Mechanical and wear behavior of al-steel solid state cladding produced by friction stir surfacing

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Abstract. Friction surfacing (FS) is a solid-state cladding method that produces a coating with minimum dilution and good metallurgical bonding. Deposition of aluminium over mild steel with using fusion based joining process is not feasible sue to the formation of iron aluminide and Fe and Al are metallurgically immiscible to each other. Hence, deposition of aluminium on steel with solid-state condition is feasible and most viable option. During the process, a rotating consumable rod is rubbed against the substrate plate under an applied axial load. The friction between rod and substrate generates a visco-plastic layer at the end of rod tip. The high temperature and pressure at interfaces aids in the cladding of the rod material on the substrate. Aluminium alloy 6351 T6 rod of 22 mm diameter was used as consumable material for surfacing on a 6mm thick SA516 Gr70 steel substrate plate. Optimized process parameters were used for the final experimental trials. Multilayer samples generated at constant Friction Surfacing variables were subjected to Pin-on-disc wear test at 40N load. Mechanical interlocking was also observed at the interface of the layers. The process was also observed to produce extremely fine grain microstructures of the deposited material due to the hot forging action involved resulting in superior wear properties.

Keywords: Friction surfacing, diffusion bonding, wear resistance, mechanical interlocking.

1 Introduction

Friction surfacing (FS) was first patented by Klopstock H. and Neelands A.R. in 1941, is a solid state machine tool based technology and is a variant of friction welding [1-2-3]. It is a surface modification technique and is subdivided into two classes, surface treatment and surface coating. The main objective of the process is to improve the mechanical properties of subsurface region. Consumable rod is used to generate the layer on the surface of the substrate in this friction surfacing while non-consumable tool is used in friction stir welding

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which create a difference between this two process. Deposition of the material is observed in the visco-plastic form [4] and temperature generation is the key influencing the generation of this visco-plastic form. Schematic diagram of the friction surfacing process is shown in the Fig 1. The key advantages of friction surfacing process are lower environmental impact, lower power consumption, higher efficiency and higher energy efficiency compared to other alternative processes [5].
The process parameters employed during the friction surfacing process is a majorly influencing the uniformity of deposited width and thickness layer. The controllable parameters of the process are spindle rotational speed, table travel speed, rate of feeding of consumable rod (in feed control mode), axial load/ pressure and diameter of consumable rod [6], While diameter of consumable rod is playing a vital role for producing visco- plastic layer on substrate [7].

Joining of dissimilar material is considered difficult due to the metallurgical immiscibility of the alloys and joining of steel to aluminum alloy also encounters similar difficulties. [8] Additionally, the higher thermal conductivity of both aluminum and steel results in difficulties in the formation of a heated layer at the interface of the consumable rod and the substrate plate that is needed to provide a good deposition layer over the substrate.
The present study focused on the wear behavior of the friction surfaced layer of Al on steel at an axial load of 40N.

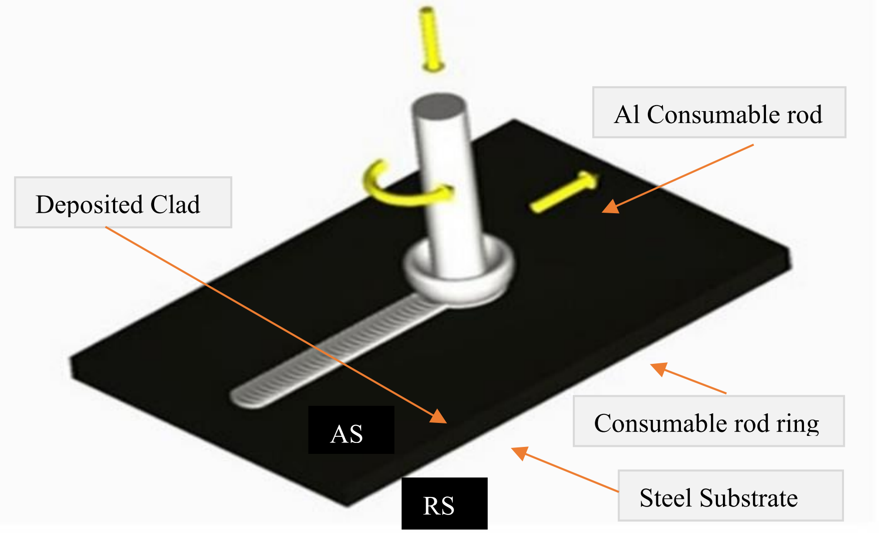


Fig. 1. Friction Surfacing Process Schematic

2 Materials and Methods.

Consumable rod AA6351 T6 of 22mm diameter rod and 100mm in length was used for surfacing on the 300 x 150 x 6mm SA 516 Gr. 70 substrate plate. Table 1 and 2 indicate the chemical composition of substrate and consumable rod material. The customized experimental set-up used is shown in Fig.2 equipped with a control panel, load cell unit, rotating drive and a facility for tilting the rod at an angle to the substrate plate. The customized friction surfacing machine set-up was developed under BRFST project used for the experimental trials which is available at Pandit Deendayal Energy University. The optimum range of spindle speed is 3000 rpm and traverse speed is 140mm/min is possible with FS customized machine. Before the process start substrate plate are grind to remove the oxide layer while consumable rod end was to be flatten for better surface contact with substrate plate. Feed- based control mode (consumable rod is pushed along its axial direction against the substrate) with optimized process parameters were employed during the actual experimental trials.

Table 1. Chemical composition of steel substrate material

Chemical Composition of Steel Base Metal (wt.%)						
	C	S	P	Mn	Si	Fe
SA 516 Gr 70 Steel Substrate	0.196	0.008	0.018	1.160	0.366	98.252

Table 2. Chemical composition of consumable rod material

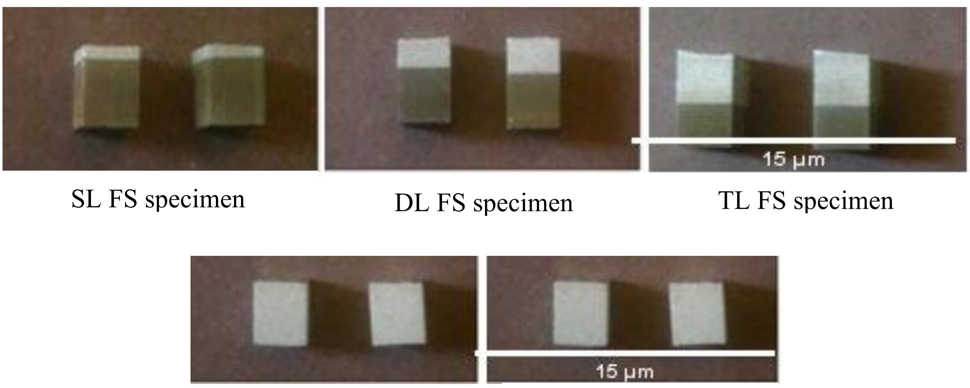
Chemical Composition of Consumable Rod Material (wt.%)					
	Mg	Si	Fe	Mn	Al
AA 6351 T6 Consumable Rod	0.620	0.870	0.178	0.660	97.600

Fig. 2. Customized friction surfacing set-up at PDEU

Hardness of the deposited cladding was measured in the through thickness direction from the center of the deposited cladded layer using WILSON WOLPERT 401 MVD test equipment. The dwell time used during testing is 10 sec on 300g load condition.

Specimen preparation is playing crucial role for micro examination of dissimilar Al-Steel cladding condition. Specimen of the deposited sample was cut out from the center of the test coupon and subjected to standard metallographic examination with different etchant reagent used, for different alloys of the dissimilar metal configuration. Keller's and Nital etchant was used for Al and steel with swabbing method.

Wear characterization was done with using 6mm x 6mm square shape pin, total track length 300m and 40N load condition and 0.1 meter/second sliding velocity was selected for the tests according to ASTM: G 99-05(2010) [9]. The tests were undertaken in dry open atmospheric condition. Samples were weighed using analytical balance (0.1mg) weighting machine before and after the wear test to determine mass loss. Wear testing was undertaken on five different samples i.e. consumable rod, consumable ring, single layer FS sample, Double layer FS sample and Triple layer FS sample. The volume loss and wear rate were calculated for all the samples using the method suggested in previous literature [10-11]. Images of the samples before testing and the location from which it was extracted is shown in Fig.3 and in Fig.4 respectively.



SL FS specimen DL FS specimen TL FS specimen

AL consumable rod sample Al consumable ring sample

Fig. 3 Friction surfacing sample from cladding POD wear test

a b c

Fig. 4 Wear sample extracting condition (A -single layer FS sample, B- Consumable Rod, C- Consumable ring)

2.1 Experimental works.

The optimized friction surfacing parameters constant indicated in Table 3 was used to deposit a single, double and triple layer on the substrate plate. With using an available process parameter range on experimental mode getting optimized range, that optimized range parameters are used in this investigation work. Majorly rotational speed in rpm, travel speed in mm/min, consumable rod diameter in mm are performed with different range and based on the deposition results of layer we used best optimized range of them for this experimental work.

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Table 3. Process parameter used in actual experimental trails.

Sr. no	Process parameter	SL FS	DL FS	TL FS
1	Spindle Rotational speed RPM	2400	2400	2400
2	Traverse Speed in mm/min	50	50	50
3	Axial rate feeding in mm/min	10-50	10-50	10-50

The single layer friction surfacing was undertaken after pre-cleaning the substrate material. Slightly higher thickness was observed at the advancing side (AS) of the single layer surface coating is slightly higher than that at the retreating side (RS). To overcome this problem, the substrate plate was rotated through180° after each layer deposition in the double and triple layer friction surfacing to alternate the AS and the RS of the deposited layer. Width and thickness uniformity was ensured through this technique in FS. Photographs of the deposited layers and macro-images of the cross section is shown in the Table 4. While Table 5 shows the average thickness and width of the coating.

Table 4. Friction surfacing samples

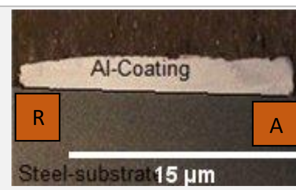
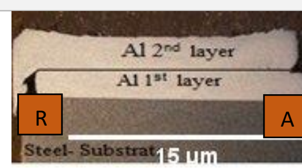
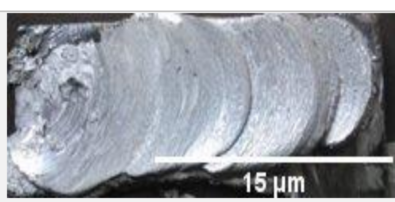
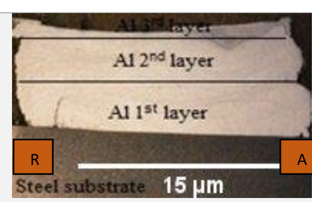
Sr.no	Specimen detail	Specimen photograph	Macro examination
1	Single layer FS	 **Depodited single layer FS**	 **Layer Cross section**
2	Double layer FS	 **Deposited duoble layer FS**	 **Layer cross section**
3	Triple layer FS	 **Deposited triple layer FS**	 **Layer cross section**

Table 5. Thickness and width of friction surfacing samples

Sr.no	Detail	Avg. Thickness in mm.	Avg. Width in mm.
1	Single layer friction surfacing	1.5	26.0
2	Double layer friction surfacing	3.2	27.8
3	Triple layer friction surfacing	5.6	30.8

3 Results and Discussion:

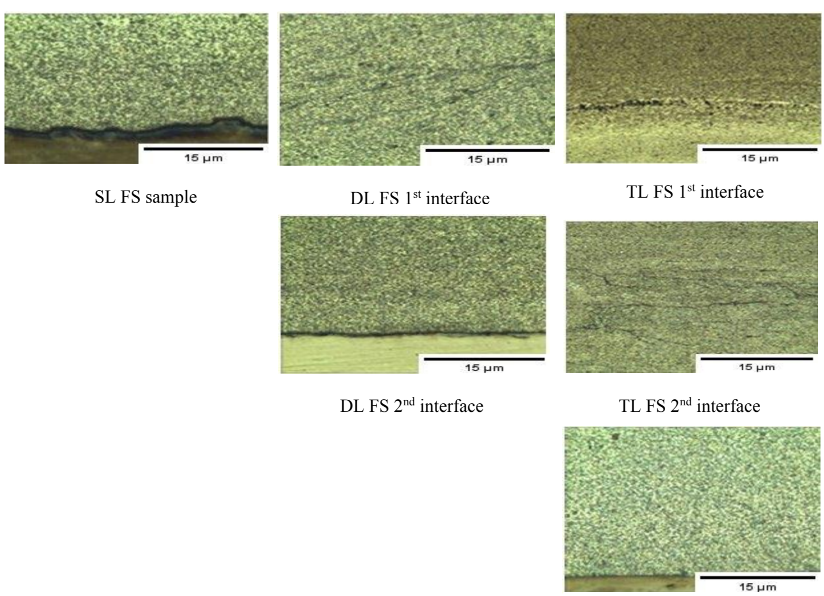
3.1 Macro examination:

Based on macro examination results presented in Table 4 the following observations can be made.

1. Reversal of the substrate plate through 180° after each layer deposition helps in formation of uniform thickness in double and triple layer FS.
2. Width being slightly lower (bond width) at the interface than the actual deposit width showing from the top.
3. Clear mechanical bonding was observed at the Al-Steel and Al-Al interface.

3.2 Micro examination:

The images of the microstructure were taken at 400X magnification. Due to the hot forging action involved during the process indicating extremely fine grained microstructure of the deposited material was noticed during the micro examination. Fig. Bonding at the Al-steel interface is only due to mechanical interlocking of the asperities in single layer, double layer and triple layer friction surfacing observed in micro examination, also a very fine grain microstructure is observed on the Al deposition layer. The optical and the SEM images shown in the Fig.6 also clearly depict the mechanical interlocking/asperities. The asperities are broken due to sliding friction from both the aluminum consumable rod rotating and travelling simultaneously in the cladding direction as well as from the steel plate surface. The broken asperities ratio is higher for Al compared to steel due to the soft material as the AL having in nature. Bonding between the substrate and deposited layer were formed due to the mechanical interlocking of AL- Steel mixed broken asperities generate the strength of cladded layer at interface. [11-12-13-14].



SL FS sample

DL FS 1st interface

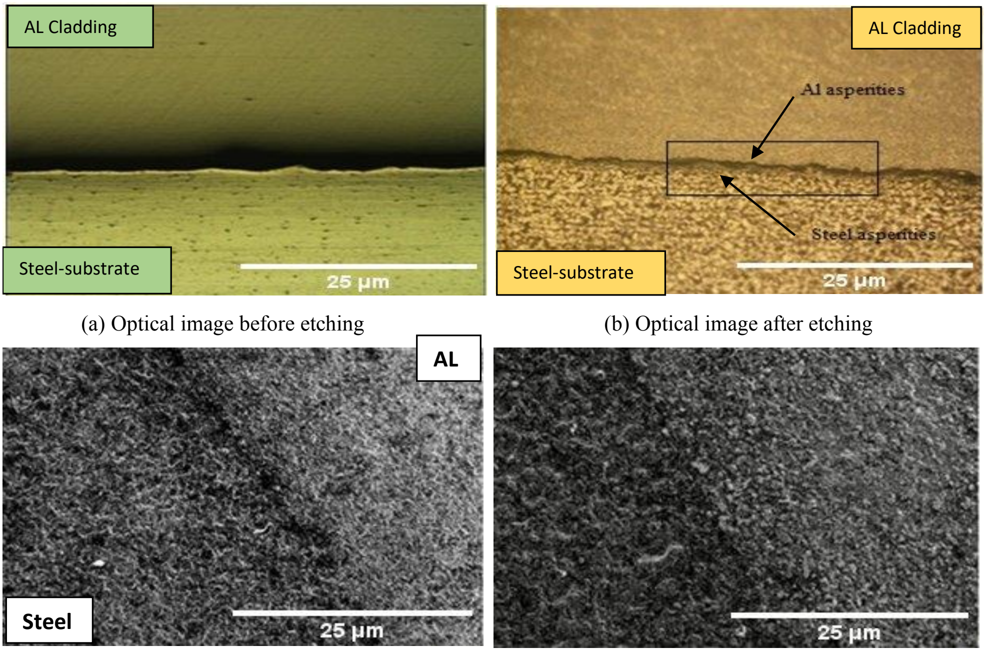
TL FS 1st interface

DL FS 2nd interface

TL FS 2nd interface

TL FS 3rd interface

Fig. 5. Microstructure of friction surfacing samples (400X Magnification)



(a) Optical image before etching (b) Optical image after etching

(c) SEM image of the interface (d) SEM image of the interface with broken asperities

Fig. 6 Mechanical interlocking due to asperities formation

3.3 Micro hardness:

Basically hardness value of Al 6000 series is 155 VHN. From the results of Fig.7 it is also found that with increasing the no. of layer of deposition hardness was improved against consumable rod. Second and third layer is getting higher hardness compare to row Al. material. It was observed that the hardness at double and triple layer of FS sample is lower than 50HV while slight higher hardness achieved with single layer FS. However, the hardness at the interface for all samples were in the same range.

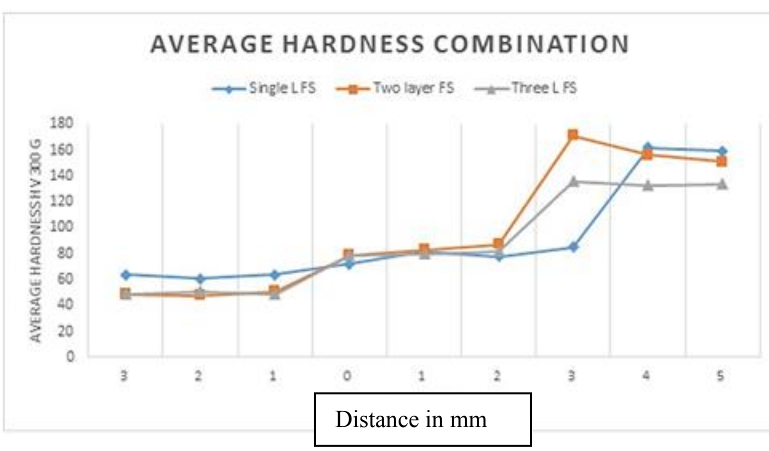


Fig. 7 Vickers hardness profile of Multilayer FS sample (0- position indicate Steel-Al Joining Interface)

Fig.5 presents micro hardness profile of different friction surface samples. The major focus of investigations is micro-hardness values at interface region of the surfacing experimental trials, the hardness variation between the single and the multi-layer processed samples in this region were relatively insignificant. The Vickers Hardness value was found at the interface region in the range of 75-88 VHN in all experimental trials.

3.4 Wear test:

The wear test results recorded in Table 6 and Fig.8 & Fig.9 indicating with the wear rate indicating in the form of weight loss. The results indicate that with increasing the no.of layer wear resistance will be improved in cladding. While the single layer deposition had a significantly high wear of 134 μ, the wear for the double and triple layer deposition significantly reduced to 104 and 90 μ respectively which amounts to approximately 22% and33% improvement in wear respectively over the single layer deposition samples. This clearly brings out that multi-layer deposit was provide significantly better wear characteristics as compared to a single layer deposition in the form of lower weight loss. In fact, the results show that the wear resistance for the triple layered sample is even superior to the wear resistance of the original consumable rod material. Analysis of the graphs indicating the wear rate also provides interesting results.

Table 6. Wear results at 40N loading condition

Sr. no	Sample id	Wear(μ)
1	Consumable rod	95
2	Consumable ring	84
3	Single layer	134
4	Double layer	104
5	Triple layer	90

The wear rate was recorded for the consumable ring compare to consumable rod. However, the rate of increase in wear of the consumable rod increased substantially during the test resulting in the wear rate of the rod increasing above that of the ring. Also, while the higher wear rate of the single layer sample was constantly recorded than that of the double and triple layer samples, the wear rate for the double and triple layer sample was initially comparable, however, the rate increased substantially for the double layer sample as compared to the triple layer sample resulting in a higher overall wear rate for the double layer sample over the triple layer sample.

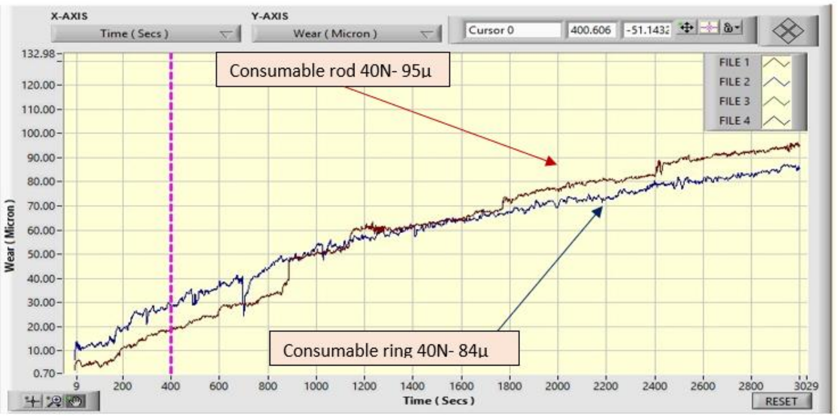


Fig. 8 Wear behavior of consumable and ring

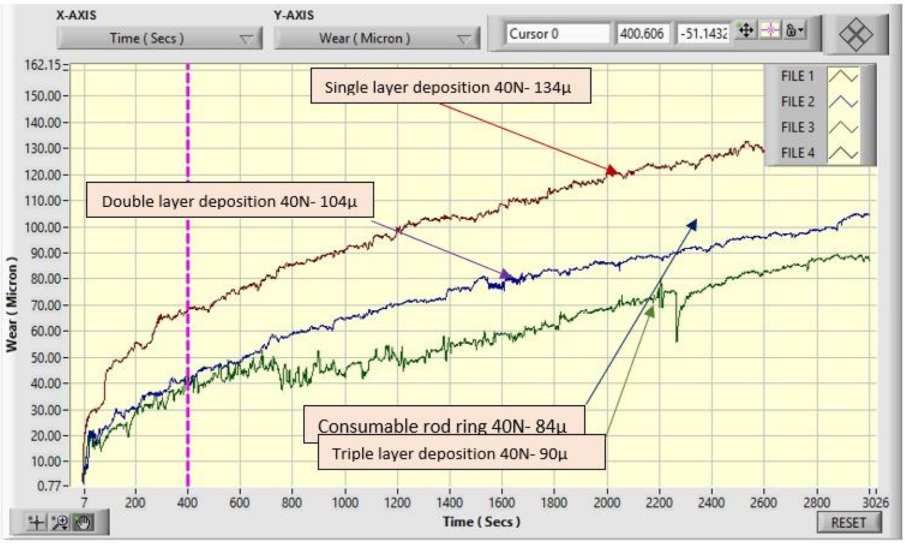


Fig. 9 Wear behavior of single, double, triple layer FS samples

3.5 Weight Loss results

The results of the weight loss of deposited cladded sample in wear test was recorded in Table 7 The weigth loss results are in line with that indicated by the wear loss tests with the weight loss for the triple layer sample being much less than the other two samples and even substantially lower than the original consumable rod. This clearly brings out the benefits of providing multiple layer depositions over the single layer deposit.

Table 7. Weigth loss calculation before and after wear test at 40N

Sr. no	Sample id	Weight Before PoD (g)	Weight After PoD(g)	Weight Loss (g)
1	Al. Consumable rod	0.576	0.560	0.016
2	Al. Consumable ring	0.600	0.564	0.036
3	FS Single layer	1.555	1.492	0.062
4	FS Double layer	0.990	0.966	0.023
5	FS Triple layer	0.582	0.579	0.002

3.5.1 Reason for the superior wear resistance of the multiple layer deposit samples

As already indicated, the bonding between the layers deposited is mainly due to the interlocking of asperites generated at the interface. The asperites are broken out from both the steel plates as well as the butting edge of the aluminum consumable rod. The interlocking of the asperites from both these sources results in the bonding at the interface.(The previous discussion on the subject refers) Steel being harder than aluminum, the asperites from the steel plate surface is lesser than that from the aluminum rod. In a single layer deposition sample, there is only one interface which is between the deposited aluminum and steel plate. The lower asperites in the steel plate results in lower interlocking for this sample. However, for the double and the triple layer deposition samples, in addition to the Al-Steel interface, there are Al-Al interfaces between the layers deposited.Due to the softer nature of the aluminium the formation of asperities is higher at the interface in case of double and triple layer of deposition, which create better bonding and hense a lower wear rate for these sample. The extremely fine grained microstructure exhibited by the double and triple deposit samples could also have contributed in the increased wear resistance of these samples compared to the single layer deposit samples.

4 Conclusions:

1. Experimental study confirms that feasibility of the multilayer friction surface coating of Al on steel substrate.
2. Macro and micro structure examination results indicate that the bonding between Al-Steel materials is formed due to the mechanical interlocking of the broken asperities mixture. It also confirms satisfactory bonding between Al-Al layers.
3. With increasing the no. of layer wear resistance of deposited layer will increase. The double and triple layered samples exhibit extremely fine grained microstructure due to the hot forging action which could be the major reason for the superior wear resistance for the double and triple layered samples.

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