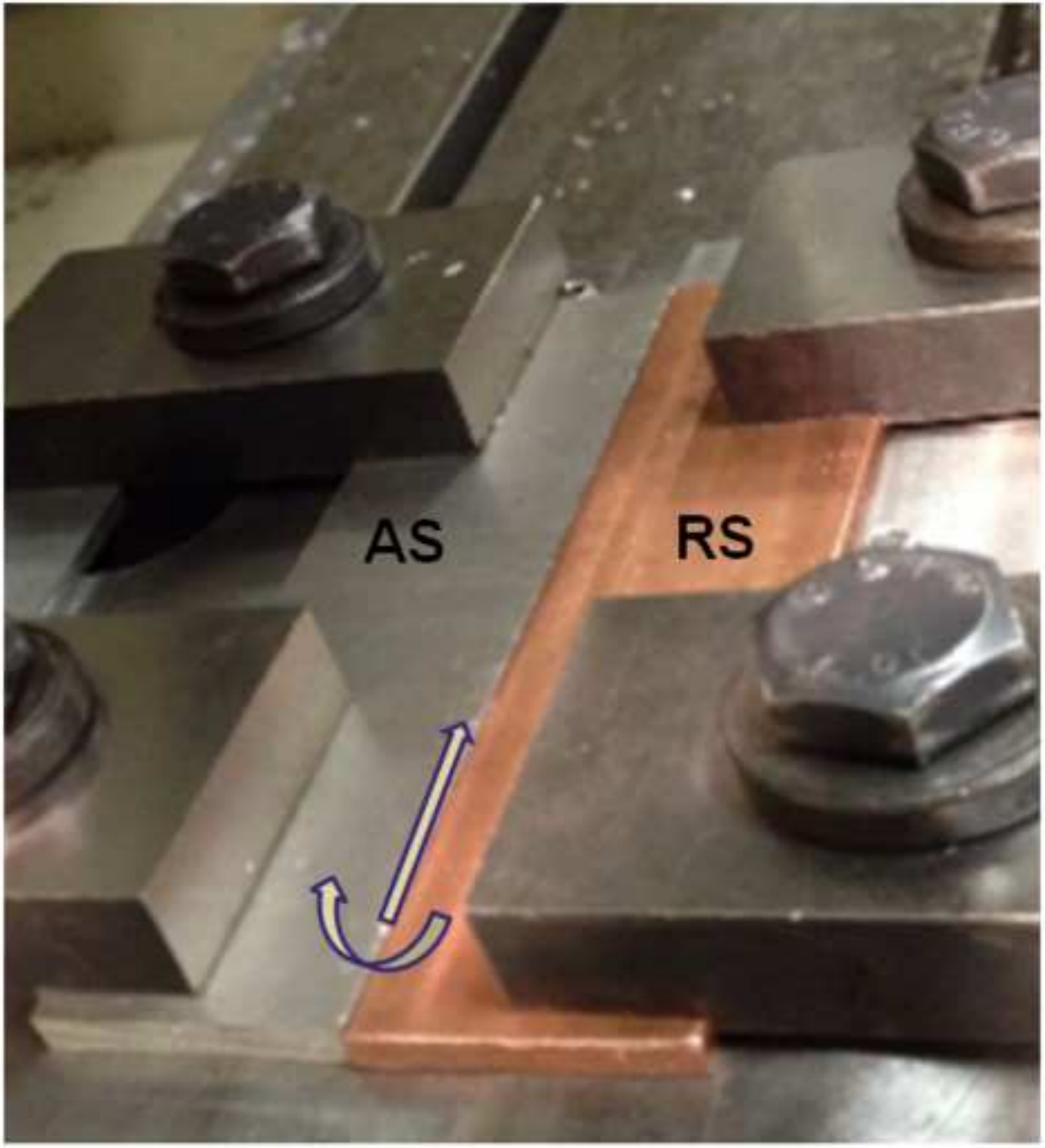

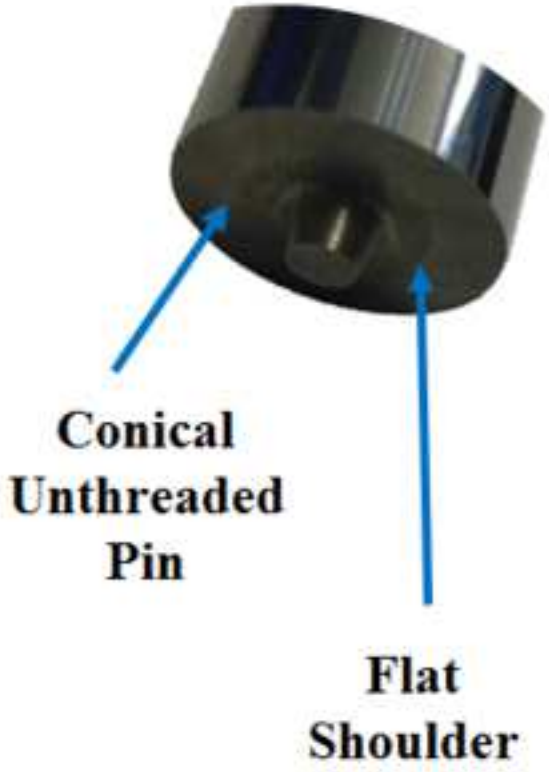

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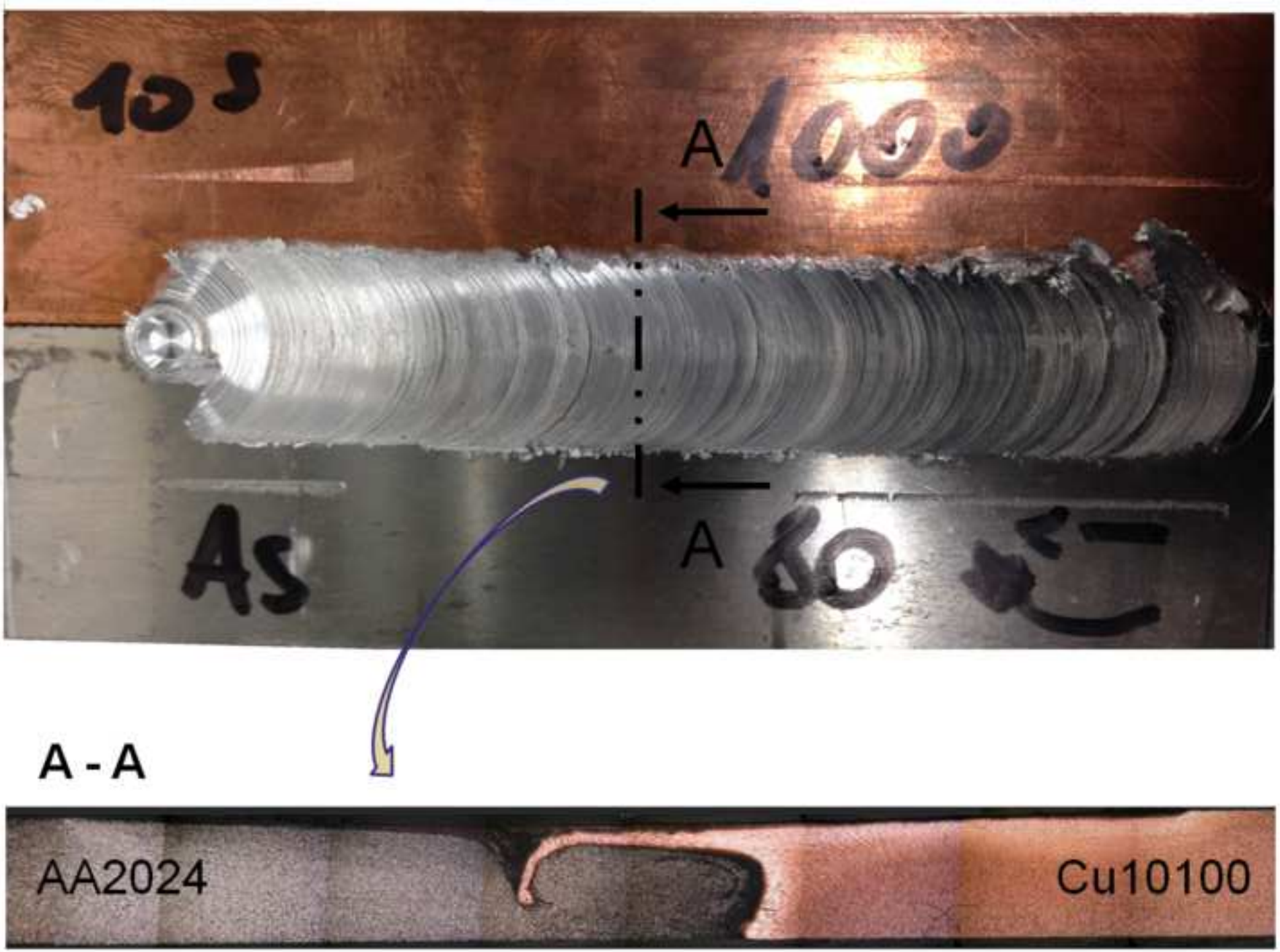

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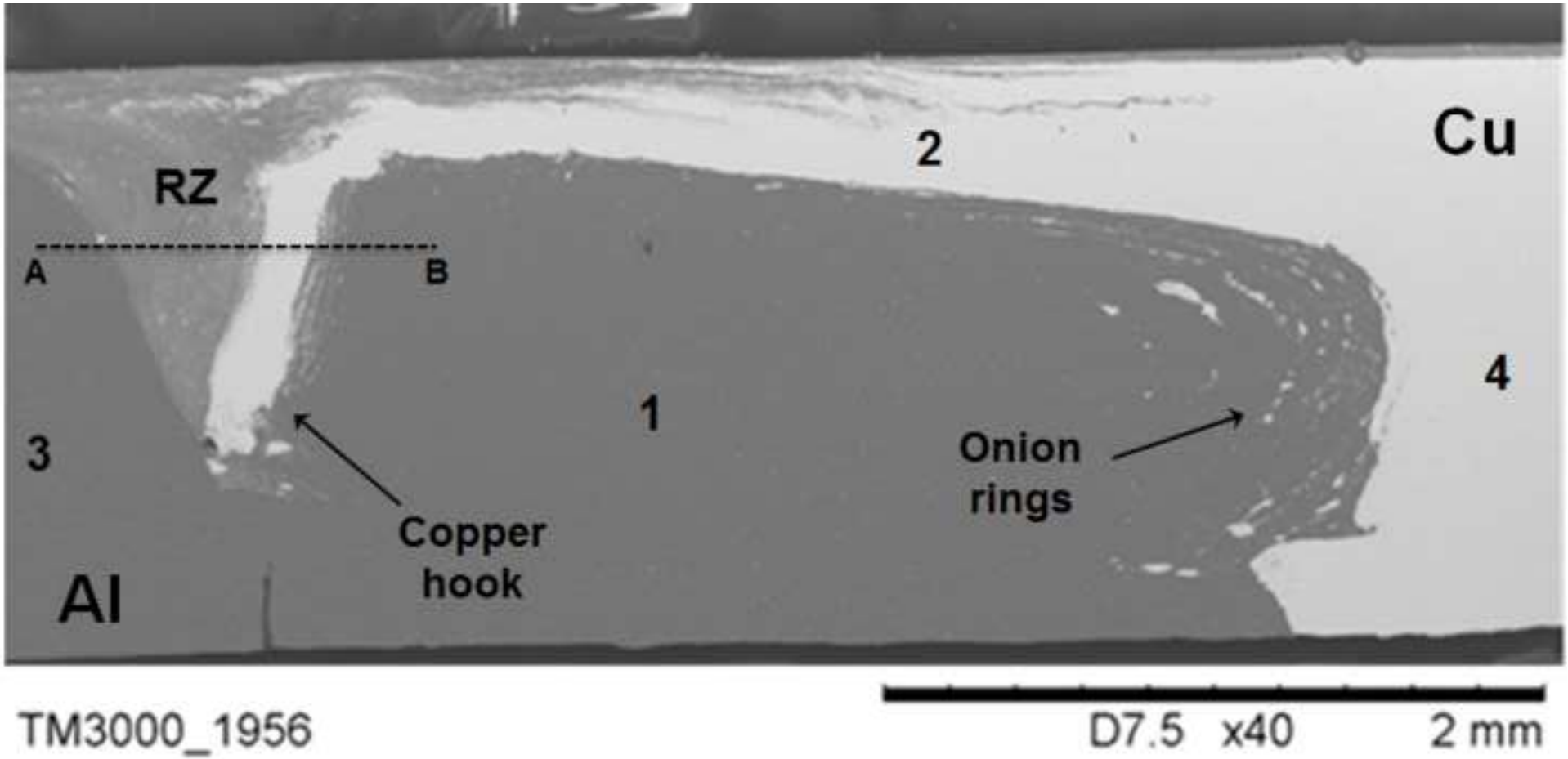

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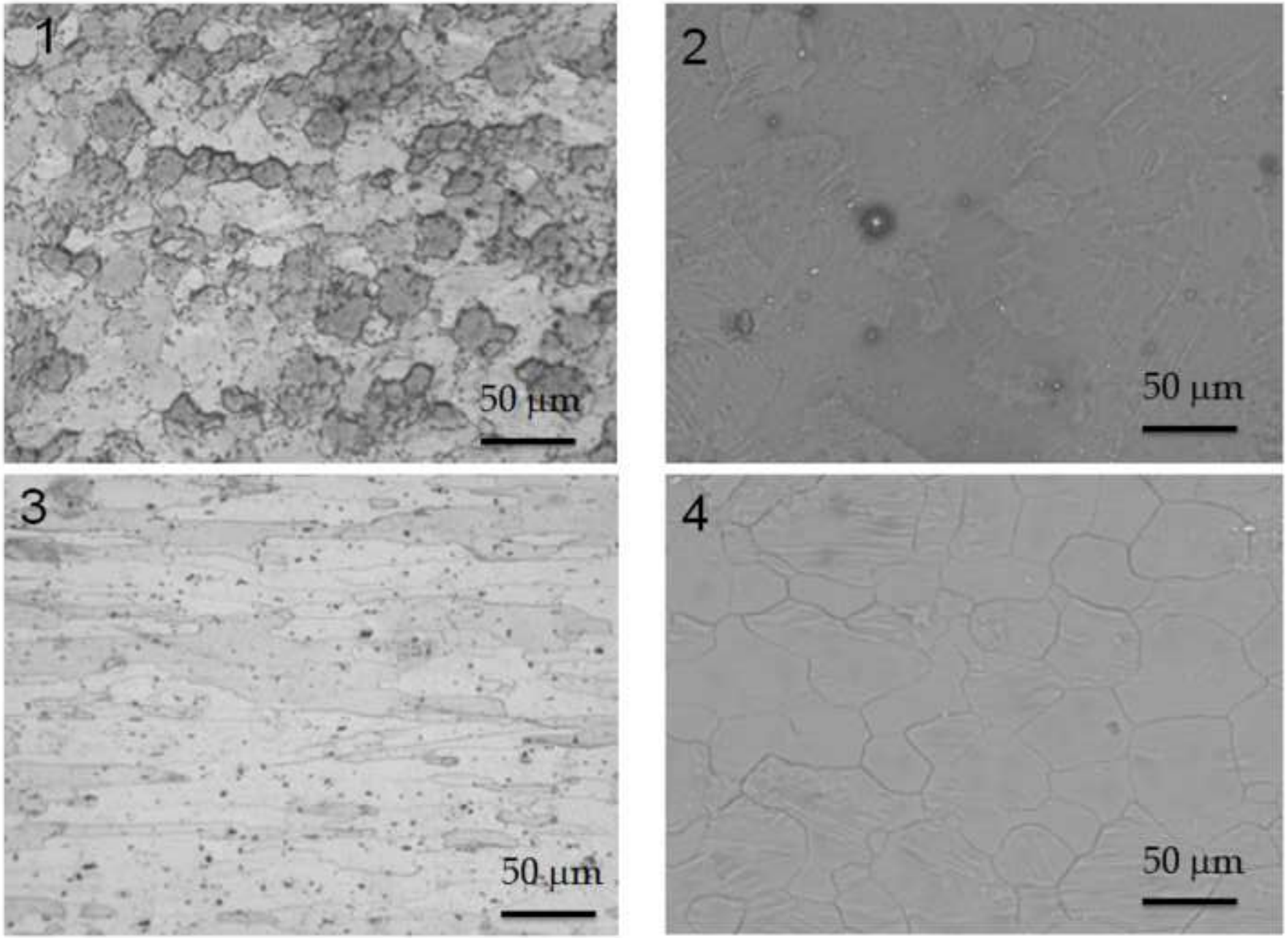

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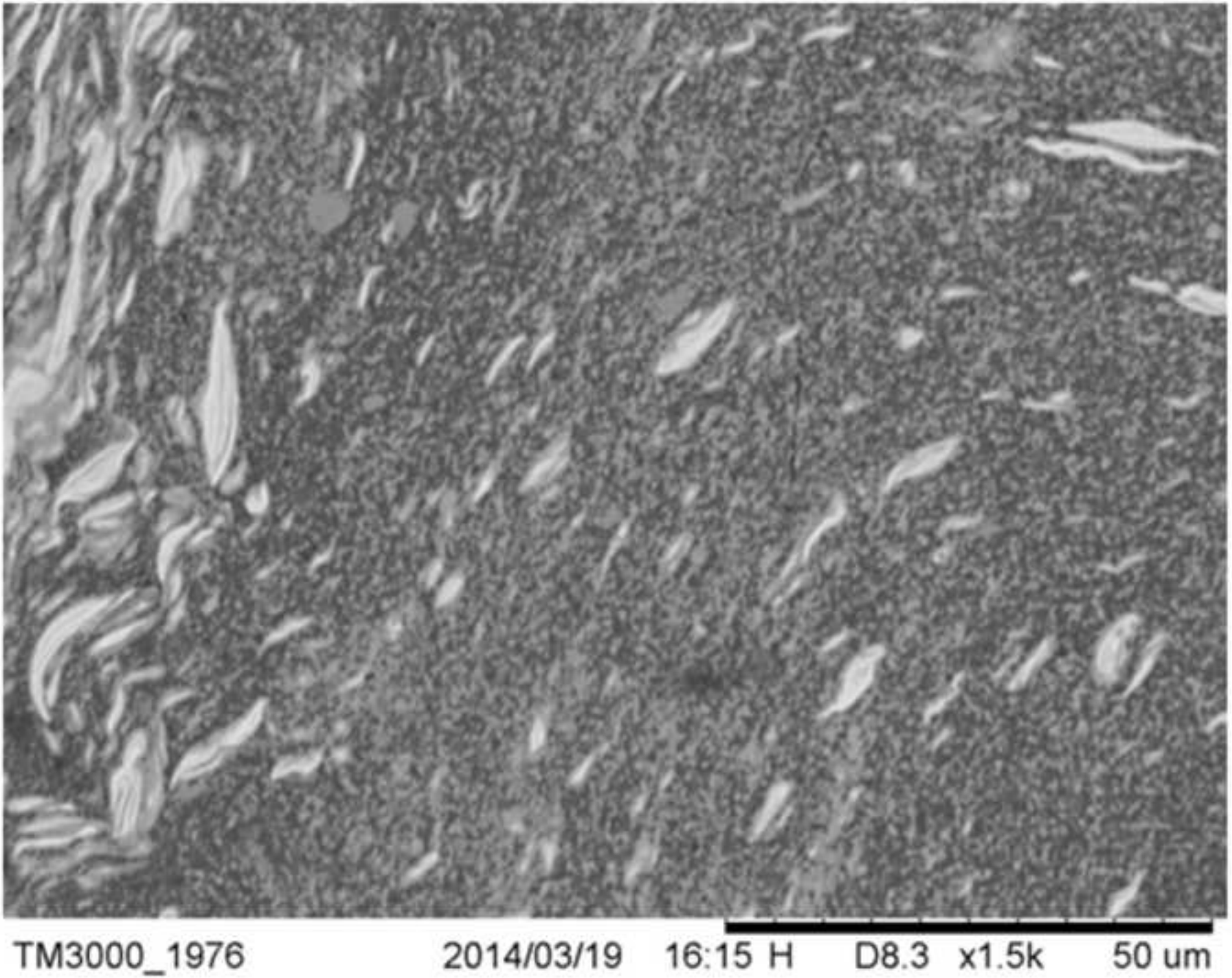

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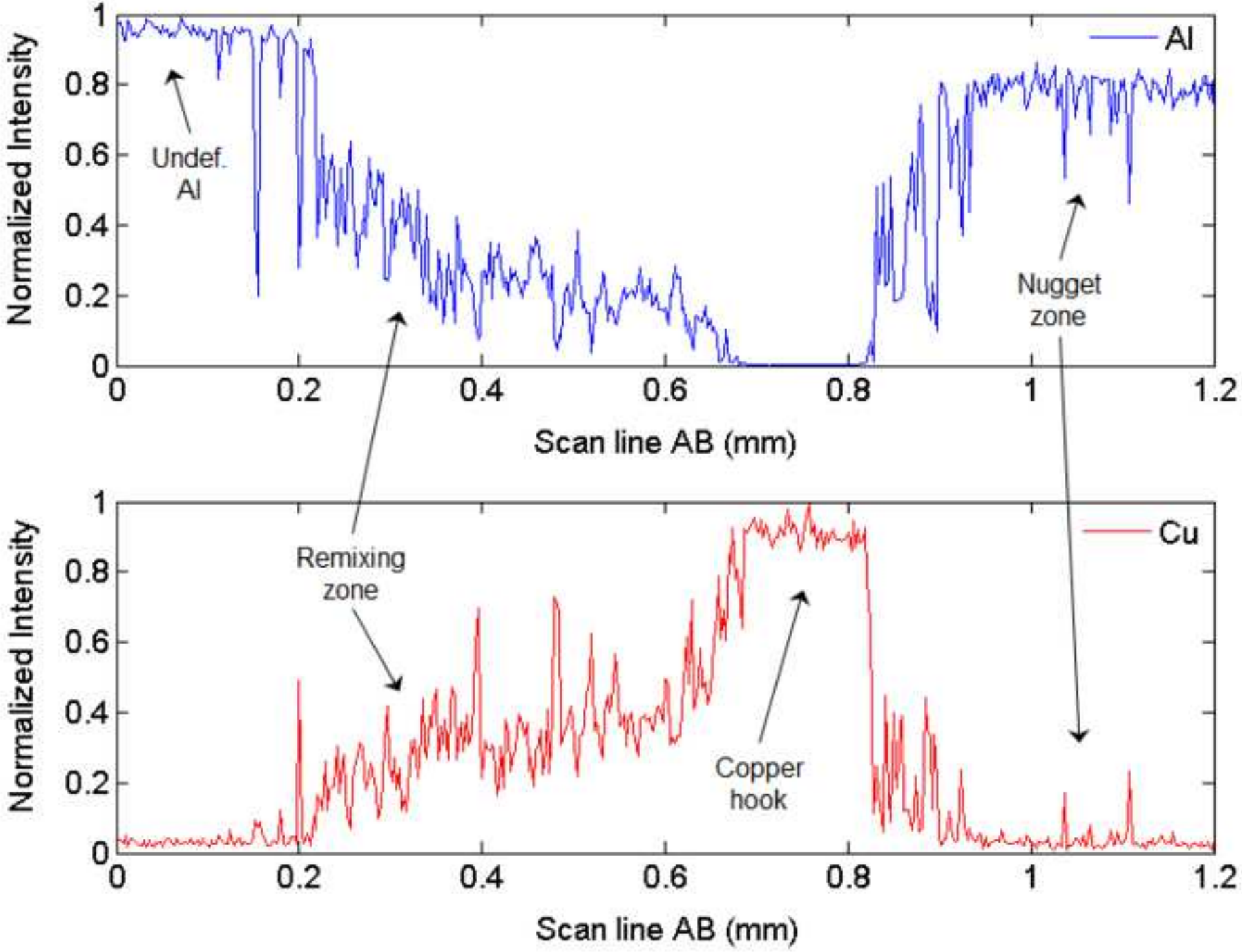

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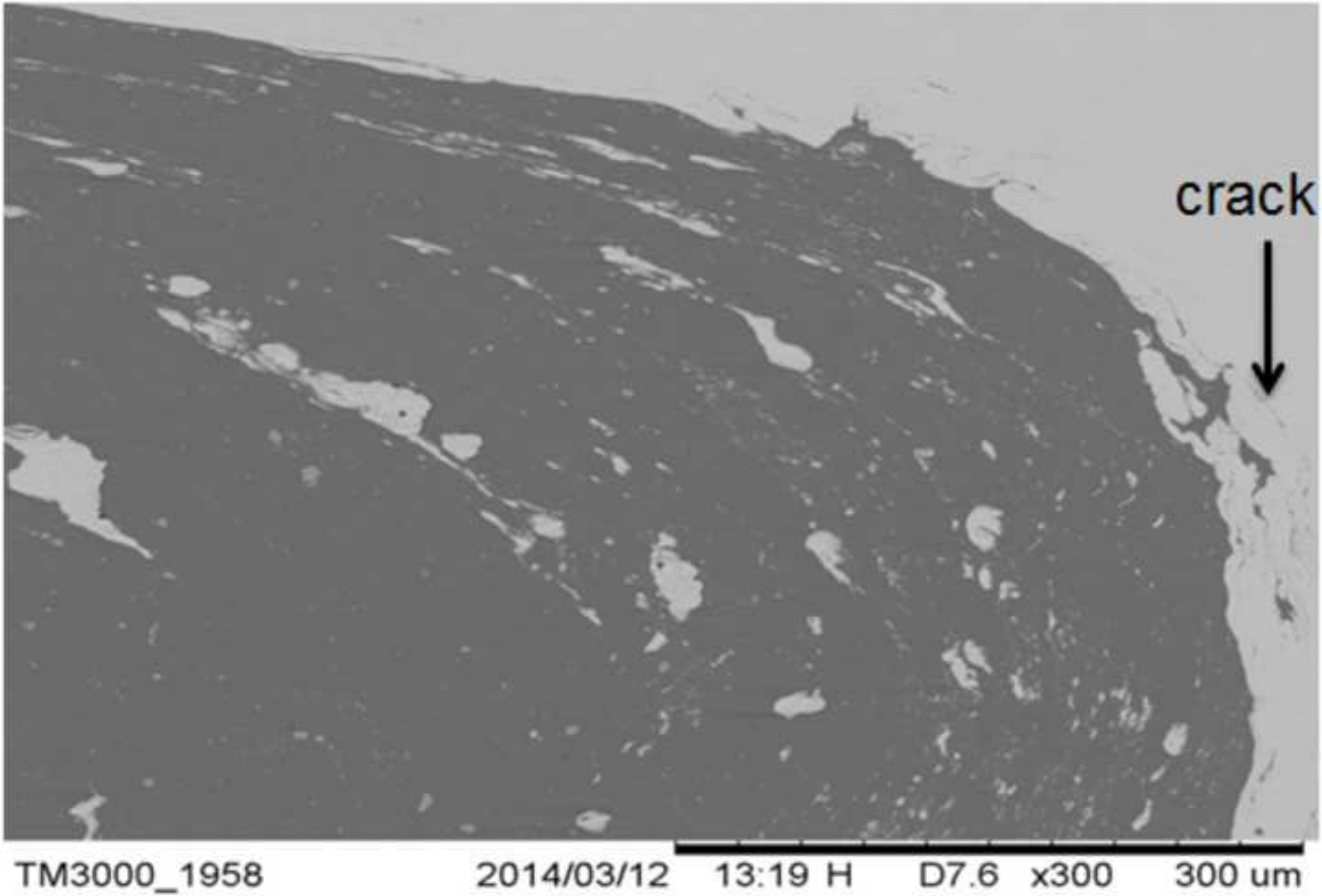

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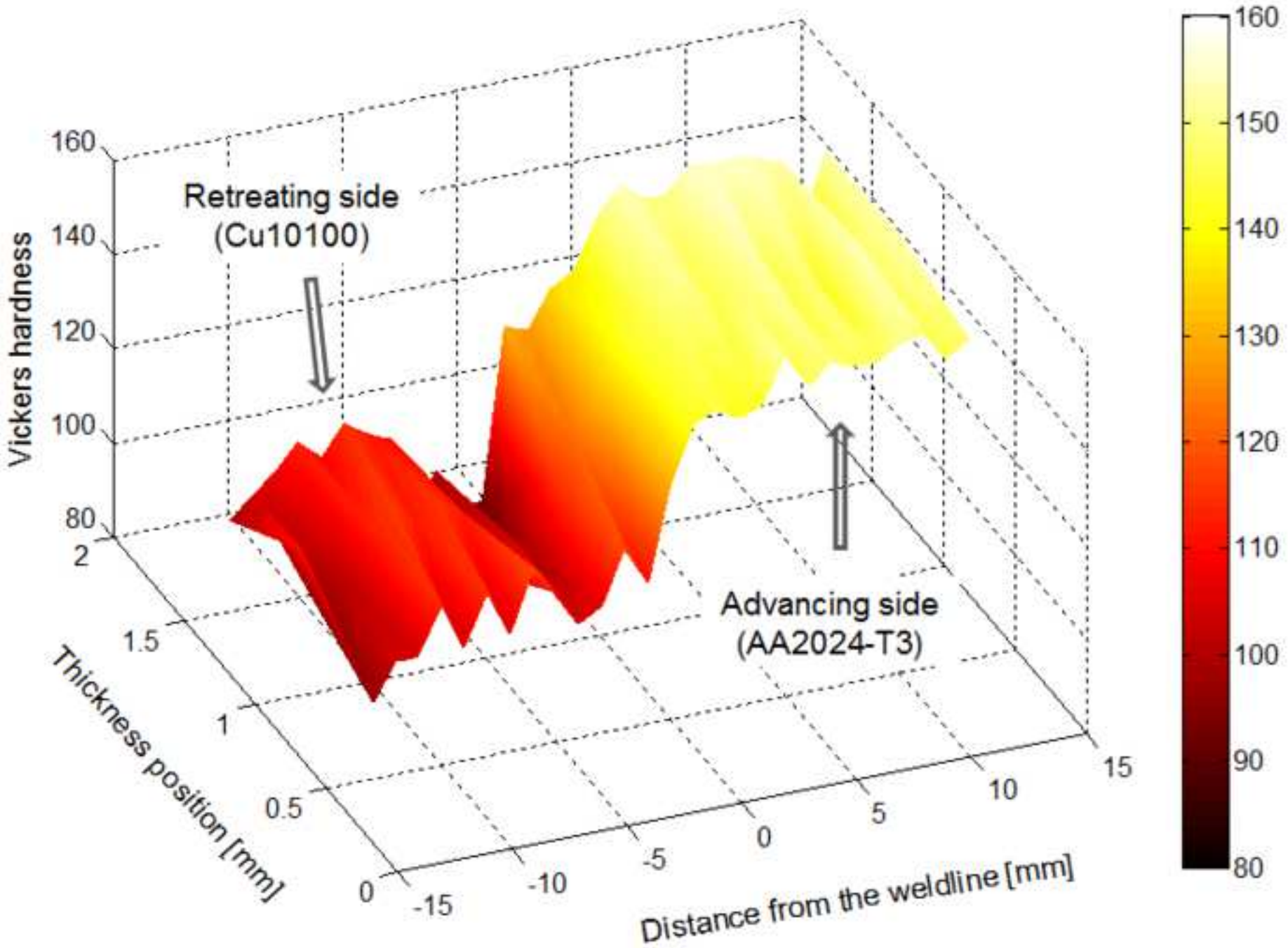

Table 1 – FSW process parameters.

Rotational speed (rpm)	Welding speed (mm/min)	Tilt angle (°)	Tool offset (mm)
1000	80	2	1.3

Table 2 – Chemical composition of IMCs precipitated during FSW process and detected in the NZ

IMC	Al (%)	Cu (%)
AlCu	52	48
Al_2Cu	65	35
Al_3Cu_4	42	58
Al_3Cu	76	24