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OPTIMIZATION OF WIRE ELECTRIC DISCHARGE MACHINING PARAMETERS OF AISI A2 TOOL STEEL MACHINING

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Abstract— **Currently, the demand is increasing for machine micro and nano size dies of complex profile with minimum post-processing operations. These dies are used primarily in dental, jewellery and optical fields. These should have explicit characters as follows: (i) a high surface finish to attain good quality with fewer defects, (ii) the corrosion formation inside the dies should be minimized to provide a good life for the components, and (iii) the strength should be good for avoiding the deformation of dies and reducing material wastage to maximize the utilization of the work material. Taking these points as the objectives, the present work has been carried out.**

In the conventional machining process, the tool contacts the workpiece and the defects are more. To overcome these drawbacks, an unconventional machining process, where the tool does not contact the workpiece, was investigated. But all unconventional machining processes are not suitable for manufacturing dies with intricate shapes; the Wire Electrical Discharge Machine (WEDM) is more suitable. The wire electrical discharge machining is a process of generating sparks between the wire electrode and the work material. The machining of the material takes place with sparks and the machined material scraps were removed with the help of a dielectric fluid. The performance of the WEDM is very low, therefore many researchers tried to improve the performance of WEDM. A Few researchers optimized the machining parameters for improving the performance. A Few investigated by changing the wire electrodes. The wire electrodes are of molybdenum, aluminum, copper and brass. The molybdenum wire electrode has good strength for high tension, but it has poor electrical conductivity; with this the spark generation is less and spark intensity is less; hence, the performance of WEDM is poor. The aluminum wire electrode‟s strength and electrical conductivity are a little better than molybdenum and the spark generation and spark intensity is average, but it has insufficient strength for high tension. Copper has good electrical conductivity, which helps in more spark generation, which in turn leads to high spark intensity. With this, the performance of WEDM increased, but it has minimum strength, cannot withstand high tension and the cost is more. So the brass wire electrode is introduced; it is a combination of zinc and copper alloy. The brass wire electrode has good electrical conductivity with more spark generation and high spark intensity, high strength and high tension, and hence the performance of WEDM is comparably high.

Index Terms— **AISI A2 Tool Steel, Wire Electric Discharge Machining, Mechanical testing, Aluminum wire electrode, etc**

I. INTRODUCTION

The Wire Electrical Discharge Machine (WEDM) performs machining based on the spark-erosion phenomenon. The 2D and 3D machining will take place only on conductive materials. The spark will occur between electrode and workpiece in the presence of dielectric fluid. The dielectric fluid is known as distilled water. The dielectric fluid is supplied in two ways, flushing and submergible. The dielectric fluid is flushed out through a nozzle on a workpiece in flushing. However, in submergible medium the workpiece is immersed inside the stream of dielectric fluid.

A. PRINCIPLE OF WEDM

The WEDM process uses the copper or brass wire of diameter 0.02 to 0.30 mm as electrodes and moves continuously up to the end of the process. The group of sparks produced by the wire electrode creates a band saw. The band saw ensures the machining in WEDM. The dielectric fluid known to be distilled water is used in the machined area. It has a unique character like no electrical conductivity. The WEDM consists of essential components such as movement of a contour control unit for the workpiece, the motion of table with workpiece along the X-axis, Y-axis, Z-axis and drives section of wire.

The power supply system provides electricity to the electrode or the wire. The pump is used to supply dielectric fluid to the machining area. The basic principle of metal removal in this process is the same as that of EDM, but in WEDM, a continuously moving wire acts as the electrode instead of a shaped electrode. In WEDM, the dielectric fluid is flushed out through a nozzle on the workspace but in EDM, the whole workpiece is submerged inside the dielectric fluid. As of now, in WEDM, both flushing and submergible medium of dielectric fluid is used. The wire is passed through a predrilled hole in the workpiece in this process. The electrical power is supplied by the electronic pulse generator, which creates a potential between the wire electrode and the workpiece. The wire moves to the edges of the hole very closely with the movement of the table. The dielectric fluid is supplied into the predrilled hole and adjusted, so that no air bubble enters the working zone. The spark gap is getting electrified with voltage. As voltage increases, the spark gap electrification increases gradually and breaks down the spark gap. The material gets converted into a molten state and vaporizes. With this action the machining is performed.

B. A2 TOOL STEEL CHARACTERISTICS

A2 Tool Steel (A2TS) is a family member of cold work steels suitable for cryogenic treatment. It is air-hardened steel with good hardness, toughness and dimensional stability in machining. The wear resistance of air hardened steels is in between water hardened steels (W series), oil-hardened steels (O series) and high chromium high carbon steels (D series), as shown in Table 1.1 (www.totalmateria.com). The toughness, tool performance, strength and product forms were better with a combination of other constituents. The physical and mechanical properties of A2TS are density 7.86 g/cm3 and melting point 1424oC. Some of the essential mechanical properties are bulk modulus 140 GPa, shear modulus 78 GPa, Poisson‟s ratio 0.27 to 0.30 and young‟s modulus 190 to 210 GPa. The initial micro Vicker's hardness of A2TS is 215 HV. It can transform from the normal conductive state to a superconductive state with cryogenic cooling.

Table 1.1 Types of cold work tool steels.

Type of tool steel	**Prefix**	**Specific types**
Cold working	Water hardening =W	W_1, W_2, W_5
	Oil hardening = O	O_1, O_2, O_6, O_7
	Medium alloy air-hardening=A	A_2, A_4, A_6, A_7, A_8,A_9, A_{10},A_{11}
	High carbon, high chromium=D	D_2, D_3, D_4, D_5, D_7

Prajapathi et al. (2013) identified that A2TS is an air-hardened tool steel that consists of 5% chromium. It has a safer hardness, less distortion and wears resistance required for making dies, punches, and molds. Cryogenic treatment is much suitable with its safer hardness and it can convert from the normal conductive state into a superconductive state easily. Therefore A series steels are better than W series, O series and D series steels. The chemical composition of A2TS is shown in Table 1.2.

Table 1.2 Chemical composition of A2TS

Elements	**Carbon**	**Chromium**	**Manganese**	**Molybdenum**	**Nickel**	**Phosphorous**	**Sulfur**	**Silicon**	**Vanadium**
%	1.05	5.16	0.44	0.51	0.18	0.02	0.02	0.47	0.18

C. RESEARCH OBJECTIVES

The research is carried out to investigate the essential aspects of the material characteristics such as Ra, CR, SH, MRR, and KW given below.

- To improve the surface finish, dimensional stability, life and strength of the material and the efficiency of WEDM for manufacturing micro or nano dies.
- To determine the percentage of improvements in the material characteristics of A2TS in normal and superconductive states machined in flushing and submergible mediums.
- To convert the NCS A2TS into SCS A2TS for increasing the material characteristics of the work material that were suitable for manufacturing micro or nano dies.
- To notice the optimized levels of the machining parameters for better material characteristics, the Taguchi optimization is used.
- To identify the influence of the machining parameters on the material characteristics, both the Taguchi ranking and regression were used.
- To formulate the mathematical equation between the machining parameters (input) and material characteristics (output) to predict the best output value.
- To notice the material characteristics behavior of the machined specimens, the test was conducted using SEM, EDAX and XRD.

II. LITERATURE SURVEY

The literature is reviewed for selecting the WEDM, work material, machining parameters, material characteristics, cryogenic treatment and morphological study. The morphological study deals with SEM, EDAX and XRD. The optimization method Taguchi is selected as it is noticed that simple and accurate method of finding optimum machining parameters levels for better performance. Faith et al. (2020) noticed that deep cryogenic treatment of Ti–6Al–4V alloy and machined in WEDM improved the results such as MRR 5% and Ra 24%. The Druvin et al. (2016) considered the machining parameters such as wire feed (m/min), pulse on (μs), pulse off (μs), cutting speed (mm/sec), for investigating machining time (min), Ra (μm) and KW (mm). The experiments are carried on cryogenically treated Ti6Al4V with WEDM process by varying machining parameters and identified the improvements such as machining time 5.75%, Ra 0.60% and KW 0.38% respectively. Saini et al. (2017) noticed Cryogenically Treated Brass Wire electrode (CTBW) and Non-Cryogenic Treated Brass Wire electrode (NCTBW) and identified the improvement in Ra is 25.17%. Kumar et al. (2021) noticed the reduction in Ra (µm) as 22.80% with NCTBW and CTBW.

Sharma et al. (2019) noticed the percentage of improvement in surface finish and MRR between CPBW and ZCDBW is 22.85% and 10.82% respectively. Khan et al. (2013) identified the improvement between the max and min value of microhardness as 36.21%. Prathipati et al. (2019) pointed that the reduction in corrosion potential by 33.50%. The coating on wire or electrode is a difficult process and costlier. Therefore wires are treated cryogenically but the wire losses its cryogenic temperature and also replacing is difficult while machining. To overcome this draw backs workpiece is treated cryogenically. Here, workpiece can replace very easily. In this current research work piece A2TS has moderate hardness and cold working nature, so it is considered for cryogenic treatment for improving the material characteristics and efficiency of WEDM.

III. EXPERIMENTAL WORK

A. WEDM MACHINE DETAILS

In WEDM, wire is treated as an electrode or tool. The electrode material is brass with a 0.25 mm diameter. The workpiece material is A2TS. The chemical composition of A2TS is tabulated in chapter 1. It is machined into specimens of size 10mm × 5mm × 11mm (length, width and height respectively).

The experimental investigation was performed on an Electronica ultimate OS WEDM. It consists of flushing and submergible mediums flow of dielectric fluid as shown in Figure 3.1. Its coordinate‟s maximum distance along the X, Y and Z axes are 350 mm, 450 mm and 250 mm respectively.

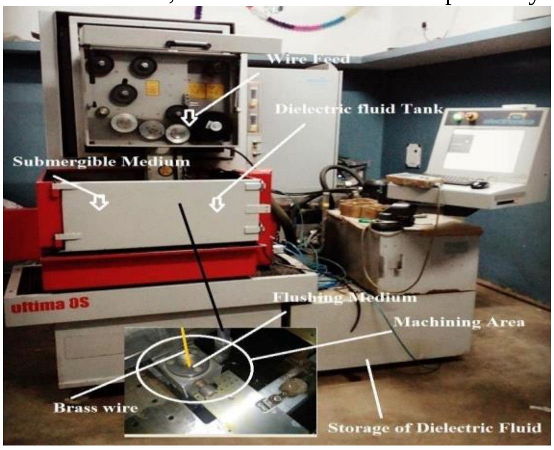

Figure 3.1 Electronica ultima OS WEDM

B. DESIGN OF EXPERIMENT

As DOE consists of the Taguchi method. The Taguchi method creates Taguchi design based on machining parameters. The store design in the worksheet generates the orthogonal array in terms of levels, as shown in Table 3.1. The machining parameters considered are seven in that six are three levels and one is two levels based on this the orthogonal array L18 is selected.

The levels were coded with machining parameters range values for quality design concern and the experimental setup is created as shown in Table 3.1.

Table 3.1 Experimental setup for 18 set of experiments

Exp. No	(A)	(B)	(C)	(D)	(E)	(F)	(G)
1	1	11	10	33	1	9	9
2	1	11	20	43	2	12	12
3	1	11	30	53	3	15	15
4	1	12	10	33	2	12	15
5	1	12	20	43	3	15	9
6	1	12	30	53	1	9	12
7	1	13	10	43	1	15	12
8	1	13	20	53	2	9	15
9	1	13	30	33	3	12	9
10	3	11	10	53	3	12	12
11	3	11	20	33	1	15	15
12	3	11	30	43	2	9	9
13	3	12	10	43	3	9	15

14	3	12	20	53	1	12	9
15	3	12	30	33	2	15	12
16	3	13	10	53	2	15	9
17	3	13	20	33	3	9	12
18	3	13	30	43	1	12	15

IV. MATERIAL CHARACTERISTICS ANALYSIS AND OPTIMIZATION

A. INVESTIGATION OF MATERIAL CHARACTERISTICS

The Ra of machined specimens in WEDM is performed using SJ-410 as shown in Figure 4.1 (Aqueel et al. 2011). The testing of Ra requires a run-up distance before starting the measurement. The run-up distance set to 0.5 mm in SJ-410 series. This distance is shortened to 0.15 mm using the narrow part measuring function. The straightness is about 0.3 to 0.5 µm over a transverse length of 25 to 50 mm and the cut-off length is 12.5 mm. The function extends the possibility in narrow location measurements such as grooves in piston rings etc.

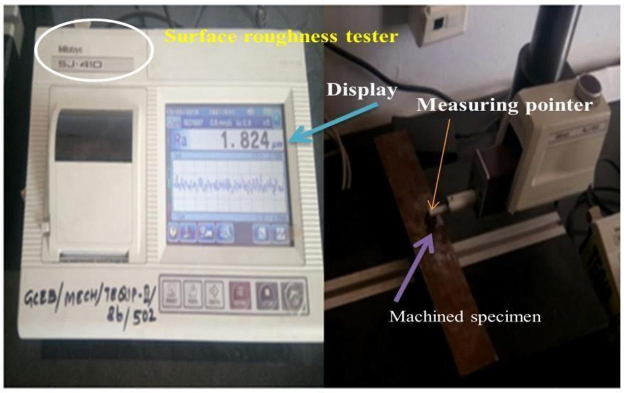

Figure 4.1 Ra tester

The weight-loss method is used for investigating the CR for machined specimens. All the specimens were thoroughly washed with distilled water and the initial weight of the specimens was noted. Then the specimens were dipped into HCl (hydrochloric acid) and allowed to soak for 270 hours (11 1/4 days) after the initial weight of the specimens were noted. Then the specimen‟s final weight is noticed. The corrosion test performed is as shown in Figure 4.2. The weight-loss method is considered for finding the CR of machined specimens, as shown in Equation 4.1 (Yinka et al. 2021). The initial weight of the sample specimen is 4.3083 g and the final weight of the sample specimen is 4.2870 g. The weight of the specimens deteriorates with oxides formation. The net difference in weight of the specimens is 0.0213 g. The weight loss is substituted in the formula of CR and the calculated value is 0.31812 mpy as shown in Table 4.1.

CR=(weight loss in grams) X (22,300)/(Adt) ……………...(4.1)

whereas, CR indicated in mils per year (mpy) penetration, A = surface area of specimen = 16.929 (sq. inch.), d = 7.86 metal density considered (g/cm3), t = time of exposure in corrosive environment (days), constant value k = 22,300, FM = flushing medium, SM = submergible medium.

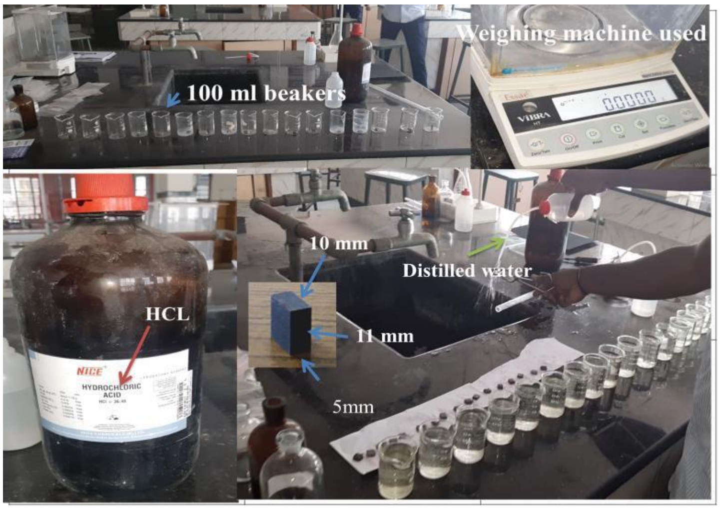

Figure 4.2 The CR testing process

The SH of the machined specimens were expressed in microhardness. The SH is measured using Micro Vickers Hardness Tester (Khan et al. 2013) developed by Wilson Wolpert Germany. The specialty of this tester is a direct display of results with concern indentation as shown in Figure 4.3 for NCS and SCS specimens machined in flushing and submergible mediums. The range of load for testing is 10 grams to 1 Kg. As per this research; the material used is tool steel. Therefore, the load induced on the specimens used diamond indentation for measuring the SH is 0.2 N (20.39 gm). The SH is displayed by measuring the length of the indentation of machined specimens. The indentations are shown in Figure 4.3. A microscopic image of indentation for a machined specimen is shown in Figure 4.4.

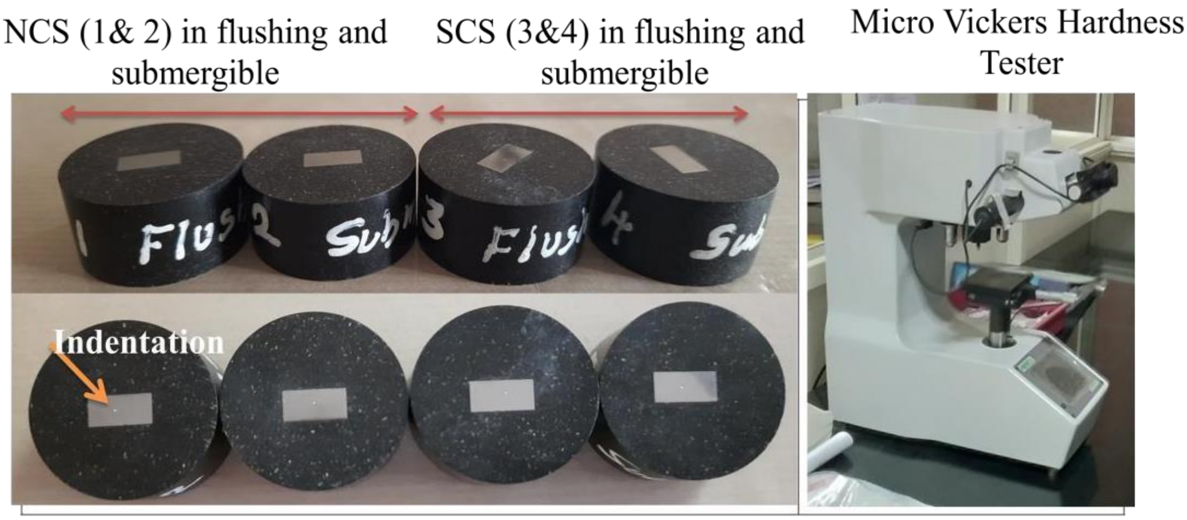

Figure 4.3 SH specimens for optimum levels along with hardness tester

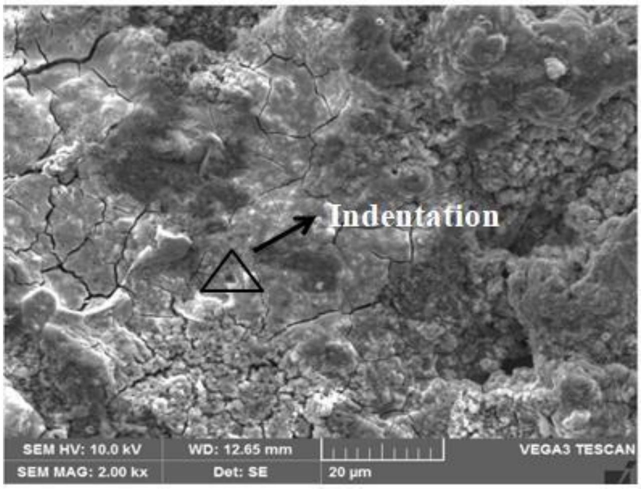

Figure 4.4 A microscopic image of indentation

V. RESULT AND DISCUSSION

A. RESULTS VALIDATION

The percentage improvements of material characteristics, the strength of regression equations and error comparison were discussed. The morphological study on the machined specimen in wire electrical discharge machining is described. The mechanism inside the machined specimen layers in the WEDM process for various states and mediums were discussed.

B. THE MATERIAL CHARACTERISTICS PERCENTAGE IMPROVEMENT

The optimum specimens values obtained from the experimental reading were compared, and the percentage of improvement was noticed for various conductive states and mediums.

- The Ra of the specimens machined in flushing medium with NCS is 3.861 µm and SCS is 2.670 µm, the SCS process shows improved percentage than NCS process and it is 30.84 as shown in Figure 5.1a.

- The Ra of the specimens machined in submergible medium with NCS is 2.821 µm and SCS is 1.752 µm, the SCS process shows improved percentage than NCS process and it is 37.89 as shown in Figure 5.1b.

- The CR of the specimens machined in flushing medium with NCS is 0.20012 mpy and SCS is 0.08487 mpy, the SCS process shows improved percentage than NCS process and it is 57.59 as shown in the Figure 5.1c.

- The CR of the specimens machined in submergible medium with NCS is 0.18013 mpy and SCS is 0.07321 mpy, the SCS process shows improved percentage than NCS process and it is 59.35 as shown in the Figure 5.1d.

- The SH of the specimens machined in flushing medium with NCS is 226 HV and SCS is 232 HV, the SCS process shows improved percentage than NCS process and it is 2.58 as shown in the Figure 5.1e.

- The SH of the specimens machined in submergible medium with NCS is 231 HV and SCS is 243 HV, the SCS process shows improved percentage than NCS process and it is 4.93 as shown in the Figure 5.1f.

- The MRR of the specimens machined in flushing medium with NCS is 15.93 mm3/min and SCS is 19.45 mm3/min, the SCS process shows improved percentage than NCS process and it is 18.09 as shown in Figure 5.1g.

- The MRR of the specimens machined in submergible medium with NCS is 21.53 mm3/min and SCS is 26.93 mm3/min, the SCS process shows improved percentage than NCS process and it is 20.02 as shown in figure 5.1h.

- The KW of the specimens machined in flushing medium with NCS is 0.7058 mm and SCS is 0.6558 mm, the SCS process shows improved percentage than NCS process and it is 7.08 as shown in the Figure 5.1i.

- The KW of the specimens machined in submergible medium with NCS is 0.6584 mm and SCS is 0.5784 mm, the SCS process shows improved percentage than NCS process and it is 12.15 as shown in the Figure 5.1j.

The percentage improvement in submergible is greater than flushing. The improvement in SCS A2TS is higher compare to NCS A2TS. The maximum improvements are seen in the SCS with the submergible medium as shown in Figure 5.1(a-j). In SCS, the electrical resistance is less compare NCS, the flow of current increases with this spark generation and spark intensity increases between the work material and electrode. Submergible medium is continous cooling process and flushing medium is a discontinuous cooling process. The continous cooling provides better resolidification of material melt and avoids formation of oxide layers on the machined specimens. Therefore, SCS A2TS provides better material characteristics than NCS A2TS, similarly the submergible medium provides better material characteristics than flushing medium.

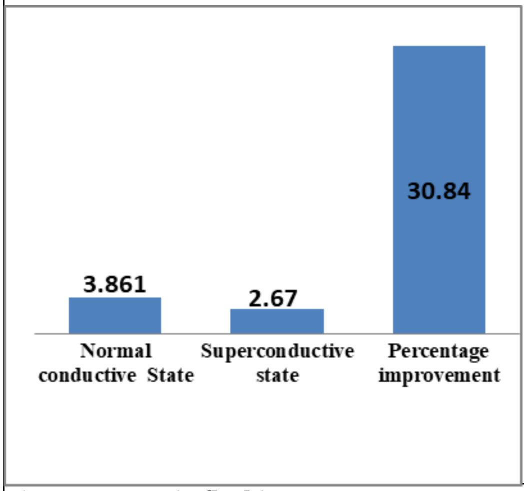

Figure 5.1a R_a in flushing.

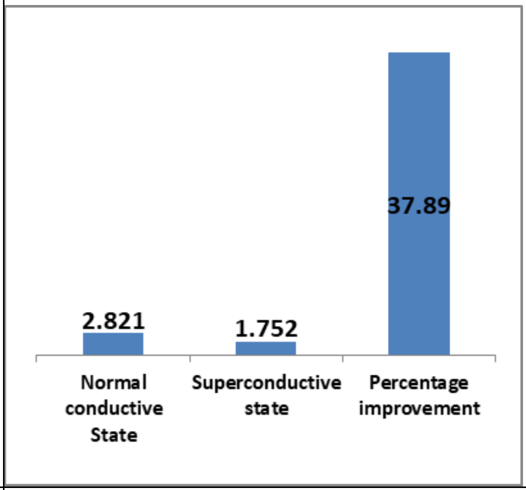

Figure 5.1b R_a in submergible.

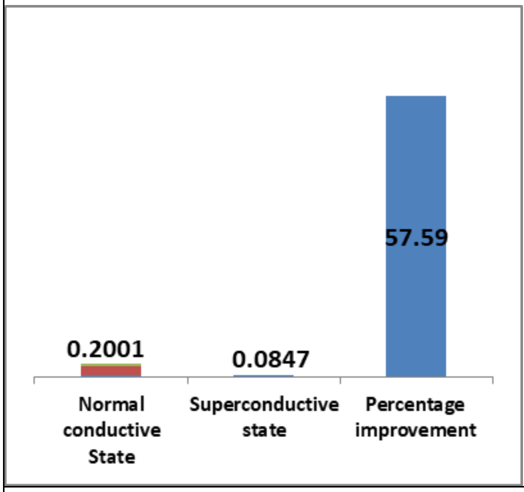

Figure 5.1c CR in flushing.

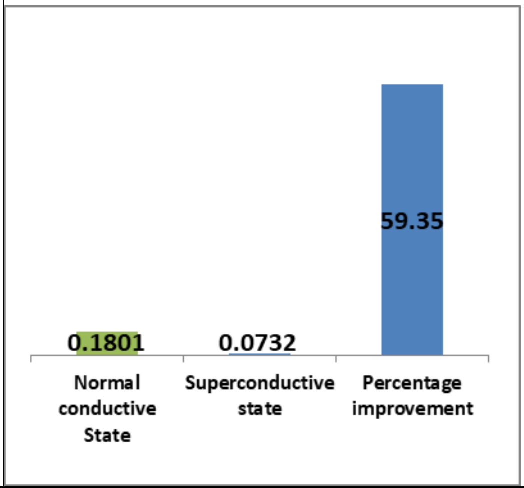

Figure 5.1d CR in submergible.

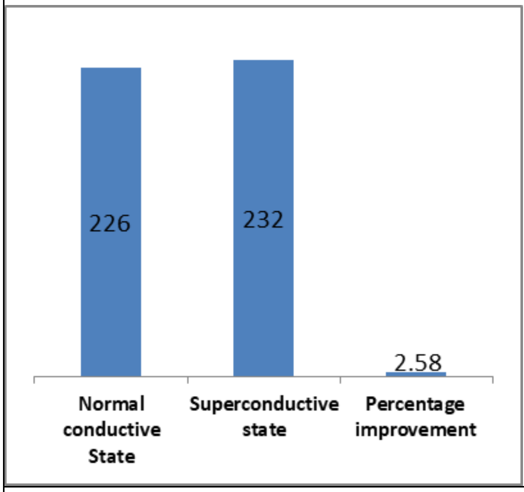

Figure 5.1e SH in flushing.

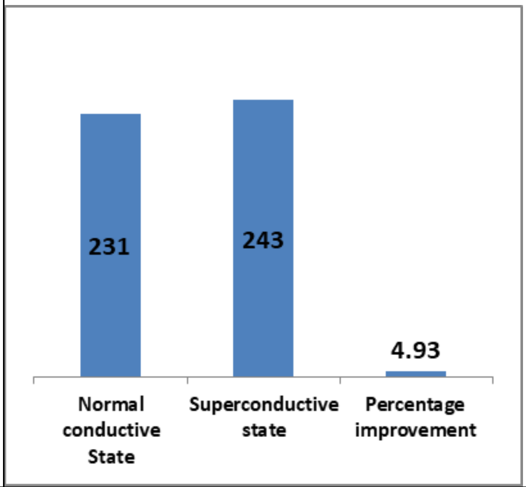

Figure 5.1f SH in submergible.

Figure 5.1 (Continued)

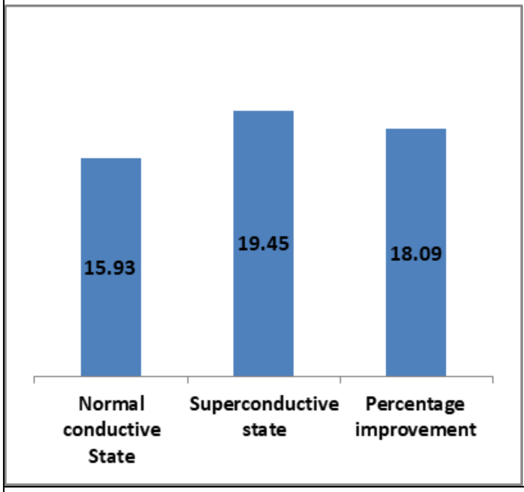

Figure 5.1g MRR in flushing.

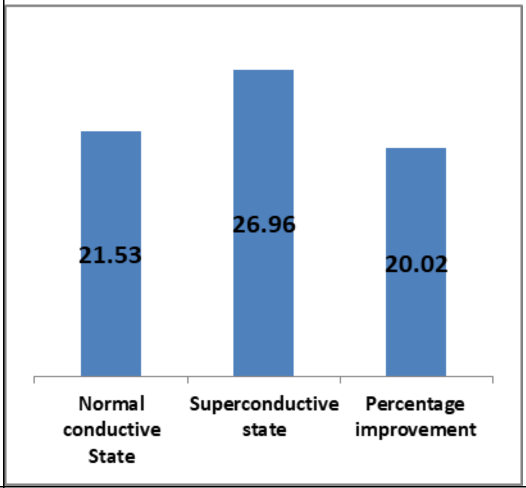

Figure 5.1h MRR in submergible.

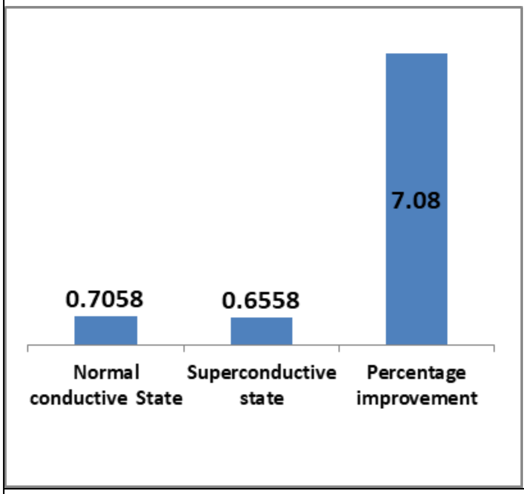

Figure 5.1i KW in flushing.

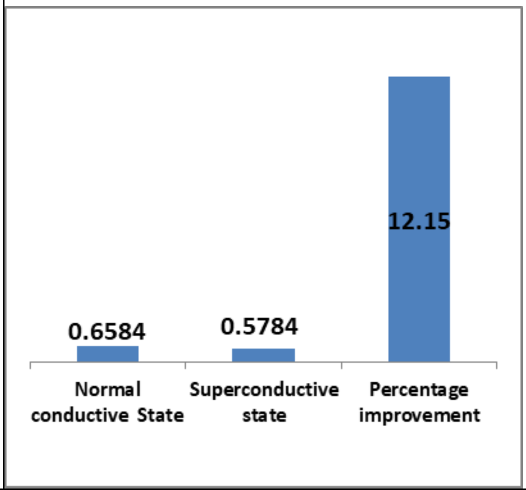

Figure 5.1j KW in submergible.

Figure 5.1(a-j) The material characteristics percentage improvements.

VI. CONCLUSIONS AND FUTURE WORK

A. CONCLUSIONS

This research investigates machining A2TS in a Normal Conductive State (NCS) and Super Conductive State (SCS) using WEDM in flushing and submergible mediums by considering the machining parameters to improve the material characteristics. The findings are given below.

- The specimens of NCS A2TS and NCS A2TS were machined in the flushing and submergible mediums. The obtained results were optimized and the optimum levels of machining parameters were selected. The machining is performed in WEDM for the improvement of material characteristics such as surface roughness (Ra), Corrosion Rate (CR), Surface Hardness (SH), Material Removal Rate (MRR) and Kerf Width (KW).

- The overall, percentage of reduction in Ra from NCS to SCS in flushing is 30.84 and in submergible 37.89. The percentage of reduction in CR from NCS to SCS in flushing is 57.59 and in submergible 59.35. The percentage of improvement in SH from NCS to SCS in flushing is 2.58 and in submergible 4.93. The percentage of improvement in MRR from NCS to SCS in flushing is 18.09 and in submergible 20.02. The percentage of reduction in KW from NCS to SCS in flushing is 7.08 and in submergible 12.15.

- Compared to the literature results as shown in section 2.10, better results for material characteristics were obtained from the current research.

- The SCS A2TS electrical resistance is reduced; with this the spark intensity between the wire and workpiece increased and this improves the material characteristics.

- The influences of machining parameters were noticed using Taguchi ranking analysis and regression. Out of seven ranks, there were seven parameters the first rank is treated as highly influenced, and the seventh rank is treated as the least influenced one. Similarly, in regression analysis, the P-test has a confidence level of 95% and a tolerance level of 5%. So, if the P-value is less than 0.05 the machining parameters are considered as highly influenced, and if the P-value is greater than 0.05 the machining parameters were considered as least influenced.

- The overall influence of the machining parameters from the Taguchi and regression analysis in various conductive states (NCS and SCS) and mediums (flushing and submergible) is noted. The highly influenced machining parameters are voltage, current, and pulse off on the Ra. On CR, the highly influenced machining parameters are current, pulse off, and fluid pressure. On SH, highly influenced machining parameters are voltage, pulse on, pulse off, and wire feed. On MRR, the highly influenced machining parameters are voltage, current, pulse off, wire feed and fluid pressure. On KW, the most influenced machining parameters are voltage and current.

- The linear plot between the machining parameters and the material characteristics of both NCS and SCS A2TS shows the variations in flushing and submergible. The Ra increases with increasing the voltage and current. The Ra is reduced by increasing the pulse off. The CR increases with increasing the current. The CR reduces with increasing the pulse off and fluid pressure. The SH increases with increasing the voltage, pulse on, and wire feed. The SH decreases with increasing the pulse off. The MRR increases with increasing the voltage, current, wire feed and fluid pressure. The MRR reduces with increasing the pulse off. The KW increases with increasing the voltage. The KW decreases with increasing the current.

B. FUTURE WORK

In future, there is one more way to attain better material characteristics in the WEDM process by considering compressed air. Compressed air is cheaper compared to nitrogen gas. Therefore the setup for compressing atmospheric air is installed. In addition to that, a cryogenic setup may also be installed. The atmospheric air was sucked into the compressor and compressed; with this the pressure and temperature were increased. Then it is passed through a condenser to reduce the temperature. After that, it is passed through the cryogenic setup, where the temperature decreases futher and reaches the cryogenic level. Then it is passed in between the wire electrode and workpiece to carry out the research.

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