Uncertainty Error Analysis on Micro Hardness of Al6061-B_4C Surface Composites Produced by Friction Surfacing

S. Mohanasundaram, S. J. Vijay, Ajay Vasanth. X, P. Ramkumar

Abstract*: Friction surfacing is a confined surface modification process of depositing a layer of a consumable tool (Mechtrode) over the base plate (Substrate). This solid-state surfacing opts for dissimilar material and erosion resistant coatings. It is also utilized for localized repairing of worn-out components. In the present study, the hardness of the coated material is compared with the substrate. In this experiment, the Al-B4C composite consumable rod is prepared with Aluminium 6061 alloy and 3, 6, 9, 12 and 15 weight % of B4C by stir casting and coated over the Aluminium 6061 alloy plate. The 25-run experiment is conducted for the combination of the rotational speed, traverse speed and axial load. The combined effect of process parameters and the increase in weight % of B4C results in the change in hardness. The hardness of the coating is enhanced by 65% than the substrate. The uncertainty analysis revealed that it has a good correlation with the hardness standard value and also it has an error of 5%. The ANOVA analysis concluded that the rotational speed and the weight percentage of the reinforcement improved the microhardness of the coating.

***Keywords*: Friction Surfacing, Error analysis, Al6061, B_4C, Surface Composite, Hardness**

I. INTRODUCTION

Surface engineering (SE) is a surface modification process that enhances the properties of the local area, they are divided into gaseous, liquid, molten and solid-state processes. SE methods are classified into nitriding, physical vapour deposition (PVD), chemical vapour deposition (CVD), laser processing, thermal spraying, cold spraying, liquid deposition techniques and friction-based techniques [1]. SE helps in improving the bonding and modifying properties of a substrate on the thin layer surface. On the other hand, the material is coated over the top surface to improve wear/ corrosion resistance and also to repair the damaged parts [2].

Friction based SE includes Friction Stir Surfacing (FSS) and Friction Stir Processing (FSP) techniques. FSP modifies the microstructure of a surface by deforming, recrystallizing and homogenizing the grain structure. Friction Surfacing (FS) is a solid-state coating process where a substrate is coated with a consumable rod by applying an axial load and rotation to it [3]. This technique of depositing a rotating consumable rod over a solid-state base material enhanced the properties on the top surface of base metal [4]. Fig. 1. exhibits an overview of the process, where a plasticized layer of the rod produced by the frictional heat at its tip is coated on the surface of the base metal [5]. The substrate material is not melted; hence, the substrate is not diluted into the deposit and the configuration of the deposit is like the consumable rod [6].

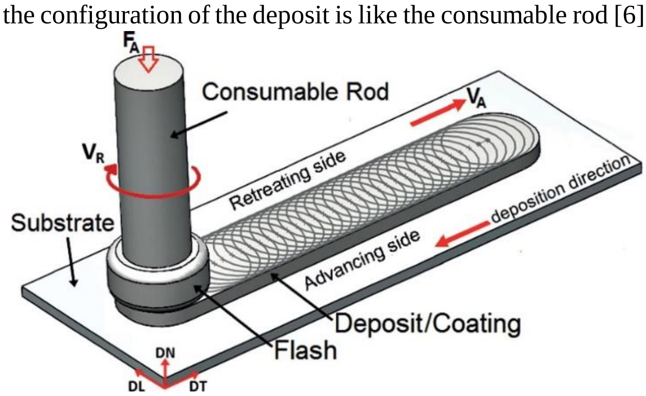

Fig. 1.Friction surfacing Schematic diagram [7]

The consumable rod coating over the substrate is inherently homogenous with improved mechanical strength and adherence. Generally, the layer at the interface continues to be integral, though the resisting load equates the softer material's ultimate tensile strength. However, the integrity of the bond at the edges of the deposit is mostly inadequate and the same has to be cleared out. The quality of the surface depends on the consumable rod that is to be deposited and when a high strength surfacing material (consumable rod) is used, the thickness of the deposit is usually on the lower side [8]. A major dominance of this process is that being a solid-phase process, metallurgically incompatible materials can be fused. Unique combinations of material properties can be achieved, which cannot usually be realized in monolithic materials. This reduces the usage of more valuable and strategic content and time [9].

The study of friction surfacing on aluminum alloys with aluminium composite mechtrode investigated the various parameters and their influence on the properties of coated layers.

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The impact of rotational tool speed and traverse speed on coating thickness, width, bonding strength and mechanical properties discussed in friction surfacing of AA5xxx coated on AA6xxx [8] and AA6082 on the AA2024 [10]. The influence of process parameters on coating thickness and width in AA5052 coating on AA5052 [11]. The hardness of the coating is higher than the substrate hardness and equals the consumable rod in the coatings of AA2xxx on AA5xxx [12]. The fracture toughness of the alloy is enhanced in the AA6082-T6 aluminum alloy on the AA2024-T3 alloy [13]. The literature revealed that there is an opportunity to develop a hard coating over a soft substrate, which is challenging. Hence in this more attempts made to coat Al6061-B_4C on Al6061 using friction surfacing.

The coated surface and substrate are characterised for hardness and error analysis deemed using the estimation values. The error analysis of estimation can surge confidence in selecting the material. The ability and aptness of this method can be applied to several industries.

II. EXPERIMENTAL PROCEDURE

A. Fabrication of consumable tool

Al 6061-T6 plates of dimensions 150mm x 150mm x 10mm were used as the substrate in this study. Boron Carbide (B_4C) was added as reinforcement into molten Al 6061 and stirred. Different weight percentages of B_4C (0, 3, 6, 9 and 12) were used to create different combinations of the composites that were poured into a cylindrical die (diameter – 25mm, length – 160mm). The cast composite rod was machined using a lathe to a size of 20mm diameter and 120mm length to fabricate the consumable rod and henceforth referred as Mechtrode. Table-I depicts the chemical composition of the substrate.

Table-I: Al 6061 Alloy Chemical composition

	Al	Mg	Si	Cr	Cu	Fe	Mn	Zn
Al6061	97.2	0.9	0.6	0.19	0.27	0.45	0.10	0.20

B. Friction Surfacing and Process Parameters

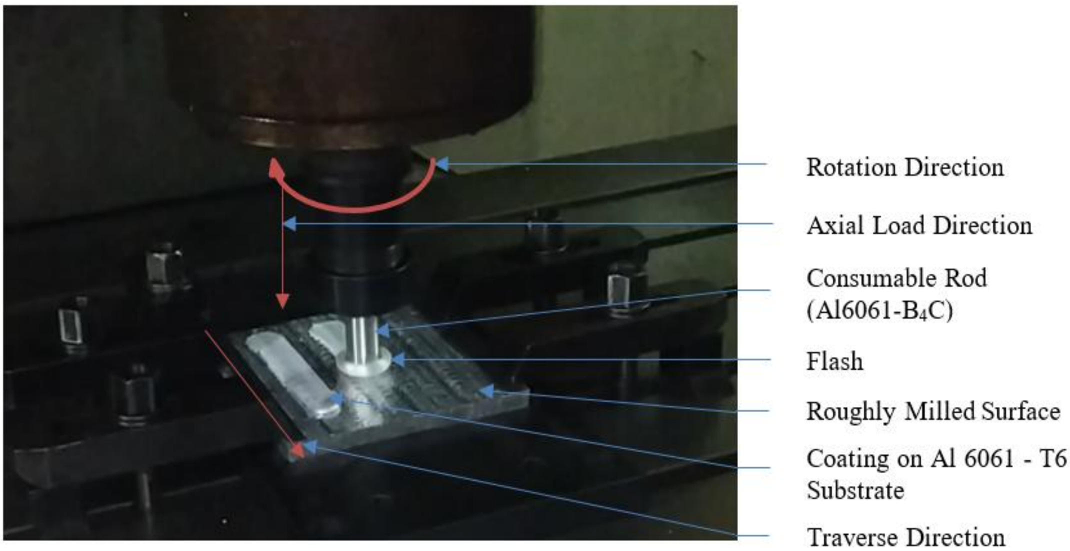

Fig. 2.Machine setup and operational directions

A Hurco VMX 24 CNC 3-axis Machining center with a spindle speed of 10000 rpm was used to perform friction deposition. The fabricated Al6061-B_4C consumable rod is allowed to rotate at a speed and hard-pressed on Al 6061 substrate with force the consumable rod is moved in the traverse direction at speed to achieve the finite thickness coating. The coating characters like thickness, width, and the amount of forging depends on the rotational speed, transverse speed, and the axial load.

Fig. 2. shows the friction surfacing machine setup and the process parameters involved (Table-II). It also indicates the operational direction of rotational speed, traverse speed and axial load. The coating integrity and quality depend on the parameters such as tool rotational speed, traverse speed and axial load. Table-II shows the various process parameters and the values for each process parameter derived based on several trial experiments.

Table-II: Process parameters and levels of experiment to perform the friction deposition

Process Parameters	Leve l 1	Level 2	Level 3	Level 4	Level 5
Weight % of B_4C	0	3	6	9	12
Rotational Speed (rpm)	1800	1900	2000	2100	2200
Traverse Speed (mm/min)	1000	1100	1200	1300	1400
Axial Load (kN)	1	2	3	4	5

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C. Design of Experiments

Four parameters with five levels were used for this study. Thus, an L25 array was formed using the Taguchi method, as it provides a simple, consistent, and systematic approach for an optimal DOE to investigate the performance and reliability of the experimental design. The L25 formed array with the process parameters is shown in Table-III.

Table-III: Orthogonal array for experiments

S. No	% B_4C	Rotational Speed (rpm)	Traverse Speed (mm/min)	Axial Load (kN)
1	0	1800	1000	1
2	0	1900	1100	2
3	0	2000	1200	3
4	0	2100	1300	4
5	0	2200	1400	5
6	3	1800	1100	3
7	3	1900	1200	4
8	3	2000	1000	5
9	3	2100	1300	1
10	3	2200	1400	2
11	6	1800	1100	5
12	6	1900	1200	1
13	6	2000	1000	2
14	6	2100	1300	3
15	6	2200	1400	4
16	9	1800	1300	2
17	9	1900	1100	3
18	9	2000	1200	4
19	9	2100	1000	5
20	9	2200	1400	1
21	12	1800	1400	4
22	12	1900	1300	5
23	12	2000	1100	1
24	12	2100	1200	2
25	12	2200	1000	3

D. Measure of Hardness

Hardness tests were made on the cross-sectioned coatings. Hardness tests were performed in the Mitutoyo HM-112 Micro-Vickers Hardness Testing Machine shown in Fig. 3. under a load of 2 N. The measurements were carried out at a distance of 200 μm between each indentation and a 10 s indentation dwell time.

Fig. 3.Vickers Microhardness testing machine

E. Uncertainty and error analysis

To determine the accuracy of the calculated outcome, the numerical indicator of the measured outcome value should be given. The uncertainty of the measured values in this study was calculated in terms of percentage standard error. Uncertainty analysis invariably represents the precision of the measured value. Thus, performing this analysis ensures that the obtained value does not deviate too much from the true value [14]. Therefore, for the 25 trails, the analysis was performed using the equations (1), (2), (3) and (4). The mentioned equations used for calculating percentage standard error is from the standard JCGM 100:2008 (Type 'A').

$$x_n = \frac{1}{n}\sum_{i=1}^{n} x_i \quad (1)$$

$$s^2 = \frac{1}{(n-1)}\sum_{i=1}^{n}\left((x_i - \bar{x})\right)^2 \quad (2)$$

$$\text{Measurement} = (x_i \pm x_n) \quad (3)$$

$$\text{Error percentage} = \frac{s}{\sqrt{n}} \times 100 \quad (4)$$

Where,

x_n – Uncertainty

n – Number of observations

$\bar{x}$ – Arithmetic Average of observation

s – Standard deviation

x_i – Independent repeated observation

III. RESULT AND DISCUSSION

The friction between the consumable rod (tool) and the substrate increase in temperature plays a critical and essential role in their bonding. To enhance the friction between mechtrode and substrate, the top surface of the substrate was roughly milled initially. The machined consumable rod was rotated with a frictional force on the substrate. Upon reaching the required rotational speed of the spindle, the consumable rod was made to move along the z-direction. When the consumable rod comes in contact with the substrate, The axial load was used to press the consumable rod into the substrate. This resulted in a rapid increase of force and torque which generated frictional heat at the tip of the consumable rod which in turn produced a flash of a viscoplastic layer, as shown in Fig. 2. The force and torque start to decrease as the mechatrode temperature decreases. Thus, the combined effect of the axial load and the temperature allows the consumable rod to diffuse with the substrate. This formed a bond between the plasticised consumable rod material with the substrate. Heat transferred into the substrate consolidates for the bonding interface and when the consumable rod was moved in the traverse direction at a constant speed, uniform coating thickness, as shown in Fig. 4. can be achieved. The influence of boron carbide particles, temperature and the axial load also increases the hardness of the coating. Microhardness of coated samples under the various combinations of process parameters is given in Table-IV.

Fig. 4.Al6061-B_4C coated over Al6061 substrate

A. Microhardness

The effect of B_4C particles weight % on the microhardness of the coating is presented in Fig. 5. The hardness increased with the amount of reinforcement particles added. The microhardness did not change and almost the same for the 3, 6 and 9 weight %. The maximum microhardness of the Al6061-B_4C composite coating was 122.7 HV. This may be the compound effect of the rotational tool speed and axial force. The increase in tool rotating speed also resulted in increasing the microhardness of the coating shown in Fig. 6. The microhardness is improved 65% significantly after friction surfacing.

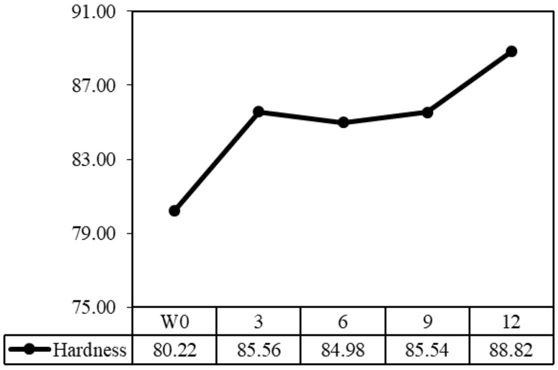

Fig. 5.Effect of B_4C weight % on hardness of the coating

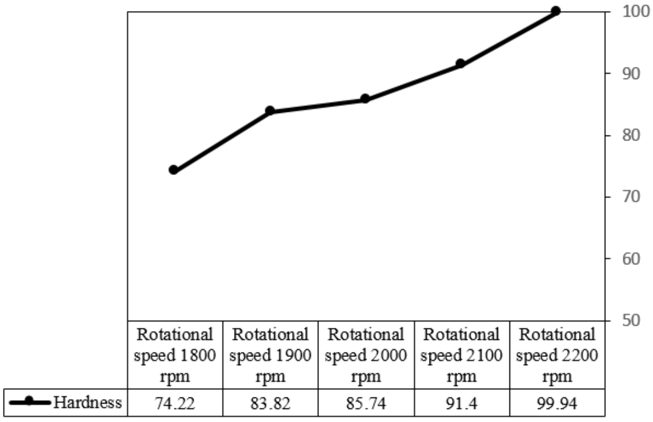

Fig. 6.Effect of rotational speed on microhardness of the coating

B. Uncertainty error analysis of microhardness

The uncertainty analysis of microhardness was performed using equations (1), (2), (3) and (4)), the value of standard error was 5% as tabulated in Table-V is well within the standard range of the standard JCGM 100:2008 (Type 'A'). From the obtained standard error, the deviation of individual value was found and has been tabulated in Table 4. And the obtained results were considerably within the permitted ± 3σ limits. Thus, the uncertainty analysis for the statistical model produced reliable estimation results for the application.

Table-IV: Experimental results on Hardness

S. No	Wt. % B_4C	Rotational Speed (rpm)	Traverse Speed (mm/min)	Axial Load (kN)	Measured Hardness Hv	Measurement
1	0	1800	1000	1	73.10	73.1 ± 3.655
2	0	1900	1100	2	76.60	76.6 ± 3.83
3	0	2000	1200	3	76.60	76.6 ± 3.83
4	0	2100	1300	4	96.40	96.4 ± 4.82
5	0	2200	1400	5	78.40	78.4 ± 3.92
6	3	1800	1100	3	98.50	98.5 ± 4.925
7	3	1900	1200	4	95.20	95.2 ± 4.76
8	3	2000	1000	5	79.70	79.7 ± 3.985
9	3	2100	1300	1	85.90	85.9 ± 4.295
10	3	2200	1400	2	68.50	68.5 ± 3.425

11	6	1800	1100	5	84.60	84.6 ± 4.23
12	6	1900	1200	1	98.20	98.2 ± 4.91
13	6	2000	1000	2	98.50	98.5 ± 4.925
14	6	2100	1300	3	69.80	69.8 ± 3.49
15	6	2200	1400	4	122.70	122.7 ± 6.135
16	9	1800	1300	2	71.30	71.3 ± 3.565
17	9	1900	1100	3	122.00	122 ± 6.1
18	9	2000	1200	4	69.60	69.6 ± 3.48
19	9	2100	1000	5	75.80	75.8 ± 3.79
20	9	2200	1400	1	89.00	89 ± 4.45
21	12	1800	1400	4	103.60	103.6 ± 5.18
22	12	1900	1300	5	67.10	67.1 ± 3.355
23	12	2000	1100	1	63.20	63.2 ± 3.16
24	12	2100	1200	2	79.10	79.1 ± 3.955
25	12	2200	1000	3	91.10	91.1 ± 4.555

Table-V: Error percentage for the hardness

Standard Deviation	0.2638
Journal standard deviation	0.0725
Standard error	0.0528
Standard Error percentage	5%

C. Analysis of Variance

ANOVA analysis using Minitab was performed to study the effect of various process parameters on microhardness. 'F' values obtained from ANOVA provided the most significant process parameter. The ANOVA results are tabulated in Table-VI, and it was evident that the contribution of rotational speed was 51.85% and reinforcement was 24.11% towards microhardness of surface. Similarly, the effect of traverse speed and the axial load was relatively low.

Table-VI: ANOVA analysis result for hardness

Source	DF	Seq SS	Adj MS	F	P	% Contribution
B_4C Wt. %	4	647.3	323.65	0.09921	0.75621	24.11
Rotational Speed	4	1392	696	0.15423	0.95873	51.85
Traverse Speed	4	234	117	0.36225	0.55438	8.72
Axial load	4	276.6	138.3	0.25214	0.62134	10.30
Error	8	134.6	67.3			5.01
Total	24	2684.5				

IV. CONCLUSIONS

From the studies conducted on friction surfacing, the following conclusions can be obtained

1. Friction surfacing has improved the hardness by 65% when compared with the substrate.
2. The measured hardness result quality validated with Type 'A' uncertainty analysis. It is observed that the evaluated result displays good connectivity with hardness standard value along with the maximum uncertainty value of ± 6.135 Hv.
3. The analysis also reveals that it has an error of 5%.
4. ANOVA analysis inferred, the contribution of rotational speed was 51.85% and the reinforcement was 24.11% and they also significantly improved the microhardness of the surface.

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