*Int. J. Mech. Eng. & Rob. Res. 2014*

International Journal of Mechanical Engineering and Robotics Research

*ISSN 2278 – 0149 www.ijmerr.com*
*Vol. 3, No. 3, July, 2014*

*Research Paper*

# DRY SLIDING WEAR OF WROUGHT AL-ALLOYS

**Aadarsh Mishra**[1]*

**Corresponding Author: **Aadarsh Mishra** ✉ aadarshm9@gmail.com*

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Aluminium alloys are very attractive compared to other materials like steels, particularly for their mechanical properties. Despite of having a relatively low density (2.7 g/cm^3 ascompared to ± 7.9 g/cm^3 of steel), they also possess high ductility (even at roomtemperature), high electrical and thermal conductivity and resistance to corrosion.However, aluminium by itself exhibits poor tribological properties and their usage, for example in automotive applications, has been limited by their inferiorstrength, rigidity and wear resistance, compared with ferrous alloys.With respect to friction and wear behaviour, it has been well understood that the tribological behaviour of aluminium alloys is strongly influenced by the mechanical, physical and chemical properties of the near-surface materials.Intimate contact between ductile materials in particular, normally involved transferred materials, which may result in theformation of a mechanically mixed layer (MML).

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***Keywords:*** Mechanical mixed layer, Al-alloys, Sliding wear theory

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## INTRODUCTION

Wherever surfaces move against each other, wear will occur; damage to one or both surfaces generally involves progressive loss of material (ASM International & 1992 Hutchings, 1992).

The rate of removal is generally slow. Although the loss of material is relatively small, it can be enough to cause complete failure of large and complex machinery. Hence, it is essential to develop a thorough understanding of the wear process, especially its mechanism andbehaviour, in order to optimize performance.Aluminum alloys and Al based composites are generally known to undergo a transition from mild wear to severe wear, depending mainly upon the sliding load and speed during dry sliding wear against steel in an ambient environment.One of the important features of the worn surfaces in the mild wear regime is formation of mixed surface layersthat are generally found to be comprised of materialsfrom the sliding surface and the counterpart. These layers are believed to be protection layers that provide the alloysan excellent wear resistance. During the sliding process, these layers are subjected to repeated compaction and

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[1] Department of Mechanical Engineering, Manipal Institute of Technology, Manipal University, Eshwar Nagar, Manipal, Karnataka- 576104.

fragmentation, and consequently, wear debris is detached from the sliding surfaces.Due to their low density and excellent corrosion resistance, aluminium has become a substitute for steels especially in structures that require high performance and weightreduction. As with most other metals, aluminium reacts with oxygen in air. A submicron thick oxide layer is formed to provide effective corrosion protection. Aluminium is also nonmagneticand non-toxic, and can be formed by all known metal working processes. At low temperatures the strength of aluminium and its alloys increases without embrittlement in contrast to most steels (Pollack, 1977). There have been a number of investigations into the formation of the mechanically mixed layers and the natureof wear debris in unlubricated sliding systems, especially during wear of Al alloys sliding against ferrous alloys.The surface layeron the worn surface of Al-Si alloys was formed by fracture and compaction of Al oxide particles during sliding wear.Two major and most common types of wear identified by Eyre (1979) that are relevant to industrial applications of aluminium alloys are abrasive and sliding wear especially for Al-Si alloys.In the case of Al-Si, generally, the hard silicon particles addition will contribute to higher hardness hence increase the wear resistance. Moreover, the particles are surrounded by softer and relatively tough matrix, which then improves the overall toughness of the material. This will lead to wear resistance by favouring more plastic behaviour (ASM Handbook, 1994). The present work was conducted to characterize the mechanically mixed layers (MML) and wear debris formedduring sliding wear of three Al base materials, namely, highpurity Al, an Al-Si alloy and an Al-Simetal matrix composite, all sliding against M2 tool steel under dry sliding conditions. In particular, chemical, microstructural and crystallo graphic characteristics of the MMLs and wear debris have been investigated using scanning electron microscopy (SEM), transmission electron microscopy (TEM) equipped for energy dispersive spectroscopy (EDS) and X-ray diffraction. As for aluminum alloys that reinforced with ceramic particles, they have shown significant improvements in mechanical and tribological properties including sliding and abrasive wear resistance (Rittner, 2000). The hard ceramic particles provide protection from furtherdetrimental surface damage. An increase of ceramic hard particles content in alloys mayenhance its wear resistance behaviour (Geng *et al*., 2009). The ageing behaviour of discontinuous reinforced metal matrix composites has been a subject of great interest, which is beneficial to optimise the ageing treatment and providing the experimental andtheoretical information for designing the composites properties (Sheu and Lin, 1997).

## EXPERIMENTAL PROCEDURE

The base alloy used in the investigation was an Al-Si casting alloy.In order to compare the microstructures of the MML and wear debris, especially the identification of phases, a high purity Al was also used. Sliding wear testswere conducted using a unidirectional block-on-ring weartest machine where wear samples of the Al alloys in cubic blocks of 8 mm*8 mm*8 mm, slid against a tempered M2tool steel in the form of a ring with an outer diameter of 25mm and width of 15 mm. The hardness of the tempered ring was 52 HRC. The sliding load was varied from 1.5 to 12 kg. The sliding speed and total sliding distance were kept constant at 15 cm/s and 1500 m, respectively. No lubricant was used in the wear tests.All samples and test rings were polished down to 0.20 µm and cleaned in a methanol bath by an ultrasonic cleaner before each wear test. In XRD analysis, the wear debris was placed as a thick paste using a fewdrops of acetone on the concave surface of a glass slide.In the case of ductile materials like aluminium alloys, most wear mechanism observed are consistent with Archard adhesive wear characterised by plastic ploughing and transfer of material from the counterface. With respect to friction and wear behaviour, numerous authors (Perrin and Rainforth, 1995, Leonard *et al*., 1997, Jiang and Tan, 1996, How andBaker, 1997 and Rigney, 1998) have concluded that the tribological behaviour is influencedby the mechanical, physical and chemical properties of these near-surface materials. In allcases, a mechanically mixed layer (MML) was present in most dry worn wrought aluminium alloys due to the repetitive sliding. However, significant differences between the MML of each alloy were observed.

## RESULTS AND DISCUSSION

It can be seen that the microstructural features of the subsurface varied along the depth below the worn surface. Except for the presence of the reinforcing SiC particles in the composite, the microstructural features of the subsurface were similar for the Al alloy and the composite.In the present study, the MML were found to contain Al, Fe (for Al/M2 case) and O (in theform of oxide), which proves the source of element in the MML obviously originated fromthe counterface. The oxides were found to be coexisted with other phases in the MML and the wear debris, which is an expected phenomenon since the wear system was exposed toair. They could provide microstructural stability as a second phase in the ultrafine grainedstructure in debris, as proposed by Rigney et al. (1984). The oxides which have been knownto form some protective and some destructive (Fischer, 1997 and Ravikiran *et al*., 1995) werethen fractured and comminuted in further sliding process.The crushed oxides can be dispersed into the mixed surface layer and act as a pinning source of the grain boundaries in the ultrafine mixture in the MML and in the wear debris. A prominent feature is the morphology of the top surface layer which contained very fine particles and agglomerate. Microvoids were also noted in the top layer, some of whichmight have coalesced and become cracks parallel to the sliding direction.As for wear debris, its formation appeared to occur by two principal mechanisms, namely, the physical displacement of material from the worn surface by the ploughing action of thehard tool steel or alumina asperities, and secondly, delamination of large sheets (up to 1.5 mmin extent) at particularly at high load like 140N. The thickness of the delamination sheetswas found broadly consistent with the thickness of the MML, although it could not bedefined with certainty whether the delamination occurred within the MML or at theMML/ substrate interface. However, the longitudinal cross-sections suggested that both mechanisms were probable.

Was the delamination of the MML (part or whole), it would be reasonable to expect acorrelation between MML thickness and specific wear rate.

**Figure 1: Mechanically Mixed Layer in the Longitudinal Cross-Section of the Worn Surface of the Al-Si Alloy at a Load of 8 kg**

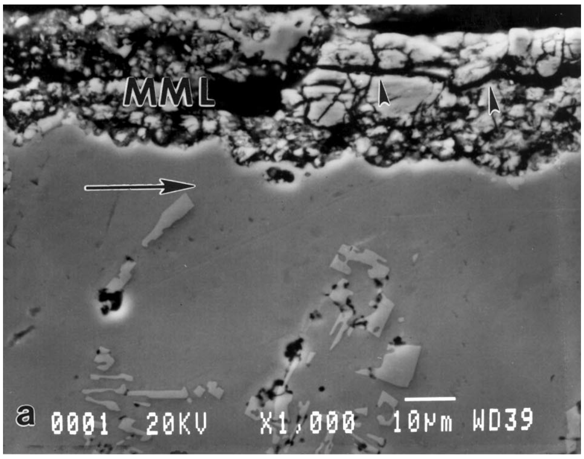
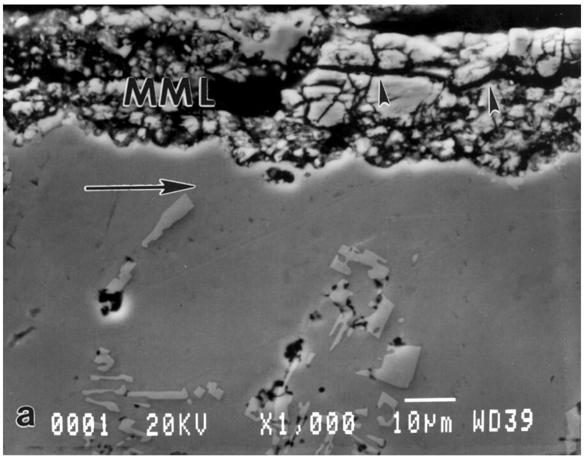
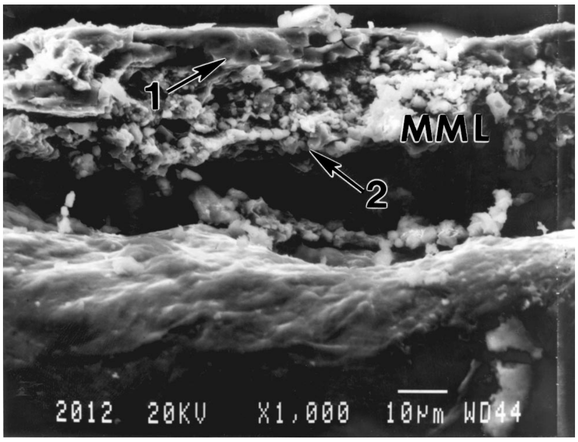


**Figure 2: Mechanically Mixed Layer in a Longitudinal Cross-Section of the Worn Surface of the Al/SiC Composite at a Load of 10 kg**



In order to confirm the transport of Fe from the steel slider into the sub surface of the worn surface, a fracture cross-section of the worn surface was analyzed. The fracture cross-section sample was obtained in a manner that a split and rejoined wear specimen was fractured perpendicular to the worn surface, and was analyzed immediately. This kind of layered structure was also found in the worn surface of the Al composite. It can beseen that the MML consisted alternately of sublayers either rich in Fe (white layer), or rich in Al (dark layer).The alternation of the two kinds of sublayers was not uniform across the entire cross-section ofthe wear track. It can also be observed that in the Al rich sublayers there were many small particles containing Fe embeddedin the Al matrix.

**Figure 3: Fractured Cross-Section of the Worn Surface of the Al Alloy at a Load of 4 kg, Showing a Layered Structure in the MML**



The atmosphere under an unlubricated wear process can strongly influence sliding wear rates with oxygen content and humidity being probably one of the important factors. In thecase of Al-alloys, it is readily combined with oxygen to form a stable oxide layer. Oxidation, may have opposing effects on the wear process; one, it degraded the surface by removing metal atoms and second, it plays protective role in reducing metallic contact and decreasethe wear rate (Degnan, 1995). However, whether or not the environment reaction has abeneficial and detrimental effect on wear rate, it depends strongly on the mechanical interaction of the reaction product with the substrate, particularly under surface plasticity condition, (Rainforth *et al*., 2002), which is in line with the present work.Wear occurs in conjunction with the dissipation of frictional energy in the contact and this is always accompanied by a rise in temperature. The frictional energy is generated by the combination of load and sliding speed and its distribution and dissipation is influenced by other contact conditions such as size and relative velocity. The results also show that the micro structures of the mechanically mixed layer (MML) were similar to those of the wear debris which detached mostly from the MML of the worn surface. The ultrafine grained structuresin the MML and the debris varied depending on the slidingload at the sliding speed used. At high loads, they containeda nanocrystalline mixture of oxides and an Fe-Al inter metallic phase, in which iron came from the counterpart steel asa result of transfer of materials and mechanical mixing during the sliding motion. At low loads, the ultrafine structures were mainly comprised of a mechanical mixture of original materials from both the contacting surfaces.

## CONCLUSION

Using SEM techniques, the present work has shown that a mechanicallymixed layer was formed in the worn surface of the Al alloyand Al composite. It was found that wear debris were mostly detached from the MML and had microstructural features similar to those of the MML. The debris and MML were comprised of a mechanical mixture of ultrafine equiaxed particles, the constituents of which varied depending on thesliding load at the sliding speed used in the present work. Elements present in the Al-alloy with high solubility in steel promoted a thick mechanically mixed layer, with higher Fe content. The effect was marked even for smallcontents in the Al-alloy.

## ACKNOWLEDGMENT

I would also like to dedicate this research work to my father Late R S Mishra and mother KL Mishra.

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