Journal of Metals, Materials and Minerals, Vol. 31, No. 1, pp. 88-94, 2021

On the mechanical properties of Al/Cu-grid/Al intermetallic composite

Hamza ESSOUSSI[1,*], and Said ETTAQI[1]

[1] *Laboratory of Energy, Materials and Sustainable Development, ENSAM, Moulay Ismail University,* 15290, *Meknes, Morocco*

***Corresponding author e-mail:** hamza.essoussi1@gmail.com

Received date:
2 February 2021
Revised date
16 March 2021
Accepted date:
22 March 2021

Keywords:
Al/Cu-grid/Al metallic composite;
Al-based composite;
Interface diffusion

Abstract

The present paper deals with the experimental investigation of new process combining static compression with high temperature as a simple way to prepare new Al/Cu-grid/Al metallic composite (MC) that consists of Aluminum matrix and Copper grid acting as ductile reinforcement stacked between the Al sheets. At the stage of composite fabrication, two different thermal cycles were tested to highlight the effect of processing temperature on the layers' adherence and the mechanical properties of the prepared composites. Consequently, the microstructural and mechanical results revealed that the compression at 630℃ for 30 min, then furnace cooled to 450℃ followed by air cooling led to improved mechanical properties and good adherence of Al sheets.

1. Introduction

Last decades, owing to their promising properties such as: improved strength, low density, corrosion resistance and toughness, the so-called metallic composites (MC) with aluminum matrix have gained a growing attention in both automotive and aerospace industries [1,2]. In this regard, based on many previous works [3-9] of aluminum-based metallic composites, there are various available types of reinforcements that can be used to obtain such type of composites (AMCs). Table 1 shows some reinforcements materials that can been used with aluminum matrix. While chemical compatibility between the matrix and the reinforcement is of main importance in the determination of the maximum temperature range of the composite use and may also impose limitations on the fabrication method [10].

It has been proved that Al-based metallic composites (AMCs) reinforced with dispersed particles, especially ceramics such as Aluminum oxide Al_2O_3, and silicon carbide SiC are the main types of metallic composites widely developed due to their low cost and simple preparation process [3], while this type of composites have some drawbacks, such as the non-uniform distribution of particles and weak coupling with the metallic matrix which all led to low strength and poor ductility [4]. In this scope Y. Wei *et al* [9] reported that these limitations can be overcame if the composite can be processed with a good manufacturing method that controls the gradient and the distribution of reinforcing particles.

Considerable efforts have been made to develop methods for the fabrication of metal-matrix composites by stacking different metals using severe plastic deformation combined with high temperatures [11]. Thus, depending on the deformation mode, it was found that equal-channel angular pressing (ECAP) [12], accumulative roll-bonding (ARB) [13], and high-pressure torsion (HPT) [11] are the main three procedures that received more attention in the most published research studies. Moreover, all the mentioned methods are performed at the solid state i.e. below the melting temperature of the bonded materials. Particularly, studies of metals bonding at the solid state [6-9] have demonstrated that with the combination of heat and pressure, the bonding mechanism between metallic layers occurs as follows: (1) development of physical contact; (2) activation of the surfaces in contact; and (3) interactions within the materials being joined. In this scope Kawakami *et al* [8] worked on Cu/Al dissimilar bonding at temperature range between the eutectic and the melting temperatures, reported that in such dissimilar bonding of Al to Cu, diffusion started from the adherence surface of both metals after the breaking of the oxide films. The combination of static compression with high temperatures can be a promising way to obtain a metallic composite since it allows obtaining a MC at the solid state [15]. Therefore, the main aim of this paper is to highlight the effect of processing parameter (temperature) on the structural and mechanical properties of Al/Cu-grid/Al metallic composites (MC) prepared by process combining high temperature with static compression.

2. Experimental procedure

The materials used in this study were a 1 mm Aluminum sheet (1100), and fine Copper grid (C110), their chemical compositions determined using X-Ray fluorescence spectrometer are shown in Table 2. As a first step in the process of AMC preparation, the Al sheet and Cu grid were cut according to the tensile specimen dimensions, then the Al specimens were mechanically polished using SiC papers from 500 to 4000 grades and cleaned using diluted hydrofluoric acid (HF) to remove any roughness and the residues of oxide layer, thus to avoid the influence of the samples' surface on the adherence

Table 1. Matrix and reinforcement materials used in IMC systems [10].

Mono-filament	Al-Matrix			
	Brittle Reinforcement		Ductile Reinforcement	
	Particles/Platelets	Fiber tows	Wires	Particles
SiC	SiC	Al_2O_3	Mo	Mo
Al_2O_3	Al_2O_3	SiC	Nb	Nb
TiB_2	Er_2O_3		Steel	W
			Cu	Cu

Table 2. Chemical composition of the used materials.

1100Al	Al	Mg	Si	Fe	Ti	--
	99.26	0.22	0.16	0.32	0.02	--
C110 (Cu-grid)	**Cu**	**Pb**	**Ni**	**Fe**	**Cr**	**Co**
	99.69	0.02	0.02	0.14	0.01	0.02

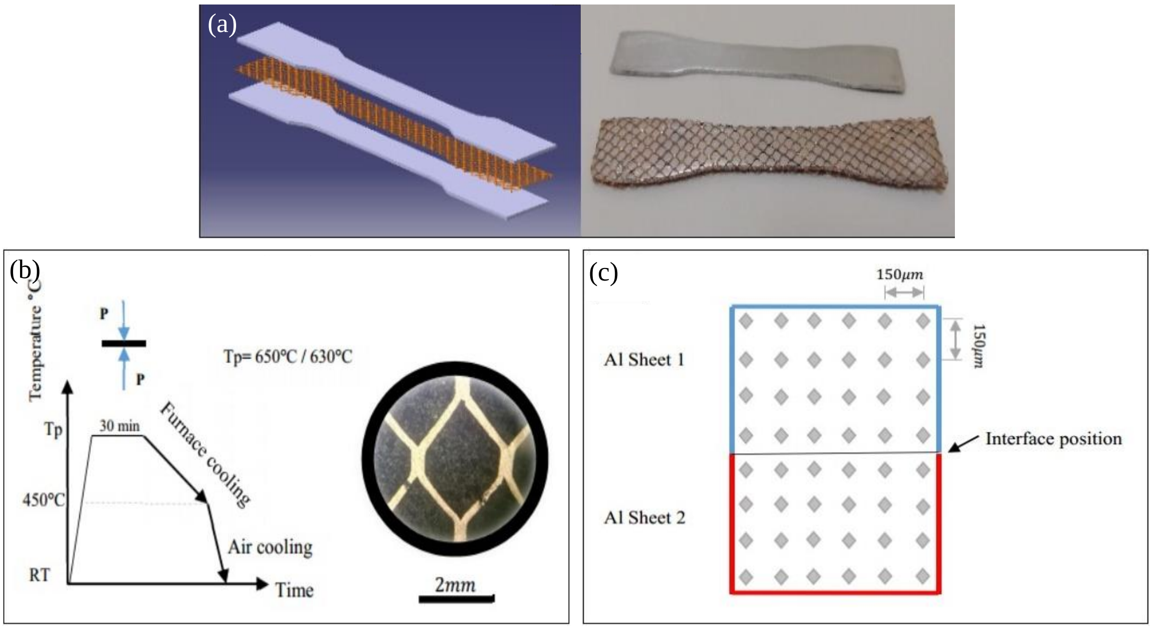

Figure 1. Schematic illustration of: (a-b) metallic composite preparation process, (c) micro-hardness measurements method.

composite compounds. Finally the prepared samples were stacked under a combination of planar static compression (roughly 40 MPa) and high temperature as illustrated in Figure 1(a)-(b). AMC-650 and AMC-630 are the references of the AMC samples resulted respectively from processing temperature Tp = 650°C and Tp = 630°C. The effect of these temperatures on the structural and final mechanical properties of the obtained composite was compared.

After the processing step, microstructural characterization of the as-processed and strained samples was done using optical microscopy (OM), besides the mechanical behavior was characterized at a constant cross head speed of 1 mm·min^{-1} using Zwick-50 KN tensile test machine, a total of 3 samples are tested in each case and average values are reported. Vickers-type micro-hardness measurements were performed under conditions of 50 gf as load and a dwell time of 10 s using a digital micro-hardness tester, the minimum distance between the centers of adjacent indentations was at least 2.5 times the diagonal of the expected minimum hardness (the lowest hardness indent will have the largest indent size) (Figure 1(c)), to avoid interactions between their regions of influence as specified in the ASTM E384-11 standard.

3. Results and discussion

3.1 Microstructural properties

Figure 2(a) and Figure 2(b) show respectively the microstructures of the Aluminum and copper gird used to prepare the Aluminum-based metallic composite (AMC). While Figure 2(c) and Figure 2(d) show respectively the optical micrographs of the as-processed AMC-650 and AMC-630 samples at the interface region.

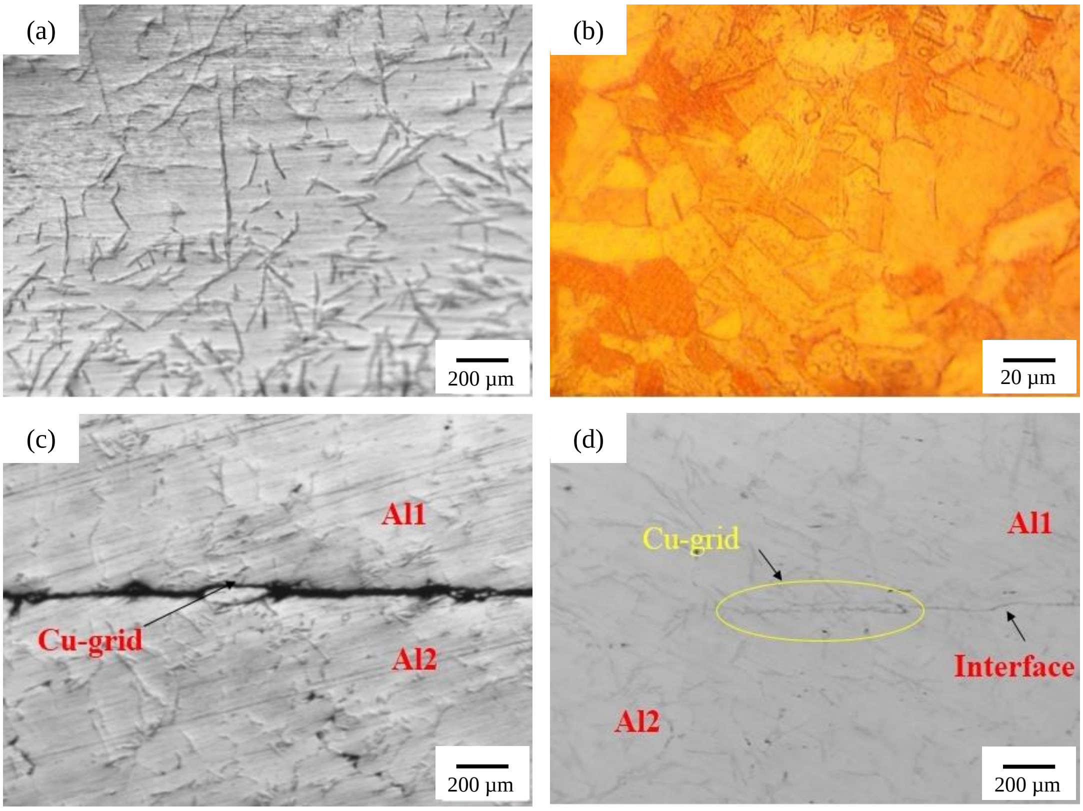

Figure 2. Optical macrographs of : (a) Al base metal, (b) Copper grid, (c) IMC-650 sample, and (d) IMC-630 sample.

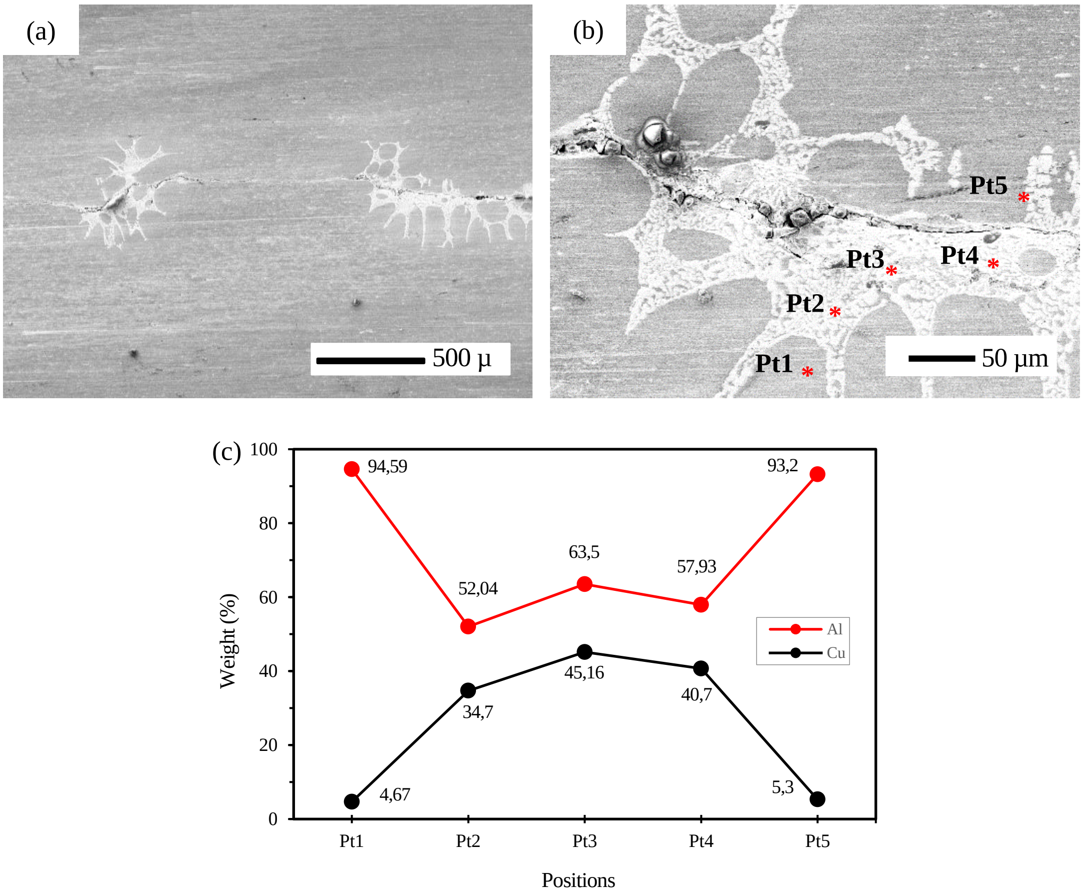

Figure 3. (a)-(b) SEM micrographs of the IMC-630 sample, (c) result of EDS analysis.

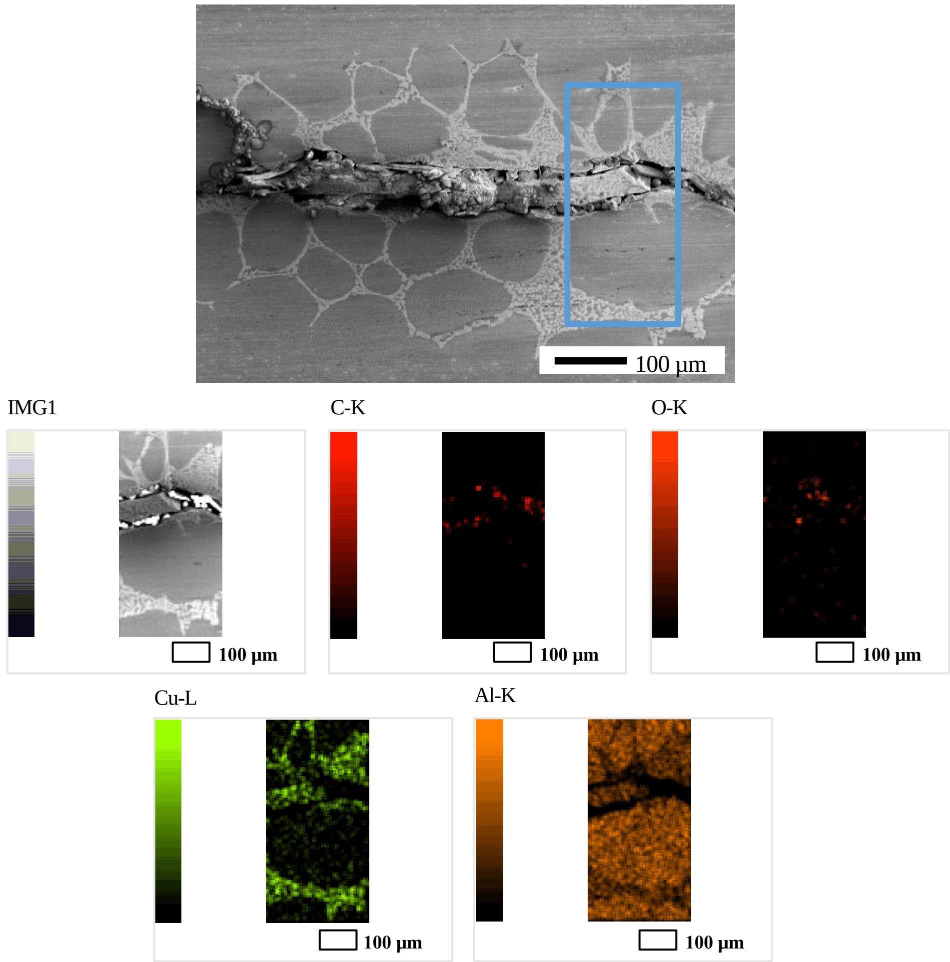

Figure 4. SEM micrographs of the IMC-650 sample at the grid position, and maps of EDS analysis.

First, the microstructures of the Al sheet (1100) base metal of the AMC matrix, and the Cu grid used as ductile reinforcement (Figure 2(a)-(b)) revealed a coarse grained microstructure in the case of Al (Figure 2(a)), while the copper-grid microstructure exhibited a finer grains as shown in Figure 2(b). Besides depending on the process temperature, two different microstructural properties especially at the interface region of the prepared composites are obtained. Thus, from the observation of the Al/Al and Al/Cu-grid interfaces shown in Figure 2(c)-(d), it can be seen that for the AMC-650 sample no effective homogeneous bonding between Al/Al surfaces is observed, whereas only Al/Cu-grid joining was occurred at one side (Figure 2(c)). In contrary, the micrograph of AMC-630 sample (Figure 2(d)) shows continuous bonding between both similar (Al/Al) and dissimilar (Al/Cu-grid) metals. Consequently, such Metallurgical bondings are mainly due to the significant interdiffusion and contact reaction (Figure 3(b)-(c)), whereas the absence of bonding between both Al sheets as well as between Al and Cu grid observed in the case of AMC-650 sample is mainly related to the oxide films may have formed due to the high temperature (650°C), these oxide films are excellent hinder to interdiffusion as shown in EDS analysis of Figure 4.

Additionally, another factor may be considered behind the present result is that at high temperature the effect of the applied pressure on keeping the contact of these surfaces is less than that of the AMC-630 sample. In this optic, according to Y-Q. Han *et al* [7] such results may be explained based on two factors, first the formation of intermetallic compounds that are dependent on the holding time because Al and Cu atoms are thermally activated, second at higher temperature, the formation of oxide films is more significant.

3.2 Tensile behavior

Figure 5 presents the engineering strain-stress curves of all samples determined in static tensile tests at room temperature, the obtained results of the prepared composite were compared each one another and with the Al base metal.

Figure 5 revealed that the tensile curves of all samples demonstrate different behaviors, the AMC-630 sample shows a significant ductility improvement, with a little strength drop. However, the AMC-650 sample shows a significant drop of both strength and ductility. Consequently, the observed behavior at the prepared composites is mainly related to the effect of the matrix (Al) grains size, as well as the bonding of Al/Al and Al/Cu-grid surfaces that depends all on the processing temperature. In the regard of this result of mechanical properties variation with processing condition S. Madhusudan *et al* [16] reported that the influence of composite fabrication conditions on the mechanical properties is more important than the effect of type and volume fraction of the reinforcement used.

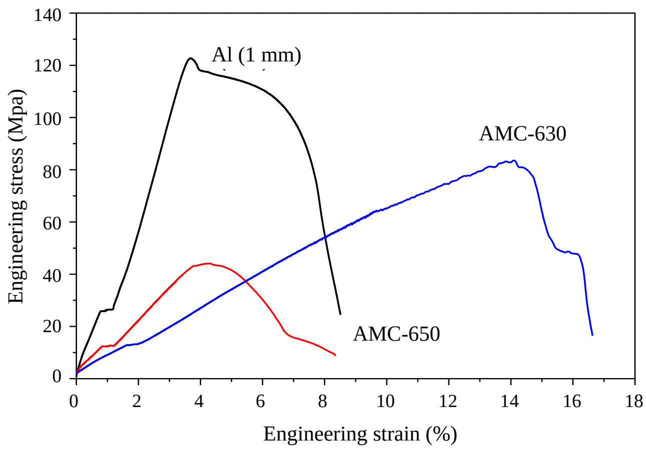

Figure 4. Engineering stress-strain curves of the base metal and the obtained IMC samples.

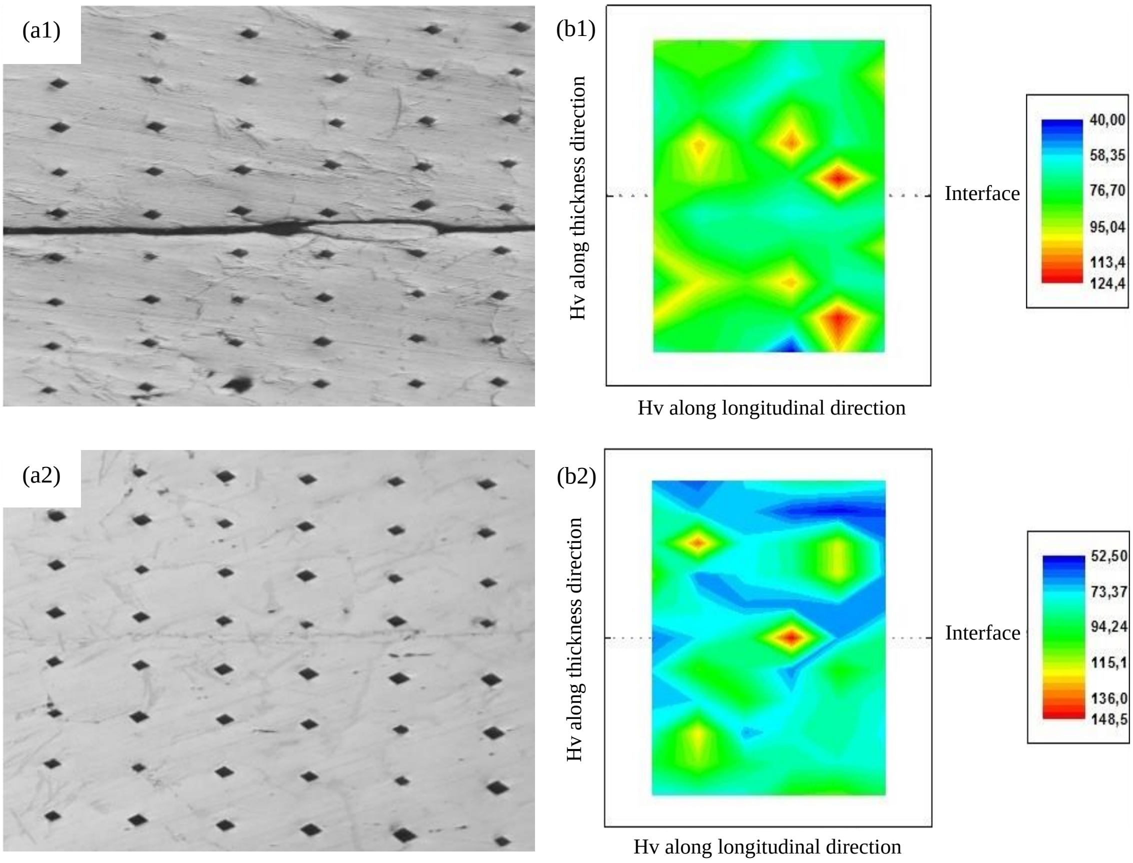

Figure 5. Vickers hardness map of (a1): AMC-650, (a2): AMC-630, (b1) and (b2) corresponding composite sample after making the micro-hardness map.

3.3 Hardness measurements

Micro-hardness maps provide a good qualitative view of the intermetallic composite in both dimensions of the composite cross-section plan. As well, in order to investigate the homogeneity of the hardening induced by the stacking of Cu-grid between two Al sheets under combined effect of static compression and high temperature.

The hardness maps of AMC-650 and AMC-630 samples shown respectively in Figure 6(b1) and Figure 6(b2) revealed that the largest variation within the prepared composites occurs through the thickness direction. Indeed, such variation can be related to the grain size generated by the temperature of composite fabrication. The heterogeneous hardness distribution is achieved in the case of the sample processed at 630°C (AMC-630), the difference of hardness distribution between the prepared samples is mainly linked to the grains size which is found fine in AMC-630 (Figure 6(a2)) comparing to that obtained in the case of IMC-650 sample that revealed coarse grains and shown homogeneous hardness distribution as shown in Figure 6(a1).

3.4 Failure mechanism

Debonding along the interface is one of the common damage mechanisms in reinforced metallic composites [17]. Particularly, the failure occurs at interfaces because they are intrinsically the weakest part of a composite as well as it where the stresses are locally concentrated due to the abrupt changes in properties and irregularities in the geometric distribution of Cu-grid in the composite structure. To that end, Figure 7(a) and Figure 5(b) present respectively the microstructures after failure of IMC-650 and IMC-630 samples.

After tensile tests, one noticeable feature of the optical observations of the fracture according cross-section plane of AMC-650 and AMC-630 samples is that different debonding of the composite's matrix can be seen. Consequently, small and discontinuous debonding of both homogeneous (Al/Al) and heterogeneous (Al/Cu-grid) joints are observed in the IMC630 sample (Figure 7(b)). While full debonding of both types of joints is observed in the case of the IMC-650 sample as shown in Figure 7(a). From that, one may conclude that the interfacial debonding leads to failure of the whole composite.

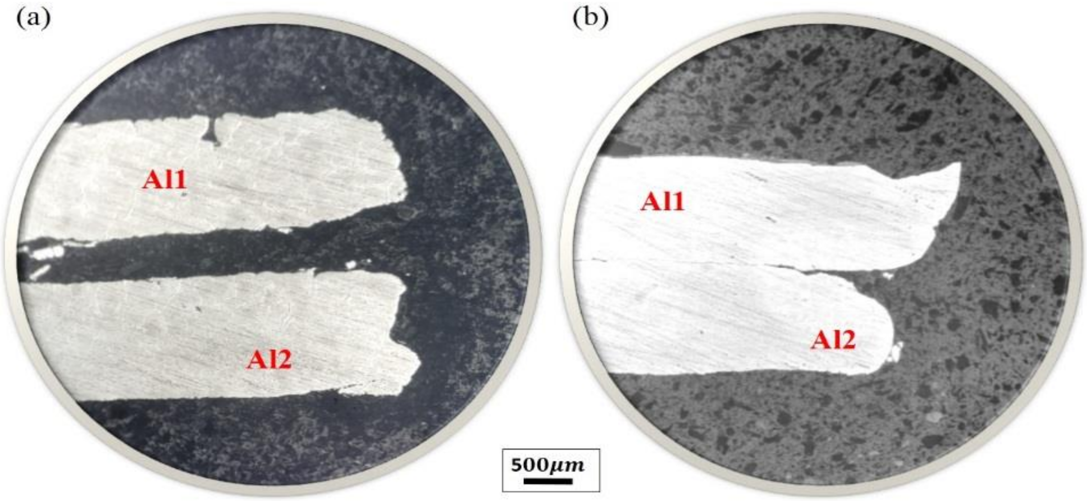

Figure 6. Optical macrographs after tensile test of: (a) IMC-650 and (b) IMC-630.

4. Conclusions

In the present work, we demonstrated the feasibility of manufacturing Intermetallic composite through a combination of static compression with high temperature. Based on the microstructural and mechanical results, the following conclusions can be drawn:

- Intermetallic composite based on Al and Cu-grid can be a promising material capable to combine the properties of the base metals and those of the reinforcement used;
- The present preparation process can be a promising design route to obtain a new intermetallic composite type;
- The temperature for (Al/Cu grid/Al) IMC fabrication is the important parameter that influences the joint microstructure, intermetallic phase formation and elements diffusion between the composite compounds;
- The design of adequate post heat treatment is crucial to improve the mechanical properties resulted from the intermetallic composite obtained with the process combining high compression with high temperature.

Acknowledgements

This work is supported by the Materials and Processing Department of National School of Arts and Crafts ENSAM-UMI-Meknes.

References

[1] P. Garg, A. Jamwal, D. Kumar, K.K. Sadasivuni, C.M. Hussain, and P. Gupta, "Advance research progresses in aluminium matrixcomposites: Manufacturing & applications," *J. Mater. Res. Technol.*, vol. 8(5), pp. 4924-4939, 2019, doi: 10.1016/j.jmrt.2019.06.028.

[2] D.K. Koli, G. Agnihotri, and R. Purohit, "Advanced aluminium matrix composites: The critical need of automotive and aerospace engineering fields," *Mater. Today Proc.*, vol. 2(4-5), pp. 3032-3041, 2015, doi: 10.1016/j.matpr.2015.07.290.

[3] R. Casati, and M. Vedani, "Metal matrix composites reinforced by nano-particles—A review," *Metals (Basel).*, vol. 4(1), pp. 65-83, 2014, doi: 10.3390/met4010065.

[4] C.-Y. Chen and W.-S. Hwang, "Effect of annealing on the interfacial structure of aluminum-copper joints," *Materials Transactions*, vol. 48(7), pp. 1938-1947, 2007. doi: 10.2320/matertrans.MER2006371.

[5] G. Heness, R. Wuhrer, and W.Y. Yeung, "Interfacial strength development of roll-bonded aluminium/copper metal laminates," *Mater. Sci. Eng. A*, vol. 483-484(1-2 C), pp. 740-742, 2008, doi: 10.1016/j.msea.2006.09.184.

[6] M. Abbasi, A. Karimi Taheri, and M.T. Salehi, "Growth rate of intermetallic compounds in Al/Cu bimetal produced by cold roll welding process," *J. Alloys Compd.*, vol. 319(1-2),

pp. 233-241, 2001, doi: 10.1016/S0925-8388(01)00872-6.

[7] Y. qiu Han, L. hua Ben, J. jin Yao, S. wei Feng, and C. jing Wu, “Investigation on the interface of Cu/Al couples during isothermal heating,” *Int. J. Miner. Metall. Mater.*, vol. 22(3), pp. 309-318, 2015, doi: 10.1007/s12613-015-1075-1.

[8] H. Kawakami, J. Suzuki, and J. Nakajima, “Bonding process of Al/Cu dissimilar bonding with liquefaction in air,” *Weld. Int.*, vol. 21(12), pp. 836-843, 2007, doi: 10.1080/09507110701843902.

[9] Y. Wei, J. Li, J. Xiong, and F. Zhang, “Investigation of interdiffusion and intermetallic compounds in Al-Cu joint produced by continuous drive friction welding,” *Eng. Sci. Technol. an Int. J.*, vol. 19(90-95), 2015, doi: 10.1016/j.jestch.2015.05.009.

[10] C.J. Boehlert, and D.B. Miracle, “Intermetallic matrix composites,” *Compr. Compos. Mater. II*, vol. 9795(95), pp. 482-524, 2017, doi: 10.1016/B978-0-12-803581-8.09979-3.

[11] A.P. Zhilyaev, and T.G. Langdon, “Using high-pressure torsion for metal processing: Fundamentals and applications,” *Prog. Mater. Sci.*, vol. 53(6), pp. 893-979, 2008, doi: 10.1016/j.pmatsci.2008.03.002.

[12] R.B. Figueiredo, and T.G. Langdon, “Fabricating ultrafine-grained materials through the application of severe plastic deformation: A review of developments in Brazil,” *Journal of Materials Research and Technology*, vol. 1(1). Elsevier Editora Ltda, pp. 55-62, 2012, doi: 10.1016/S2238-7854(12)70010-8.

[13] Y. Saito, N. Tsuji, H. Utsunomiya, T. Sakai, and R.G. Hong, “Ultra-fine grained bulk aluminum produced by accumulative roll-bonding (ARB) process,” *Scr. Mater.*, vol. 39(9), pp. 1221-1227, 1998, doi: 10.1016/S1359-6462(98)00302-9.

[14] X. Fu, R. Wang, Q. Zhu, P. Wang, and Y. Zuo, “Effect of annealing on the interface and mechanical properties of Cu-Al-Cu laminated composite prepared with cold rolling,” *Materials (Basel).*, vol. 13(2), 2020, doi: 10.3390/ma13020369.

[15] Y.H. Yang, G.Y. Lin, D.D. Chen, R. Zhang, D.Z. Wang, and F. Qi, “Fabrication of Al-Cu laminated composites by diffusion rolling procedure,” *Mater. Sci. Technol. (United Kingdom)*, vol. 30(8), pp. 973-976, 2014, doi: 10.1179/1743284713Y.0000000397.

[16] S. Madhusudan, M.M.M. Sarcar, and N.B.R.M. Rao, “Mechanical properties of aluminum-copper(p) composite metallic materials,” *J. Appl. Res. Technol.*, vol. 14(5), pp. 293-299, 2016, doi: 10.1016/j.jart.2016.05.009.

[17] J. K. Kim, and Y. wing Mai, “High strength, high fracture toughness fibre composites with interface control-A review,” *Compos. Sci. Technol.*, vol. 41(4), pp. 333-378, 1991, doi: 10.1016/0266-3538(91)90072-W.