CHAPTER-2

Experimental Details and Methodology

2.1. Introduction

This chapter contains the experimental detail followed in the present investigation. Under this section material selection, experimental set-up and characterization of EDMed samples have been discussed.

2.2. Selection Criteria for Material

Each of the EDM experiments was performed with die steel (High Carbon High Chromium) as the workpiece material. The die steel is selected because of its vast material grains composition. Also, the carbon content is high carbon (1.77%) which stand for the different behaviour of several carbon and alloy steel. Owing to its wide application in the area of electro-discharge machining, the die steel is commonly used in the die manufacturing industries. It is also appropriate for components with more hardness as well as wear resistance. Rectangular die steel ($10x10x75mm^3$) of dimensions were selected as workpiece material. This die steel is chosen in the manufacturing of punches and dies. Shear blades, cold rolls, gauses as well as plastic mold (Merdan & Arnell, 1991). The composition of die steel is listed in Table 2.1.

Table 2.1. Chemical composition of die steel

Chemical element	**Fe**	**C**	**Cr**	**Mn**	**P**	**Si**	**S**	**Mo**	**Ni**
%	Balance	1.77	12.8	0.41	0.02	0.50	0.04	0.11	0.12

The tool electrode materials must be good electrically conductive, high melting point, easily machinable and low wear rate, low cost and easily available. It is difficult to observe all the properties in any one of the electrodes for the specific appliance (Jameson, 2001). In this present experiment, the electrodes used were

70mm long with the cross-sectional area of 10mm ×10mm. There are three electrodes used for machining purpose namely copper, copper tungsten and graphite. Graphite shows good machinability, low wear rate, and high conductivity. On the other hand, copper reveals high stable and relatively low wear rate. Copper tungsten shows low wear rate, expensive and cannot be easily shaped (Jain, 2009).

2.3. Experimental Set-up and Conditions

EDM is used to determine measure material removal rate, tool wear and relative wear ratio. An advanced Z-NC EDM type (Model: electronica Z-NC EDM, India) was used for machining and performance analysis. All the machining performance are discussed below. The samples were prepared with belt grinding to get a flat surface. Further, Rectangular die steel samples (10x10x75mm^3) were machined by three different tool materials namely; Cu, Cu-w and graphite (cross section 10 x10 mm^2) under both polarity conditions (straight and reverse polarity) using die-sinking EDM mode. To analyze the material removal of the die steel, the process parameters namely pulse current (4A,6A.9A), gap voltage (30V,39V,50V) and pulse on time (200 µs,400µs,750µs) were varied for the machining. The material removal rate is calculated weighing the samples using a precise electronic digital balance (least count 0.0001g) before and after the EDM machining. This observation along with measurement determines the material removal rate at every recommended machining time throughout the EDM experiments. Table 2.2 narrates the properties of all tools.

Table 2.2. Important properties of tools

Tool Material	Thermal Conductivity (W/m-°K)	Melting Point (°C)	Electrical Resistivity (ohm-cm)	Specific Heat Capacity (J/g-°C)
Graphite	400	3675	14	0.720
Copper	391	1084	1.69	0.385
Copper tungsten	139	3500	5.5	0.214

Simultaneously, the tool wear was also evaluated. The tool wear process is similar to the material removal method as both specimen and tool are used as electrodes in EDM. Tool wear is obtained from the bombardment of either electron or positive-ion: a positive electrode, the tool wear produced due to the bombardment of electrons. On the other hand, at the negative electrode, the tool wear is generated due to the bombardment of positive ions. As negative or positive ions collide into the electrode surface, heat is liberated. The heat vaporizes the tool, and every spark erodes lower quantity of tool. This erosion of tool is known as tool wear. For each trial, to calculate tool wear ratio, the weight measurement of the tool was taken using the same balance for both non-machined and machined sample. Simultaneously, machining time was recorded for each experiment. The tool wear ratio is calculated using Eq.2.1

$$TWR(mm^3/\min) = \frac{W_{tb} - W_{ta}}{t} \qquad (2.1)$$

where, W_{tb} and W_{ta} represents for weights of tool previous to and later than machining. t is machining time.

Electrode wear ratio (EWR) - It is calculated by weight loss method considering both electrodes. It is the fraction of electrode wear volume (EWV) to workpiece removal volume (refer Eq.2.2)

$$EWR = \frac{EWV}{WRV} \qquad (2.2)$$

Polarity- The polarity of both workpiece and tool decides transfer of both positive ions and electrons. Therefore, various researcher expresses workpiece and tool as straight and reverse polarity (Jameson, 2001). In this current investigation, two polarities for the experiment were selected for a study. As per the polarity, the effect of change machinability indices in EDM namely MRR, TW, relative wear rate as well as on surface integrity parameter like surface roughness, change in microhardness, residual stress, etc. were analyzed. The EDM process parameters namely pulse current (I_p), gap voltage (V_g), pulse duration (T_{on}) as well as energy generated were described following section.

2.4 . EDM of die steel

EDM tests were undertaken on D2 die steel. All the workpieces were having the similar rectangular shape (10X15X75 mm^3). Simultaneously, all the electrodes namely copper, graphite, copper -tungsten used for the experiment were having the square shape (10X10 mm^2). Table 2.3 lists all the experimental conditions used in this EDM operation.

In this experimental study, the machining time for each cut is 20 min. This machining time is selected because of two reasons. First one is that from literature study, it was observed that for a significant amount of material removal and good surface integrity, the machining time was more than 15 minute and closer to 20 minutes. The second reason was the hardness of the die steel. Because die steel is harder material and EDM process is also time taking process. Therefore, the minimum period is required for material removal which would help to study MRR and surface integrity. After the pilot test, the range of input parameters (pulse current, pulse on time and voltage) were decided as per one factor at a time approach in which the effect of the individual parameter was studied keeping another parameter at a fixed level or middle level. Therefore to find out the setup input parameters that have maximum MRR and minimum surface roughness within the range we performed the experimentation by using DOE techniques.

In this experiment, we have full factorial design as 3^3 or 27 experiments. To reduce the number of experiment fractional factorial design is used. But fractional factorial design uses two methods. One is the Taguchi method, and other is RSM. In Taguchi method L9, L18 or L27 orthogonal array was used for experiments. But optimization of the process parameters is not possible using the Taguchi method. Therefore, to obtain the optimization of process parameters again, Grey relation was used. Also, there were a significant limitation of using the Taguchi method. In this method, it is difficult to maintain the interaction effect among the process parameters. To overcome this limitation, response surface methodology RSM was preferred. There are two types of response surface methodology were used for an experiments such as Box-Benhken Design (BBD) and Central Composite Design (CCD) method. In this experimental work, the central composite design method is used for experimentations.

All experiments were conducted on Electronica ZNC-EDM using statistical Design of Experiment (DOE). This Design of experiment is used to propose the regression models and reduce the number of experiments. Analysis of Variance (ANOVA) analysis was performed for interpretation and to verify the sufficiency of proposed models. Full factorial tests using three parameters (factors) at three levels were carried out with five central points. Eight trials comprise 2^3 factorial design along with five times repeated central point were considered. These additional centre points are applied to assess the experimental error, which used as a yardstick to verify whether measured differences in the data are statistically significant or otherwise. Table 2.3 shows the levels of EDM parameters. In this experimental study, the machining time for each cut 20 min.

Table 2.3. Experimental Condition for EDM of die steel

EDM Machine	**ZNC-Electronica**
Work piece	die steel (HCHCr)
Tool material	Copper, Graphite, Copper tungsten
Machining Time (min)	20 min for each cut.
Pulse Current (Amp)	4,6,9
Gap voltage (V)	30,39,50
Pulse duration (μs)	200,400,750
Die electric fluid	EDM Oil (grade EDM 40)

A quadratic mathematical model has been discussed to represent the process behaviour of EDM operation. Experiment has been carried out using three input process parameters namely pulse current, V and Ton. The data have been related to process responses namely MRR, TW, SR, residual stress, microhardness, the peak of Barkhausen Noise and arms of Barkhausen Noise.

Therefore the mathematical model developed which was used to investigate and optimize the process parameters producing optimum values of machining response which was described in Eq.2.3.

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^{\,2} + \sum_{i\langle 1} \beta_{ij} x_i x_j + \varepsilon \qquad (2.3)$$

Where

x_i, x_j are input process parameters.

$\beta_0, \beta_{ii}, \beta_{ij}$ are unknown parameters or regression coefficient.

E is random error

In this experiment I_p, V_g and T_{on} are input variables

Table 2.4 shows the Design of Experiment used for present work. And, Table 2.5 illustrates the design matrix combining of thirteen trials. The run order (rank) was arbitrarily performed to decrease the influence of unrelated variables.

Table 2.4. Level of Independent Variable in EDM

Parameters	Unit	Low	Centre	High
Coding		-1	0	+1
Pulse Current (I_p)	amp.	4	6	9
Gap Voltage (V_g)	V	30	39	50
Pulse duration (T_{on})	μs	200	400	750

This method allows developing the second order empirical models associating with machinability indices in the machining process with the all EDM process parameters by regression analysis. It is expressed in equation 2.3. As per full factorial design with five central points, a total of thirteen experiments need to be performed as illustrated in Table 2.5.

Table 2.5. Experimental Condition in EDM

Sr. No.	Run order	I_p (Amp.)	V_g (Voltage)	T_{on} (μs)	Coding		
					X_1	X_2	X_3
1	II	9	50	750	1	1	1
2	VIII	9	30	750	1	-1	1
3	IV	4	50	750	-1	1	1
4	VI	4	30	750	-1	-1	1
5	I	9	50	200	1	1	-1
6	VII	9	30	200	1	-1	-1
7	III	4	50	200	-1	1	-1
8	V	4	30	200	-1	-1	-1
9	IX	6	39	400	0	0	0
10	X	6	39	400	0	0	0
11	XI	6	39	400	0	0	0
12	XII	6	39	400	0	0	0
13	XIII	6	39	400	0	0	0

2.5. Characterization of EDMed samples

2.5.1. Surface roughness Measurement

The surface roughness of the EDMed surface was drawn by a 2-D profilometer (Model: Mitutoyo SJ-410) moving the diamond stylus over the machined surface in the transverse (refer Figure). Taly profile version 3.1.9 software uses the data for analysis of SR. Figure 2.1 illustrates the original EDMed surface profile including, both roughness and waviness profile traced by a profilometer.

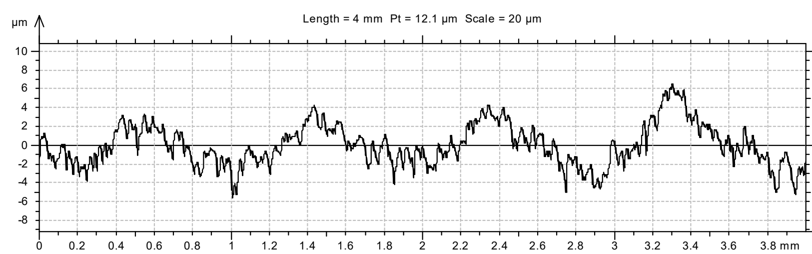

Figure 2.1. Original EDM Surface Profile

Figure 2.2 shows waviness profile of machined sample. Figure 2.3. shows surface roughness profile which has been subtracted from the original profile.

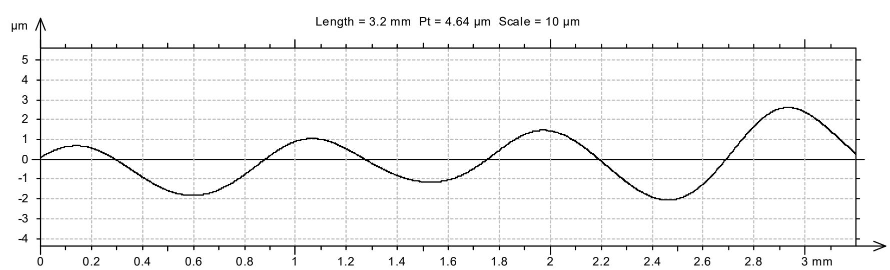

Figure 2.2. Waviness Profile

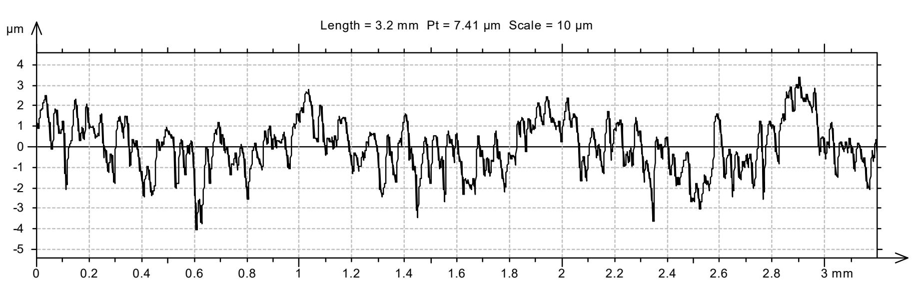

Figure 2.3. Surface roughness Profile

Tally profile version 3.1.9 software along with Gaussian filter is used to study surface roughness (Ra) value profile. All the measurements were carried out in the neighbourhood from the middle-point of the machined surface, where maximum steady EDM conditions were obtained. In this research work, the analysis of surface roughness is emphasized on the universally recognized ISO 4287:1977 Standard, and on crucial calculated factor is arithmetic average of absolute (Ra) and measured from the centre line.

2.5.2. Microhardness analysis

Microhardness (HV) of the surface of the EDMed sample was measured using the recommended microhardness tester, (Micro Combi Tester, Switzerland). During this test, 50 gm load is applied for 10 second dwell time on the machined surface using indenter initiating from 25 µm distance from the edge. Microhardness was taken at an altered distance beneath the upper surface by an increase of 50µm for every measurement. At three places, below the edge with equal distance, three microhardness calculations were taken. The resultant of microhardness was calculated by taking the average of all three measurements. The distance between the indent is also maintained to overcome the interference. The loss of material near to the surface is one of the major problems. This limitation is 2.5 times the indentation diagonal as recommended by ASTM E 92 standard.

2.5.3 Metallographic analysis

All the EDMed specimens were segmented perpendicular to the machined surface and along the machining direction for practiced for metallographic study. Furthermore, these samples were afterward cold molded in a sample mount press (MNNIT-Allahabad, India) by phenolic resin powder (a mixture of Powder and liquid). To ensure the edge retention, two pieces of each sample were fixed together face to face with epoxy adhesive. These sectioned samples were cleaned using various emery papers with the consecutively fine grit of mesh of 220, 400, 600, 800, 1000,1200. The cloth along with Al_2O_3 paste is used for polishing and at last diamond polished on auto-disc/manual polishing machine to found a reflected like surface, washed with lab detergent, and then etching for about 15 seconds using 2% initial solution. The specimens were instantly washed using running water and dried with hot air for investigations surface profile of the EDMed surface using a metallurgical optical microscope (Axio Imager.Z2m, German). Figure 2.4 & 2.5 illustrates sectional metallographic of EDMed sample. The depth profile of the microhardness in EDMed sample is shown in Figure 2.4.

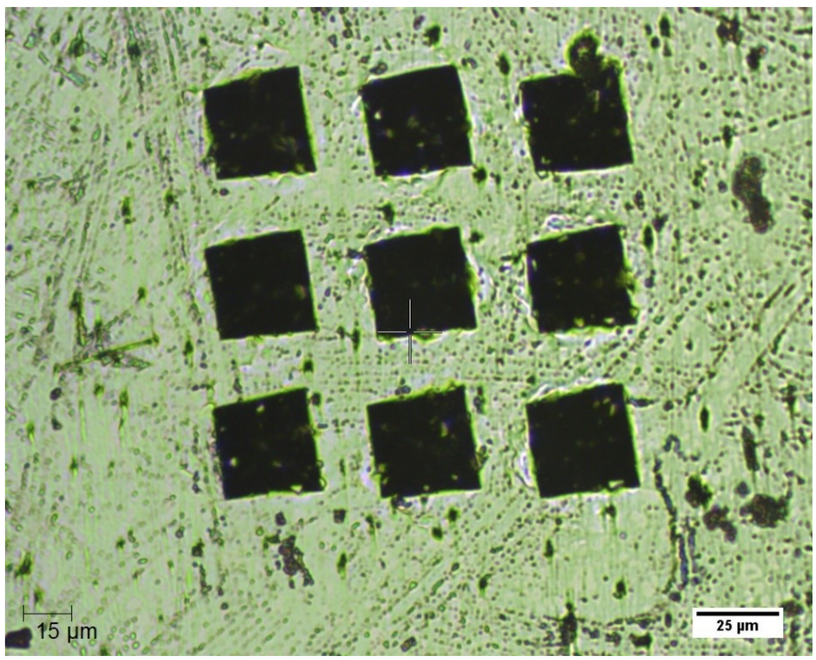

Figure 2.4. Depth profile of the microhardness measured in EDMed Sample (Material: die steel, Electrode: graphite, Polarity: straight, 6A/39V/400µs)

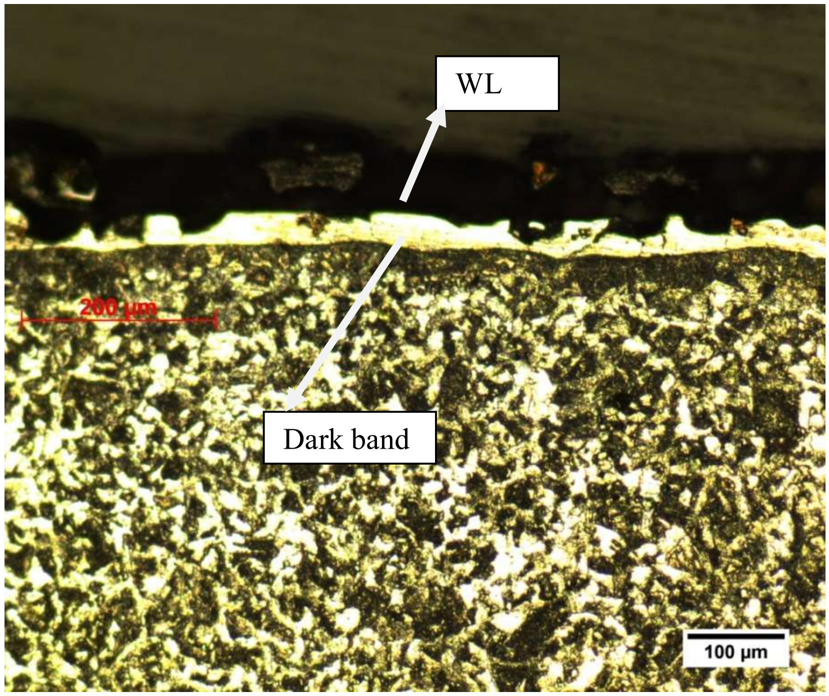

Figure 2.5. Optical micrograph of recast layer of machined sample obtained by standard EDM (Material: die steel, Electrode: Cu, Polarity: reverse, 4A/50V/750µs)

2.5.4 X-ray diffraction

2.5.4.1 Residual Stress Measurement

Residual stresses in the machined workpiece were calculated by XRD technique using Brucker diffractometer with a certain range of tilted angles from −45° to +45°. The residual stress is uniaxial in magnitudes. Data Collector software with 2θ values is used to gather scan parameters selected to include the Fe-Kα doublet for {211} planes: $110 \leq 2\theta \leq 113$. Also, Philips X'pert stress software is used to examine the resulting spectra. Pearson VII method was utilized to determine the peak position on the diffracted intensity plots, after stripping of the Kα2 signal.

Further, a suitable X-ray elastic constant (XEC) is selected from the XEC database to study the stress parameters. The traditional sin2Ψ method was used to attain total.

$$\sigma = \frac{E}{(1+\nu)\sin^2\Psi}\frac{\cot\theta}{2}\{\Delta 2\theta\} \qquad (2.4)$$

where σ = stress to be measured

E = Young's modulus of crystallographic plane, *ν* = Poisson ratio of the material, *θ* = peak position, *Δ2θ* = change in peak position. Figure 2.6 presents the resultant graph between 2*θ* and $\sin^2\Psi$. The slope of the straight line fitted to the 2*θ* against $\sin^2\Psi$ determines the stress value.

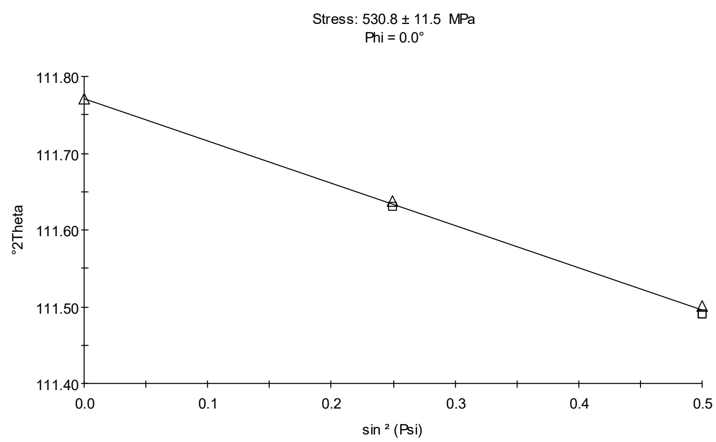

Figure 2.6. Stress value between 2*θ* and $\sin^2\Psi$

Table 2.6: Parameters for XRD residual stress measurement

Radiation	Co-Kα
Current	20 mA
Voltage	40 kv
Step size	0.05
Number of steps	60
Number of scan	5

2.5.4.2. Barkhausen Noise Analysis

The Barkhausen Noise measurements were conducted with the industrial obtainable μ scan/Rollscan-300 system manufactured by Stresstech, Finland. A plane surface probe associated with Barkhausen Noise signal pick-up coil winded at the midpoint was executed to implement the magnetic field and to accept the Barkhausen Noise signal as Barkhausen Noise signal is the surface dependent phenomenon. Therefore, the Machined workpiece was washed before Barkhausen Noise measurement by isopropyl alcohol. The middle region of the magnetized EDMed workpiece was considered a position for both Barkhausen Noise and XRD measurement. For every trial, three explanations were measured and investigated by μ-scan software to record the rms and the peak value of Barkhausen Noise signal. Average value of investigated Barkhausen Noise parameters (the entire unit is random manner) was taken for study. Magnetizing voltage and magnetizing frequency are selected by carrying out preliminary trials. The supplied magnetizing voltage and frequency should give adequate Barkhausen Noise signal. This sufficient value of both voltage and frequency should not disturb the magnetizing signal because of magnetic coupling between the magnetizing coil and magnetized sample. This disturbance of the magnetizing signal may spoil the sensor. It might be highlighted that the magnetizing frequency magnetizing voltage was not changed throughout the experimental domain. The Barkhausen Noise signal has flowed through a band-pass filter. The frequency of the band pass filter was regulated for the highest sensitivity at close to surface deepness where the most spoil was predicted.

Figure 2.7.Barkhausen Noise analyzer with sensor

Table 2.7.Parameters used in Barkhausen Noise Analysis

Magnetizing voltage	4 volts
Magnetizing frequency	100 Hz
Filter	70–200 kHz
No. of burst	4

2.5.5. EDM of die steel using L9 orthogonal array

To optimize the performance characteristics, The experiment was planned according to Taguchi's L9 orthogonal array. The basis on these variables and levels as registered in Table 2.8, an orthogonal array (L9) combination of nine trials have been carried out using both the polarity of the electrode on EDM.

Table 2.8. Level of Independent Variable in EDM

Parameters	**Unit**	**Low**	**Centre**	**High**
Coding		-1	0	+1
Peak Current (I_p)	Amp.	4	6	9
Gap Voltage (V_g)	V	30	39	50
Pulse duration(T_{on})	μs	200	400	750
Duty Cycle (τ)	-	4	7	9

Table 2.9. Layout of L9 orthogonal array for experimentation

Sr. No.	I_p	V_g	T_{on}	τ
1	-1	-1	-1	-1
2	0	0	-1	0
3	+1	+1	-1	+1
4	+1	0	0	-1
5	-1	+1	0	0
6	0	-1	0	+1
7	0	+1	+1	0
8	+1	-1	+1	0
9	-1	0	+1	+1

Table 2.10. Experimental Condition in EDM

Sr. No.	**I_p**	**V_g**	**T_{on}**	**τ**	**Coding**			
	(A)	**(V)**	**(μs)**		X_1	X_2	X_3	X_4
1	4	30	200	4	-1	-1	-1	-1
2	6	39	200	7	0	0	-1	0
3	9	50	200	9	+1	+1	-1	+1
4	9	39	400	4	+1	0	0	-1
5	4	50	400	7	-1	+1	0	0
6	6	30	400	9	0	-1	0	+1
7	6	50	750	7	0	+1	+1	0
8	9	30	750	7	+1	-1	+1	0
9	4	39	750	9	-1	0	+1	+1