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Multiple Operations for Optimization of Wire Electrical Discharge Machining Through Process Parameters for Inconel 600 Using Gray Relational Analyses

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ABSTRACT: INCONEL (nickel-chromium-iron) alloy 600 is a standard engineering material for applications which require resistance to corrosion and heat. The alloy also has excellent mechanical properties and presents the desirable combination of high strength and good workability.
The high nickel content gives the alloy resistance to corrosion by many organic and inorganic compounds and also makes it virtually immune to chloride-ion stress-corrosion cracking. Chromium confers resistance to sulfur compounds and also provides resistance to oxidizing conditions at high temperatures or in corrosive solutions. The alloy is not precipitation hard enable; it is hardened and strengthened only by cold work. The versatility of INCONEL alloy 600 has led to its use in a variety of applications involving temperatures from cryogenic to above 2000°F (1095°C). The alloy is used extensively in the chemical industry for its strength and corrosion resistance. Applications include heaters, stills, bubble towers and condensers for processing of fatty acids; evaporator tubes, tube sheets and flaking trays for the manufacture of sodium sulfide; and equipment for handling aphetic acid in the manufacture of paper pulp.
KEYWORDS: Inconel 600, Mini tab. Taguchi’s, WEDM.

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I. INTRODUCTION

The propensity of thermally stabilized Inconel 600 to undergo low temperature stress corrosion cracking (SCC) in sulfur bearing environments has been investigated with U-bends and slow strain rate testing. The results have been compared with those of sensitized Inconel 600. The potential dependence of crack propagation rate has been established in a single test by using several U-bends held at different potentials by choosing an appropriate electrical circuitry. The difference in SCC susceptibility of the sensitized and stabilized materials has been discussed in terms of the grain boundary chromium depletion and resultant intergranular attack in boiling ferric sulfate-sulfuric acid tests, and electrochemical potential kinetic reactivation (EPR) tests.

Inconel is a family of austenitic nickel-chromium-based super alloys.Inconel alloys are oxidation-corrosion-resistant materials well suited for service in extreme environments subjected to pressure and heat. When heated, Inconel forms a thick, stable, passivating oxide layer protecting the surface from further attack. Inconel retains strength over a wide temperature range, attractive for high temperature applications where aluminum and steel would succumb to creep as a result of thermally induced crystal vacancies. Inconel's high temperature strength is developed by solid solution strengthening or precipitation hardening, depending on the alloy.

Inconel alloys are typically used in high temperature applications. Common trade names for Inconel Alloy 625 include: Inconel 625, Chronin 625, Altemp 625, Haynes 625, Nickelvac 625 and Nicrofer 6020.[4] Inconel Alloy 600 include: NA14, N06600, BS3076, 2.4816, NCr15Fe (FR), NiCr15Fe (EU) and NiCr15Fe8 (DE). Inconel 718 include: Nicrofer 5219, Superimphy 718, Haynes 718, Pyromet 718, Supermet 718, and Udimet 718.

Table 1: Properties of Inconel 600

Property	Metric
Density	84035 kg/m3
Melting Point	1355 °C
Co-Efficient of Expansion	2.4 µm/m °C (26-110°C)
Modulus of Rigidity	77 kN/mm^2
Modulus of elasticity	205.4 kN/mm^2
Specific Heat	408 J/kg K
Thermal Conductivity	9.7 W/m K

II. PROSSES OF NON-CONVENTIONAL MACHINING

The non-conventional machining methods came into existence due to the need of higher accuracies and quality of surface finish, and the impediments in conventional machining of hard and difficult-to-machine materials. The increasing utility of such materials in the modern industry has forced research engineers to develop non-conventional machining methods, so as to have full advantage of these costly materials.

However there are some common parameters to be taken into consideration for selecting a particular process like:

- Physical properties of the work material,
- Type of operation required,
- Shape and size required to be produced,
- Process capabilities & process economy.

In non-conventional machining methods, there is no direct contact between the tool and the work piece; hence the tool needs not be harder than the job, and there is no mechanical stress.

Mechanical processes

In mechanical processes, metal removal takes place either by the mechanism of simple shear or by erosion mechanism where high velocity particles are used as transfer media and pneumatic/hydraulic pressure acts as a source of energy. It includes ultrasonic machining (USM), water jet machining (WJM), abrasive jet machining (AJM), etc. The schematic diagram of abrasive jet machining is shown in fig.

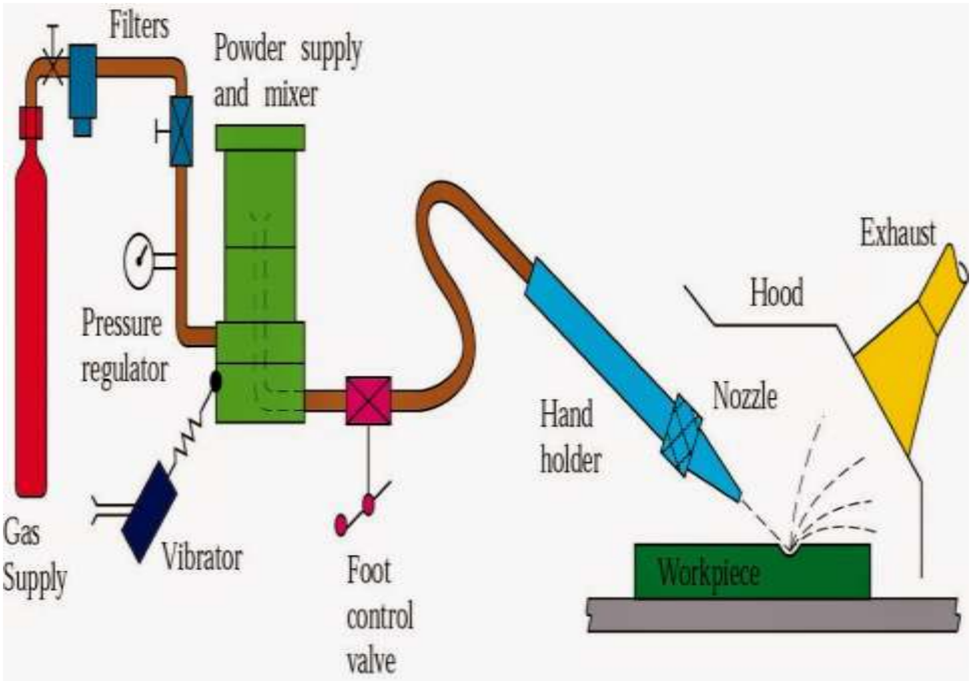

Fig. Abrasive jet machining

III. PROCESS PARAMETER OF WIRE EDM

The process parameters that affect WEDM process are classified as electrical parameters and non-electrical parameters.

Electrical parameters:

1. Pulse on Time-The pulse on time is the current flowing in each cycle (Fig.1.10). During this time the voltage is applied across the electrodes. It is referred as T_{on} and represents the duration of time in micro seconds, µs. The T_{on} setting time range available on the machine tool is 1-131 (µs). The single pulse discharge energy increases with increasing T_{on} period,

resulting in higher cutting rate. With higher values of Ton, however, surface roughness tends to be higher. The higher value of discharge energy may also cause wire breakage.

2. Pulse off Time -The pulse off time is the time in between the two simultaneous sparks occurs during this part of cycle the voltage is absent. It is referred as T_{off} and represents the duration of time in micro seconds, µs. The T_{off} setting time range available on the machine tool is 00 – 63 (µs). With a lower value of T_{off}, there are more number of discharges in a given time, resulting in increase in the sparking efficiency. As a result, the cutting rate also increases. Using very low values of T_{off} period, however, may cause wire breakage which in turn reduces the cutting efficiency. As and when the discharge conditions become unstable, one can increase the T_{off} period.

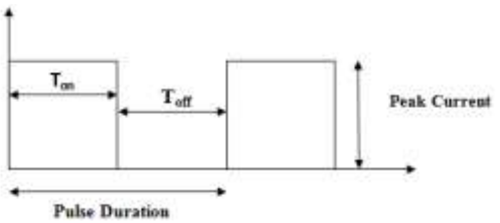

Fig. Series of Electrical Pulses at the Inter Electrode Gap

3. Peak Current -Peak current is the maximum value of the current passing through the electrodes for the given pulse and it is represented by IP. The IP setting current range available on the machine is 10–230 ampere. Increase in the IP value will increase the pulse discharge energy which in turn can improve the cutting rate further.
4. Spark Gap Voltage -The spark gap voltage is a reference voltage for the actual gap between the work piece and the wire used for cutting. It is represented by SV. The SV voltage range available on the present machine is 00 – 99 (V).

Non-Electrical parameters

1. Electrode material -Engineering materials having higher thermal conductivity, electrical conductive, melting point and cheapness are used as a tool material for Wire EDM process of machining. Copper and brass wire are used as a tool electrode in Wire EDM. They all have good wear characteristics and betters sparking condition for machining. In present work, Brass wire electrode with 0.25mm diameter has been used.
2. Wire Feed-Wire feed is the rate at which the wire-electrode travels along the wire guide path and is fed continuously for sparking. The wire feed range available on the present WEDM machine is 1–15 m/min. It is always desirable to set the wire feed to maximum. This results in less wire breakage, better machining stability and slightly more cutting speed.
3. Wire Tension -Wire tension determines how much the wire is to be stretched between upper and lower wire guides. This is a gram-equivalent load with which the continuously fed wire is kept under tension so that it remains straight between the wire guides. More the thickness of job more is the tension required. Improper setting of tension may result in the job inaccuracies as well as wire breakage. The wire tension range available on the machine is 1-15 (g).
4. Flushing Pressure -Flushing Pressure is for selection of flushing input pressure of the dielectric. The flushing pressure range on this machine is either 1 (High) or 0 (low). High input pressure of water dielectric is necessary for cutting with higher values of pulse power and also while cutting the work piece of more thickness. Low input pressure is used for thin work piece and in trim cuts.
5. Servo Feed -Servo feed setting decides the servo speed; the servo speed, at the set value of SF, can vary in proportion with the gap voltage (normal feed mode) or can be held constant while machining (with constant feed mode).

IV. TAGUCHI BASED GREY RELATIONAL ANALYSIS (TGRA)

In the present experimental study, the effects of process parameters on performance measures have been determined using Taguchi based Grey Relational Analysis (TGRA).

4.4.1 Taguchi's method

The Taguchi method, a powerful tool in quality optimization for manufacturing processes, transfers results into S/N ratio to evaluate the performance characteristics for each level. It has been inferred from the published work that Taguchi method concentrates on the optimization of single performance measure. The traditional Taguchi approach cannot be able to solve multi-objective optimization problem.

4.4.2 Grey Relational analysis (GRA)

Grey relational analysis is a normalization-based evaluation technique requiring a sample of only limited size, of discrete sequential data to enable reliable modeling and estimation of system behavior. Multiple performance objectives are in

high demand the industrial field, and the analysis is complicated due to demand for the large measured value. Since, the original Taguchi method is only possible to optimize single performance objective.
To overcome this, the Taguchi method coupled with grey relational analysis is used. This approach can solve multi-response optimization problem simultaneously. The Taguchi Based Grey Relational Analysis (TGRA) will be utilized in the present work to facilitate in multi-objective optimization. With the help of grey relational analysis, the experimental results will be normalized in the range of zero to one. Further, based on normalized experimental data, grey relational coefficient is calculated to represent the relational ship between the desired and actual experiment data.

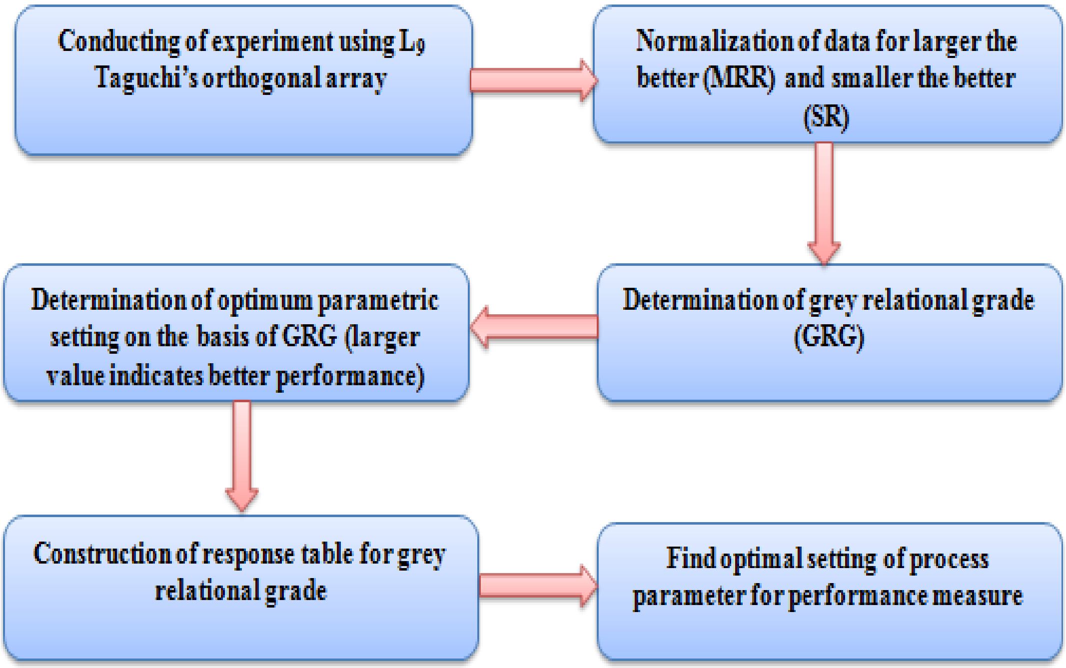

Fig. Flow chart to find optimal setting of process parameter

Run order	Factors			
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table 2: Standard layout of Taguchi's L_9 (3^4) orthogonal array

V. EXPERIMENTATION

The experimental aspects of present study. The objective of the experimentation is to optimize the process parameters in wire electrical discharge machining (WEDM) during machining of super alloy INCONEL 601. A L9 (3^4) orthogonal array was employed to study the effect of peak current (I_p), Pulse on time (T_{on}), Wire tension (WT) and feed rate (WFR). The performance measures considered are Material removal rate (mm^3/min) and Surface roughness (µs).

Composition of work material
Work material Inconel 600, which is basically alloy of nickel-chromium and molybdenum is presented and the composition of the same is presented in the Table

Table 3: Composition of work material

Ni %	Cr %	Fe %	Mn %	Cu %	Si %	C %	S %
72	14	7	1	0.50	0.50	0.15	0.01

Tool material
A thin wire is used as tool electrode in wire electrical discharge machining (WEDM). The wire electrode is required to have a sufficient tensile strength and should be of uniform diameter and free from kink or twist.

Table 4: Composition of Brass Wire

Component	Wt.%
C	65-68
Zn	33.4
Pb	2.3-3.4
Fe	Max 0.36
Other	Max 0.6

Table 5: Mechanical properties of Brass Wire

Mechanical properties	Metric
Ultimate Tensile Strength	334-462 MPa
Tensile strength, Yield	122-308 MPa
Elongation at Break	52%
Modulus of Elasticity	94 GPa
Bulk Modulus	130 GPa
Poisson's Ratio	0.21
Machinability	100%
Shear Modulus	36 GPa

Table 6: Specification of WEDM machine used in the present study

Electronica Machine Tools Ltd, Pune	
Model	Elektra sprincut 734
Design	Fixed column, moving table
Table size	440 X 650
Max. work piece height	200 mm
Max. work piece weight	500 Kg
Main table traverse (x, y)	300, 400 mm
Auxiliary table traverse (U, v)	80, 80 mm
Wire electrode diameter	0.25 mm(standard)
Dielectric fluid	Deionized Water
Generator	ELPULS-40 A DLX
Interpolation	Linear & Circular
Least input increment	0.0001 mm
Least command input (X,Y,U,V)	0.0005 mm
Input power supply	3 Phase, AC 415 V, 50 HZ
Connected load	10 KVA
Average power consumption	6-7 KVA

Process parameters

In the present research work on the basis of literature review peak current (I_p), Pulse on time (T_{on}), Wire tension (WT) and feed rate (WFR) have been considered as process parameters. Thus, each process parameters were assigned three levels based the preliminary experiment conducted.

The process parameters along with their levels, considered for the present study is given in Table and constant parameters given in Table.

Table 7: Process parameters considered and their level

Factor	Name	Symbol	Unit	Levels		
A	Peak current	I_p	A	55	100	135
B	Pulse on time	T_{on}	µs	105	117	127
C	Wire tension	WT	N	7	8	9
D	Wire feed rate	WF	m/min	5	7	10

Table 8: Parameters kept constant during experiments

Parameters	Symbol	Unit	Value
Pulse off time	T_{off}	µs	51
Dielectric fluid pressure	WP	kgf/cm^2	14
Spark gap voltage	SV	V	43
Servo feed	SF	mm/min	2200
Cutting Tool	Brass wire of diameter 0.24 mm		
Work piece height	7 mm		

VI. EXPERIMENTAL DESIGN

In the present research work, L_9 orthogonal array has been chosen for the purpose of investigation. The number of treatment condition is equal to the number of row in orthogonal array and must be equal to or greater than the degree of freedom of different parameters considered. As per Taguchi experimental design philosophy a set of three levels assigned to each process parameter has two degree of freedom (DOE). This gives a total of 8 degree of freedom for four process parameters namely peak current, pulse-on time, wire tension and wire feed rate selected in present study. The total degree of freedom for the four factors is 8. So, the array selected fulfils the criterion for selection of array. Experimental layout of L_9 (3^4) orthogonal array used in present work is shown in Table.

Table 9: Experimental lay out using L9 (3^4) orthogonal array

Run	Peak Current I_p(A)	Pulse-ON time T_{on} (µs)	Wire Tension WT (N)	Wire feed rate WFR (m/min)
1	70	118	18	16
2	70	128	19	18
3	70	128	20	20
4	110	118	19	20
5	110	128	20	16
6	110	138	18	18
7	150	118	20	18
8	150	128	18	20
9	150	138	19	16

Table 10: Experimental results of present work

Run	Peak Current Ip(A)	Pulse-ON time Ton (µs)	Wire Tension WT (g)	Wire feed rate, WFR (m/min)	Performance Measures					
					MRR (mm^3/min)	MRR (mm^3/min)	Average (mm^3/min)	SR (µs)	SR (µs)	Average (µs)
1	70	118	18	16	138.4	140.8	139.6	0.89	0.91	0.90
2	70	128	19	18	229.6	233.2	231.4	1.44	1.58	1.51
3	70	138	20	20	236.8	239.2	238	1.60	1.64	1.60
4	110	118	19	20	145.6	148	146.8	0.99	1.01	1.00
5	110	128	20	16	290.8	293.2	292	1.68	1.72	1.70
6	110	138	18	18	355.6	358	356.8	1.77	1.79	1.78
7	150	118	20	18	158.8	160.6	159.7	1.21	1.26	1.22
8	150	128	18	20	296.8	298	297.4	2.02	2.16	2.09
9	150	138	19	16	397.6	401.2	399.4	2.76	2.69	2.72

VII. RESULT AND DISCUSSIONS

This chapter contains the analysis of the result obtained from the present work. The effect of various process parameters during wire electrical discharge machining of Inconel 600 with Brass tool electrode will be studied. The experimental data has been collected from the experiments, and will be optimized with Taguchi based grey relational analysis (TGRA) using MATLAB software and MINI TAB software.

Table 11: Normalization of the experimental result for performance measures: MRR, SR

Exp. run	Data normalizing			
	MRR (mm^3/min)		SR (µs)	
Ideal value	1	2	1	2
1	2.0000	2.0000	0.5737	0.5737
2	0.818	0.8172	0.6745	0.6739
3	0.8033	0.8043	0.6976	0.6968
4	1.0701	1.0702	0.4880	0.5852
5	0.7049	0.6060	0.7016	0.7008
6	0.6178	0.6190	0.7205	0.7153
7	1.0196	1.0113	0.6192	0.6205
8	0.6956	0.6985	0.7796	0.8048
9	0.5737	0.5737	1.1000	1.2000

Table 12: GRG for each experimental run

Exp run	GRG	Order
1	0.8368	1
2	0.7457	7
3	0.7503	5
4	0.8279	3
5	0.7036	8
6	0.6667	9
7	0.8166	4
8	0.7462	6
9	0.8350	2

Table 13: Response Table for Grey Relational Grade

Levels	Ip (A)	Ton (µs)	WT (N)	WF (m/min)
1	0.7776	0.8271	0.7636	0.7499
2	0.7327	0.7318	0.7418	0.8035
3	0.8000	0.7513	0.7195	0.7568
Delta	0.1673	0.1953	0.1441	0.1536
Rank	2	1	4	3

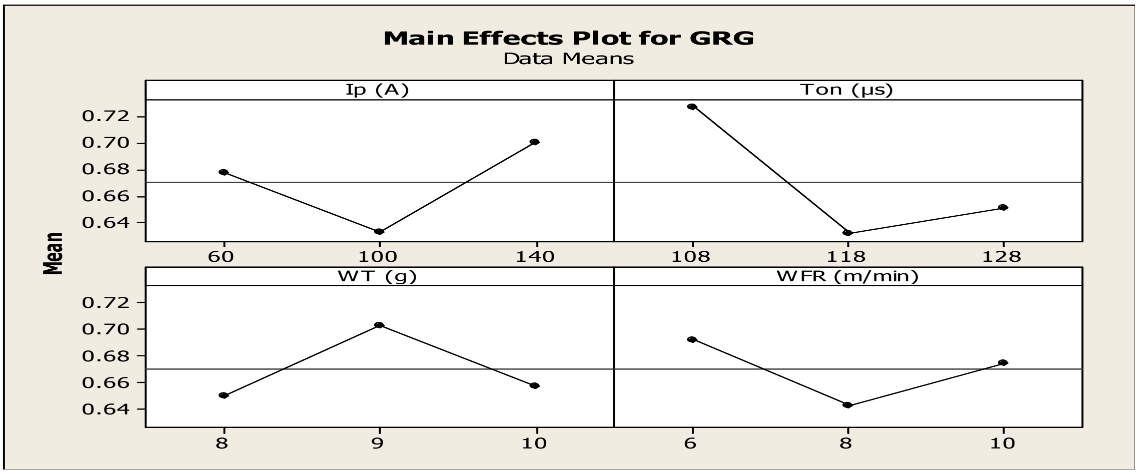

Fig. Main effect plot for GRG

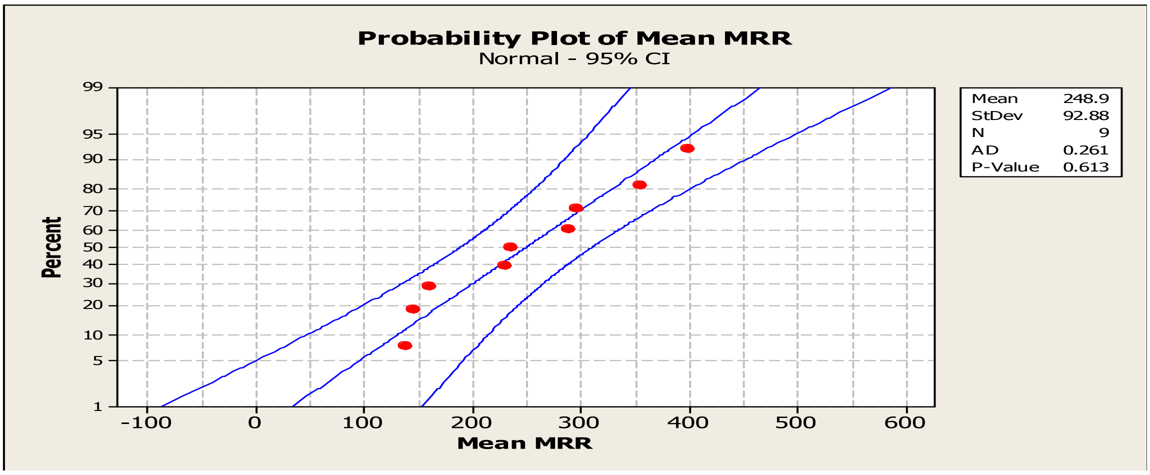

Fig. Probability plot of MRR

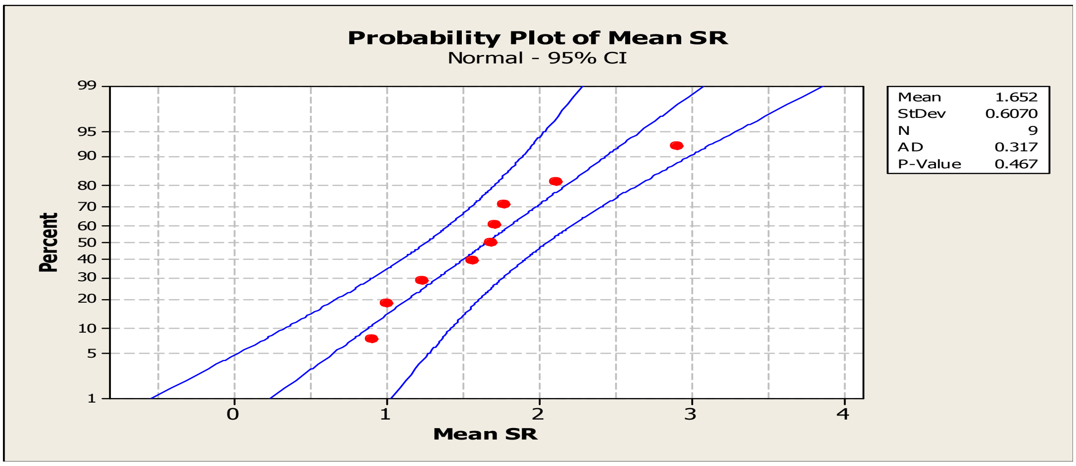

Fig. Probability plot of SR

VIII. CONCLUSION

In the experimental work, attempts to determine the optimal parametric setting for response characteristics namely material removal rate and surface roughness. In addition, to optimize for all the two responses, the Taguchi Based Grey Relational Analysis (TGRA) adopted to optimize the complicated inter-relationship among multi-performance characteristics. It is observed that the TGRA greatly simplifies the multi-optimization, and moreover do not require any complex mathematical objective computations. The various conclusions which have been observed from result and discussions are given below:

1. The greatest GRG value provide optimal parametric setting are peak current (Level 3), pulse on time (Level 1), wire feed rate (Level 1), wire tension (Level 2) which mean that the optimal process parameters, 140 A peak current, 108 µs pulse on time, 9 g wire tension, 6 m/min wire feed rate.
2. The response table for grey relational grade makes ranks which decides the most effective parameters namely pulse on time (rank 1), peak current (rank 2), wire feed rate (rank 3), wire tension (rank 4).
3. The pulse on time has the strongest effect among the other process parameters used to study the multi-performance characteristics, followed by peak current, wire feed rate and wire tension.
4. When pulse on time and peak current increases, higher MRR were achieved due to the larger discharge energy.
5. It is seen that cutting rate almost remains constant with increase in the wire tension. Though, with increase in wire tension, the machining stability increases as vibrations get restricted. It is absented that the increment in wire tension does not have much influence on cutting rate.

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