Key Engineering Materials
ISSN: 1662-9795, Vol. 796, pp 67-73
doi:10.4028/www.scientific.net/KEM.796.67

Submitted: 2018-09-25
Revised: 2018-11-26
Accepted: 2018-12-27
Online: 2019-03-22

Mechanical Behaviour of Sputtered Aluminium Thin Films under High Sliding Loads

Fredrick M. Mwema[1,a*], Esther T. Akinlabi[1,b], O.P. Oladijo[1,2,c]

[1]Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg 2006, South Africa

[2]Department of Chemical, Materials and Metallurgical Engineering, Botswana International University of Science and Technology, Private Bag 16, Palapye, Botswana

[a*]fredrick.mwema@dkut.ac.ke, [b]etakinlabi@gmail.com, [c]seyiphilip@gmail.com

Keywords: Aluminium; thin films; sputtering; substrate temperature; wear.

Abstract. In this work, the wear behaviour of thin aluminium thin films (thickness range of 750-1500 nm) deposited on rough stainless-steel substrate through radio-frequency (rf) magnetron sputtering at varying substrate temperature (T_s) was studied. The films were studied under extremely high wear loads of 30 N and 50 N. The coefficient of friction and material loss are characterised as functions of the T_s of the deposited aluminium films. It was observed that due to the evolving microstructural and roughness properties of the films, the material behaviour of the films under extremely high sliding loads significantly depend on the substrate temperature. The most significant coefficient of friction was observed at 60ºC and 80ºC, and highest material loss was recorded at 100ºC. The material loss and variation of the coefficient of friction were related to the morphology (porosity and roughness) of the sputtered thin films.

Introduction

Aluminium thin films have found applications in solar, optical and microelectronics fields and as such, they are deposited on metal, silicon, glass or polymer substrates. Regardless of the substrate of deposition, thin films (including Al films) suffer from various mechanical problems such as delamination and cracking [1]. Thin films experience mechanical loading during machining, assembling to other sections or application. Furthermore, when deposited on glass for optical applications, Al films are frequently exposed to various sliding or wear loads during scouring and cleaning. As such, comprehension of deformation, failure and material removal during sliding mechanical loading of thin films is crucial. In a recent review, Kang and Huang [2] have indicated that nanoindentation, scratch/wear tests can study the failure mechanisms of thin films. In mechanical loading of thin films, three failure modes are experienced: (i) delamination at the interface due to residual compression (ii) cracking across the thickness of the film and (iii) decohesion of the films due to cracking of the substrate [2].

Various studies have explored the failure modes for different thin films under sliding loads (wear studies). Geng *et al.* [3] reported on the mechanical stability of 10 nm thin Ag films under sliding contact loads. The wear failure mechanisms of Al-based films has also been reported [4], [5]. The wear failure of films and coatings depend on the type and nature of substrate [6] and the deposition conditions of the film such as temperature [7]. The failure mechanisms of soft multilayer films have also been described [2], [8]. Despite extensive research on properties of Al thin films, their behaviour under extreme mechanical loading is not understood. This work, therefore, explores the mechanical behaviour of these films subjected to extreme sliding/wear loads.

Methodology

The sputtering process of the aluminium films used in this study has been described elsewhere [9]. The films were prepared at varying substrate temperatures of 44.5ºC, 60ºC, 80ºC and 100ºC and at RF power of 200 W for 2 hours. The film thickness varied between 750 nm to 1.5μm. The field emission scanning electron microscopy (FESEM) and atomic force microscopy (AFM) measurements were undertaken on the samples before the wear test. Wear analyses were conducted using a multifunctional tribometer (*Rtec-instruments, San Jose, CA, USA*). The equipment can perform tribology, indentation, scratch and mechanical tests and has a maximum reciprocating speed of 50 mm/s. It has inbuilt imaging modules such as interferometer, microscopes, AFM and Raman spectrometer. The experiment was conducted on a ball-on-flat mode at room temperature under dry (unlubricated) wear conditions. Table 1 shows the wear test parameters used in this study.

Table 1. Wear test parameters

Item	Parameter
Wear type	Cyclic, ball-on-flat test
Lubrication	Dry/unlubricated
Ball size	6.350 mm
Sliding velocity	1 mm/s
Sliding length	3 mm
Loading type	Constant
Loads	30 N, 50 N
Dwell time	5 s
Cycle time	30 s

Results and Discussion

Fig. 1 shows the SEM micrographs of the Al films deposited on the stainless-steel substrates at various substrate temperatures. The substrate roughness was measured to be about ~50-100 nm whereas the roughness after deposition of the films were 16.08, 18.91, 16.19, 11.71 nm at of 44.5°C, 60°C, 80°C and 100°C respectively. As shown, the microstructure develops gradually with the substrate temperature. The films deposited at 44.5-80°C were characterised by amorphous and porous structure whereas, at 100°C, the structure consisted of large, crystalline and less-porous structures. Similar microstructural evolutions were reported for Al thin films sputtered at varying substrate temperature [10]. Figs. 2 and 3 show the variation of coefficient of friction (μ) with the sliding time of the Al films sputtered at different T_s at loads of 30N and 50N respectively. The plots are presented for only one cycle of the reciprocating action of the steel ball on the film surface since the variation of μ with time was the same throughout the sliding time. For both loads and at each T_s, the μ increased rapidly up to 0.05 at 0.1 seconds, and then an oscillatory variation of about 0.05 observed to 0.9 seconds. These observations were replicated for each cycle of reciprocation of the steel ball motion on the surface of the Al thin films. For both loads, the average higher values of μ were obtained at 80°C and 60°C than at 44.5°C and 100°C. These observations can be related to high roughness and porosity in the films deposited at 80°C and 60°C. The μ at 100°C is very low, which can be related to significantly developed surface morphology (Fig. 1d) and very low roughness value-the aluminium film is softer than the substrate and therefore easily spalled off the surface under extreme sliding loads.

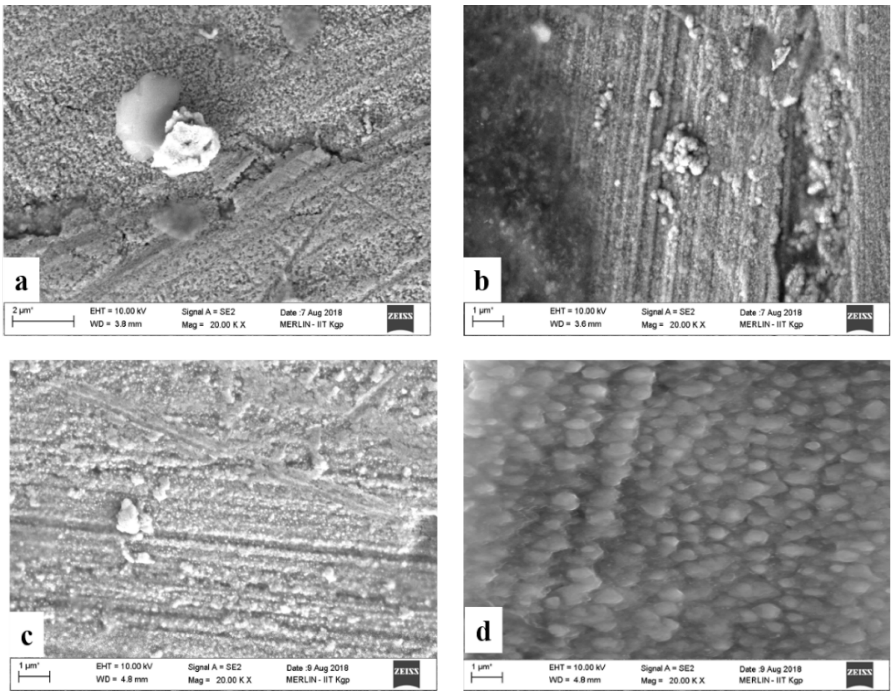

Figure 1. Morphology of the surface of Al thin films sputtered at (a) 44.5ºC (b) 60ºC (c) 80ºC and (d) 100ºC.

The influence of the normal applied load on to coefficient of friction (μ) for the films is shown in Fig. 4. As observed for all the samples, the average μ was lower at 30N for the forward stroke of the reciprocating steel ball and vice versa for the return stroke. The volume of material loss during the sliding loading of the Al films is shown in Fig. 5. The highest volume loss of the surface material was observed at 100ºC whereas the lowest volume loss was seen at 80ºC. As expected, the surface with the highest coefficient of friction and roughness would exert the highest resistance to the sliding of the steel ball, and therefore less material loss was recorded. These results were further related to the wear track contours and depths shown in Figs. 6 and 7. Deeper wear tracks with larger areas of the exposed substrate (blue coloured) were observed at 100ºC. At 80ºC, the wear track appeared densified and continuous as seen in Figs. 6c and 7c. According to these wear tracks, the material loss, in this case, occurred through abrasion between the Al film and the hard steel ball.

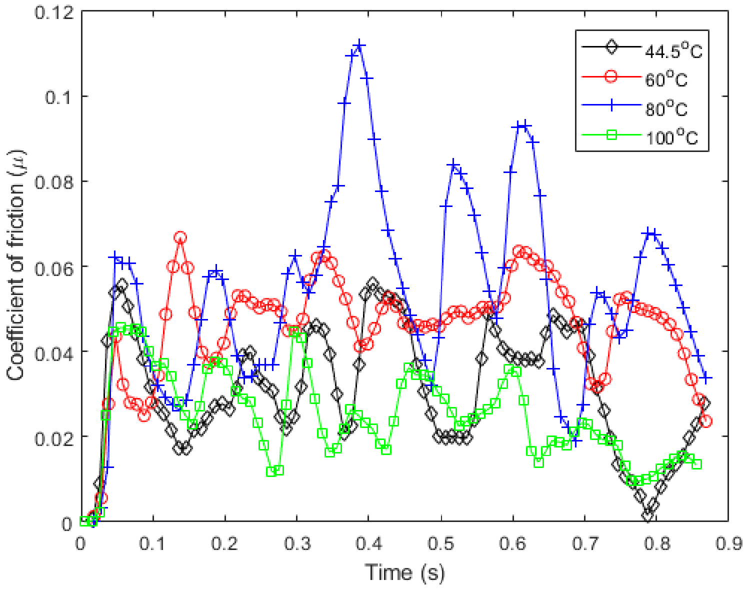

Figure 2. The variation of coefficient of friction (μ) with time during the dry sliding at a normal load of 30N along the surfaces of Al films sputtered at different substrate temperatures.

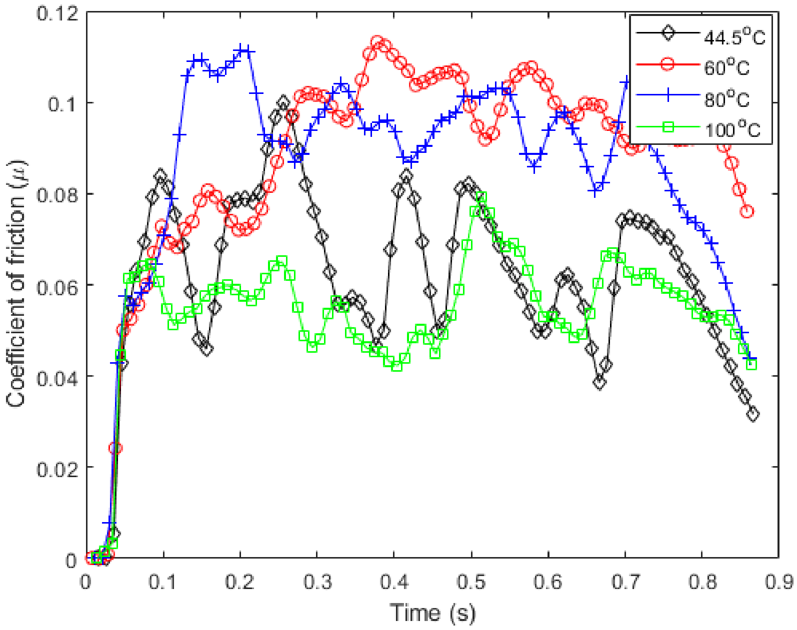

Figure 3. The variation of coefficient of friction (μ) with time during the dry sliding at a normal load of 50N along the surfaces of Al films sputtered at different substrate temperatures.

To understand the wear behaviour of the Al films exhibiting high roughness and porosity, an atomic/microscale scheme illustrated in Fig. 8 was adopted. During the initial stages of the steel ball loading across the surface of the film, atoms move to occupy the porous regions. However, resistance to the motion of the structures is expected due to the smaller sizes of the pores compared to their sizes. As the loading persists, some structures break down while others undergo plastic deformation and flow within the coating surface. These mechanisms result in mechanical densification (rather than loss of the material) of the film structure. The densification increases the contact area between the ball and wear track hence leading to increase in coefficient of friction. This densification is the reason for continuous wear track observed in Figs. 6c and 7c. The high density of the film offers high resistance to the ball sliding and hence high coefficient of friction. Through optical imaging, Fig. 9, the densification and material removal on the surface of the films were illustrated. As shown, at 44.5°C, there was more area of the substrate exposed than at 80°C.

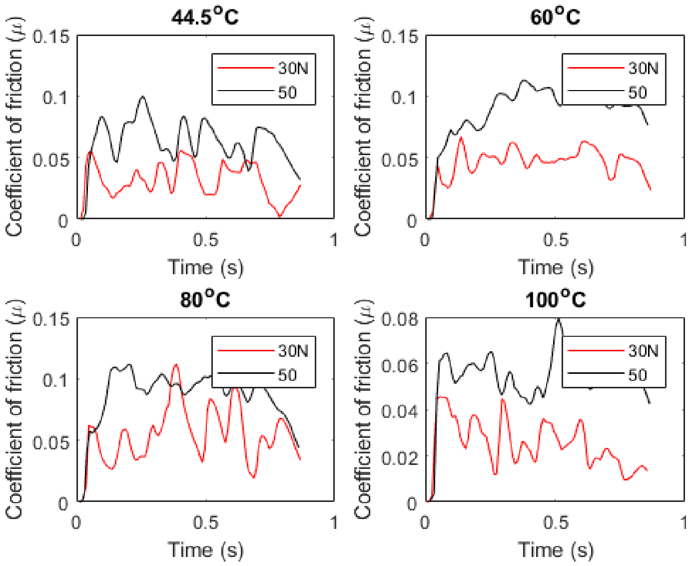

Figure 4. Comparing the coefficients of friction of the films under 30N and 50N.

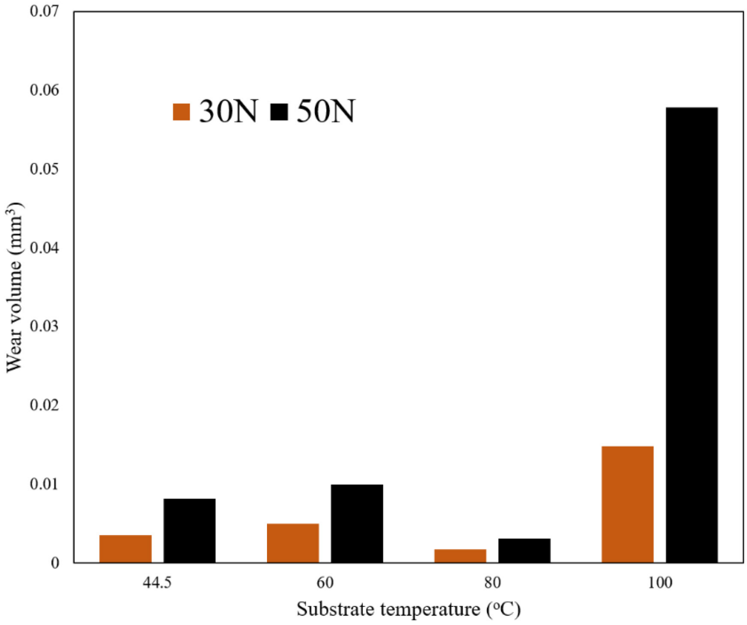

Figure 5. The total volume of material loss during the sliding wear of the films at 30N and 50N loads.

As seen in Figs. 6-9, the failure of the coating under extreme loads is through plastic deformation and complex stress states existing within the contact region. As the ball slides across the surface of the film, it deforms and then ploughs the films and therefore leading to material removal.

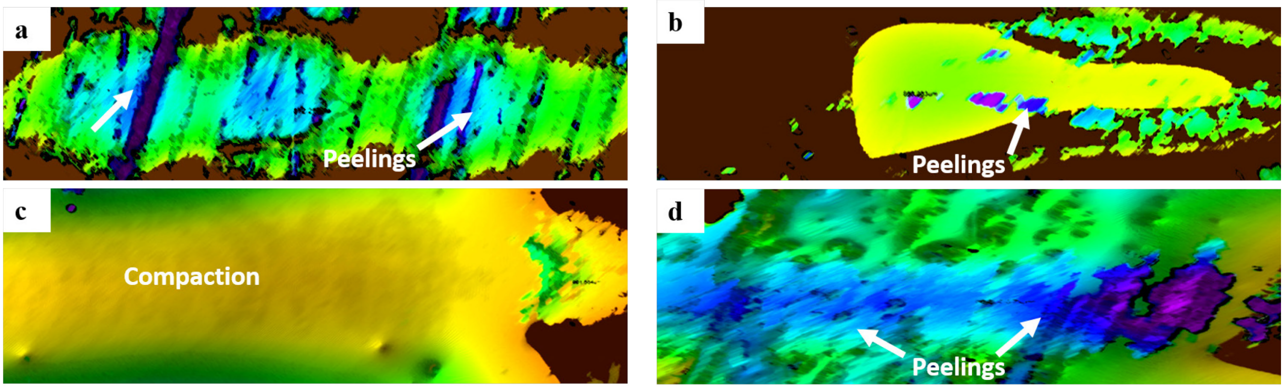

Figure 6. Wear track contours at 30N for Al films sputtered at (a) 44.5°C (b) 60°C (c) 80°C and (d) 100°C. The blue colour indicates the substrate surfaces.

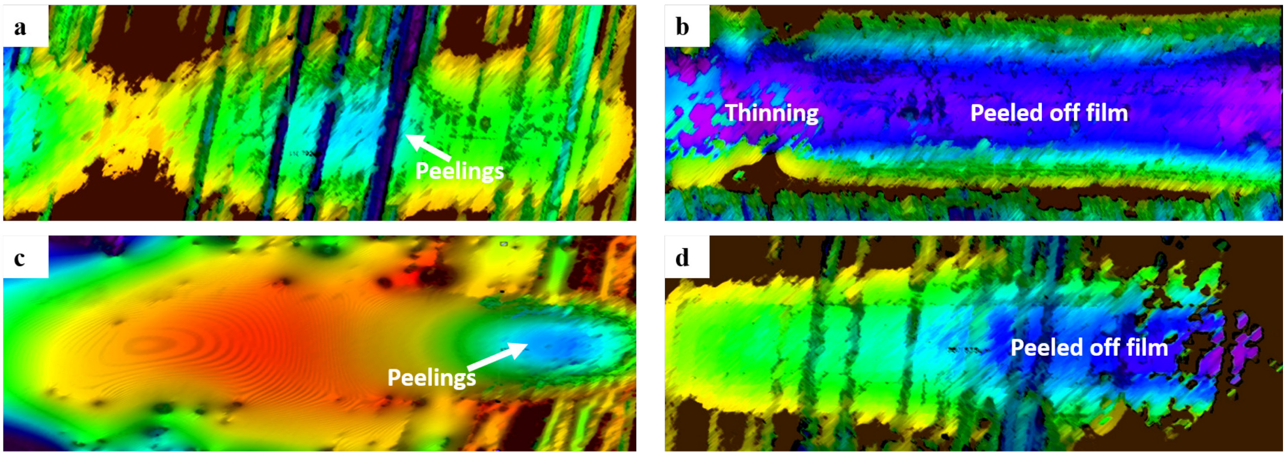

Figure 7. Wear track contours at 50N for Al films sputtered at (a) 44.5ºC (b) 60ºC (c) 80ºC and (d) 100ºC. The blue colour indicates the substrate surfaces.

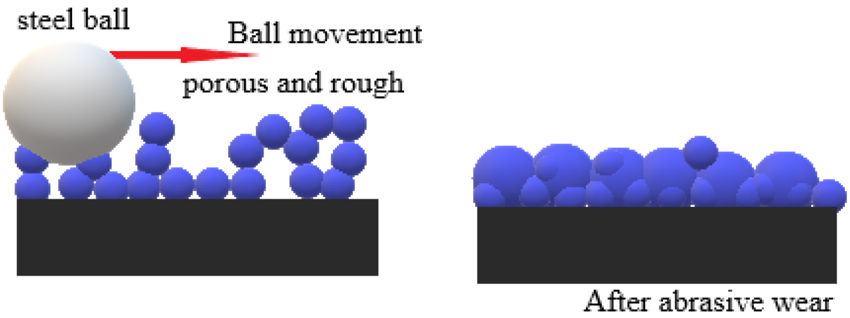

Figure 8. Illustrating the microscale wear occurrences during the reciprocating steel ball loading on the rough and porous thin film coating (blue colour). This behaviour is well depicted by the films deposited at 80ºC.

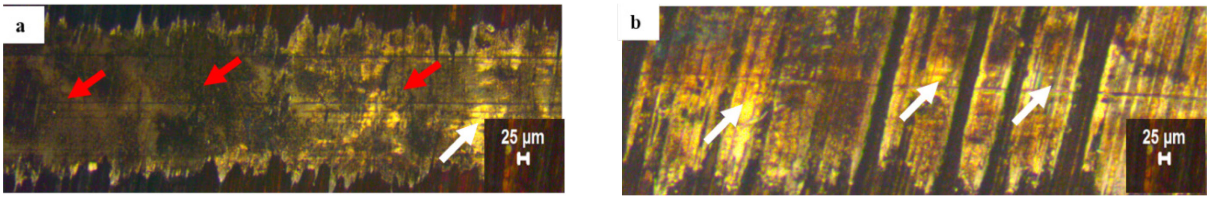

Figure 9. Optical pictures of the contact regions at 50N loading on films sputtered at (a) 80ºC and (b) 44.5ºC. The red arrows in (a) show the lumped films resulting from the mechanism illustrated in Fig. 8 whereas the white arrows in both pictures indicate exposed substrate surface after removal of the films due to ploughing effect caused by the extreme loads.

Summary

Under very high sliding loads, thin Al films undergo plastic deformation and then delaminate off the substrate surface. The coefficient of friction and material failure in wear loading were lower and higher respectively at 100ºC. The low material loss and high coefficient of friction were observed in films deposited at 80ºC. It was established that at this temperature, the films are porous and rough and that the sliding loads led to densification (rather than material removal) of the film structure as explained by the microscale wear scheme. The study suggests that the behaviour of Al thin films under extreme loading is mostly influenced by roughness and porosity of the microstructure rather than the deposition temperature.

Acknowledgments

We acknowledge the University research committee (URC), the University of Johannesburg for sponsoring the research student working on this project. We acknowledge Mr Leso of the Department of Chemical, Materials and Metallurgical Engineering, Botswana International University of Science and Technology for assisting with wear test.

References

[1] A. G. Evans, M. D. Drory, M. S. Hu, The cracking a decohesion of thin films, J. Mater. Res. 3 (1988) 1043–1049.

[2] C. W. Kang, H. Huang, Deformation, failure and removal mechanisms of thin film structures in abrasive machining, Adv. Manuf. 5 (2017) 1–19.

[3] X. Geng, Z. Zhang, E. Barthel, D. Dalmas, Mechanical stability under sliding contact of thin silver film embedded in brittle multilayer, Wear. 276–277 (2012) 111–120.

[4] D. Cong et al., Wear behavior of corroded Al-Al2O3 composite coatings prepared by cold spray, Surf. Coatings Technol. (2017) 326 247–254.

[5] C. H. Chang, M. C. Jeng, C. Y. Su, C. L. Chang, An investigation of thermal sprayed aluminum/hard anodic composite coating on wear and corrosion resistant performance, Thin Solid Films. 517 (2009) 5265–5269.

[6] O. P. Oladijo, N. Sacks, L. A. Cornish, A. M. Venter, Effect of substrate on the 3 body abrasion wear of HVOF WC-17 wt.% Co coatings, Int. J. Refract. Met. Hard Mater. 35 (2012) 288–294.

[7] F. Changjie, C. En, Effects of Substrate Temperature on Microstructure and Tribological Properties of Ti-Al-Si-Cu-N Films Deposited by Magnetron Sputtering, Rare Met. Mater. Eng. 46 (2017) 1497–1502.

[8] M. Anand, G. Burmistroviene, I. Tudela, R. Verbickas, G. Lowman, Y. Zhang, Tribological evaluation of soft metallic multilayer coatings for wear applications based on a multiple pass scratch test method, Wear. 388–389 (2017) 39–46.

[9] F. M. Mwema, O. P. Oladijo, T. S. Sathiaraj, E. T. Akinlabi, Atomic force microscopy analysis of surface topography of pure thin aluminium films, Mater. Res. Express. 5 (2018) 1–15.

[10] F. M. Mwema, O. P. Oladijo, E. T. Akinlabi, Effect of substrate temperature on Aluminium thin films prepared by RF-magnetron sputtering, Materials Today: Proceedings. 5 (2018) 20464-20473.