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Surface treatment of Al7075 Matrix by TiC particles via hybrid ball milling and tungsten inert gas cladding

M. Toozandehjani, F. Ostovan, E. Shafiei, K. R. Jamaludin, A. Amrin, E. Hasanzadeh

Surface composite coatings of Al7075 containing titanium carbide (TiC) particles were fabricated using a hybrid ball milling and gas tungsten inert (TIG) cladding process. Initially, TiC particles were deposited on the surface of Al7075 substrate within ball milling process. The surface melting of Al7075 was then performed by TIG welding at two different current intensities of 80 A and 100 A. From microstructural point of view, a dense, uniform and metallurgically well-bonded Al7075-TiC coating was successfully obtained on the surface of Al7075 substrate which confirmed by SEM, XRD and EDX as well as micro-hardness results. However, composite coating TIG cladded at lower welding current of 80 A provided better properties compared to composite coating cladded at 100 A. The micro-hardness and wear properties of Al7075-TiC coating were found to be significantly improved as compared to Al7075 substrate due to the well dispersed and dense TiC particles.

KEYWORDS: ALUMINUM COMPOSITE COATING; TIG CLADDING; MICROSTRUCTURE; WEAR

INTRODUCTION

In petrochemical industry and offshore applications, the functionality of metallic components is often lost through wear by various modes such as abrasion, impact or corrosion [1,2]. In order to counteract such problem and to extend the service life of metallic components, surface treatment of these metallic components is necessary without altering the bulk material properties [2,3]. One of the approaches for improvement of surface properties of metallic components is alloying or formation of surface composite coating on the surface of in-service component. Effective utilization of composite materials not only enhances the performance of products particularly in term of strength, corrosion and wear resistance but also reduces the cost and size of the materials [4,5]. Employing composite materials provides significant economic benefits such as energy savings and lower maintenance cost [5].

The surface coating processes usually require deposition of a coating layer onto the surface of the substrate at different thicknesses [1,6,7]. The cladding processes is a popular method for deposition of thick surface coating layer to improve corrosion and wear resistances of the substrate [1,2]. The cladding process is usually carried out by high-density

Meysam Toozandehjani, Khairur Rijal Jamaludin, Astuty Amrin
Razak Faculty of Technology and Informatics, Universiti Teknologi Malaysia Kuala Lumpur, 54100, Kuala Lumpur, Malaysia

Farhad Ostovan, Ehsan Shafiei, Ehsan Hasanzadeh
Department of Material science and Engineering, Islamic Azad University, Bandar Abbas Branch, Bandar Abbas, Hormozgan, Iran Corresponding author: Farhad Ostovan f.ostovan@gmail.com

energy arc welding process such as SMAW, GMAW, SAW and GTAW as well as laser welding [3,8-12]. TIG cladding process using gas tungsten arc welding (GTAW) or tungsten inert gas (TIG) welding is one of the feasible possible approaches to fabricate surface composite coatings [13,14]. TIG cladding process include rapid deposition of a relatively thick coating layer which is metallurgically well bonded to the substrate. The major features of TIG cladding are cost-effectiveness, flexibility and accessibility compare to other cladding processes [14]. The TIG cladding process has been used to develop hard and wear resistant coating by incorporating TiB, SiC, Al_2O_3 and other hard ceramic particles over various substrates. It has been reported that TIG cladded composite layer containing these ceramic particles remarkably enhances friction and wear resistance owing to their high hardness, thermal stability and high wear resistance of these particles [15,16].

In this research, a combination of ball milling and TIG cladding process has been employed to fabricate Al7075-TiC surface composite onto the surface of Al7075 substrate. Al7075 alloy is one of most important alloys used in marine industries which require high wear and corrosion resistant. TiC particles were initially deposited on the surface of Al7075 substrate within ball milling process. The Al7075-TiC composite coatings were deposited at two different welding currents. The obtained Al7075-TiC composite coatings were investigated in term of microstructure, hardness and wear behaviour.

Materials and Methods

Rectangular Al7075 substrate were supplied in 300 X 500 mm X 10 mm dimensions from IRALCO (Arak, Iran). Table 1 shows the chemical composition of as-received Al7075 alloy. The substrate plate was cut into small 40 mm X 30 mm blocks using wire electrical discharge machining. TiC particles with an average particle size of 100 µm were also supplied from Alfa Aesar.

Tab.1 - The chemical composition of as-received Al7075 alloy (wt.%).

Ni	Cr	Fe	Mn	Si	Zn	Mg	Cu	Al
0.01	0.07	0.77	0.21	0.71	5.19	1.81	1.5	Base

Initially, 20 gr TiC particles, Al7075 blocks and 200 gr grinding balls were charged into a standard 700 ml tungsten carbide ball milling jar. Ball milling process was carried out using a Retsch PM 100 planetary ball milling machine at room temperature. The mixture was ball milled at the rotational speed of 300 rpm for 8 h under an argon atmosphere. No process control agent (PCA) was added to the powder mixture. Optimum ball milling variables were determined by previous experiments done by authors. The detail of ball milling procedure can be the previous works done by authors [17-20].

After completion of ball milling process, TIG welding process was used for surface melting of the aluminum substrate. TIG welding was carried out using a cone-like tungsten electrode with diameter 2.4 mm while protected using an Argon gas with a purity of 99.99 %. The TIG process parameters are presented in Table 2. TIG process was carried out in direct current electrode negative (DCEN) mode [21]. It provides the higher heat input to the workpiece and results in deeper weld penetration. Argon gas was chosen over Helium since it provides large amount of heat [22]. Typically, flow rate of Argon shielding gas used in TIG welding is in the range of 9 to 14 L/min. The flow rate of Argon was set at 14 liters per minute (L/M) to provide adequate protection of the weld pool and avoiding increased turbulence and aspirate air. After the completion of TIG cladding process, a thick and rough coating layer of 1-2 mm was formed on the surface of Al7075 substrate which was free on any void or crack.

Tab.2 - Process variables of TIG cladding process used for manufacturing Al7075-TiC composite coatings.

Ni	Cr	Fe	Mn	Si	Zn	Mg
1	80	15-20	DCEN	14	4-6	130
2	100					163

In order to reveal the microstructure of Al7075-TiC coating, the surface of Al7075-TiC coating was prepared using a standard metallographic procedure. The Keller solution (1ml HF, 1.5 ml HCl, 2.5ml HNO3, and 95 ml H2O) was as the etchant. The microstructure of Al7075-TiC composite coating was observed by optical microscope (Leitz Metallux 3), SEM equipped with EDS (MIRA3-TESCAN) and FESEM (7600F, JEOL Inc.). An X-ray Diffractometer (BRUKER-D8) equipped with a 1-D (LYNXEYE) fast detector was used to phase analysis of Al7075-TiC composite coating. The X-ray source was CuKαwith a wavelength of 1.54060 Å. The scans were performed with 0.015 °/min step size, exposure time of 0.1 s/step and 2-theta (2θ) range of 5°-120°. The XRD patterns were analyzed using X'Pert High Score software.

The hardness measurements were performed to construct hardness profile in order to depict the hardness in different regions from the coating surface down to the substrate. The Vickers hardness testing machine (KOOPA, UV1) was employed to apply load of 300 gf and dwell time of 15 s at three different points and the average was reported. The wear test was conducted using a standard pin-on-disc abrasive wear test equipment (THV-5D) at room temperature. Sliding wear test was carried out in a ball-on-disk configuration. The Al7075-TiC samples were slid against a 4 mm ball-bearing steel at a constant load of 40 N, the sliding speed of 150 rpm and constant test duration of 3600 s. The sliding wear tests were carried out at room temperature without lubricant. The abrasive wear values were reported in term of weight loss as a function of sliding distance of 200, 400, 600, 800, and 1000 m. The weight measurements were done using an analytical balance with the accuracy of 0.1 mg. Finally, the worn surfaces of Al7075-TiC composite coatings were investigated using SEM.

RESULTS AND DISCUSSION

The cross-sectional morphology of the Al7075-TiC surface composite processed by TIG cladding at both 80 A and 100 A is shown in Fig. 1. First of all, it can be seen that a dense Al7075-TiC composite layer of 1-2 mm thickness is formed on the top surface of Al7075 substrate at both 80 A and 100 A through diffusion of the pre-applied TiC layer into the Al7075 substrate (Figs 1a and 1b). In both welding currents, Al7075-TiC is well bonded to the Al7075 substrate and there is no porosity or crack in TIG cladded Al7075-TiC composite coatings. An interface reaction occurs between TiC particles and Al7075 matrix and interfacial bonding links TiC particles to Al7075 substrate. Peng et al [23] have also successfully fabricated clad layer containing TiC particles onto carbon steel with a good metallurgical bond between the clad layer and the substrate. It seems that welding current of 80 A is enough to dissolve TiC particles into molten metal and form a composite coating layer. By increasing welding current to 100 A, the depth of molten metal pool increases due to higher heat input as reported in Table 2, resulting in a thicker composite coating on the surface of Al7075 substrate. The typical optical micrographs of Al7075 substrate and Al7075-TiC composites at both 80 A and 100 A is shown in Figs 1c-e.

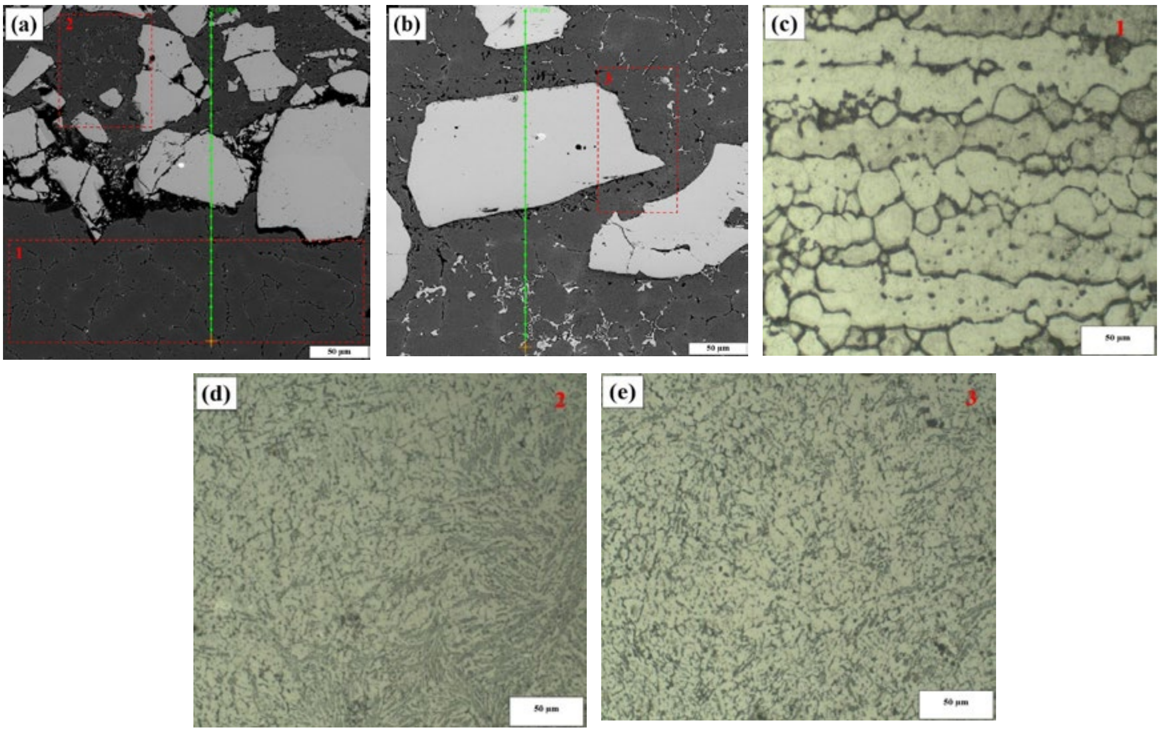
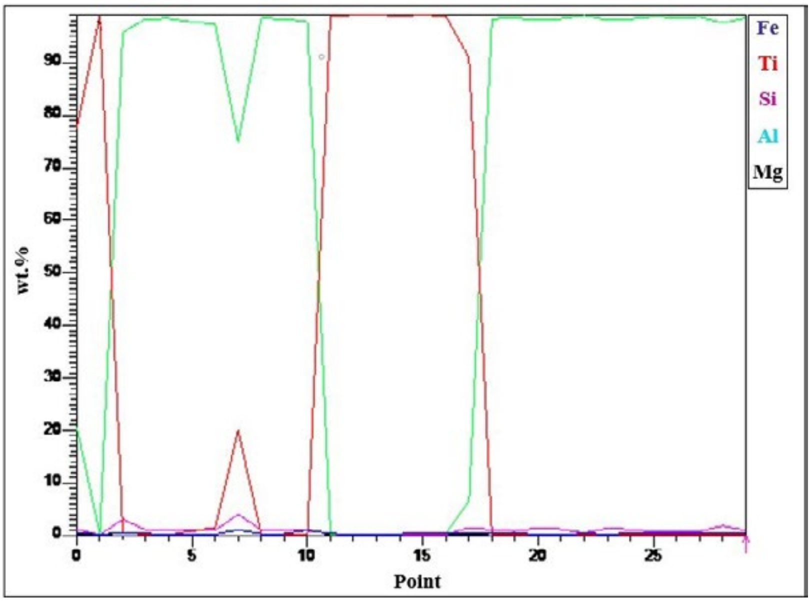


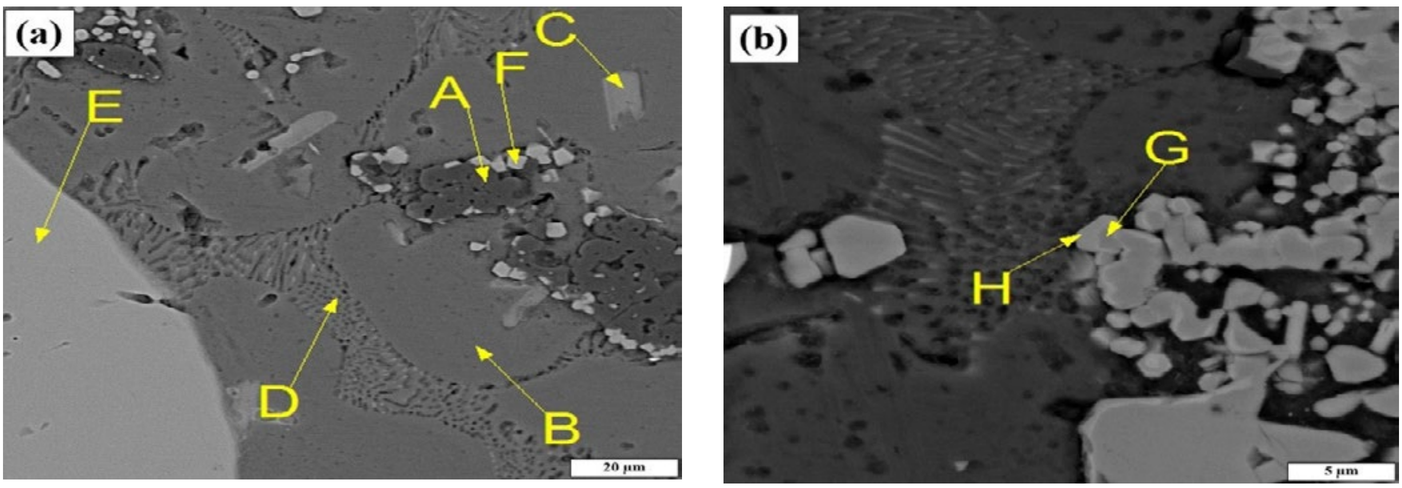
Fig.1 - Cross-section microstructure of Al7075-TiC composite coating TIG cladded at a) 80 A, b) 100 A and c-e) optical micrographs of different sections of Al7075 substrate and Al7075-TiC composite coatings.

Fig. 2 shows the linear EDS spectrum across cross-section of Al7075-TiC composite coating TIG cladded at 100 A. The linear EDS analysis was carried out at 30 different points as indicated in Fig. 1a. It can be observed that the concentration of Ti (wt.%) in the composition of Al7075-TiC composite coating is much higher than the substrate indicative of the diffusion of TiC particles into Al7075 substrate due to surface melting during TIG cladding process. The similar trend is also observable in Al7075-TiC composite TIG cladded at 100 A. The presence of Fe at very small amount in the composition may be due to formation of (Ti, Fe)C carbide as a result of dissolution of Fe originated from contaminations into Al7075-TiC composite coating.

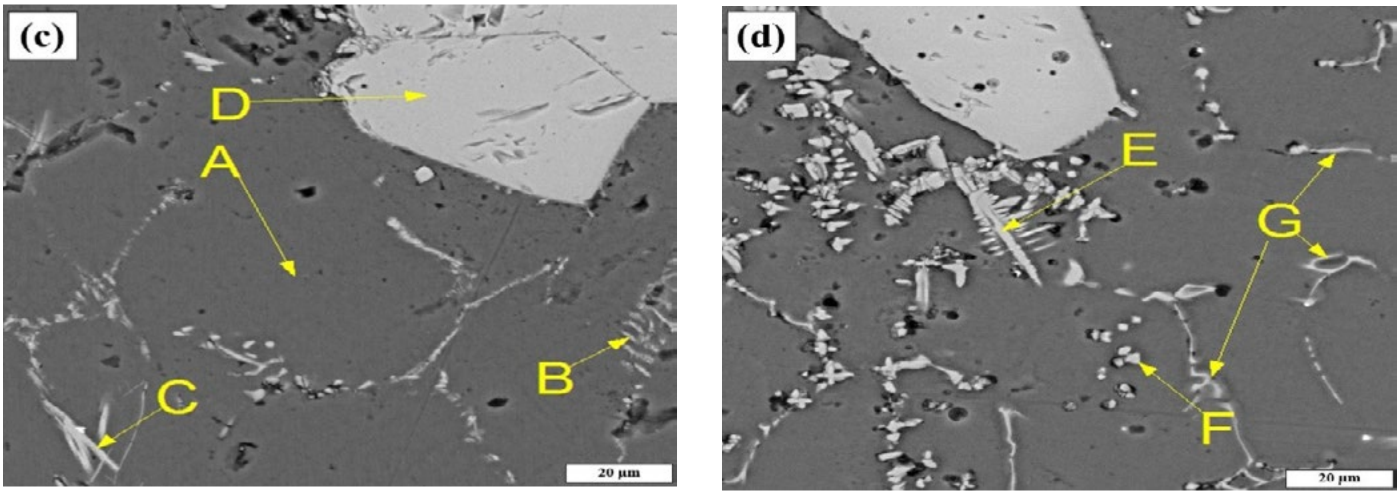


points	Chemical composition (wt %)				
	Mg	Al	Si	Ti	Fe
1-5	-	98.41	1.13	0.15	0.31
5-7	-	97.34	1.00	1.41	0.24
7-12	0.09	0.31	0.4	98.82	0.37
12-14	0.17	0.30	0.23	99.06	0.25
14-18	0.34	6.59	1.51	90.96	0.60
18-30	-	98.54	0.96	0.11	0.39

Fig. 2 - EDS spectrum of the Al7075-TiC composite coating layer TIG cladded at 100 A.



	Chemical composition (wt %)								
	O	Mg	Al	Si	Ti	Cr	Mn	Fe	Cu
A	49.66	0.17	48.25	1.00	0.43	0.05	0.06	0.09	0.28
B	-	-	97.90	1.48	0.14	-	0.08	0.10	0.030
C	-	-	66.55	1.97	30.91	0.46	-	0.11	-
D	-	-	95.46	2.36	-	0.09	-	2.09	-
E	-	0.17	0.39	0.26	98.95	0.10		0.13	-
F	-	0.21	7.13	0.82	91.58	0.12	-	0.14	-
G	-	-	2.56	1.14	96.30	-	-	-	-
H	-	-	17.42	1.99	80.59	-	-	-	-



Region	Chemical composition (wt %)								
	O	Mg	Al	Si	Ti	Cr	Mn	Fe	Cu
A	-	0.04	97.72	1.72	-	-	0.11	0.1	0.31
B	-	0.07	92.53	1.63	-	-	-	5.47	0.31
C	-	0.10	66.51	2.11	-	-	-	30.56	0.72
D	-	0.44	0.52	0.39	98.00	-	0.17	0.13	0.34
E	-	0.52	9.86	1.01	86.90	-	0.13	1.12	0.46
F	-	0.54	12.89	0.34	85.30	-	0.23	0.32	0.37

Fig.3- SEM micrographs and EDS analysis of the specified points in the Al-TiC composite layer TIG cladded at a,b) 80 A and c,d) 100 A

Due to the high heat input generated during TIG cladding process (130-163 J/mm), the surface melting occurs in a very thin layer of Al7075 substrate and TiC particles are distributed within the matrix of Al7075 substrate. During solidification of Al7075-TiC composite coating, the nucleation of TiC particles begins and they grow as a dendritic structure within the molten pool. It should be mentioned that a non-uniformity in microstructure occurs in the composite coating processed at 100 A due to higher heat input (163 J/mm). Fig. 3 reveals that Al7075-TiC surface composite coating consists of TiC particles (white) distributed in in the Al7075 matrix (dark) as also revealed by EDS semi-quantitative chemical analysis. The chemical composition of selected points in Al7075-TiC composite coatings as tabulate below the corresponding figures. The presence of TiC particles in Al7075-TiC composite coatings is also confirmed by EDS elemental mapping as shown in Fig. 4. The EDS mapping shows that Ti is reasonably high at Al7075-TiC coating layer.

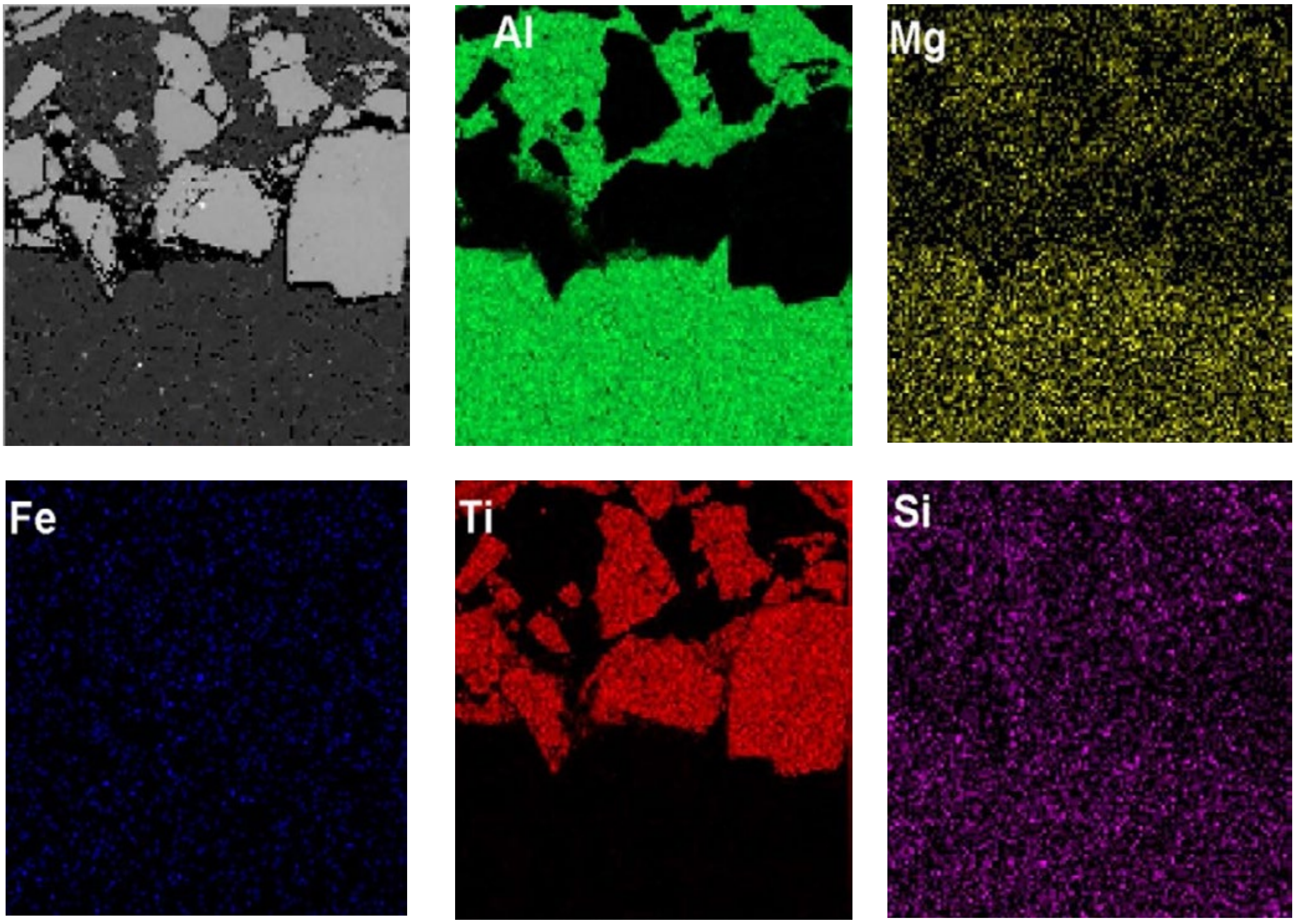


Fig.4 - EDS elemental map of the Al7075-TiC composite coating layer TIG cladded at 80 A.

Fig. 5 shows the X-ray diffraction patterns of Al7075-TiC surface composites TIG cladded at both 80 A and 100 A welding currents. The XRD patterns of Al7075-TiC composite coatings contain Al7075 and TiC peaks as the main phases presented in the microstructure. No peak related to un-wanted phases or compounds was found in the XRD patterns of Al7075-TiC composite coatings indicating occurrence of no reaction between TiC and Al7075 substrate. The XRD results are consistent with EDS results as discussed earlier.

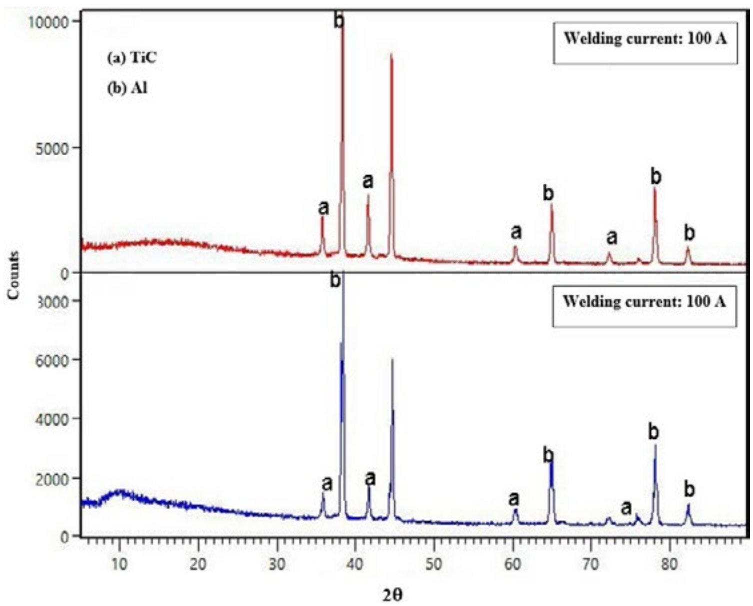


Fig.5 - XRD pattern of the Al7075-TiC surface composite coating layers TIG cladded at current welding of 80 A and 100 A.

The distribution of micro-hardness along the cross section of Al7075-TiC composite coating from the top surfaces of composite coating down to the inner substrate is presented in Fig. 6. The Al7075-TiC composite coatings display remarkably higher HV values compared to Al7075 substrate. The highest HV value of 114 HV was recorded at the surface of Al7075-TiC composite coating layer TIG processed at 80 A which was about 53% higher than Al7075 substrate (52 HV). The main reason for higher HV values is the presence of the well-dispersed TiC particles in the microstructure of Al7075-TiC composite coating along with refined and compact microstructure TIG processed composites. According to literature, the micro-hardness of the composite coatings is closely associated to content and distribution of reinforcement particles [24,25]. In fact, the maximum micro-hardness values were recorded at the near-surface of both Al7075-TiC composite coatings. The slight improvement of the HV at near-surface of both Al7075-TiC composites is mainly due to work hardening of coating structure at near-surface layers [26].

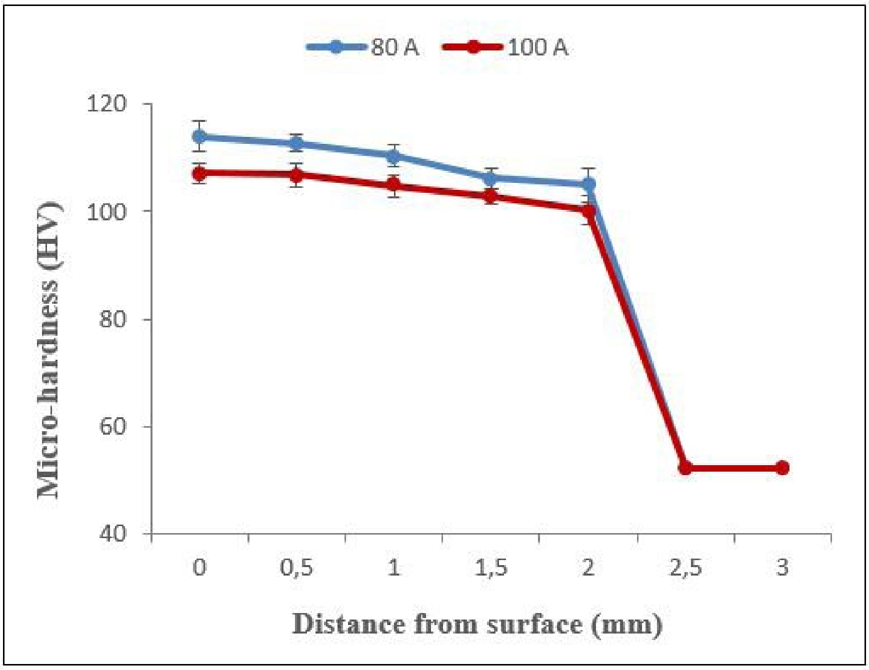


Fig.6 - Micro-hardness distribution along the profile in the cross section of Al7075-TiC composite coating TIG cladded at current welding of 80 A and 100 A.

It should be mentioned that HV values vary in a narrow range suggesting that TiC particles are uniformly distributed in the composite layer. It was previously observed that TIG processed Al7075-TiC coatings have a nearly uniform structure. A uniform structure with uniformly distributed TiC particles leads to a more uniform HV distribution in Al7075-TiC composite coatings. However, Al7075-TiC coating TIG cladded at 80 A shows a relatively higher hardness owing to a nearly uniform structure at the upper surface of Al7075 substrate.

Fig. 7 represent the wear loss variation of Al7075 substrate and Al7075-TiC composite coating layers as a function of sliding distance. In general, the wear rate of samples increases with increasing sliding distances up to 1000 m. It can be seen that Al7075-TiC composite coating layers show considerably lower weight loss and higher friction stability than Al7075 substrate which implies remarkable enhancement of wear resistance of Al7075-TiC composite coating. At sliding distance of 1000 m, for example, the weight loss of Al7075-TiC composite layer processed at both welding currents of 80 A and 100 A was approximately 43 mg and 38 mg, respectively which was much lower than that of Al7075 substrate (180 mg). In addition, it is observed that Al7075-TiC composite coating. At sliding distance of 1000 m, for example, the weight loss of Al7075-TiC TIG cladded at 100 A shows lower wear rate compared to its counterpart processed at 80 A.

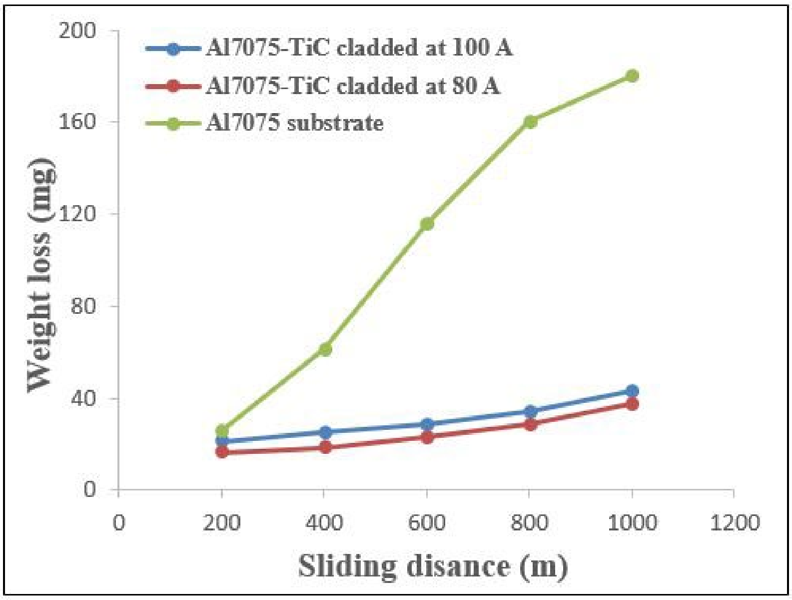


Fig.7 - Weight loss variation of Al7075 substrate and Al7075-TiC composite coatings TIG processed at 80 A and 100 A as a function of sliding distance.

The wear resistance and micro-hardness of Al7075-TiC composite coatings vary in the same manner. As discussed earlier, Al7075-TiC composite coating possess enhanced HV values therefore an enriched abrasive wear resistance is expected. It is well stablished that the wear resistance of a coating is closely associated to its hardness [26,27]. According to Rabinowicz and Tanner [27], the volume of abrasion loss is related to hardness according the following formula:

$$V = kPL/H$$

V: Volume of abrasion loss; H: Microhardness; P: Applied loading force; L: Coefficient of wear.

The enhanced wear resistance of Al7075-TiC composite coatings is attributed to the presence of hard TiC phases. Hard TiC carbides are act as a barrier to the movement of an abrasive tool and improves the wear resistance. Abhinavaram et al., [28] have reported the improvement of hardness and wear properties of Al7075 by incorporation of WC using TIG. Peng [29] also reported the effectiveness of hard TiC clad layer on improvement of wear resistant of carbon steel. According to Peng [30], TiC provide better wear resistance than that of WC and TiN. The wear scar area of the specimen with TiC cladding was only one-tenth that of carbon steel without cladding. In addition, uniform distribution of TiC particles further increases the wear resistance of Al7075-TiC composite coating. According to Srivastava and Das [31], the more carbide particles are found in the coating and the carbides are more homogeneously distributed, the greater the wear resistance of Al substrate.

Fig. 8 presents the surface morphologies of Al7075 substrate and the TIG cladded Al7075-TiC composite coatings after wear test. The worn surface morphology of Al7075 substrate is characterized by plowing grooves, spalling pits and debris (Fig. 8a). There are deep and wide plowing grooves which extended in the sliding direction during wear test (Fig. 8a). The absence of hard TiC particles causes the microplowing of the substrate when steel pin moves against the surface of substrate during wear test. The surface morphology of Al7075-TiC composite coatings seems to be significantly less abraded than Al7075 substrate. The worn surfaces of Al7075-TiC composite coatings are shown in Figs. 8b and 8c wherein morphology contains less and shallow grooves compared to Al7075 substrate. This suggests that the primary wear mechanism of the composites is abrasive wear.

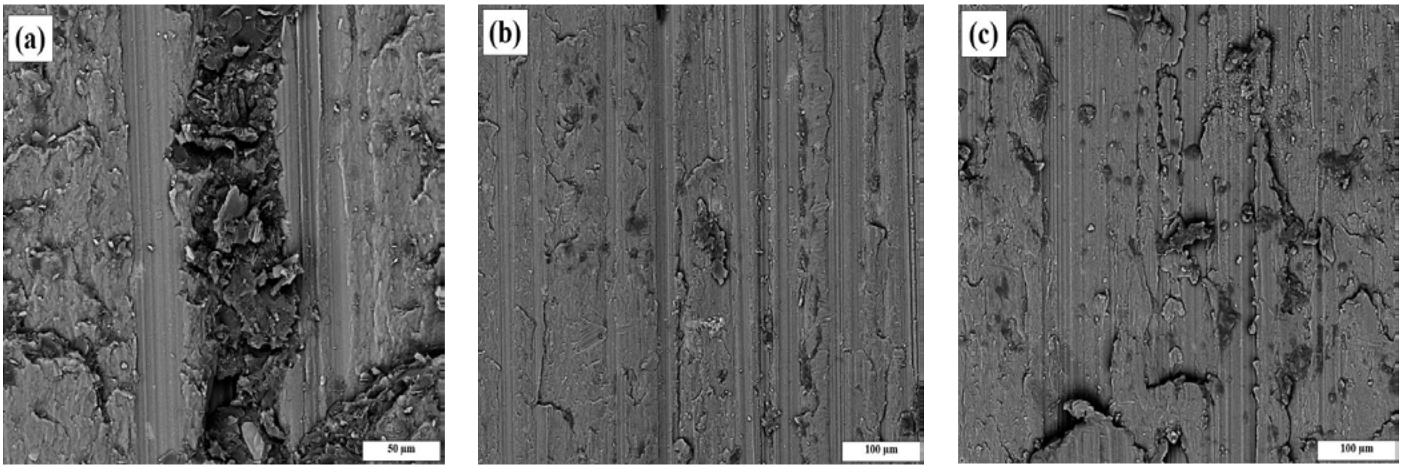


Fig.8 - Worn surface of a) Al7075 substrate and Al7075-TiC composite coating TIG cladded at b) welding currents of 80 A, c) welding currents 100 A.

CONCLUSIONS

A dense Al7075-TiC composite coating was successfully processed on the surface of Al7075 substrate where metallurgically well-bonded to the substrate. TiC particles were found to be dispersed uniformly throughout microstructure of composite coating. The hardness of Al7075-TiC composite layers was found to be more than double (114 HV) that of Al7075 substrate (52 HV). Similarly, wear rate of Al7075-TiC composite layers was remarkably lower that Al7075 substrate showing enhancement wear resistance of Al7075-TiC composite coating based on the weight loss measurements.

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