Management Systems
in
Production Engineering

2025, Volume 33, Issue 2, pp. 251-257

Date of submission of the article to the Editor: 06/2024
Date of acceptance of the article by the Editor: 04/2025

DOI 10.2478/mspe-2025-0024

EFFECT OF NANO POWDERS (SiO_2 – GRAPHITE) DIELECTRIC MIXTURE ON SURFACE INTEGRITY IN MACHINING OF STAINLESS STEEL 304L

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Abstract:
One of the applications of electrical discharge machining nowadays, mainly nano powder mix electrical discharge machining, is to produce high-quality surface integrity materials. To achieve good results, change the input process settings as needed. The current study investigates the effect of discharge current, pulse on time (P_{on}), pulse off time (P_{off}), powder concentration, and mixing ratio of SiO_2 – graphite nano powder on SR – surface roughness, EWR – electrode wear rate, and MRR – material removal rate during electrical discharge machining (EDM) of 304L stainless steel. A cylindrical copper electrode with a diameter of 16 mm and a length of 40 mm was used as a tool electrode in this novel machining method. The experiment used a MINITAB 18 half-factorial design with five components and five levels. A total of 24 tests (12 for conventional EDM and 12 for NPMEDM) were performed using various combinations of input elements. The findings revealed that adding silicon dioxide-graphite nanoparticles to an EDM kerosene dielectric significantly boosted the MRR while decreasing the EWR and SR. This study looks into modifying dielectrics with SiO_2 – graphite nano powder to improve machining performance. The performance of this newly invented nano powder-mixed electrical discharge machining (NPMEDM) technology is compared to traditional EDM. The average MRR increases from 0.1263 to 0.1324 g/min, EWR decreases from 0.0066 to 0.0052 g/min, and SR climbs from 5.381 to 5.063 µm.

Key words: electrical discharge machining, graphite nano powder, SiO_2, nano powder, stainless steel 304L

INTRODUCTION

The current study focuses on one of the most challenging materials, stainless steel 304L. If this material is machined using traditional procedures, the tool may be damaged, and the workpiece may suffer internal stress. Electrical discharge machining (EDM) is used to mill the stainless steel 304L to address this issue. This study aims to achieve a greater material removal rate, lower surface roughness, and electrode wear rate by improving input process parameters. In this experiment, a copper wire electrode was used. According to the experimental results, adding graphite nano powder in dielectric increases the surface roughness of the machined surface. MRR has dramatically improved; however, EWR has declined.

LITERATURE REVIEW

Electricity had a more significant impact in increasing the MRR while decreasing the EWR and SR. This study looks into the possibilities of dielectric. Effectively utilizing various unconventional machining techniques' capabilities necessitates carefully selecting the optimal strategy for a given application [1, 2]. One of the most prevalent unique machining technologies is EDM (electrical discharge machining). This approach has effectively superseded older methods of cutting hard materials. Previously, the EDM method was limited to milling electrically conductive materials, but with technical developments, ceramics and composites may now be machined [3]. It generates complex shapes, uneven proportions, intricate designs, and microscopic openings [4]. MRR (material removal rate), EWR (electrode wear rate), SR (surface roughness), and other machining reactions are used to evaluate EDM performance [5, 6]. EDM is employed in various industries, including gear manufacturing, mold and die fabrication, aerospace, automotive, biotechnology, sports, electronics, medical, jewelry, and toys [7, 8, 9, 10, 11] – modification by adding SiO_2 – graphite nano powder to improve performance.
Several scholars [12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24] investigated the effect of adding powder to the dielectric fluid on the effectiveness of the EDM process. It is referred to as PMEDM (powder mix electrical discharge machining). Powders such as aluminum [12, 13], graphite

[14, 15], silicon [16, 17], silicon carbide [18, 19], tungsten [20, 21], chromium [22], titanium [23, 24], and others have been tested. These studies found that adding powder to the EDM dielectric improves machining effectiveness, surface finish, and material removal rate. The particle size might vary from micro to nano. A few research have been conducted employing CNT and nano powder mixed dielectric in EDM.

CNT and nano powders of different materials are used. Carbon nanotubes hold immense potential for use in a variety of applications. They have high electrical and thermal conductivity, strength, stiffness, and durability. MWCNTs are made up of multiple layers of graphite wrapped into tubes. This study aimed to compile disparate data on CNT and nano powder mixed dielectric fluid usage and their impact on EDM process performance.

The effect of particle size incorporated in dielectric fluid on the surface properties of the electrical discharge machined SKD-11 was examined. Aluminum, chromium, copper, and silicon carbide were additive powders. They discovered that smaller particles (70-80 nm) produce higher surface quality. It was also found that particle size had an inverse effect on the recast layer, with smaller particle sizes resulting in a thicker recast layer [25]. They investigated the impact of powder additives suspended in dielectric on crater characteristics for micro-EDM during stainless steel machining. They used Daphne Cut HL-25 dielectric fluid and SiC nano powder (45-55 nm). The passage of charges between the tool and the workpiece was minimized, resulting in a constant depth and smaller crater size. A smaller crater with a larger volume of re-solidified material was detected within the crater chamber [26], and the influence of nano powder suspended in the dielectric fluid was explored on the surface roughness of AISI 420 stainless mold steel during micro-EDM. Idemitsu Daphne Cut HL25-S dielectric fluid and silicon carbide and aluminum oxide particles were used. The tool electrode was composed of tungsten. Surface roughness was minimized using SiC and Al_2O_3 microparticles [27].

The surface characteristics of AISI D2 tool steel were examined using the EDM method. Machining was carried out with a copper electrode and single-walled carbon nanotubes (SWCNT) mixed in kerosene dielectric. It was revealed that workpieces machined with SWCNT-added dielectric had a higher surface quality and fewer microcracks. Setting the machine parameters to low pulse energy produced an outstanding machined nano finish [28]. They looked into how adding graphite nano powder to the dielectric improved surface characteristics in cemented tungsten carbide micro-EDMs. A tungsten tool and an oil dielectric called "Total FINA ELF EDM3" were employed. Surface quality and MRR improved, whereas TWR decreased. The more significant spark gap enhanced surface topography and crater distribution [29].

Nano graphite powder floating in kerosene dielectric was investigated during micro-EDM of silver-tungsten workpieces. The tool's substance was tungsten, and its particle size was 55 nm. They discovered improvements in both surface quality and machining timing. Because of the particle size, the suspension of nano graphite powder caused a large spark gap, resulting in a lower electric discharge power density and, consequently, a lower explosion force [30]. They examined how the size of carbon nanotubes affected the wear characteristics of a copper-based CNT composite tool during SKD11 stainless steel EDM operation. The dielectric fluid utilized was EDF-K. This study found that copper-based CNT hybrid tools had a 50-72% reduced wear ratio than electrolytic copper tools. The composite device's wear resistance was related to the size of the CNTs [31]. They investigated the influence of multi-walled carbon nanotubes combined with kerosene dielectric on EMD performance. They employed titanium alloy (Ti-6Al-4V) as the workpiece material. Combining CNT significantly improved MRR and surface quality while decreasing white layer thickness [32]. Carbon nanotubes were studied for their influence on EDM performance and surface quality in NAK80 die steel. Dielectric kerosene was mixed with CNTs. It was discovered that employing CNT improved both surface quality and EDM performance [33]. They looked at the effect of multi-walled carbon nanotubes in kerosene dielectric during AISI H13 tool steel EDM operation. Copper was used in the manufacture of tools. When MWCNTs were added, the machining process became more efficient, particularly when the machining parameters were adjusted to low pulse discharges [34].

The performance of EDM operation during Inconel 718 machining was investigated using titanium carbide nano powder added kerosene dielectric. A brass tool was used for machining. It was reported that adding nano powder boosted MRR while decreasing TWR [35] – using multi-walled carbon nanotubes (MWCNTs) in the dielectric fluid to machine Al-10% SiCp MMC during EDM. Copper was employed as a tooling material throughout the machining process. When MWCNTs were added to the dielectric fluid, MRR, and surface quality improved dramatically [36]. The effects of adding carbon nanotubes into the oil flux ELF2 dielectric during the Ti-6Al-4V EDM process were investigated. Copper was used as the tool material in this experiment. When carbon nanotubes were combined with dielectric, surface microcracks decreased. CNT particles also reduced MRR, TWR, and SR [37]. They looked into the performance of an EDM technique for milling Inconel 825 with an Al_2O_3 nano powder mixed dielectric. When nano powder was added to the deionized water dielectric fluid, MRR, and surface roughness improved significantly. Copper was used as a machining tool. They discovered that low-cost Al_2O_3 powder can be used effectively in industrial applications [38]. The impact of graphite nano powder mixed EDM oil dielectric on Inconel 718 micro-wire electrical discharge machining has been evaluated [39].

Nanofluids are made up of dielectric and nanometer-sized (1-100 nm) particles. Nanoparticles have a single characteristic: a high surface area to volume ratio, dimension-dependent physical properties, and low kinetic energy. The most intriguing aspect of Nanofluids is that a small amount of nanoparticle addition results in a tenfold improvement in heat conductivity above what is theoretically anticipated. Adding 0.3 vol.% copper nanoparticles to ethylene glycol increased its thermal conductivity by 40% [40].

Heat transfer fluids (HTFs) are employed in various industrial and municipal applications, such as air conditioning, transportation, energy supply, and electronic cooling. Water, oils, glycols, and fluorocarbons are examples of earlier HTFs with low thermal conductivities. Research and development efforts were made to improve the heat transfer properties of liquids. Solid metal materials such as silver, copper, and iron, as well as nonmetal materials such as alumina, CuO, SiC, and carbon nanotubes, have far higher thermal conductivities than previous HTFs, which combined solid particles of micron or millimeter size with base fluids or slurries. Large solid particles, on the other hand, induce surface abrasion, microchannel obstruction, pipeline corrosion, and increased pressure loss, severely limiting potential applications [41].

Surface polishing with SiC and Al_2O_3 nano powder reduced average surface roughness by 14% and 24%, respectively. There were no minute cracks on the machined surface. Inconel superalloys are nickel-based alloys utilized in high-pressure and high-temperature applications such as gas turbines, electric power generation equipment, nuclear reactors, high-temperature chemical containers, and electric power generation equipment [42].

They studied the effect of nanoparticle additions on SR. They discovered that Al_2O_3 and silicon carbide nanoparticles lowered the SR of stainless steel micro-EDM [18]. The impact of graphite nano powder on micro-EDM of SKH-51 tool steel was investigated [43].

The current study focuses on one of the most challenging materials, stainless steel 304L. If this material is machined using traditional procedures, the tool may be damaged, and the workpiece may suffer internal stress. Electrical discharge machining (EDM) is used to mill the stainless steel 304L to address this issue. This study aims to achieve a greater material removal rate, lower surface roughness, and electrode wear rate by improving input process parameters. In this experiment, a copper wire electrode was used. According to the experimental results, adding graphite nano powder in dielectric increases the surface roughness of the machined surface. MRR has dramatically improved; however, EWR has declined.

METHODOLOGY OF RESEARCH

The stainless steel 304L is used as a workpiece in this project. Nanoparticles are made from silicon dioxide (SiO_2) and graphite. Using a 1-5 g/l concentration and a mix fraction of 30-70% SiO_2 with graphite balanced to integrate with kerosene dielectric. Figure 1 shows the workpiece dimensions (25.4 mm diameter x 5 mm thickness).

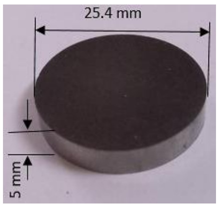

Fig. 1 Workpiece before machining (25.4 mm diameter x 5mm Thickness)

The machining properties of stainless steel 304L are investigated utilizing the electric discharge machining (EDM) process. As shown in Figure 2, the current study's tests are carried out on a numerically controlled electric discharge machine with the model number (CM 323+50N (CHAMBER EDM)).

Fig. 2 Electric discharge machine

Kerosene is utilized as a dielectric fluid. Figure 3 shows how the tests are carried out using a cylindrical copper electrode with a diameter of 16 mm and a length of 40 mm.

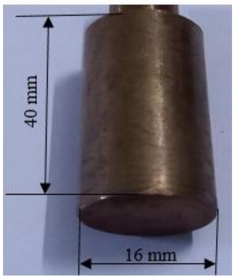

Fig. 3 Copper electrode (16 mm diameter x 40 mm length)

Table 1 contains complete measurements and thermophysical properties of the selected electrode.

Table 1
Specifications and thermophysical properties of the copper electrode

Diameter of tool (mm)	**16**
Tool length (mm)	40
Specific heat capacity (J/kg-ºC)	385
Thermal conductivity (W/m-ºC)	385
Thermal diffusivity (m^2/s)	1.11×10^{-4}
Density (Kg/m^3)	8960
Melting point (ºC)	1085
Thermal expansion coefficient at 20ºC (/ºC)	16.5×10^{-6}

Table 2 shows the chemical composition of the workpiece stainless steel 304L and the electrode characteristics and workpiece composition tested by the Ministry of Oil and Midland Refineries Company. This experiment mixed 50-nm graphite particles and 50-nm silicon dioxide with a kerosene dielectric.

Table 2
Chemical composition of stainless steel 304L

Chemical element	Cr	Ni	Mn	Cu	Si	P	Ni	C	S	Fe
% composition	18.37	8.19	1.8	0.58	0.54	0.039	0.037	0.021	0.019	Balance

Table 3 shows some of the critical and practical nano-powder specifications used in the NPMEDM process, as tested at the University of Technology/Nano Center.

Table 3
The effective physical properties of nanoparticles in NPMEDM

Nanoparticles	Density (g/cm^3)	Thermal Conductivity (W/cmK)	Electrical Resistivity (μΩ.cm)	Particle size (nm)
graphite	1.8	5	10^4	50
SiO^2	2.4	1.3	10^8-10^{12}	50

Machining experiments using the response surface methodology (RSM) are conducted using the MINITAB 18. The study's input parameters include the electric discharge current, particle concentration, pulse on/off period, and nanoparticle percentage. There are five stages of testing for each parameter. Screening experiments are performed to choose the parameter's lower and upper ranges. Table 4 contains a list of parameters and their respective ranges.

Table 4
Parameters and their levels

No.	Parameters	Levels	
		Low (-1)	High (+1)
1	Pulse off time (μs)	25	125
2	Pulse on time (μs)	50	250
3	Peak current (A)	20	40
4	Mix of powder (% SiO_2)	30	70
5	Concentration (g/l)	1	5

Response characteristics include surface roughness (SR), electrode wear rate (EWR), and material removal rate (MRR). The weight loss method is used to compute the MRR and EWR. The SR is measured using the Mahr Marsuf PS1 roughness tester, which averages three measurements from the cutting surface in different directions. Additionally, silicon dioxide nano powder is used in studies as a basis for determining particle composition percentage. The EDM machine's low voltage mode is used for all experiments.

The material removal rate (g/min) and electrode wear rate (g/min) due to machining time are computed using Equations (1) and (2), respectively.

$$MRR = \frac{InitialWeightofwork - FinalWeightofwork}{MachiningTime} \quad (1)$$

$$EWR = \frac{InitialWeightofElectrode - FinalWeightofElectrode}{MachiningTime} \quad (2)$$

RESULTS AND DISCUSSIONS

Twelve trials were carried out with identical input process settings and conditions, once for conventional EDM and then for NPMEDM for the primary three input parameters discharge current (I_p), pulse on time (P_{on}), and pulse off time (P_{off}) in addition to powder concentration and mixing ratio of SiO_2 – graphite nano powder. The results were then discussed using measured material removal rate, electrode wear rate, and surface roughness values.

Effect on MRR

Twelve tests are carried out to estimate the mean value of MRR and EWR using pure kerosene dielectric and then adding nanoparticles to kerosene dielectric. Figure 4 depicts the machined workpiece.

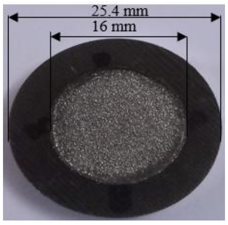

Fig. 4 Workpiece after machining

A good surface quality for hard materials such as stainless steel 304L produces a high MRR value. The mean MRR for 304L in kerosene dielectric and kerosene mixture with nanoparticles is 0.1263 g/min. In this investigation, as reported in Table 5, the values were 0.1324 g/min.

Table 5
Minitab 18 software experimental matrix for material removal rate for conventional electrical discharge machining and nano powder mixed electrical discharge machining

Run	Samples	I_p (A)	P_{on} (μs)	P_{off} (μs)	Con. (g/l)	Mix of powder SiO_2(%) graphite balance	MRR_{conv} (g/min)	MRR_p (g/min)
1	1	40	50	125	1	30	0.0500	0.0514
2	2	40	250	25	5	30	0.2221	0.2496
3	3	20	250	125	1	70	0.0760	0.0761
4	4	40	50	125	5	30	0.0490	0.0493
5	5	40	250	25	5	70	0.2160	0.2415
6	6	40	250	125	1	70	0.2013	0.2018
7	7	20	250	125	5	30	0.0733	0.0739
8	8	20	50	125	5	70	0.0220	0.0227
9	9	20	50	25	5	70	0.1450	0.1496
10	10	40	50	25	1	70	0.2421	0.2437
11	11	20	250	25	1	30	0.1246	0.1347
12	12	20	50	25	1	30	0.0936	0.0942
						Mean	**0.1263**	**0.1324**

where: I_p = Peak current, P_{off} = Pule off time, MRR_{conv} = MRR for conventional EDM, P_{on} = Pulse on time, Con. = Powder concentration, MRR_p = MRR for NPMEDM.

The results reveal that the value of MRR increases when nanoparticle (SiO_2 – graphite) concentration and SiO_2 % increase, as shown in Figure 5.

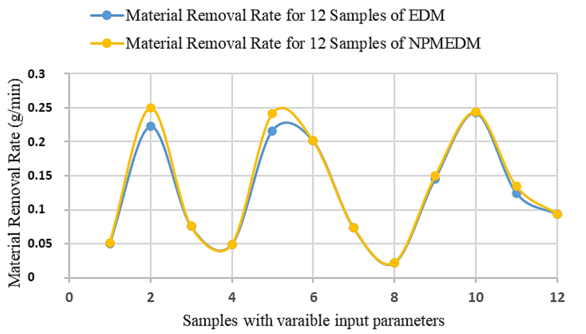

Fig. 5 The difference in the effect on material removal rate between electrical discharge machining (EDM) and nano powder mixed electrical discharge machining (NPMEDM)

Before machining, the original weight of the sample was assessed using analytical balance equipment. The measuring equipment can measure up to 300 g of weight with an accuracy of 0.0001 g.

Effect on EWR

A lower EWR value is preferable to successfully manufacturing hard materials like stainless steel 304L. The average value of EWR for 304L in kerosene dielectric and kerosene mix with nanoparticles is 0.0066 g/min. As stated in Table 6, the current experiment yielded 0.0052 g/min.

Table 6

Minitab 18 software experimental matrix for electrode wear rate for conventional electrical discharge machining and nano powder mixed electrical discharge machining

Run	Samples	I_p (A)	P_{on} (µs)	P_{off} (µs)	Con. (g/l)	Mix of powder SiO_2(%) graphite balance	EWR_{conv} (g/min)	EWR_p (g/min)
1	1	40	50	125	1	30	0.0035	0.0030
2	2	40	250	25	5	30	0.0014	0.0010
3	3	20	250	125	1	70	0.0003	0.0001
4	4	40	50	125	5	30	0.0130	0.0114
5	5	40	250	25	5	70	0.0020	0.0006
6	6	40	250	125	1	70	0.0013	0.0009
7	7	20	250	125	5	30	0.0005	0.0002
8	8	20	50	125	5	70	0.0018	0.0013
9	9	20	50	25	5	70	0.0075	0.0049
10	10	40	50	25	1	70	0.0421	0.0345
11	11	20	250	25	1	30	0.0005	0.0003
12	12	20	50	25	1	30	0.0055	0.0045
						Mean	**0.0066**	**0.0052**

where: I_p = Peak current, P_{off} = Pule off time, EWR_{conv} = EWR for conventional EDM, P_{on} = Pulse on time, Con. = Powder concentration, EWR_p = EWR for NPMEDM.

The results show that reduced EWR occurs at lower current values (20 A), higher pulse on time (250 µs), higher pulse off time (125 µs), lower powder concentrations (1 g/l), and a powder mix ratio (SiO2-graphite) of (70-30) wt%. However, as seen in Table 6, the average value of EWR is reduced.

Table 6 demonstrates that adding SiO_2 and graphite nanoparticles to kerosene dielectric reduces the EWR value, as illustrated in Figure 6.

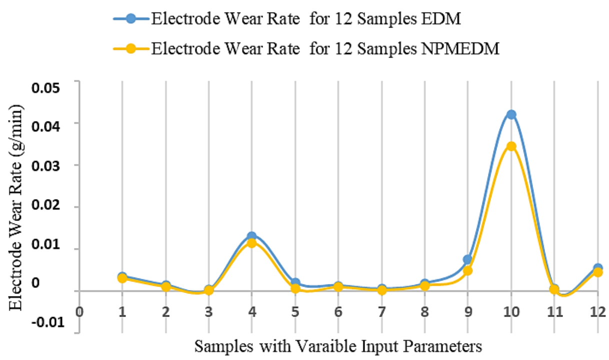

Fig. 6 The difference in the effect on electrode wear rate between electrical discharge machining (EDM) and nano powder mixed electrical discharge machining (NPMEDM)

Effect on SR

After the samples undergo the EDM process, experimental tests to measure surface roughness are conducted. The surface roughness tester, Mahr Marsuf PS1, is used to measure roughness. The test employed a cut-off wavelength of 1.25 mm.

The current study found that the average surface roughness (SR) for 304L in kerosene dielectric and kerosene mix with nanoparticles is 5.381 µm and 5.063 µm, respectively (Table 7).

Table 7

Minitab 18 software experimental matrix for surface roughness for conventional electrical discharge machining and nano powder mixed electrical discharge machining

Run	Samples	I_p (A)	P_{on} (µs)	P_{off} (µs)	Con. (g/l)	Mix of powder SiO_2(%) graphite balance	SR_{conv} (µm)	SR_p (µm)
1	1	40	50	125	1	30	5.544	4.824
2	2	40	250	25	5	30	5.168	5.140
3	3	20	250	125	1	70	4.986	4.857
4	4	40	50	125	5	30	4.771	4.062
5	5	40	250	25	5	70	6.930	6.656
6	6	40	250	125	1	70	6.162	6.110
7	7	20	250	125	5	30	6.585	6.345
8	8	20	50	125	5	70	6.131	5.933
9	9	20	50	25	5	70	4.584	4.461
10	10	40	50	25	1	70	3.912	3.911
11	11	20	250	25	1	30	5.952	5.181
12	12	20	50	25	1	30	3.843	3.274
						Mean	**5.381**	**5.063**

where: I_p = Peak current, P_{off} = Pule off time, SR_{conv} = SR for conventional EDM, P_{on} = Pulse on time, Con. = Powder concentration, SR_p = SR for NPMEDM.

Adding nanoparticles to kerosene dielectric reduces surface roughness after machining, as illustrated in Figure 7.

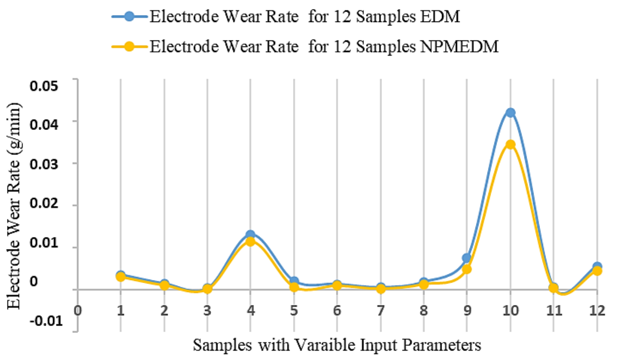

Fig. 7 The difference in the effect on surface roughness between electrical discharge machining (EDM) and nano powder mixed electrical discharge machining (NPMEDM)

CONCLUSION

The current work compares the output responses of EDM, such as SR, MRR, and EWR, for conventional EDM and NPMEDM. SiO_2 and graphite nanoparticles have electrical solid conductivity and physical qualities that decrease Kerosene breakdown strength and spark delay time, and the material removal rate is increased when nanoparticle concentration is mixed with the kerosene dielectric fluid. That makes the thermal conductivity of nanofluid much higher than that of conventional dielectric and increases the material removal rate. It is found that MRR increases at larger discharge currents. By increasing the percentage of graphite particles during discharge current (40 A), particle concentration (5 g/l), pulse on time (250 µs), and pulse off time (25 µs), the MRR at (Run No. 2) is improved by 12.5%. SR decreases at lower discharge currents; by reducing the discharge current (20 A), the particle concentration (1 g/l), the pulse on time (250 µs), and the pulse off time (25 µs), the relative silicon dioxide particle composition is decreased to 30%, which results at (Run No. 11) improvement about 13.7% in SR.

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