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Surface Modification of Hastelloy through Cu and Ti Powder Incorporated Electric Discharge Alloying Technique

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The objective of the research was to combine the machining and coating process through the Electric Discharge Alloying (EDA) technique by incorporating copper (Cu) and titanium (Ti) powder in the dielectric medium. Material removal from the surface, coating of the workpiece, and reinforcing coating with strong carbide particles all occurred at the same time by regulating the process. It was the first technical report on such a comprehensive method. The EDS spot analysis confirmed that presence of carbon, copper, and titanium on the surface and EDS mapping inveterate the existence of reinforced particles on the coating. The Ti incorporated samples showed enhanced wear resistance due to the formation of a protective tribo layer.

Keywords: surface modification, composite coating, EDM, surface analysis, PMEDM, wear.

1. INTRODUCTION

Hastelloy expended in boiler construction because of its exceptional tribological and mechanical characteristics at high temperatures [1]. Wear, structural fracture, spalling, and plastic deformation are significant failure mode in the industry and reduce productivity, protective coatings over the surface overcome these issues [2]. Attempts were made to coat base materials using physical vapor deposition, thermal spraying, chemical vapor deposition, ion migration, electroplating, and spray atomization but surface preparation and processing increase the cost of the product [3]. Electric Discharge Alloying (EDA) a cost-effective technique, Carburization and rapid quenching formed a recast layer on the surface improved the wear resistance and hardness of the specimen [4]. Coating is attained, when machined with conventional electrode connected to negative polarity, machined with powder metallurgy manufactured electrode and suspending powders in the dielectric fluid [5].

The structure and properties of the coated layer are controlled by the spark gap arc characteristics and dielectric flushing conditions [6]. Electrodes must be connected in reverse polarity to accomplish surface modification in the suspended dielectric media [7]. Carbon in the hydrocarbon dissolved and reacted with the doped elements to form their respective carbides at high plasma temperatures [8]. The workpiece was positive and the tool electrode was negative for such applications. For the same powder concentration, the two main parameters that influenced the doping characteristics were pulse current and pulse duration [9]. With a negatively polarized copper electrode and titanium powder in kerosene dielectric, a titanium carbide coating of hardness 1600 HV was produced on carbon steel [10]. TiN on the work surface was obtained by adding urea to distilled water as the dielectric medium for machining titanium, resulting in better friction and wear characteristics [11]. Numerous attempts were made by the researchers for modifying the surface using the EDA process but no reports were available on machining cum composite coating on the surface. In this research an attempt was made to combine machining and composite coating on the surface of the Hastelloy through the EDA process.

2. MATERIALS AND METHODS

Hastelloy used for the fabrication of boiler structural parts was selected for examination, and it was connected to the negative polarity of the die sink EDM machine, the copper tool was connected to the positive terminal. Hastelloy machined with Cu and Ti incorporated dielectric medium for 20 minutes at 50 A current, 80 µs ton, and 4 mm gap distance with flushing turned off for the final 5 minutes. Experiments performed by varying Cu and Ti concentration (0, 5, 10, 15 g/l), the machined surface was analyzed with SEM, EDS point analysis and EDS mapping. Pin on disc wear experiments were conducted on the developed surface according to the ASTM G99 standards (load – 50 N, distance – 2000 m, velocity – 3 m/s).

3. RESULT AND DISCUSSION

The electrodes were connected in reverse polarity with the objective of attaining a hybrid coating reinforced with tougher carbide particles. More carbon atoms were discharged from the dielectric fluid over time, and with the flushing switched off, machined debris and incorporated particles were retained in the spark gap; when the temperature reached 2500 °C, both elements reacted and coated as respective carbide molecules on the machined surface. The machined surface topography of Hastelloy

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processed in Cu powder incorporated dielectric medium showed materials dunes, cracks on the coated surface and resolidified material as depicted in Fig. 1.

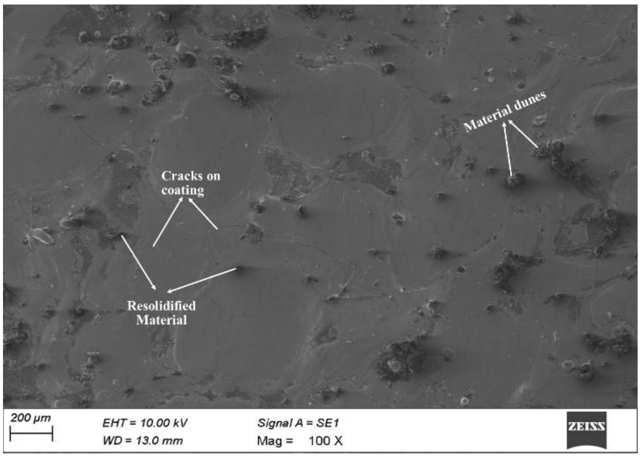
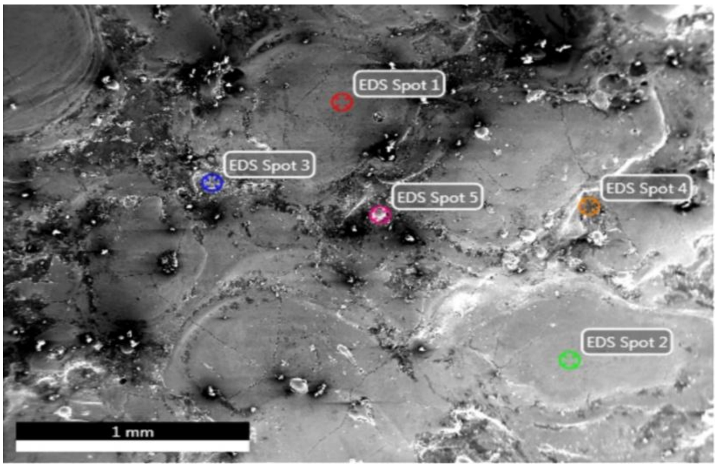
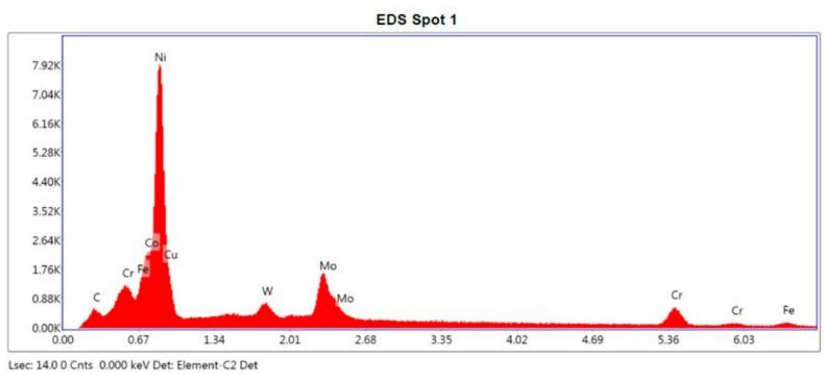


Fig. 1. SEM of Hastelloy machined surface processed in Cu-incorporated dielectric medium

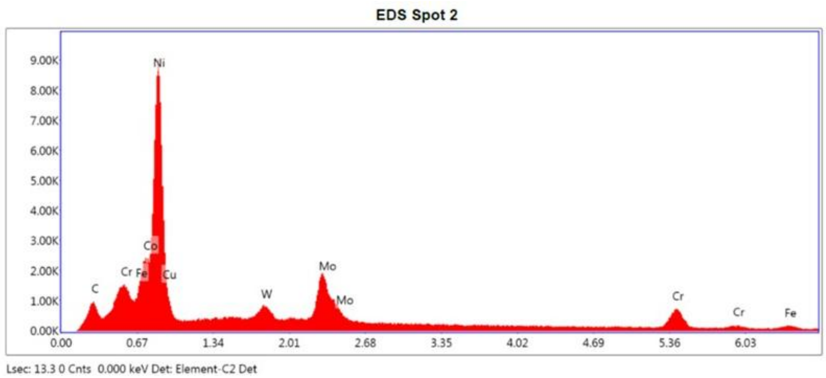
Cracks of categorization type-I were observed, originated at various spots and ended in a common point, materials dunes formed as a result of surface boiling and resolidified materials a reattachment of machined debris on the surface [12]. The coating attained in crest and cracks are observed at the border of the crests, arresting it can improve the tribological property.

With the aid of EDS spot analysis, it was observed, Cu and C were the elements formed on the alloyed surface as result of particle suspension and dielectric breakdown as shown in Fig. 2. The composition of the C on spot 1 was 0.05 which revealed that the surface was coated only with Cu and it was 1.46 % in spot 2, confirming that the composition of elemental deposition on the surface was an uncontrollable factor. The composition of the Cu and C in the coated borders ranged between 78 – 79 percent as indicated in spot 3 and 4, signifying that Cu_2C_2 composites developed but not coated the whole surface [13].





Element	Weight %	Atomic %	Error %
C K	0.05	0.24	96.66
FeL	2.44	2.67	10.87
CoL	3.96	4.11	8.01
NiL	47.09	49.07	5.43
CuL	5.10	4.91	10.92
W M	2.51	0.84	10.11
MoL	14.00	8.93	5.97
CrK	24.85	29.23	6.81



Element	Weight %	Atomic %	Error %
C K	1.46	7.05	16.05
FeL	2.37	2.46	11.06
CoL	4.00	3.92	8.12
NiL	46.71	46.00	5.57
CuL	1.56	1.42	20.85
W M	2.72	0.86	9.28
MoL	14.71	8.87	5.77
CrK	26.47	29.43	6.70

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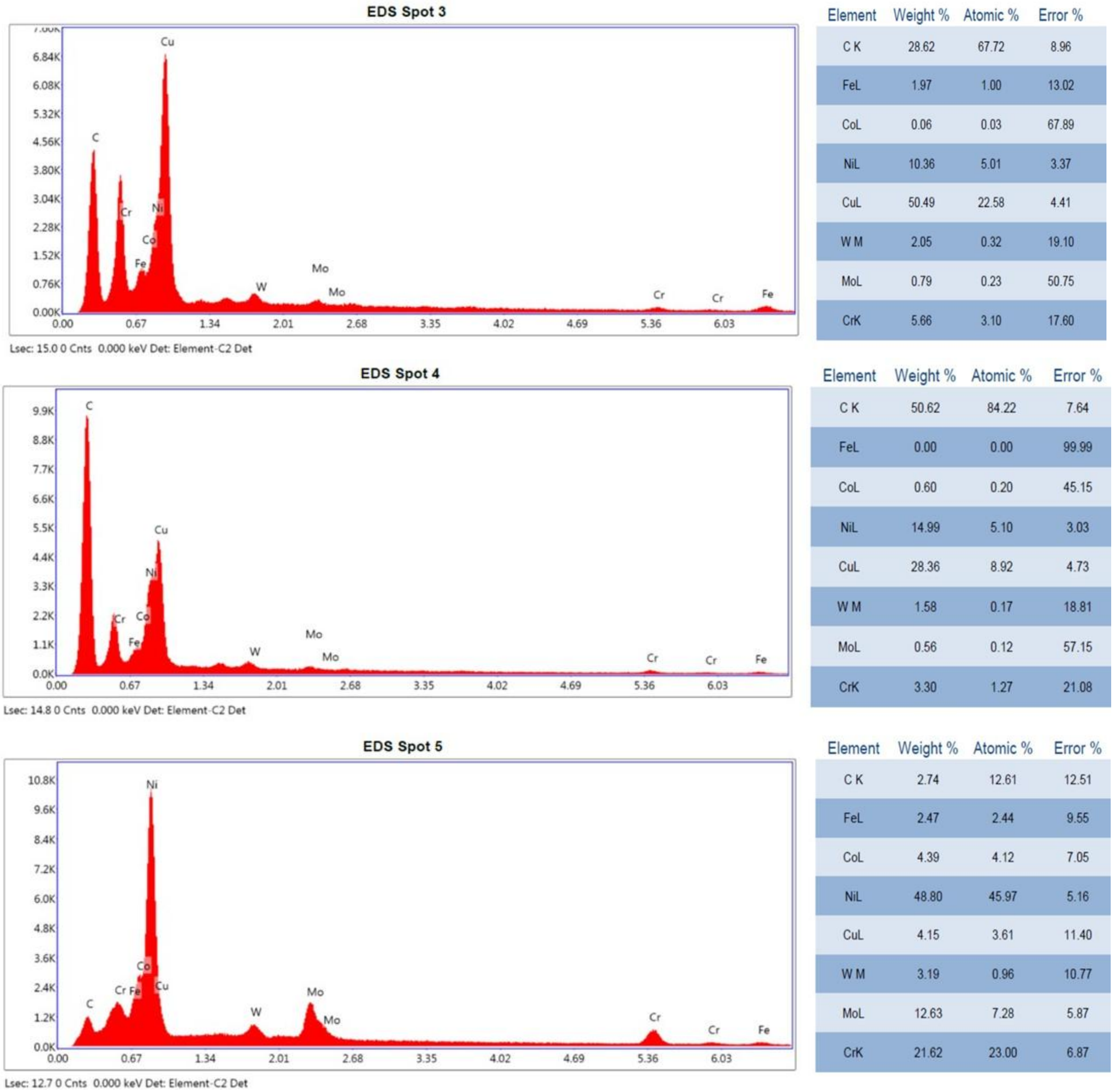


EDS Spot 3

Element	Weight %	Atomic %	Error %
C K	28.62	67.72	8.96
FeL	1.97	1.00	13.02
CoL	0.06	0.03	67.89
NiL	10.36	5.01	3.37
CuL	50.49	22.58	4.41
W M	2.05	0.32	19.10
MoL	0.79	0.23	50.75
CrK	5.66	3.10	17.60

EDS Spot 4

Element	Weight %	Atomic %	Error %
C K	50.62	84.22	7.64
FeL	0.00	0.00	99.99
CoL	0.60	0.20	45.15
NiL	14.99	5.10	3.03
CuL	28.36	8.92	4.73
W M	1.58	0.17	18.81
MoL	0.56	0.12	57.15
CrK	3.30	1.27	21.08

EDS Spot 5

Element	Weight %	Atomic %	Error %
C K	2.74	12.61	12.51
FeL	2.47	2.44	9.55
CoL	4.39	4.12	7.05
NiL	48.80	45.97	5.16
CuL	4.15	3.61	11.40
W M	3.19	0.96	10.77
MoL	12.63	7.28	5.87
CrK	21.62	23.00	6.87

Fig. 2. EDS spot analysis of machined surface processed in Cu incorporated dielectric medium

The composition of Ni on the globules i.e. spot 5 was 48 % confirming that the materials were removed from the Hastelloy before the coating process. The surface was subsequently studied using EDS mapping to assess the element deposition across the machined surface for further clarification as depicted in Fig. 3.

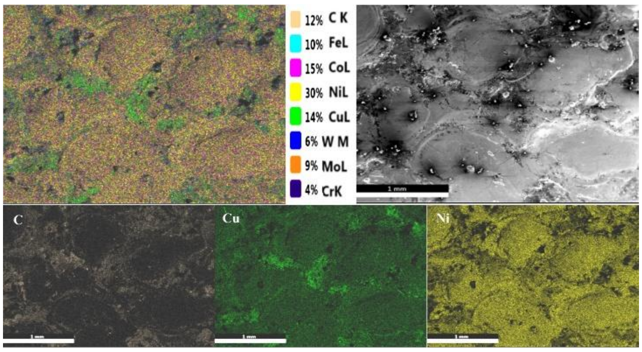


Fig. 3. Elemental mapping of machined surface processed in Cu-incorporated dielectric medium

The major composition of C was present at the coated margins, and the increased green hue suggested that the concentration of Cu was higher at the boundaries, confirming the formation of Cu_2C_2 at the borders. Cu was 14 percent of the machined surface's composition, and it was evenly distributed over the surface [14]. The objective of achieving a composite coating on the surface was not accomplished, but a composite surface was formed.

The microstructure of the surface machined with Ti incorporated dielectric fluid revealed that the Cu_2C_2 was evenly deposited throughout the surface as massif. Globules, micro pits and resolidified materials are some of the defects observed on the coated surface as shown in Fig. 4. The cracks were not observed on the surface inveterate that inclusion of Ti powder arrest the crack. By discharge channel, the molten material was splattered away and coated as plain patches [15]. The elemental analysis confirmed that Cu, C and Ti were the elements formed on the coated surface as depicted in Fig. 5. When exposed to high temperature dielectric fluid breakdown and discharged C atom, it reacted with Cu debris deposited as the C_2Cu_2 on the machined surface. Titanium was revealed on the surface as a result of dispersion in dielectric fluid.

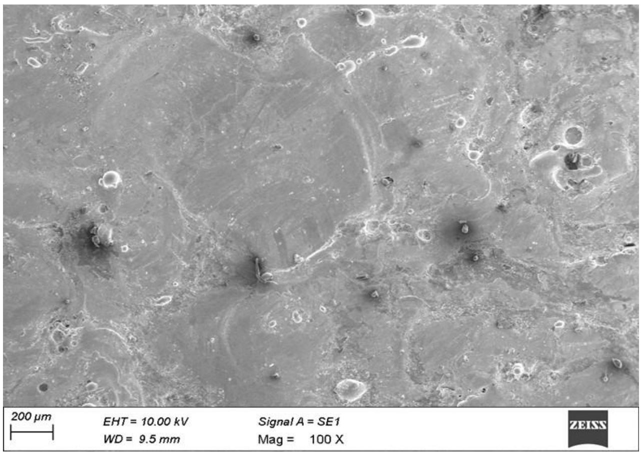
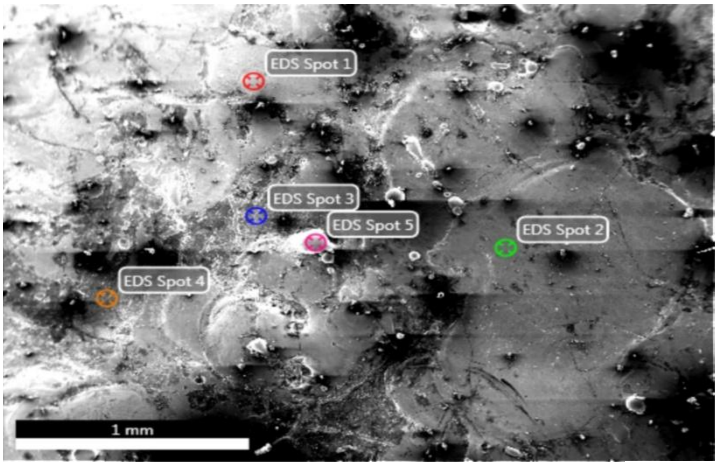
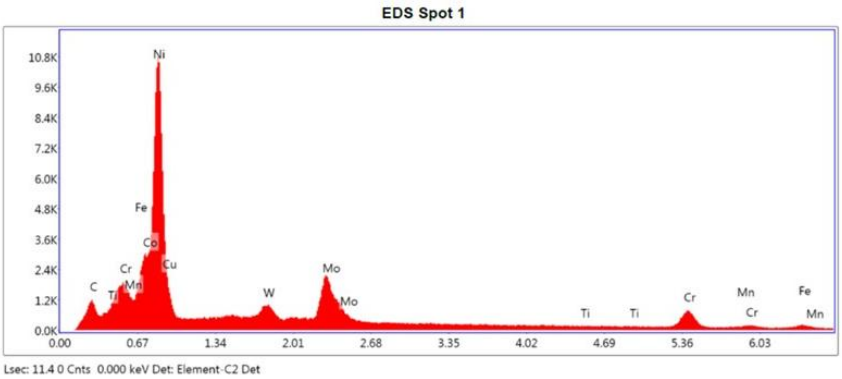


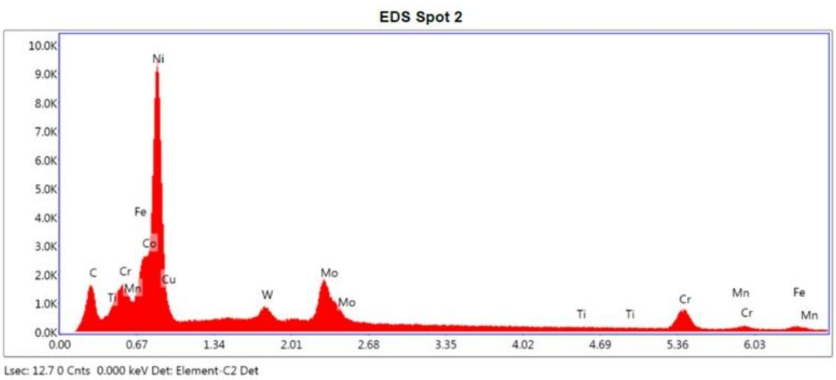
Fig. 4. SEM of Hastelloy machined surface processed in Ti-incorporated dielectric medium

Interestingly, the titanium element's weight percentage did not transcend 1 % in any of the spots, indicating that tool materials coated more effectively than powder dispersed in the dielectric fluid. The elemental analysis revealed a novel finding, the composition of the Cu and C on the coated patches and the patch borders differed significantly. The integrated weight percentage of Cu_2C_2 on the coated patches ranges from 4.6 to 4.8 wt.%, as indicated in the spots 1 and 2. When it was analyzed on the patch boundaries, it substantially increased to the range of 75 to 77 wt.% as observed in the spot 3 and 4. The topography resembles the microstructure of the particle reinforced composites [16]. The composition of the resolidified substance (spot no. 5) revealed that the majority of the element was Ni alloy, which was the work piece's base metal. It confirmed that the materials were removed from the work piece until the flushing was turned off.





Element	Weight %	Atomic %	Error %
C K	1.64	7.86	14.06
FeL	2.17	2.23	10.11
CoL	4.18	4.08	7.49
NiL	45.73	44.80	5.44
CuL	3.64	3.29	11.86
W M	3.18	1.00	10.77
MoL	13.33	7.99	5.75
TiK	0.67	0.80	29.83
CrK	22.06	24.40	6.93
MnK	3.40	3.56	25.46



Element	Weight %	Atomic %	Error %
C K	4.19	18.00	11.23
FeL	1.96	1.81	12.29
CoL	4.20	3.67	8.12
NiL	45.25	39.75	5.62
CuL	0.59	0.48	37.46
W M	2.14	0.60	9.46
MoL	12.21	6.56	5.90
TiK	0.91	0.98	25.92
CrK	25.29	25.08	6.80
MnK	3.27	3.07	29.48

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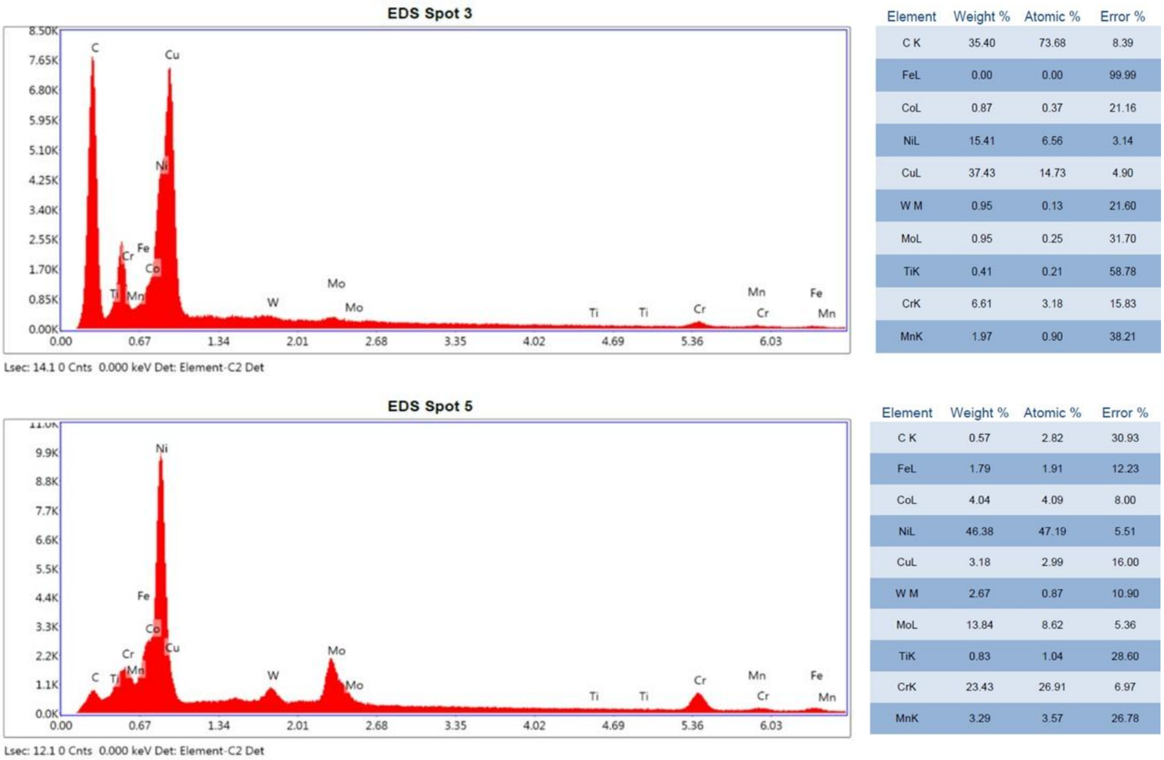

Fig. 5. EDS spot analysis of machined surface processed in Ti-incorporated dielectric medium

The microstructure confirmed that material removal from the surface, coating of the work piece and reinforcing coating with strong carbide particles, all transpired at the same time.

The surface was analyzed using SEM with EDS mapping to get more clarification on the aforementioned perspective, as shown in Fig. 6. The mapping showed that Cu and C were homogeneously coated all over the surface and coating occurred in patches.

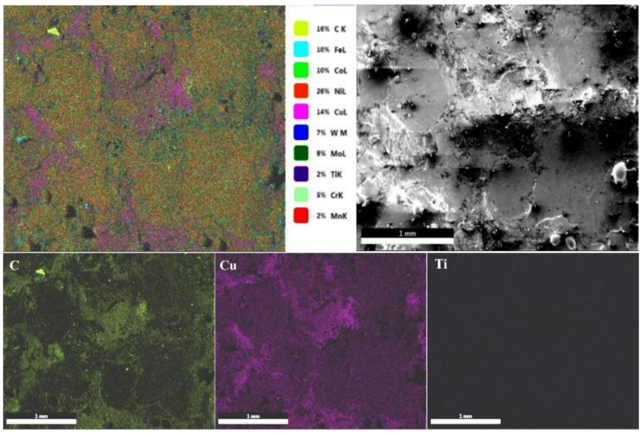

Fig. 6. Elemental mapping of machined surface processed in Ti-incorporated dielectric medium

At the coating boundaries, the elements intensified and reinforced the coated surface. The mixed element analysis showed that the reinforced particles C_2Cu_2 were uniformly distributed over the coated materials [17]. According to many research reports, the specimens with this microstructure may improve their tribology and mechanical characteristics, further investigation is needed. As the Ton was set at 80 μs, the produced heat was retained inside the machined gap for a prolonged amount of time, promoting the reaction between Cu and C, bonded as the harder Cu_2C_2 particles on the coated boundaries and eradicated cracks on the coated borders. When machined in a pure dielectric medium C_2Cu_2 was not coated on the surface confirming that the occurrence of bridging in reverse polarity results in the coating of the substrate. Researchers claimed that the incorporated powder particles react with C deposited as carbides on the machined surface, however, contemporary study findings contradicted these claims [18]. Plasma channel with high intensity, the addition of titanium in the form of oxides, and salts may enable the reaction between powder and discharged atom, depositing the TiC over the surface, further investigation is required. The research results confirmed that the incorporation of Ti acts as a catalyst that prompts the reaction of C and Cu and the formed carbides were uniformly deposited over the surface.

As titanium particles are blended with dielectric oil to coat the Cu_2C_2 on the surface if copper is a tool, the results raise a number of research questions. To deposit any other material carbide, what is the combination of tool and incorporated particles, the optimal concentration of particles, and if any tweaks to the electrical process parameters make it possible to deposit incorporated particles, a deep investigation required.

The wear behaviour of the sample produced through Cu and Ti incorporated dielectric medium was performed to analyse the wear resistance of the coatings. The worn surface morphology of Ti-incorporated samples showed abrasive and adhesive wear mechanisms as depicted in the Fig. 7. The surface revealed prominent grooves running parallel to the sliding direction, which confirmed the presence of abrasive particles causing material removal through ploughing action.

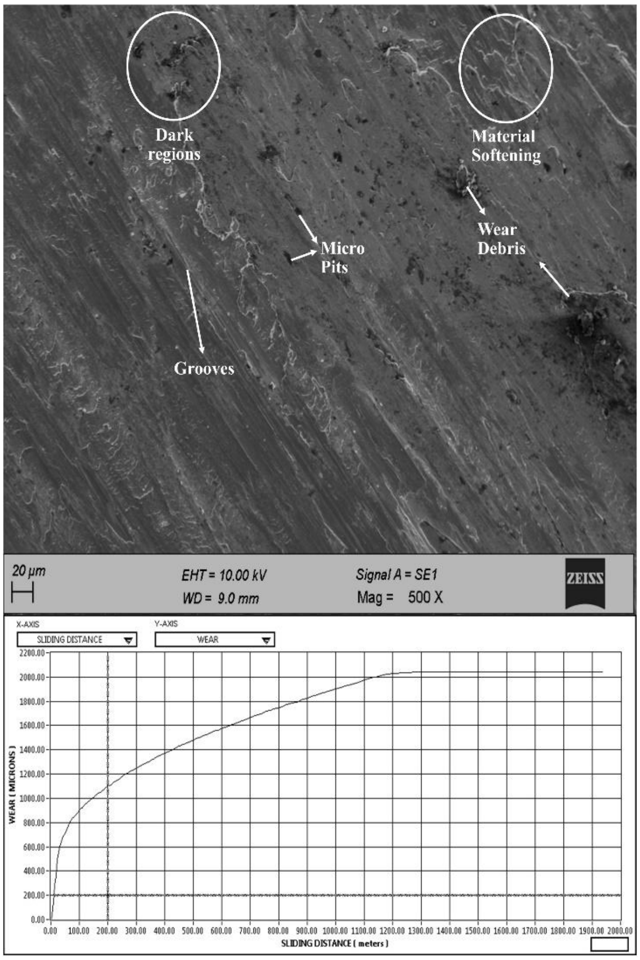

Fig. 7. Wear behavior and worn surface morphology of Ti-incorporated samples

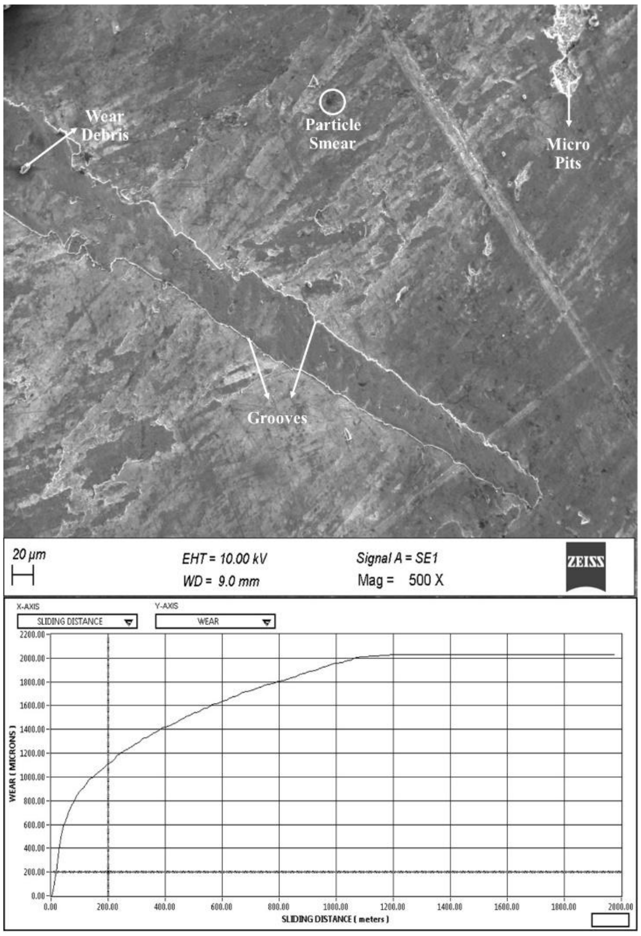

Fig. 8. Wear behavior and worn surface morphology of Cu-incorporated samples

These grooves indicate that micro-cutting and micro-ploughing are the dominant wear mechanisms, leading to surface deterioration over prolonged sliding. The presence of micro pits signifies localized material detachment, due to subsurface crack propagation. Dark regions are observed on the worn surface, which could be attributed to phase transformation caused by frictional heating which is indicative of thermal effects, leading to surface embrittlement. Evidence of material softening is visible in certain areas, confirming that the surface experienced temperature-induced plastic deformation. The wear performance analysis, based on the graph showed rapid wear at the initial stage. As sliding distance increases, the wear rate showed gradual increase, indicating a transition to a stable wear regime.

For Cu incorporated samples micro pits were observed on the surface which confirmed the localized material detachment as shown in Fig. 8. The presence of particle smears across the worn surface revealed that the softened material has been transferred and redistributed due to high contact stresses and frictional heating. The detachment of small particles is evident which act as third-body abrasives. The Cu-incorporated surface exhibits prominent grooves, wear debris, and particle smearing, indicating a dominant abrasive wear mechanism. However, the Ti-incorporated surface demonstrates reduced groove severity and a more uniform wear pattern, suggesting better resistance to material removal.

The wear progression curve for Ti-incorporated material showed a lower wear rate over extended sliding distances, indicating enhanced tribological stability. The presence of Ti prompts the formation of a protective tribo layer, thereby offering superior wear resistance compared to Cu-incorporated samples.

4. CONCLUSIONS

The surface of the Hastelloy was successfully modified utilizing EDA techniques

1. When Cu was mixed, the surface was not coated with C_2Cu_2, but with pure copper. When machined in Ti particle included media, the surface was coated and reinforced with C_2Cu_2, as confirmed by EDS mapping.
2. EDS spot analysis confirmed the sequential process of material removal and subsequent deposition in the spark gap. The presence of Ni and other base material elements in the coated layer indicates initial material removal, while the detected Cu and Ti elements confirm successful deposition from the dielectric medium. Materials dunes, globules, resolidified material, micro cracks and micro pits are some of the defects observed on the coated surface. The incorporation of Ti particles acts as a catalyst for the coating of C_2Cu_2 on the surface.
3. The Ti-incorporated material exhibits superior wear resistance than the Cu-incorporated samples as evidenced by formation of a protective tribo layer. This novel alloying technique integrates machining as well as

coating process which enhances the productivity of the manufacturing sector.

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