MICROSTRUCTURAL CHARACTERIZATION OF RECYCLED AL–CU CHIPS PROCESSED BY FRICTION STIR CONSOLIDATION IN A CYLINDRICAL DIE

D. S. Falih[1], S. K. Hussein[1], O. S. Barrak[2,3], S. Chatti[3*]

[1]Technical College of Management - Baghdad, Middle Technical University, Baghdad, Iraq
[2]Polytechnic College of Engineering - Baghdad, Middle Technical University, Baghdad, Iraq
[3]Laboratory of Mechanical Engineering, National Engineering School of Monastir, Monastir, Tunisia
*Corresponding author's e-mail address: sami.chatti@udo.edu

ABSTRACT

In this work, the microstructural evolution and hardness response of aluminum (AA2024) and high-purity copper machining chips consolidated by the friction stir consolidation (FSC) process using a cylindrical die and pinless tool configuration were studied. Microhardness tests and microstructural analysis were used to assess the effect of three essential processing parameters: tool rotation, preheating time, and chip weight. The hardness measurements showed a clear dependence on heat input and plastic deformation conditions, with regions rich in aluminum reaction showing the highest level of strengthening at optimal consolidation conditions, whereas zones rich in copper only show improvement to the hardness when a sufficient amount of thermal-mechanical energy has been put into the system. The intermediate hardness in the Al–Cu interfacial region indicated an order of magnitude change with a corresponding variation in material flow, chip breakage, and solid-state bonding. SEM observation demonstrated less porosity, better chip dispersion, and stronger microstructure at the higher rotating speed. EDS elemental maps exhibited localized Al–Cu diffusion, but no evidence of the continuous intermetallic layers was identified, while XRD patterns showed only FCC-Al and FCC-Cu, confirming that the FSC thermal cycle was still below the level needed for equilibrium phase formation of Al–Cu compounds. The consolidated disks obtained were dense, well-bonded, and fine-grained, indicating that the FSC has the potential to serve as an energy-efficient, eco-friendly approach for converting metallic machining waste into utility-based solid parts.

KEYWORDS: Friction Stir Consolidation (FSC), recycled chips, aluminum, copper, cylindrical die

1. INTRODUCTION

It is essential to recycle machining waste chips in order to minimize the influence on the environment and the consumption of resources. The recycling of the waste aluminium alloy (Al) chips may be one effective technique where FSC offers a possible solution. This solid-state consolidation method bonds metallic chips together without melting them. Earlier research has shown that aluminium machining chips can be successfully formed into dense sections using FSC. Therefore, only a limited number of papers have discussed the FSC of copper (Cu) chips, and even less work has been done on the microstructural characteristics of consolidated materials [1-3]. The aim of this work is to provide evidence-based, quantitative characterization of the microstructural features in commercial recycled Cu and Al chips prepared through FSC [4-5].

To determine the mechanisms governing grain structure, precipitates, and defect formation during high plastic deformation and severe local heating, microstructural features in friction stir consolidated (FSC) recycled copper and aluminium chips pressed with a single cylindrical die are analysed. These parameters are crucial for the mechanical behaviour and reliability of hybrid joints. Grain refinement and precipitate behaviour are significant to chip consolidation, which occurs in the FSC operation. The experimental techniques, materials, and characterization procedures used to measure the microstructural evolution due to severe plastic deformation and localized heating in the cylindrical die FSC process [6-8].

Aluminum and copper are widely used materials in the design and manufacture of such devices. The increasing demand for industrial applications today has also been found to have considerable potential to

Date of submission/acceptance: 15.11.2025/15.12.2025 https://doi.org/10.35219/awet.2025.01

generate metal waste. This recycling part, especially in the fields of component repair and remanufacture, is discovered to be particularly advantageous because it is less energy-intensive to process. Efficient recycling of this scrap also contributes to the continuous development and commercialization of green materials [9-11]. The moisture absorption of the recycled machining chip through reprocessing is a relatively less investigated area in which much greater research has been done by several eminent researchers. Although heating remains one of the central themes in the development process, there is a growing sentiment to simplify lubrication systems. For this reason, already processed chips have been studied for treatment, as their properties can be beneficial. They are also highly surface-available and excellent at interacting with the surroundings through surface diffusion [12-13]. The machine is typically lubricated during machining. Contamination from waste lubricants is usually less of a concern, especially in processes that focus on green or lean manufacturing principles. Accordingly, this increases the likelihood of recycling and using aluminium and copper scrap so that some new findings could have an impact on the actions of trade in the future [14-15]. Descriptions of various metal shavings, particles, and chips have been discussed in several experimental investigations. However, the ferromagnetic particles participating in some of the process operations, like extrusion and consolidation, are not visualized. Consequently, more work is required to determine the subtleties of these important processing stages. This ambiguity is a challenge for their practical use as well as the optimization of these materials in large-scale materials [16-17]. Product bulk material is obtained by friction stir consolidation (FSC) of recycled copper and aluminium chips using a cylindrical die, resulting in high-quality homogeneous bulk materials with enhanced density, reduced porosity, and homogenized microstructure. This new process is of fundamental significance regarding several aspects, such as interfacial diffusion, grain growth, and mechanical behaviours of densified materials [18-19]. By detailed microstructural analysis, the distribution and morphology of chips incorporated into the consolidation matrix were examined, revealing key features such as grain refinement and the evolution of dislocation density and interfacial bonding during the FSC process. Here, the effects of tool temperature, pressure, and revolution speed are important to obtain significant enhancements in the properties of the drive-train base by utilizing higher-strength tool material. The effects of these parameters are significant in achieving optimal benefits from FSC in producing high-quality parts from recycled metallic chips [20-23].

Friction stir consolidation has clear advantages over traditional recycling methods such as melting and refining, hot extrusion, or powder metallurgy. Melting-based recycling needs high-temperature furnaces, often above 600 to 700 °C for aluminum and over 1000 °C for copper, which leads to significant oxidation losses and high CO_2 emissions. In contrast, FSC works entirely in the solid state, so there is no melt loss, and much less energy is needed. Traditional extrusion or compaction methods can leave pores and weak chip-to-chip bonds. FSC, however, uses strong plastic deformation and dynamic recovery to create finer microstructures, which improve bonding and reduce voids. Recent studies show that FSC can use 30 to 60% less energy and produce stronger recycled materials than fusion-based methods. This makes it a modern and sustainable option among current recycling technologies.

Previous studies have contributed a lot, but most examine single-metal chip consolidation or discuss it in broad terms. Only a few have closely examined how Al–Cu chips bond at their interfaces. It is also uncommon for research to use microhardness profiling, SEM/EDS mapping, and XRD phase evaluation together to study the thermomechanical effects of FSC on hybrid recycled chips. Because of this gap, there is a need for research focused on microstructure, which is the main new feature of this study.

This work discusses the feasibility of recycling aluminium and copper chips after machining to produce a new material and how this recycling affects their strength and microstructure. Use the Friction Stir Consolidation method with a cylindrical die. It tests how tool speed, preheating time, and chip weight affect the microstructure of disc-bonded Al-Cu composites.

2. EXPERIMENTAL PROCEDURE

2.1. Materials

Aluminium Alloy AA2024 (Al-93.25, Si-0.34, Mg-1.10, Mn-0.52, Fe-1.34, Cu-3.4, Zn-0.005) and High-Purity Copper (99.9%Cu) were chosen as the base materials for consolidating the chips. The metallic chips were produced during a controlled machining process using a CNC milling machine. The raw material bars were machined at a feed rate of 100-200 mm/min and a depth of cut of 0.5 mm using a carbide cutting tool. Choose these settings so the chip retains its shape and is only slightly affected by heat. The chips were 0.1 mm thick and 0.2 mm long, as shown in figure 1. Consistent chip sizes help with even mixing and better consolidation during the next friction stir processing step.

2.2. Friction Stir Consolidation Process

The discs were produced using friction stir consolidation (FSC) in two main steps. First, metallic chips were pressed together, then consolidated by frictional stirring. To begin, a measured amount of chips was placed in a cylindrical die attached to a backing plate with a fixture system (Fig. 2). The chips were pressed using a hydraulic press at 10 MPa for about 5 seconds, as shown in figure 3a. This step bonded the chips and reduced voids before stirring. A typical compacted sample, 25 mm in diameter, is shown in figure 3b, which demonstrates the even distribution and stability of the pre-consolidated material. Then, the chips were reloaded onto a solid disk using the same die, support plate, and equipment. When the CNC was set up with the FSC-loaded die, as shown in figure 2, the FSC process was completed. The FSC tool used in this study was a pinless cylindrical shoulder tool made of hardened tool steel, with a 25 mm shoulder diameter and a flat bottom surface. No probe or pin was used to prevent copper–aluminum expulsion during consolidation.

The spinning load remained stable until the sample was compressed, after which the spinning force dropped at the center. Heat generated by the process gradually softened the surface. Once enough heat was produced, the specimen was pressed in by about 1 mm, further compacting the disk. The disk continued to spin, generating more heat as it pressed against the load. As the metal components became hot, they bonded together. Continued rotation and pressure created softened areas that helped form a smooth, even surface on the disk.

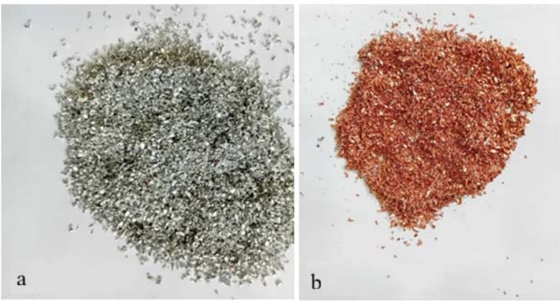

Fig. 1. (a) Aluminum chips, (b) Copper Chips

Fig. 2. FSC Process

Fig. 3. Chips pre-compact: a) compaction machine; b) compacted chips

2.3. Process Parameters

Friction stir consolidation processing of chips was carried out using a cylindrical die fitted with a tool steel punch with a 25 mm diameter to achieve the maximum temperature at the chip disk. Select three key process variables and document the effect of each on the quality of consolidated discs. The characteristics are chip weight, preheating time, and tool rotation speed, as shown in figure 4.

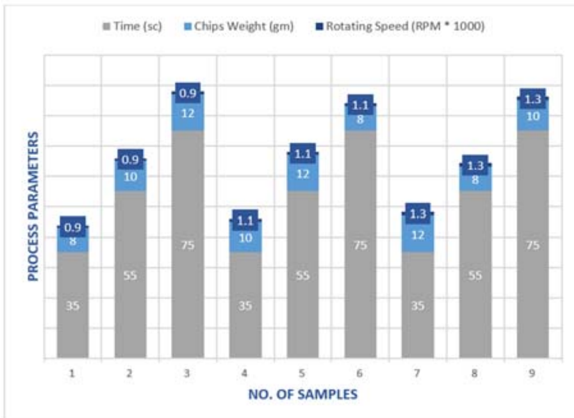

Fig. 4. Process parameters

Fig. 5. FSC specimen: a) front view; b) side view

A fixed plunge depth of 1 mm was used for all samples during the friction stir consolidation (FSC) process (Fig. 5). Maintaining depth consistency was an advantage because it allowed the tool to take a more even bite of material and minimized any variance in how the material flowed across samples.

2.4. Microhardness Test

Microhardness measurements were performed using a standard method. Each sample was mounted, ground with SiC paper, and polished to a mirror finish. Microhardness of the consolidated copper and aluminum chips was tested using a Vickers indenter according to ASTM standards to study the effect of processing parameters on microhardness. Circular impressions with a load of 200 g and a dwell time of 10 s were performed on consolidated 3-5 mm pieces; at least nine points per sample were measured. Each study contained three initial tests conducted at specifically chosen locations in 3 regions (Al, Cu, and Al + Cu), and three subsequent tests per region were performed (Fig. 6). Among them, zones of copper with added aluminium and near the boundaries were selected for measuring the distribution of microhardness to facilitate further research. At each marked position, the mean of 3 readings was used as the microhardness value, and the standard deviation was calculated for reliability**.**

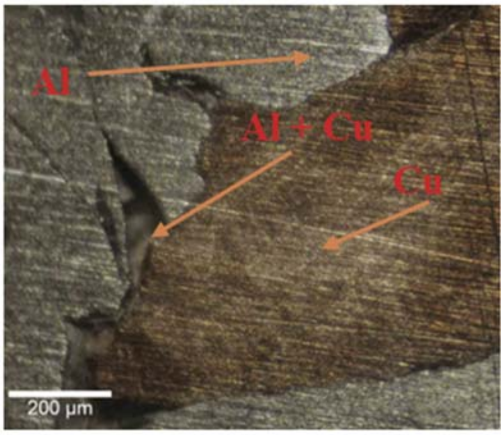

Fig. 6. Region of the microhardness test

2.5. Scanning Electron Microscope (SEM), Energy Dispersive Spectroscopy (EDS), X-ray Diffraction (XRD) Test

Used a high-resolution field-emission scanning electron microscope (FE-SEM) for SEM analysis, operating at 15 to 20 kV with a working distance of 8 to 12 mm. A secondary-electron detector captured the surface morphology, and a backscattered-electron detector showed compositional contrast. For EDS spectra and elemental maps, a silicon-drift detector (SDD) with 129 eV resolution at Mn-Kα, running at 20 kV and 10 nA. Mapping times were 60 to 120 seconds per frame to ensure reliable quantification. Before observation, we mounted and carbon-coated all samples to about 10 nm thickness to prevent charging. Performed XRD measurements with a diffractometer using Cu Kα radiation (λ = 1.5406 Å), set at 40 kV and 30 mA. Scans covered 2θ from 20° to 90° with a 0.02° step size and a scanning rate of 1° per minute. These settings provided enough peak resolution to detect subtle structural features and to distinguish between FCC-Al, FCC-Cu, and possible intermetallic phases.

3. RESULTS AND DISCUSSION

The experiment began with a matrix using three processing parameters: tool rotation speed, chip weight, and preheating time. These combinations led to nine FSC trials, as shown in figure 4. During consolidation, only five samples formed stable discs with good structural integrity. Four trials failed due to insufficient heat or because chips were expelled from the die. As a result, only the five successful samples are included in the microhardness and microstructural analysis in figure 7.

The Al and Cu chips, as well as their FSC consolidated discs, were tested for microhardness and subjected to microstructural examinations, which enabled correlation of processing conditions with material response. The hardness results showed a significant correlation with heat input and plastic straining during consolidation. Samples treated with higher tool rotation, 1300 rpm in particular, showed a significant increment in the hardness, indicating further fragmentation of the chips and improvement of the plastic flow, coupled with more γ-MCIs formation. When samples did not have enough preheating time, both the Al-rich and Cu-rich regions showed low hardness. There was not enough thermal softening, and the interfacial bonding was poor.

The Al, Cu, and Al-Cu areas (Fig. 7) of the microhardness measurements. Figure 7 demonstrated that hardness is significantly influenced by the tool rotational speed, the weight of chips, and the moment of preheating. A distinctive increase in hardness of the aluminium areas was observed in samples 3 and 7 due to the suitable thermal–mechanical conditions whereby values exceeded 200 HV. Low melting temperatures (sample 4) except for the copper region, and they are increased at registering enough deformation energy, especially in sample 7. The hardness of Al–Cu interfacial transition zones was found to be intermediate and correlated with the extent of mixing/bonding of conditions tested; In addition, peak interface hardness was also seen at test 7.

Role of chip mass was content-based on hardness response; as-deposited samples with heavier chips showed a higher resistance to densification, and therefore demanded a higher energy input to obtain the same compaction. Observed soft local areas and weakly bonded chip surfaces at low heat input. On the contrary, a better balanced heat generation enhanced interlocking and porosity minimizing, dislocation density increased, and with it also hardness.

On the whole, microhardness results verify that FSC has a notable effect on strengthening mechanisms of consolidated Al–Cu chips by severe plastic deformation, increasing mixing of the chips and better interface forming. The highest and very similar hardness value of sample 7 supports that this processing condition has the best compromise between temperature, pressure, and material flow for the consolidation [11, 19].

The increase in hardness matches what previous studies on recycled chip consolidation have found, including severe plastic deformation, dynamic recovery, and refined grain structures. Our results agree with Puleo et al. and Ingarao et al. [5, 21], who also saw better consolidation and less porosity at higher rotational speeds. The observed, where the best consolidation happened with a balance of thermal and mechanical input, supports existing models that highlight the combined roles of rotation speed, heat, and chip flow.

The hardness of the samples depends on the local thermomechanical conditions during FSC. Faster tool rotation creates more heat and plastic strain, which breaks up chips and supports dynamic recovery and recrystallization. As a result, hardness increases. If the preheating time is too short, the chips do not soften enough, leading to less plastic flow at the interface. This results in uneven bonding, and some areas in samples with little heating show lower hardness.

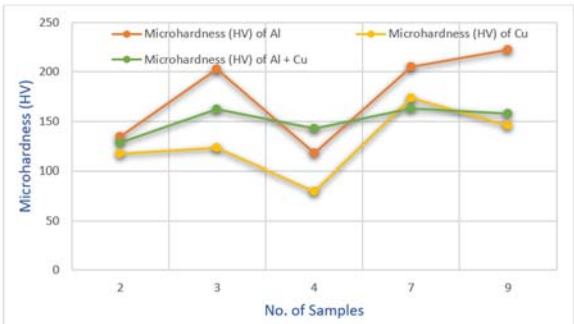

Fig. 7. Microhardness (HV) profiles of consolidated Al-Cu

SEM micrographs showed evidence of bonded chip and interface consolidation between the Al and Cu regions. As shown in figure 8, the transition band at the Al–Cu interface is continuous but quite irregular, with several sites of localized microvoids ranging in size from 0.9 to 2.2 µm, indicating insufficient material flow to fill all encapsulated gaps during the stirring process. These voids are surface-breaking and discontinuous, thus verifying that FSC manipulation successfully reduced porosity but was unable to eliminate all interfacial discontinuities.

The high-luminance elongated strips observed along the interface are attributed to plastically stretched aluminium that has undergone substantial deformation under combined rotational shear and axial pressure. The measured interfacial deformation thicknesses (about 1–2 µm) indicate strong localized strain, which is typical of friction-induced dynamic crushing. This is in agreement with the development of fine microstructural layers at bond interfaces, a standard hallmark of solid-state bonding during FSC.

The elemental mapping (Fig. 9) indicates a clear distinction in the chemical gradient between the two sides of the interface. The aluminum-rich region (blue) smoothly transitions into the copper-rich zone (purple), and a narrow diffusion zone is observed at the edge, where both elements can be detected. This gradient confirms that a shallow interdiffusion between Al and Cu (albeit with some degree of overlap into the bulk) was observed, which complements the earlier conclusion that bonding occurred mainly by severe plastic deformation (SPD) and mechanical entanglement rather than extensive metallurgical interdiffusion. No continuous intermetallic layer was observed, and the interface remained clear, as expected at the moderate temperatures of a pinless FSC tool.

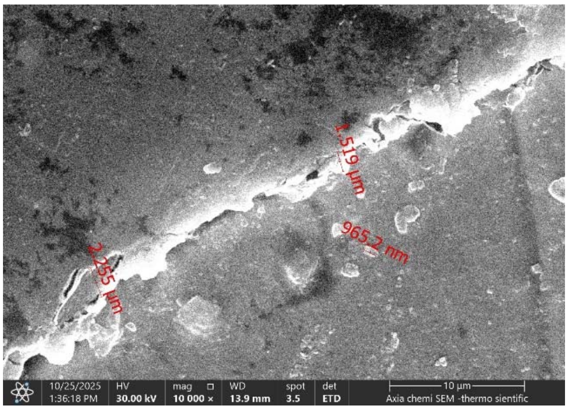

Fig. 8. SEM of Chip

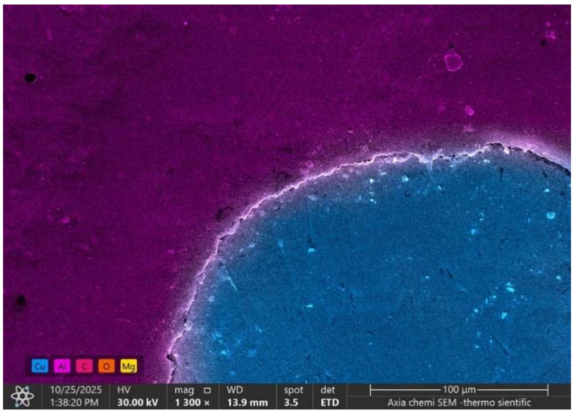

Fig. 9. SEM morphology in the consolidated Al- Cu chip region

Higher tool rotational velocities led to better chip mixing, improved material flow, and a more homogeneous interface, due to a smoother transition zone with less void formation. However, at lower rotations, heat generation was not high enough, presumably leading to little softening of the chip and a rough interface containing unbonded single-particle chips. These observations provide evidence that sufficient thermal–mechanical energy is required to achieve complete consolidation during FSC.

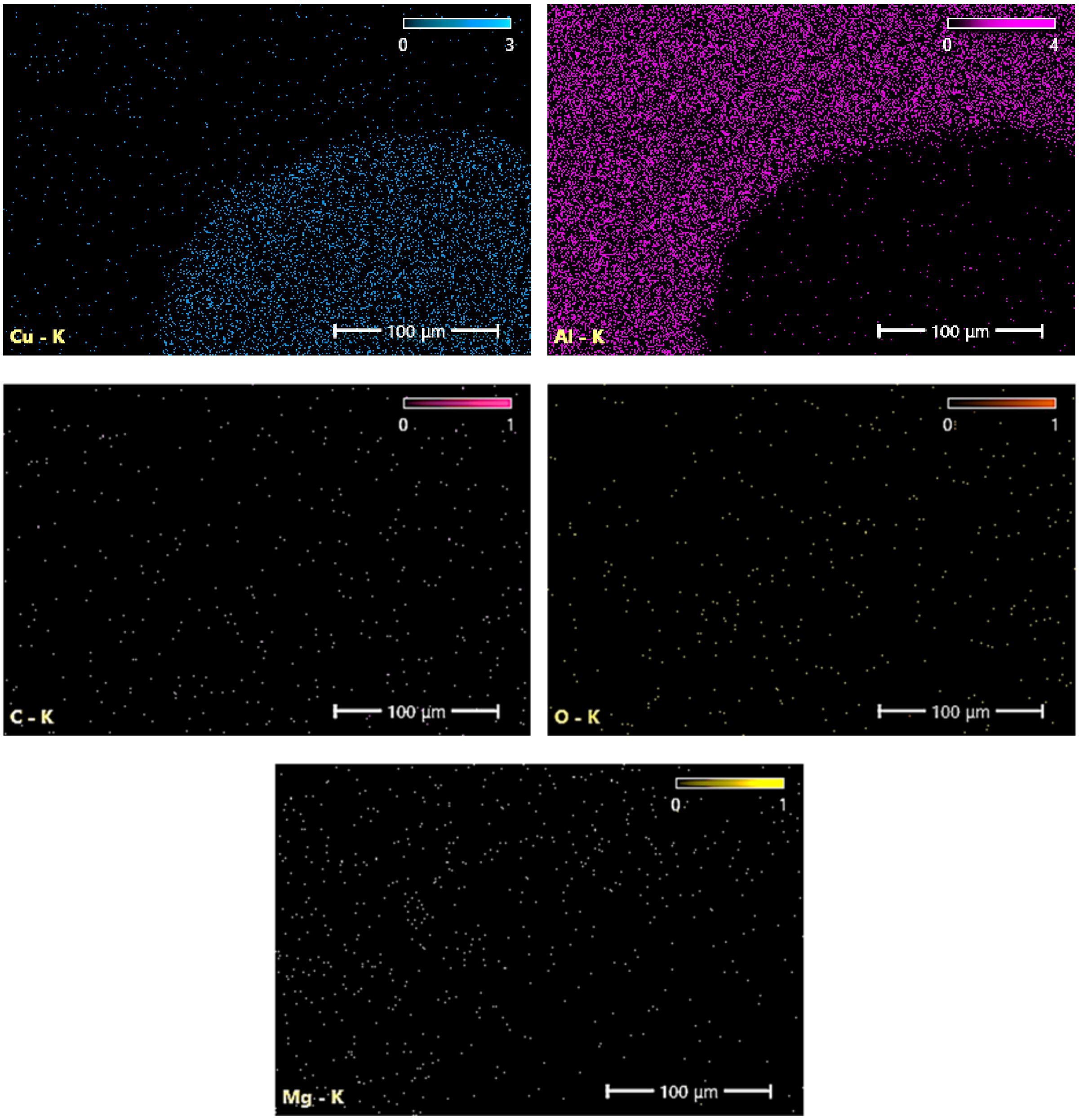

Fig. 10. EDS of Al–Cu Interface Area

From the elemental mapping and EDS spectrum (Fig. 10 and 11), it is evident that the distribution of elements at the Al–Cu interface formed by FSC was different. The point-spectrum investigation reveals that the analysed area is primarily composed of aluminium (56.3 wt%) and copper (27.9 wt%), with admixtures of carbon, oxygen, and magnesium arising from surface contamination and the AA2024 substrate, respectively. The EDS maps show a clear boundary between the two metals: The aluminium region looks uniformly enriched in Al, and the copper domain has similarly intense Cu spots with relatively low content of aluminium. The interface shows a thin mixed zone where overlapping Al and Cu signals imply a localized solid-state diffusion rather than prolonged homogenization to form intermetallic compounds.

The lack of a quasi-continuous Al–Cu intermetallic layer remains a significant finding. Although copper is well known for forming IMCs at high temperatures in cast or heat-treated Al–Cu alloys, EDS did not detect precipitation of stable intermetallic phases at the FSC temperature. This is in line with the thermal properties of the pinless tool design, which result in a modest temperature profile dominated by intense plastic straining rather than extended heating to high temperatures. No clustering or segregation, a common sign of IMCs, is observed in the elemental maps; therefore, it can be concluded that bonding was predominantly achieved by mechanical interlocking and plastic mixing at the interface. EDS analysis displays a chemically sharp, well-adhered interface, with minimal oxidation and no discernible intermetallics. It is due to a solid-state FSC process and confirms the model of the localized diffusion and strain-assisted bonding between recycled Al and Cu chips [15].

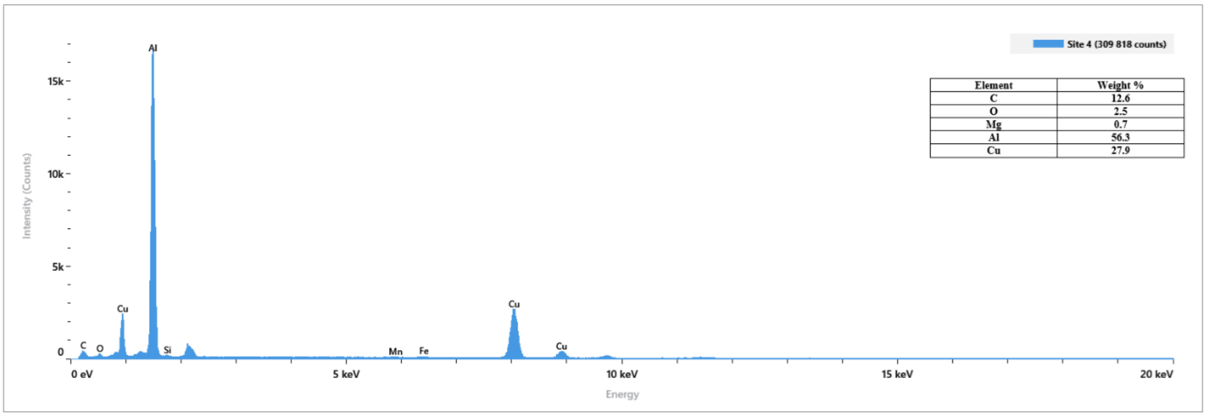

Fig. 11. EDS Elemental Analysis of Al–Cu Composite

The X-ray diffraction (XRD) pattern of the consolidated Al–Cu chips (Fig. 12) exhibits only the feature peaks of face-centered cubic (FCC) aluminum and copper. There were no diffraction peaks pertaining to Al–Cu intermetallics (such as θ–$CuAl_2$ or γ–Cu_9Al_4). The absence of these phases demonstrates that the friction stir consolidation process did not attain temperatures or exposure times sufficient to form stable intermetallics. This is consistent with the relatively short tool-chip contact time and the low thermal profile created by the pinless modified FSC tool setting.

The presence of the Al and Cu peaks is a clear indication that bonding between the chips occurred mainly through SPD, mechanical interlocking, and local solid-state diffusion rather than the nucleation of newphases. This can be explained by the EDS elemental mapping, which showed a very narrow diffusion zone at the interface but no continuous compound layer. Mechanical ductility should be maintained if brittle intermetallics are absent, as there would be no poorly bonded Al–Cu interfaces that could lead to brittle intermetallic phases [15].

XRD analyses support the SEM and EDS results and indicate that FSC primarily forms a bimetallic Al–Cu composite with a finer microstructure, without damaging intermetallic compounds.

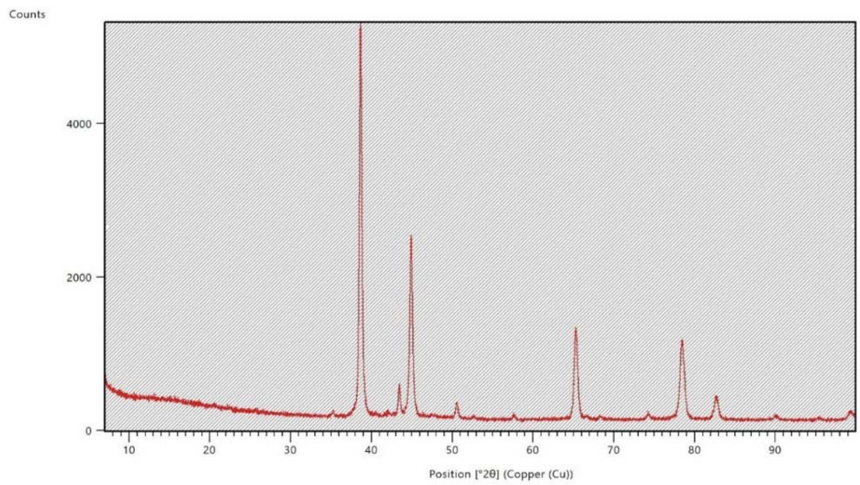

Fig. 12. XRD Characterization of Al–Cu Composite

The results show that consolidated Al–Cu chips become stronger due to severe plastic deformation, uneven heat generation, and local interfacial flow. Hardness tests indicate that tool rotation speed mainly affects how the chips break apart, recover, and recrystallize. SEM, EDS, and XRD analyses did not find intermetallic compounds, so the bonding is mostly mechanical, relying on plastic entanglement and short-range diffusion instead of forming new phases. This explains why hardness increases even when no new phases form. The uneven interface at shorter preheating times also shows that chip consolidation depends on early thermal softening. When there is not enough heat, the material moves less, and consolidation is limited. Overall, the results clearly connect process parameters to changes in microstructure and mechanical properties.

4. CONCLUSIONS

This research demonstrated that FSC with a cylindrical die is an efficient and environmentally friendly process for recycling Al-Cu chips into dense, mechanically enhanced bimetallic disks. These results can be summarized as follows:

1. microhardness profiles indicated a significant influence of the aforementioned processing parameters on the response; sample 7 had the highest hardness in both the Al and Cu regions, attributed to better overall thermal-mechanical input, while sample 4 received insufficient heat, forming large soft zones.
2. SEM observations support the micro-chips having fine structure, low porosity, and good metallography bonding, especially when a higher rotation speed was selected with an appropriate preheating treatment to induce strong plastic flow and increase interfacial bonding.
3. the EDS results showed a clear elemental-mapping transition zone between Al and Cu, without extensive solid-state diffusion, suggesting strong mechanical interlocks rather than continuous intermetallic layers.
4. the XRD analysis displays that at the temperatures imparted by FSC, only FCC-Al and FCC-Cu phases were formed, indicating that all temperatures achieved were below those required to generate the brittle Al–Cu intermetallics, which is a good sign for retaining ductility and structural integrity.
5. the combination of the tool rotation, chip weight, and preheating time influenced bonding quality, interfacial flow, and microstructure refinement, underscoring the importance of thermomechanical symmetry during FSC.

REFERENCES

[1] **Puleo R.**, **Latif A.**, **Ingarao G.**, **Di Lorenzo R.**, **Fratini L.**, *Solid bonding criteria design for aluminum chips recycling through friction stir consolidation*, Journal of Materials Processing Technology, 2023, vol. 319, 118080.

[2] **Barrak O. S.**, **Hamzah M. M.**, **Hussein S. K.**, *Friction stir spot welding of pure copper (C11000) with pre-holed threaded aluminum alloys (AA5052)*, Journal of Applied Sciences and Engineering, 2022, vol. 26, iss. 8, pp. 1103–1110.

[3] **Hameed O. H.**, **Hamzah M. M.**, **Saad M. L.**, **Abduljabbr G. R.**, **Barrak A. S.**, **Abduljaleel Y. W.**, *Thermal and Mechanical Analysis of Polyvinyl Chloride (PVC) to Polyethylene (PE) Bonding via Friction Stir Spot Welding Process*, Journal of Techniques, 2025, vol. 7, iss. 2, pp. 60–66.

[4] **Khedr M.**, **Hamada A.**, **Järvenpää A.**, **Elkatatny S.**, **Abd-Elaziem W.**, *Review on the solid-state welding of steels: Diffusion bonding and friction stir welding processes*, Metals, 2023, vol. 13, iss. 1, pp. 54.

[5] **Puleo R.**, **Latif A.**, **Ingarao G.**, **Fratini L.**, *A generalized parametric model for the bonding occurrence prediction in friction stir consolidation of aluminum alloys chips*, Journal of Manufacturing Processes, 2024, vol. 131, pp. 604–618.

[6] **Wang N. et al.**, *Prediction and characterization of microstructure evolution based on deep learning method and in-situ scanning electron microscope*, Materials Characterization, 2023, vol. 204, 113230.

[7] **Saad M. L.**, **Sar M. H.**, **Barrak O. S.**, **Hussein S. K.**, **Hussein A. K.**, *Fuzzy logic model analysis of shear force in aluminium/polyethylene lap joined by hot press*, IOP Conference Series: Materials Science and Engineering, 2019, vol. 518, iss. 3, 032007.

[8] **Pereloma E.**, **Wang J.**, **Beladi H.**, **Singh N.**, **Timokhina I.**, *Solute segregation, clustering and interphase precipitation in Ti-Mo-Nb microalloyed steel studied by correlated EBSD and atom probe tomography*, Materials Characterization, 2024, vol. 216, 114273.

[9] **Hussein A. K.**, **Barrak O. S.**, **Hamzah M. M.**, **Hussein S. K.**, *Friction stir welding AA6061-T6 with multi-objective optimization of parameters*, Advanced Science and Technology Research Journal, 2025, vol. 19, iss. 10, pp. 162–172.

[10] **Vahidi H.** et al., *A review of grain boundary and heterointerface characterization in polycrystalline oxides by (scanning) transmission electron microscopy*, Crystals, 2021, vol. 11, iss. 8, 878.

[11] **Mahmoud S. E. D.**, **El-Gamasy R.**, **El-Wahab A. A. A.**, *Mechanical behavior of hot extruded aluminum 6082 chip*, Scientific Reports, 2024, vol. 14, iss. 1, 6381.

[12] **Rached S.**, **Chaabene A.**, **Chatti S.**, *Enhancing friction stir welding performance: Finite element simulation study using filler material*, Annals of Dunarea de Jos University of Galati, Fascicle XII, Welding Equipment and Technology, 2024, vol. 35, pp. 79–92.

[13] **Zhu Y. et al.**, *The coming wave of aluminum sheet scrap from vehicle recycling in the United States*, Resources, Conservation & Recycling, 2021, vol. 164, 105208.

[14] **Naeim N.**, **El-Asfoury M. S.**, *Effect of copper cooperation to customize sustainable aluminum alloy through recycling approach*, Journal of Mechanical Science and Technology, 2024, vol. 38, pp. 1187–1195.

[15] **Abbas N. M.**, *An experimental and numerical investigation of machining chips behavior in compaction and consolidation processes*, Ph.D. dissertation, University of South Carolina, 2018.

[16] **Hussein A. K. et al.**, *Impact of tailored nanomaterials on mechanical and thermal behavior of polymer composites*, Engineering for Rural Development, 2025.

[17] **Batista C. D.**, **Fernandes A. A. M. d. N. d. P.**, **Vieira M. T. F.**, **Emadinia O.**, *From machining chips to raw material for powder metallurgy—A review*, Materials, 2021, vol. 14, iss. 18, 5432.

[18] **Kennerknecht T.**, *Fatigue of micro molded materials—aluminum bronze and yttria stabilized zirconia*, KIT Scientific Publishing, 2014, vol. 45.

[19] **Beltrán A. S.** et al., *Statistical and microstructural analyses of Al–C–Cu composites synthesized using the solid-state route*, Materials, 2021, vol. 14, iss. 8, pp. 1969.

[20] **Noga P.**, **Tuz L.**, **Żaba K.**, **Zwoliński A.**, *Analysis of microstructure and mechanical properties of AlSi11 after chip recycling, co-extrusion, and arc welding*, Materials, 2021, vol. 14, iss. 11, pp. 3124.

[21] **Ingarao G.**, **Amato M.**, **Latif A.**, **La Rosa A. D.**, **Di Lorenzo R.**, **Fratini L.**, *Life cycle assessment of aluminum alloys chips recycling through single and multi-step friction stir consolidation processes*, Journal of Manufacturing Systems, 2023, vol. 68, pp. 651–659.

[22] **Sar M. H. et al.**, *Friction stir spot welding (FSSW) of dissimilar aluminum alloys (AA5052 with AA6061)*, AIP Conference Proceedings, 2024, vol. 3105, iss. 1, 020025.

[23] **Abdul Wahed S. N.**, **Hussein S. K.**, **Al-Saadi M. H.**, *Disc forming by friction stir consolidation of AA2024 chips*, Journal of Techniques, 2022, vol. 4, iss. 1, pp. 1–8.