EFFECT OF TITANIUM ON THE MICROSTRUCTURE, HARDNESS, AND WEAR BEHAVIOR OF HYPOEUTECTIC Al-4%Ni ALLOY

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Hypoeutectic Al-4Ni alloy with various titanium proportions (0.2, 0.4, 0.6 and 0.8%) was prepared, analyzed and tested. Optical microscope, SEM and EDS were used to characterize the microstructure while hardness and pin on disk technique were used to explore the properties of prepared Al-4Ni-xTi alloys. Results of the experimental work showed that $TiAl_3$ had a crucial role on α-Al refining. Hardness was increased and wear rate decreased as the titanium proportion increased. Furthermore, Al_3Ni was globularized in the subsurface damage zone during sliding at all applied loads.

Keywords: microstructure, Al-4Ni alloy, Ti addition, hardness, wear behavior

1. Introduction

Aluminum alloys as important engineering materials in either wrought or cast forms, depending on the alloying elements present, have relatively high strength and low density characteristics [1,2]. Nickel is one of the most favorable elements added to pure aluminum to improve the mechanical properties [3]. Nickel solubility is low in aluminum; subsequently, several intermetallic compounds can be created. Most intermetallic compounds are strong, hard and have stability at high temperatures because of their crystal structures associated with having a high melting temperature. Nickel aluminides have attractive properties as low density, corrosion and wear resistance, as well as resistance against oxidation, fatigue, carbonization and deformation. Particular attraction of nickel aluminides is related to high strength retention at high temperature [4]. These characteristics enable the intermetallic compound to make it preferable to enhance the performance of vehicles, engines, tools, heat exchangers, pumps, mold parts as well as several parts in manufacturing [5, 6].

The microstructure of binary hypoeutectic aluminum-nickel alloys is characterized by dendritic growth of α-Al and eutectic formation (α + β), in which α symbolizes the phase rich with aluminum and β symbolizes the Al_3Ni compound. Hard Al_3Ni acts as a structure reinforcement and provides Al-Ni

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alloys higher mechanical strength which can allow the design of products to have appropriate mechanical properties [7, 8].

The implementation of a reasonable strategy to enhance the Al-Ni alloys properties is done by the addition of transition metals (TM). Two essential groups of TM can be classified according to their solubility in aluminum. The first group (TM1) has relatively high solubility in aluminum like Sc, V, Cr, Mn, Ti, Hf, Mo and Zr. The second group (TM2) has extremely low solubility in aluminum such as Ce, Ni, and Fe, making constituent particles or eutectics. Increasing solidification rate enhances TM1 solubility in aluminum; however, it does not change TM2 solubility [9]. Among TM1, the increase in titanium particularly in Ti-containing Al alloys increases the wear resistance as a result of increased hardness by the existence of hard-phase of Al_3Ti intermetallic compound [1].

R.S. Yaseen et al (1983) [10] found that Al-Al_3Ni eutectic alloy exhibited mild wear and it underwent plastic deformation followed by Al_3Ni fragmentation under all bearing pressures in the subsurface. The microstructure of Al-(6-14)Ni alloys produced by employing vacuum melting was studied by A. Juarez and H. Jones (1998) [11]. They found that Al_3Ni grown in dendritic manners usually aligns well with the direction of growth in a matrix of a cellular eutectic. G. Gonzalez et al (2008) [12] showed that the ribbon prepared utilizing melt spinning from Al–4Ni alloy was consisted of globular Al_9Ni_2 like structure with the 100 nm size within Al matrix and concentrated at the grain boundaries. M.V. Cante et al (2010) [13] noticed that the mechanical properties were increased for Al-(1-5)Ni alloys by increasing the proportion of alloy solute and diminishing primary and secondary DAS. E. Karakose and M. Keskin (2011) [14] found that α-Al and fine Al_3Ni were evolved in the alloy matrix and the mechanical properties were improved, as a consequence of changing the microstructure of Al–3Ni alloys that resulted from conventional casting and melt-spinning process.

The upward directionally solidified Al–5.7Ni alloy at distinct solidification parameters was studied by H. Kaya et al (2012) [15]. They deduced that the electrical resistivity and hardness increased with increasing temperature gradient and growth rate. R. Yamanoglu et al (2013) [16] investigated the impact of nickel in the concentration of 1 to 5% on the properties of aluminum alloys and they showed that the hardness increased with increasing nickel concentration and severe wear deterioration was recognized at low as well as high nickel concentration.

There are several studies on Al-Ni alloys in the literatures. However, studies on the hardness and wear properties that have practical applications for near eutectic Al-Ni alloys containing titanium are scarce. Thus, the current research was conducted to study the evolution of microstructure, hardness as well as wear properties of Al-4Ni alloy containing various proportions of titanium (0.2-0.8%Ti).

2. Materials and Methods

Commercial purity aluminum, pure nickel and Al-Ti master alloy, their chemical compositions illustrated in table 1, were used as starting materials. The chemical compositions were determined using a spectrometer type max device. Al-4Ni alloy was manufactured from Al-22Ni master alloy and commercial purity aluminum. Titanium has been added as an Al-5Ti master alloy in different proportions (0.2, 0.4, 0.6 and 0.8%) to the Al-4Ni molten alloy. The molten was poured into an unheated copper mold having a cylindrical cavity (diameter 12 mm, height 80 mm). Table 2 showed the chemical analysis of prepared Al-22Ni master alloy and Al-4Ni-xTi alloys. The pouring temperature of Al-4Ni alloys was set at 950 °C. Calcium chloride flux ($CaCl_2$) was used to remove gases dissolved in the melt of Al-Ni alloys.

Table 1

Weight percentage chemical composition of the starting materials used

Elements (wt.%) / Materials	Cu	Si	Fe	Zn	Mn	Ti	Ni	Al
Pure Al	0.036	0.214	0.095	0.005	0.003	0.001	0.002	Bal.
Pure Ni	0.201	-	0.330	-	0.214	-	Bal.	-
Al-Ti master alloy	0.023	0.181	0.245	0.474	0.018	5.00	0.040	Bal.

Table 2

Weight percentage chemical composition of prepared Al-22Ni master alloy and Al-4Ni-xTi alloys

Elements (wt.%) / Materials	Ni	Cu	Si	Fe	Zn	Ti	Al
Al-Ni master alloy	22.2	0.027	0.180	0.081	0.003	0.00	Bal.
Al-4Ni alloy	4.41	0.029	0.20	0.083	0.004	0.00	Bal.
Al-4Ni-0.2Ti alloy	3.85	0.031	0.197	0.083	0.004	0.28	Bal.
Al-4Ni-0.4Ti alloy	4.16	0.030	0.98	0.086	0.004	0.41	Bal.
Al-4Ni-0.6Ti alloy	4.00	0.032	0.21	0.082	0.004	0.57	Bal.
Al-4Ni-0.8Ti alloy	3.75	0.030	0.21	0.088	0.004	0.72	Bal.

Metallographic study was achieved using Nikon optical microscope after grinding, polishing and etching. The specimens were etched with diluted HF etching solution (0.5% HF in distilled water) in order to manifest the microscopic structure.

The hardness test of Al-Ni-xTi alloys was performed utilizing Vickers hardness testing machine. Five readings were taken for each specimen of Al-Ni alloys using the load of 0.4 kg with 10 s hold time. Wear test was done using pin-on-disk wear machine with a 35 HRC steel disc rotating continuously and it was considered as a counterface (Fig. 1). Wear test specimens of diameter 10 mm and height 20 mm were prepared utilizing cutting and turning processes. An oblique section using a 5 degree taper section of the worn surface was taken to study the nature of subsurface damage and characterize the presence of deformed Al_3Ni.

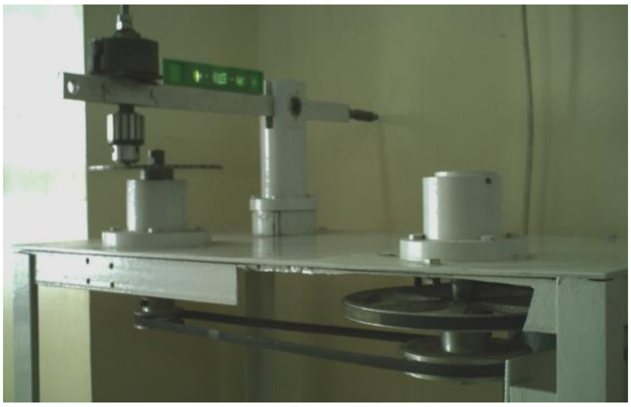

Fig. 1 Pin-on-disk wear machine

Microstructure of Al-4Ni alloys and features of worn surface topography of wear test specimens were characterized utilizing TESCAN/VEGA3 LM SEM. Analysis of the cast elements distribution in the Al-4Ni alloys was performed utilizing EDS equipped with SEM.

3. Results and Discussion

The microstructure of prepared Al-4Ni alloy (Fig. 2a) was consisted of α-Al and eutectic phases where the eutectic composed of α-Al and lamellar Al_3Ni (Fig. 2b). The equilibrium Al-Ni phase diagram clearly indicated the existence of only the rich α-Al and the Al_3Ni intermetallic compound at the nickel concentration of 4% [17]. X-ray mapping confirmed the distribution of nickel in Al-4Ni alloy as illustrated in figure 3. The analysis revealed that aluminum was combined with nickel, especially in Al_3Ni, in highest concentricity in eutectic and lowest in α-Al. Moreover, the analysis of X-ray element map and microstructure observation confirmed the formation of α-Al and eutectic in the Al-4Ni alloy. Obviously, α-Al has grown dendritically in the Al-4Ni alloy matrix. Titanium addition had a considerable influence on the microstructure, especially on the α-Al as shown in Fig. 4. It has been experimentally found that the maximum titanium solubility did not exceed 1% in the Al-6Ni alloy which served for $TiAl_3$

nucleation in the alloy matrix [9]. Therefore, adding Ti to the Al-4Ni alloy improves the α-Al refining. The α-Al refining was increased with the increase of titanium proportion in the Al-4Ni alloy matrix as illustrated in table 3. This could be attributed to the effect of titanium that promoted the formation of $TiAl_3$ and encouraged the nucleation of α-Al. EDS of Al-4Ni-0.8Ti alloy pointed out to the evolution of anomalous Ti enriched phase as shown in Fig. 5. We can suggest that it was TiAl intermetallic compound, in the form of needle and cross, distinguished by angular contour that had smooth brinks. The analysis of X-ray mapping also showed that the alloying elements were distributed homogenously in the alloy matrix.

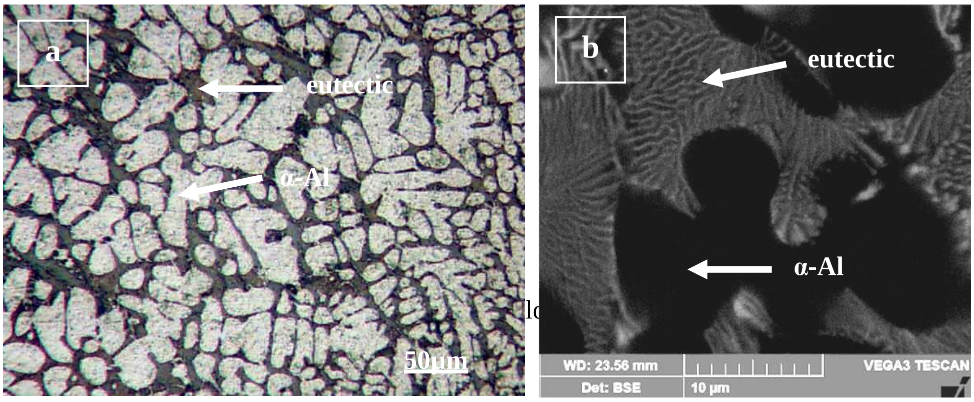

Fig. 2 Microstructure of binary Al-4Ni alloy (a) optical image (b) SEM imag

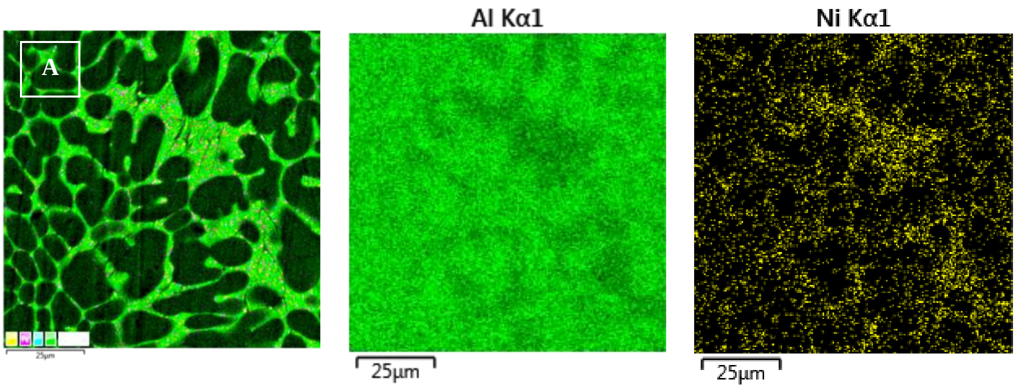

Fig. 3 Area analysis of chemical elements of Al-4Ni alloy: image of secondary electrons (A) and map of main elements distribution

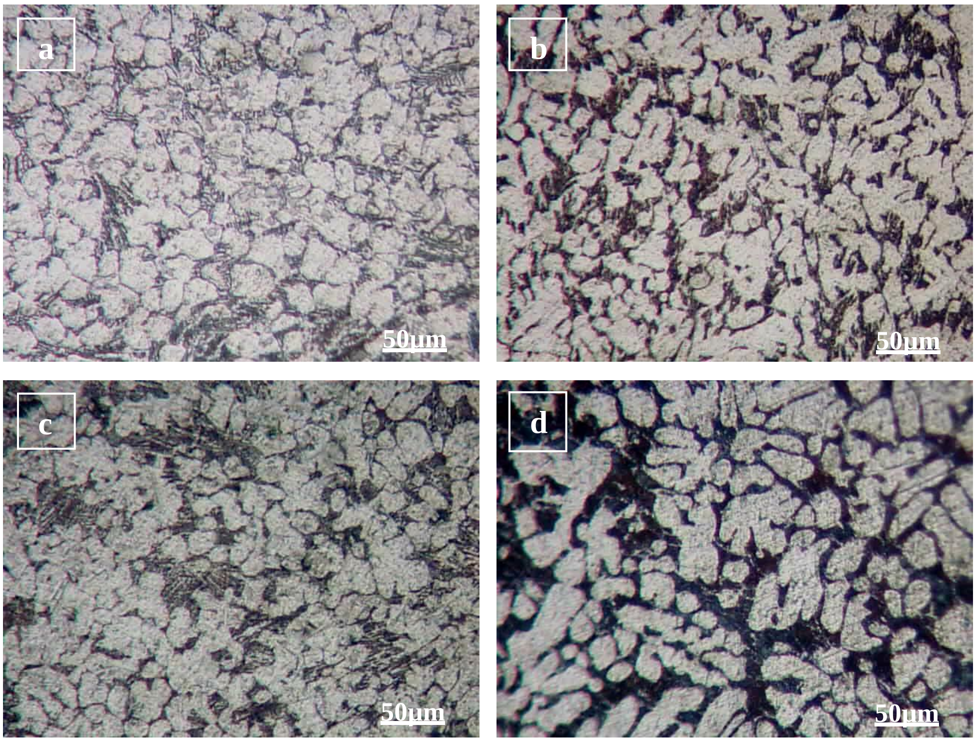

Fig. 4 Microstructure of Al-4Ni-xTi alloys containing (a) 0.2%Ti, (b) 0.4%Ti, (c) 0.6%Ti and (d) 0.8%Ti

Table 3

α-Al average size in relation to Ti% in Al-4Ni-xTi alloys

Ti%	**Average size of α-Al (μm)**
0	22
0.2	20
0.4	18
0.6	17
0.8	15

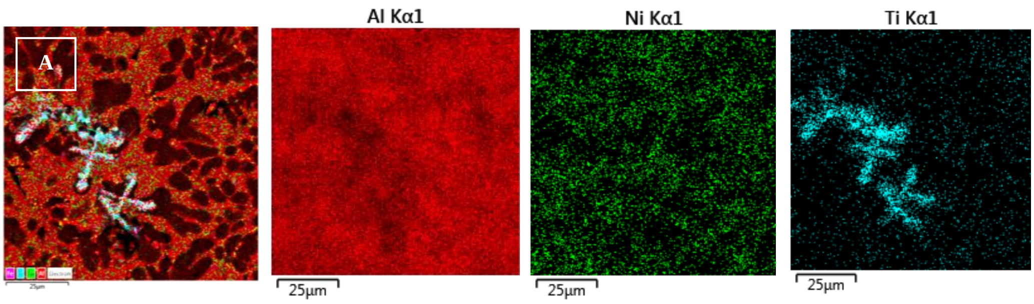

Fig. 5 Area analysis of chemical elements of Al-4Ni-0.8Ti alloy: image of secondary electrons (A) and map of main elements distribution

The addition of titanium had an important influence on rising the hardness of Al-4Ni alloy where the hardness increased linearly with the increase of titanium (Fig. 6). This could be related to the effect of α-Al refining and hampering influence of $TiAl_3$ on dislocation movement.

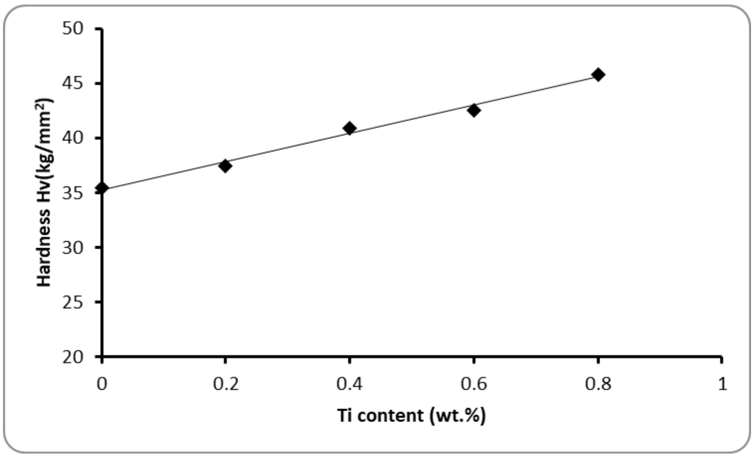

Fig. 6 Hardness under the influence of different titanium proportions in Al-4Ni alloy

The impact of adding titanium on the wear rate under various applied loads for Al-4Ni alloy is shown in Fig. 7. Clearly, the wear rate tended to decrease with an increase in the proportion of titanium added. This could be related to $TiAl_3$ which refined the solidification microstructure and thus increased the hardness as described above. Therefore, the wear rate tended to decrease with the increasing hardness. This observation coincides with the common relation between hardness and wear rate reported elsewhere [18]. Fig. 7 also showed an increased wear rate with the increased load applied as a consequence of increasing the actual contact area among mating surfaces. Dry sliding of Al-Ni-xTi alloys was performed at room temperature on the steel counterface. Increased plastic deformation of asperities during sliding with increased applied load led to rise the actual contact area among the mating surfaces. The contact of asperities during sliding occurred when the application of load was started. The contact was weak when low load applied. Therefore, the oxidation of asperities would be occurred and the oxidized wear debris would be fractured and compacted in the interface among the surfaces of pin and the counterface. The increased applied load would make metallic wear the predominant mechanism for removing the material. Therefore, plastic deformation and fracture are characteristics of Al-Ni alloys surface through metallic wear.

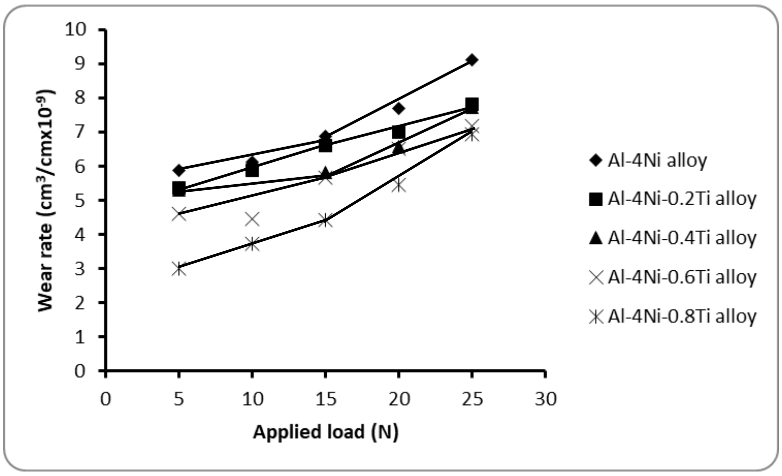

Fig. 7 Wear behavior under the influence of various applied loads for Al-4Ni-xTi alloys

The wear affected subsurface zone of Al-4Ni alloys can be divided into three subzones (Fig. 8).

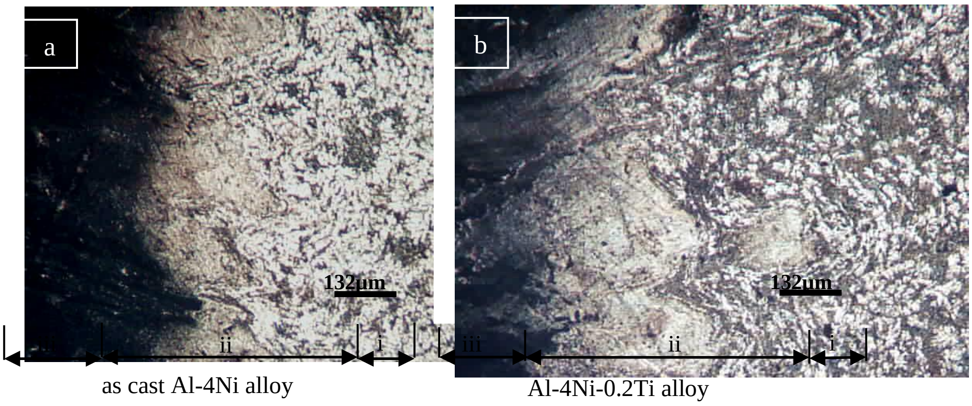

Fig. 8 Wear affected subsurface zone of Al-Ni alloys at applied loads of (a) 5N and (b) 15N

These subzones included (i) Al-Ni alloy matrix that was not affected by plastic deformation, (ii) subsurface damage distinguished by plastic deformation and Al_3Ni globularization close to the worn surface, and finally (iii) worn surface. The Al_3Ni globularization occurred in Al-Ni-xTi alloys at all applied loads. The Al_3Ni globularization increased with increased load applied. The Al_3Ni globularization could be explained in several stages including, the deformation of Al_3Ni, the fragmentation of deformed Al_3Ni, and finally globularization of fragmented Al_3Ni due to the concentration of high temperature close to the worn surface. The relationship between subsurface damage depth versus titanium proportion of Al-4Ni alloy showed that the subsurface damage depth at constant applied load decreased with increasing titanium proportion via increased hardness (Fig. 9). The relationship between subsurface damage depth and applied load disclosed that the subsurface damage depth at a constant titanium proportion increased with an increment in the applied load due to increased deformation with increased applied load in the subsurface zone (Fig. 10).

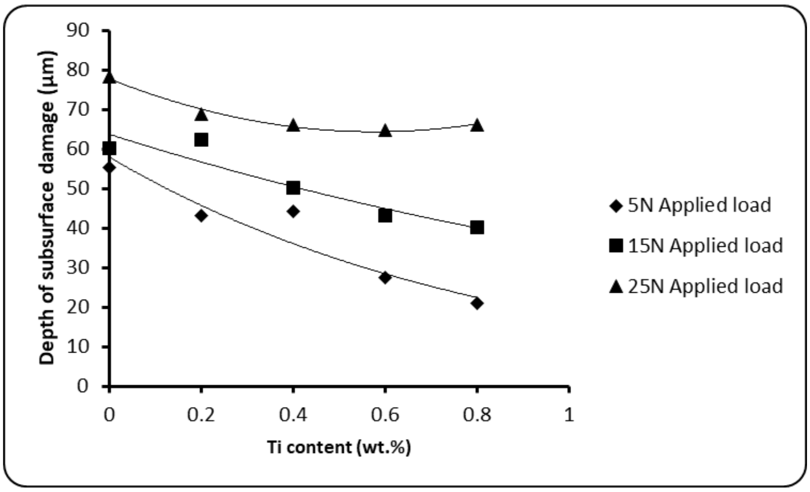

Fig. 9 Impact of titanium proportion on the subsurface damage depth of Al-4Ni alloy at various applied loads

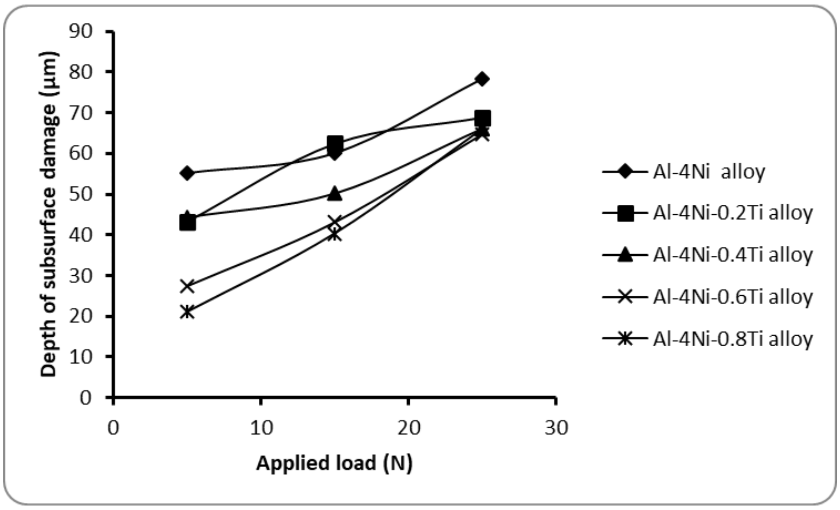

Fig. 10 Impact of applied load on the subsurface damage depth of Al-4Ni-xTi alloys

Wear test and the scanning electron microscopy have tremendously contributed towards a comprehensive study of the wear mechanisms of materials.

Studying the worn surface of Al-4Ni-xTi alloys at 15 N applied load illustrated that the roof tile laminates were the major worn surface characteristic through sliding (Fig.11). Distinct layers on the worn surface could be clearly recognized for Al-4Ni alloys. It was not only the mechanism for removing materials, without any doubt, but it was linked to other mechanisms to make wear among the surfaces of the pin and the counterface. The fine grooves recognized on the worn surface were directly related to the effect of ploughing (Fig. 11a), where the increase in the applied load increased the width and depth of the wear tracks. Increasing the hardness of the Al-4Ni alloy via titanium addition reduced the plastic deformation of the pin surface during sliding. It was observed especially at applied load greater than 15 N during wear test of Al-Ni alloys, the occurrence of particle transfer from pin surface to the counterface which increased with increasing the applied load. These particles adhered to the counterface were increased material removal and created grooves. Grooves were decreased during plastic deformation, and cracks were generated leading to material removal from the Al-4Ni-0.8Ti alloy pin surface (Fig. 11b). Furthermore, the laminated nature was observed at the sides of the crater, and a thin material peninsula appeared ready to separate.

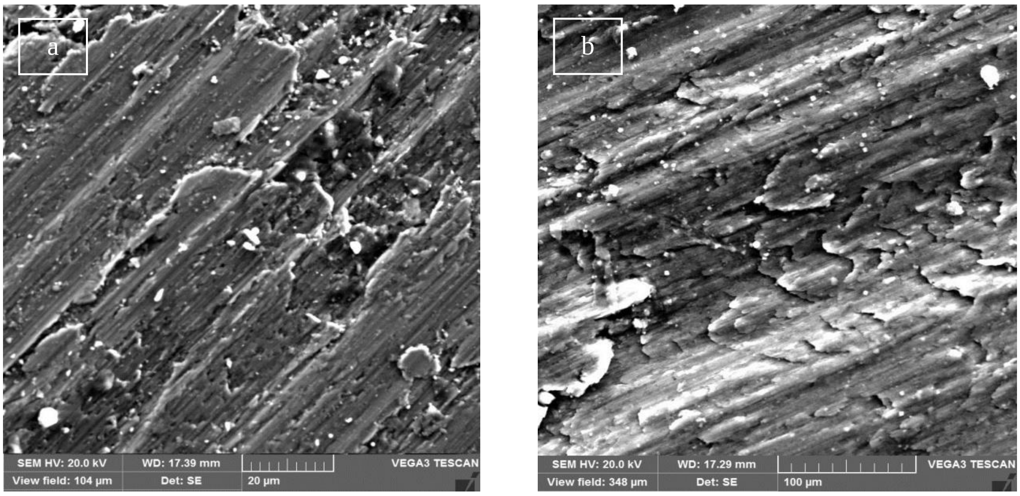

Fig. 11 SEM images appear a worn surface at applied load of 15N (a) Al-4Ni alloy and (b) Al-4Ni-0.8Ti alloy

4. Conclusion

The microstructure associated with the titanium addition to the Al-4Ni alloy resulted in α-Al refining and it was directly proportional to the titanium proportion. Additionally, α-Al in the A-4Ni alloy matrix had fully growing dendritically. The hardness of Al-4Ni alloy increased linearly with increased titanium proportion as a result of α-Al refining and/or Al_3Ti effects in the matrix.

The increased titanium proportion in Al-4Ni alloy lowered the wear rate. Moreover, two wear mechanisms occurred in Al-Ni alloys that involve dry sliding on a steel counterface. These mechanisms were oxidative-metallic and metallic wear. Furthermore, the Al_3Ni deformation in subsurface of Al-Ni alloys during wear test and high temperature established close to the worn surface resulted in Al_3Ni globularization.

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