

Article

Optimization of Wire EDM Process Parameters for Machining Hybrid Composites Using Grey Relational Analysis

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Abstract: The materials used in engineering have seen a significant transformation in the contemporary world. Numerous composites are employed to overcome these problems because conventional materials are unable to meet the needs of current applications. For quite some time, professional engineers and researchers have been captivated by the problem of choosing the best machining parameters for new composite materials. Wire electrical discharge machining is a popular unconventional machining process that is often used for making complex shapes. Numerous process parameters influence the WEDM process. Thus, to achieve affordable and high-quality machining, the right set of process parameters must be provided. Finding the wire cut EDM optimized settings for the fabricated LM5/ZrO₂/Gr composite is the main aim of this research. The chosen input parameters are the wire feed, pulse on and pulse off times, the gap voltage, and the reinforcing percentage. In this study, LM5/ZrO₂/Gr composites were made from stir casting with 6-weight percent ZrO₂ as the reinforcement and varying graphite percentages of 2, 3, and 4 wt%. Then they were machined in WEDM using L₂₇ OA to seek the best parameters for machining by adjusting the input parameters. The findings were analysed by means of grey relation analysis (GRA) to achieve the supreme material removal rate (MRR), lowest surface roughness (SR), and a smaller kerf width (K_w) simultaneously. GRA determines the impact of the machining variables on the standard characteristics and tests the impact of the machining parameters. Confirmation experiments were performed finally to acquire the best findings. The experimental findings and GRA show that the ideal process conditions for achieving the highest grey relational grade (GRG) are 6% ZrO₂ with 2% graphite reinforcement, a wire feed of 6 m/min, a pulse off time (T_{off}) of 40 μs, a pulse on time (T_{on}) of 110 μs, and a gap voltage (GV) of 20 V. The gap voltage (22.87%) has the greatest impact on the GRG according to analysis of variance (ANOVA), subsequent to the interaction between the pulse on time and the gap voltage (16.73%), pulse on time (15.28%), and pulse off time (14.42%). The predicted value of the GRG is 0.679; however, the experimental GRG value is 0.672. The values are well-aligned between the expected and the experimental results. The error is only 3.29%, which is really little. Finally, mathematical models were created for each response.

Keywords: hybrid composites; wire EDM; grey relational analysis; DoE; ANOVA



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1. Introduction

In most circumstances, material selection is a paradoxical decision-making process. It is quite hard to discover a unique material with the requisite properties for engineering

applications since lightweight materials are unlikely to have adequate strength. Brittle materials are unlikely to be good in stiffness, toughness, and fatigue resistance [1]. A composite is a blend of two or additional phases chemically different on a micro level, divided by an apparent peculiarity, and simply identifiable. The matrix is the persistent constituent that is most often present in more significant amounts. In making a composite, it is widely assumed that the properties will be improved. The second portion is called the reinforcement because it improves or strengthens the matrix's mechanical characteristics [2]. Metal matrix composites (MMCs) are constructed using metals and elements that are alloyed, each of which contributes to the desirable characteristics of the main metal. The plentiful supply of aluminium and how it is utilized in a variety of technological uses make aluminium matrix composites (AMCs) the most varied and well-liked MMCs. Aluminium is a lightweight metal with excellent durability, a high strength-to-weight ratio, and thermal resistance. AMCs have outperformed their competing metals in the vast majority of applications. One of the essential characteristics of aluminium metal is its lightness, which is why it is used in alloys and composites [3].

The LM5 alloy hybrid composites are the most recent generation of composites that have attracted the industry's interest due to their optimal balance of mechanical properties [4]. Boron carbide, alumina, silicon nitride, aluminium nitride, zirconia, and zirconium nitride are some examples of commonly used ceramic reinforcements. Ceramics come in non-conductive, conductive, and semi-conductive varieties [5]. ZrO_2 , being a tough and fragile material, easily mixes with the softer aluminium matrix [6]. Graphite is a well-known solid lubricant that can be used as an additional reinforcement. The incorporation of graphite into the aluminium matrix improves the resilience to wear of dry sliding while lowering sliding friction. As a result, the composite's durability and rigidity are increased. Graphite is a renowned solid lubricant with the added benefit of a low-slung density [7]. It acts as a lubricating layer among the composite, and the surface is rubbed in graphite-reinforced AMCs, reducing the wear of the composite material without the need for standard solid and liquid lubricants. The reinforcement that is included in the composite material has been shown to boost the toughness of LM5 reinforced with ZrO_2 and graphite.

AMCs exhibit elevated energy consumption, high equipment costs, low machinability and surface quality, and significant cutting tool wear out, which make traditional processing impractical for AMCs [8]. Aluminium matrix composites (AMCs) are unconventional lightweight metals with good wear resistance, high strength, and low thermal expansion. They are used widely in industry [9,10]. The hardness and presence of reinforcement make it difficult to machine using traditional techniques, particularly when precise parts and intricate shapes are needed, which have slowed the development of MMCs [11]. The application of conventional equipment for the processing of tough composites resulted in high tool wear and shortened the tool life due to the rough characteristics of the reinforcement ceramic fragments. The alloy Al-Mg with 6-weight percentage ZrO_2 and 2, 3, and 4weight percentage graphite was selected because of its excellent dry slide durability qualities. Whilst the aluminium reinforcing enhances the characteristics, it also makes the composite harder, which makes machining extremely challenging. Even though it can be performed to use cutting-edge, new machining processes like water jet cutting and laser-based machining, the machinery is expensive, and the work piece height is constrained [12]. As a result, efficient cutting that generates a superior surface quality whilst preserving precision is required [13]. Wire EDM is therefore the best choice for machining composites since complicated and complex shapes are easy to control and process.

Optimization of wire EDM process parameters using GRA is needed to examine the machinability of manufactured composites [14]. Even with the most up-to-date CNC WEDM equipment, determining the optimal operating settings for achieving improved accuracy in WEDM is a significant challenge [15]. An unconventional method in machining, such as electrical discharge machining (EDM), might be appropriate because it removes particles from the material's surface by intermittently sparking electricity. In contrast

with traditional procedures that employ abrasion for material removal, no direct physical contact involves the tool and the work piece so that tool wear out does not occur quickly in WEDM [16]. The tool and the work piece are electrodes that help in material removal. The tool is a harder material than the work piece to remove more material from the work piece. The operation cost is high, as it takes a longer time for machining by surface erosion in EDM [17]. The GV, I_p , T_{on} , and flushing pressure (p) are the input parameters that have the most impact on EDM machining. The duration between two subsequent sparks in an EDM is controlled by the T_{off} despite being a less important element [18]. Because of this, it is crucial to set the T_{off} correctly in order to prevent poor flushing and an unintended raise in the time needed for machining. In order to accomplish a minimal R_a and K_w with a high MRR, these crucial input variables must be tuned. If there is a lot of metal-to-metal contact in applications, a relatively small R_a is crucial [19]. Additionally, the time required for machining and tooling cost are reduced when the MRR is high. This necessitates multi-objective parameter optimization, which can be accomplished using a variety of methods, including genetic algorithms, ant colony optimization, etc. One such method is grey relation analysis (GRA), which aids in finding the best set of input parameters that ultimately leads to the accomplishment of all goals. As implied by its name, GRA locates the optimal outcome in the grey area positioned among the white zone, which has all available information, and the black region, which does not. GRA offers the optimal operating settings that can be configured to attain all objectives all together as for a wide range of input situations [20].

Design of experiments (DoE)-based optimization techniques may be employed as well to identify the ideal parametric variable that has the greatest impact on performance measurements. One method utilized in manufacturing sectors to find the optimal production conditions is optimizing parameters through DoE, which is crucial for enterprises to produce excellent products at cheaper prices [21].

Wire electrical discharge machining is a popular unconventional machining process that is often used for making complex shapes. Numerous process parameters influence the WEDM process. Thus, to achieve affordable and high-quality machining, the right set of process parameters must be provided. Finding the wire cut EDM optimized settings for fabricated LM5/ZrO₂/Gr hybrid composites is the main aim of this research. Grey relational analysis has been utilized to identify the optimum process parameters.

2. Literature Survey

MRR, surface roughness, and kerf are the three vital output parameters that need to be controlled by selecting the best input parameters when performing WEDM. The surface quality improves the materials' fatigue strength, resistance to corrosion, and fracture toughness, and it also decreases friction, as can be seen in Martynenko et al. 2020 [22]. A high GRG value will enhance productivity. The SR becomes worse when the pulse period increases, while the SR declines with a hike in the discharge current or load current factor and flushing pressure. With a higher current, T_{on} , and GV, the surface roughness of composites rises [23]. The kerf, or cutting width, determines the dimensional stability of the final parts. The kerf increases with the peak current and decreases with the tool travel speed and pulse on time when cutting hybrid composites.

Until now, authors have relied heavily on GRA and various other statistical tests to define the impact of process parameters [24]. Process optimization on WEDM aluminium alloy reinforced with ZrO₂ and graphite has received relatively little attention. The machinability behaviour of a hybrid aluminium-based composite with changed percentages in graphite and a persistent proportion of zirconium di oxide was investigated in this present work. With T_{on} , GV, WF, and T_{off} as the input variables and SR and kerf as the output response, the WEDM process was chosen for machinability tests [25].

GRA helps to achieve optimum parameters for attaining more MRR and a minimum SR and kerf simultaneously. For multi-objective optimization, GRA was used to investigate how EDM parameters affect machining parameters like MRR, SR, and K_w . According to

reports, the SR is mostly influenced by the maximum current of the EDM [26]. The ANOVA approach was employed to determine the contribution made by all of the input parameters and errors in the discrepancy of answers. The user can then focus on the significant element that is most probable to lead to an alteration in the responses by assessing the role of the parameters in the changed responses and the impact of single parameters on the response variation [27].

As a result, obtaining a clear relationship between both the operating conditions and their performance is complex. For devices like WEDM, optimizing operational parameters is critical for the successful machining of any materials. When characteristics such as wire tension, wire velocity T_{on} and T_{off} , electrolytes, feed rate, and flushing pressure are considered, higher results can be improved [28]. A longer pulse duration and shorter pulse off time must be avoided in the direction to achieve the best MRR. In particular, the pulse energy and duration of pulse on time have an impact on the MRR. Furthermore, the tool's form, polarity, and abrasives considerably impact the process capabilities. A longer pulse duration and negative polarity are necessary for a higher MRR [29]. It was marginally reduced at high peak current levels due to contamination of the gap produced by increased debris and loosened ceramic barriers. The GRG was projected to decrease since no sparking occurred during the pulse-off-time interval. With a drop in the frequency of sparks over a specific period of the machining cycle, a dramatic fall in the MRR occurred at the highest pulse off time [30].

According to James et al., hybrid metal matrix composites are cutting-edge materials utilized in the automotive and aerospace industries for light-weight, high-strength applications. Amongst the several methods used to create hybrid metal matrix composites, stir casting is an easy and affordable method. Aluminium 6061 was selected as the metal matrix, while zirconium dioxide (ZrO_2) and aluminium oxide (Al_2O_3), respectively, were used as reinforcements. The composites were made up of 90% Aluminium 6061, 5% ZrO_2 , and 5% Al_2O_3 . The amounts of ZrO_2 and Al_2O_3 were limited to 10% to avoid cluster formation and to minimize the weight. For the reinforcing particles to achieve a good bonding with the metal matrix, their average size was between 55 and 65 microns [31].

According to Urtekin et al., high-Cr white cast irons (HCCIs) with a Cr percentage ranging from 12 to 17% have a structure that contains chromium carbide, which makes machining extremely challenging. As a result, HCCIs' machinability has never been advantageous. In this work, three different heat treatment procedures were applied to specially moulded HCCI samples: softening, casting (without heat treatment), and toughened heat treatment. In this work, their goal was to experimentally examine the changes in the features of HCCI samples, wire speed, pulse on time, pulse of time, and cutting performance during the WEDM process. The Taguchi method was used with an L_{18} orthogonal array, and an experimental research was prepared. After that, an optimization analysis was conducted utilizing mathematical models and performance outcomes from ANOVA. The present investigation looks at surface roughness and the material removal rate as the experimental outcomes. This experimental investigation found that when the pulse on time rose, so did the rate of material removal and surface roughness. Afterwards, surface roughness, micro hardness, scanning electron microscopy, and X-ray spectroscopy (EDS) were used to examine the morphological and structural characteristics of machined specimens. They also had their electrical conductivity assessed [32].

According to Arunadevi et al., wire EDM is one of the unconventional machining methods, which is frequently used to accurately and effectively carve hard materials. The necessary ingredients are collected, the composite is constructed using the stir casting method, and wire EDM is employed for the machining. The primary goals are to raise the MRR and lower the SR. To examine the output parameters and to accomplish their goals, five input factors were taken into consideration, including pulse on, voltage, pulse off, bed speed, and current. They came to the conclusion that it is challenging to concurrently discover the optimal solution for all the objectives in a realistic setting [33].

Ramanan et al. investigated surface roughness and the material removal rate, two machining quality metrics in their work. Metal matrix composites were created using activated charcoal in various percentages as reinforcements and aluminium 7075 as the matrix. The density, hardness, impact strength, and ultimate tensile strength were all measured for the specimens. In a wire-cut electrical discharge machine, the best samples were used to carry out the machining operation. The findings were made after 27 rounds of tests using the response surface methodology. The surface roughness and material removal rate were used to gauge how well the samples were machined. According to the results of the ANOVA analysis, the servo speed significantly influences how well a work piece is machined. Only the maximum MRR and the lowest SR have been discussed; the kerf has not been examined [34].

According to Malik Shadab et al., the existence of reinforcements makes them challenging to machine to meet industrial standards. Consequently, in order to increase output performance in terms of product quality, the machining process parameters must be optimized. Several factors, including T_{on} , T_{off} , induced current, and WF, have an impact on the overall performance of the wire electrical discharge machining (WEDM) process. One of the unconventional machining techniques is WEDM. Using Minitab-17's linear regression analysis, a relationship was formed between the process parameters and the output responses. The Taguchi L_{25} orthogonal array was required for the experiments that were conducted. The material removal rate, cutting speed, and surface roughness were all taken into account when machining composite materials; the kerf was not included in the study [35].

For the most recently designed magnesium metal matrix composite, Kavimani et al. reviewed the evaluation and examination of the effects of the WEDM parameter on the MRR and R_a . To investigate their impacts on the intended result responses (MRR and R_a), two material parameters—the reinforcement weight percentage and SiC reinforcement percentage—as well as three machining parameters—the pulse on time, pulse off time, and wire feed rate—were chosen. Then, Taguchi coupled grey relation analysis was used to examine the output response variables like the MRR and R_a . It was discovered that the WF trend increased linearly for both the MRR and R_a . The WF (98.19%) was shown to be the parameter with the greatest impact on the MRR, followed by the T_{on} and IP, according to the analysis of variance and the S/N ratio. The parameters that had the greatest impact on the R_a were the T_{on} (74.63%), IP, and WF [36].

The manufacturing of two advanced ceramics utilizing wire-cut electrical discharge machining (EDM), which was developing as one of the most promising techniques for the manufacturing of advanced ceramics, was covered by Lok and Lee. Sialon and Al_2O_3 -TiC, two varieties of sophisticated ceramics, were effectively processed using the wire-cut EDM method. The study investigated the machining performance at varying cutting parameters with respect to the material removal rate and surface finish. The flexural strength information gathered from the three-point and four-point-quarter bend test methods were used to further investigate the level of surface damage resulting from this thermal machining procedure. The findings demonstrated that the wire-cut EDM process is a practical material processing technique for advanced ceramic machining; nevertheless, more research must be conducted to determine how to enhance the surface integrity and polish of the machined ceramics [37].

This research work deals with the wire EDM machining and multi-objective optimization of LM5/ ZrO_2 /Gr composites, which have not been reported before by any researcher. Many studies have investigated the optimization of the WEDM process by considering only a few characteristics. WEDM of LM5/6% ZrO_2 /2,3 and 4% Gr was investigated in the current research work with five control parameters to achieve the maximum MRR, SR, and kerf simultaneously in the WEDM process. Utilizing the information from these experiments, the effect of all the control parameters on the responses was analysed, and finally the mathematical models for each response were created.

3. Materials and Fabrication

3.1. Materials

LM5: The base alloy used in this research work is LM5 (Kamatchi metals, Ambattur, Chennai). The LM5 alloy has good resistance to corrosion and better machining properties. It is appropriate for thin castings because of its good fluidity. As they are particularly sensitive to the presence of oxygen, atmospheric moisture, hydrating agents, etc., LM5 alloys require extra care during preparation. LM5 Aluminium alloy has pre-eminent protection to corrosion among all cast aluminium alloys. They have bright polished finish and have the ability to anodize with a pleasant usual appearance of aluminium. They are therefore popular in food processing equipment, decorative castings, pipe fittings in chemical and marine systems, dairy, and ornamental/architectural applications [38]. Chemical composition of LM5 aluminium alloy using optical emission spectroscopy is given in Table 1.

Table 1. Chemical Composition of Aluminium Alloy (LM5).

Cu	Mg	Si	Mn	Fe	Pb	Zn	Al
0.032	3.299	0.212	0.022	0.268	0.02	0.01	Balance

Zirconia (ZrO_2): In the LM5 matrix, zirconia (Mincometsal, Bengaluru) particles of 60 to 80 μm were used as reinforcement. Zirconia (ZrO_2) has numerous striking properties, like little specific gravity, elevated hardness, and elastic modulus, which help it to be widely used in aerospace and marine applications. As only trivial work is addressed on AMCs with zirconium di oxide as reinforcement, an effort was made to fabricate LM5/ ZrO_2 hybrid composites.

Graphite: In the LM5 matrix, graphite particles of 23 μm were used as another reinforcement. The addition of graphite (Graphite India Ltd., Bengaluru) particles decreases the density of aluminium alloys. Graphite has unique qualities, like low thermal conductivity, outstanding thermal resistance, strong thermal shock resistance, enhanced stiffness, and increased strength, among others.

In our earlier work, three composites, LM5/3% ZrO_2 , LM5/6% ZrO_2 , LM5/9% ZrO_2 , were fabricated, and mechanical characterization was conducted. It was found that LM5/6% ZrO_2 yielded better properties, so we added graphite a solid lubricant of 2, 3, and 4 wt% to study the enhancement in mechanical and machining characteristics [39].

3.2. Manufacturing of LM5/ ZrO_2 /Gr Hybrid Composites

Very small ingots of LM5 alloys were laid in a crucible and melted to the desired temperature of 850⁰ C in a muffle furnace. For the LM5 aluminium alloy, zirconium di oxide composites (6%) with graphite (2, 3, and 4%) were then produced by means of stir casting. The ZrO_2 particles of size 60 to 80 μm and graphite particles of size 23 μm were preheated at 150⁰ C for a period of 20 min in a furnace to get rid of the moisture. Then the preheated ZrO_2 and graphite was further added into the liquefied aluminium. The mechanical stirrer continuously stirred the mixture. The stirring time was maintained around 7 min at an impeller speed of 400 rpm. In the meantime, hexachloroethane tablets were put into the melt to eradicate the annoying gases in the liquefy melt and also to progress the quality of aluminium composite castings [40]. The melt pouring temperature was sustained at 750⁰ C and casted in a preheated permanent die. AMC plates of size 100 × 10 × 5 mm were made with matrix LM5, and 6% ZrO_2 and graphite (2%, 3%, 4%) as reinforcement were used as the work piece material.

3.3. Microstructural Study of Fabricated Hybrid Composites by Optical Microscopy and SEM

Metallographic investigations offer a substantial analytical tool and excellent quality control. All composites have been sampled, and each of their surfaces were meticulously

shined to a mirror-like gloss. The main objective of microstructural investigation is to confirm uniform dispersion of reinforcing particles in the matrix [41].

Sample preparation typically entails the following steps: cutting, mounting, emery polishing using various abrasive sheets with mesh sizes ranging from 220 to 1500, and polishing using velvet cloth and alumina paste. The specimens were then etched using HF solution prior to microscopic examination. When revealed with an optical microscope, the microstructure is essentially the low-scale configuration of a material. It is defined as the arrangement of a produced material substratum [42].

In the optical photo micrographs (Figure 1), the reinforcement particles are distributed uniformly across the matrix. In the microstructure of MMCs containing 3% and 6% ZrO_2 , the dispersed form of composite ZrO_2 particles can be noticed. The particles are found in the primary aluminium grains. At the grain boundaries, MgAl_2 eutectic elements that did not liquefy during solidification were triggered. The degree of magnification is $200\times$. The first phase of aluminium contains granules that are 40 to 60 microns in size [43].

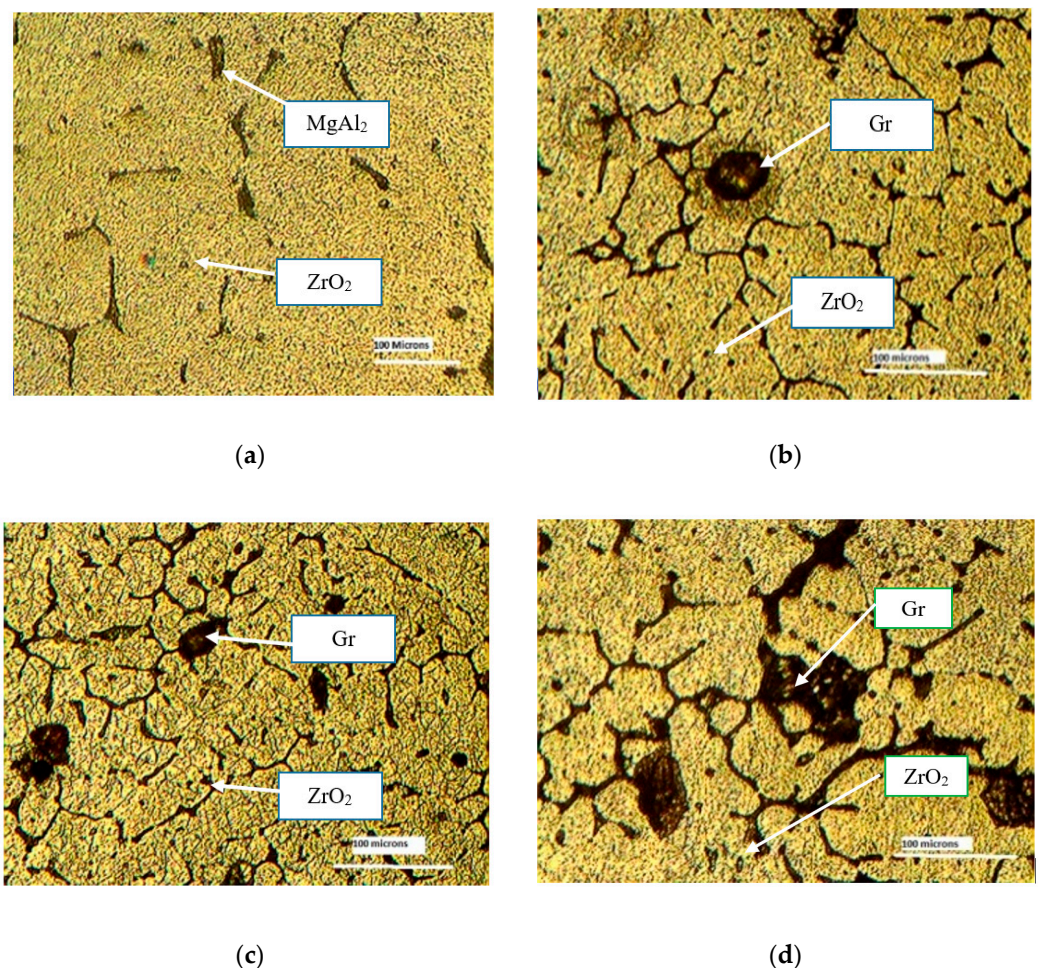


Figure 1. Microstructure of fabricated hybrid composites (a) LM5 + 6% ZrO_2 (b) LM5 + 6% ZrO_2 + 2%Gr; (c) LM5 + 6% ZrO_2 + 3%Gr (d) LM5 + 6% ZrO_2 + 4%Gr.

Figure 2 displays SEM pictures of LM5/ ZrO_2 /Gr hybrid composites. Through these figures, the pretty homogenous scattering of reinforced ZrO_2 particles and Gr with aluminium alloy is clearly revealed. Additionally, it can be seen in the micrographs that the volume fraction increases as the weight percentage of reinforcement increases. ZrO_2 is a white field and graphite particles appearing as a black field within the micrographs.

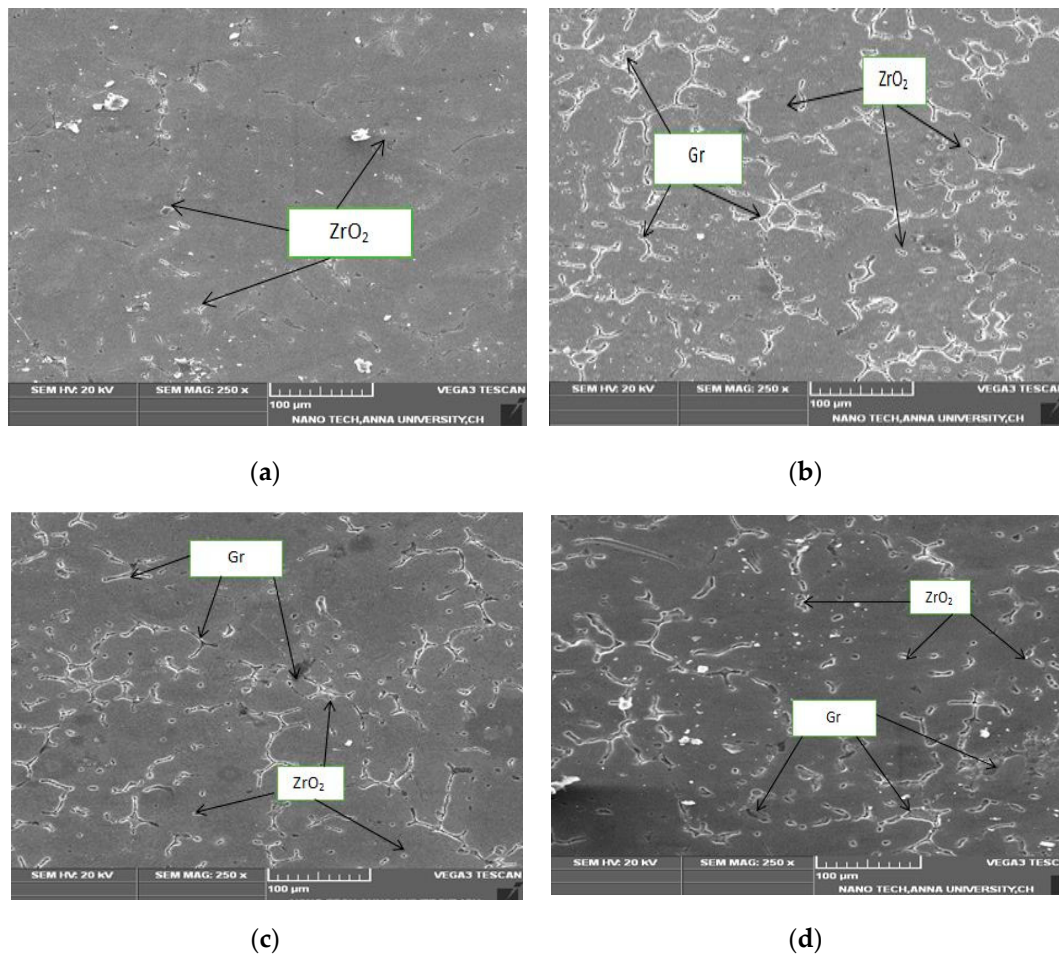


Figure 2. SEM images of fabricated hybrid composites. (a) LM5 + 6%ZrO₂ (b) LM5 + 6% ZrO₂ + 2%Gr (c) LM5 + 6% ZrO₂ + 3%Gr (d) LM5 + 6% ZrO₂ + 4%Gr.

3.4. Wire EDM of LM5/ZrO₂/Gr Hybrid Composites

WEDM is an unconventional machining technique where electricity is used effectively to cut any material that conducts electricity using a tiny copper or brass wire that is electrically charged as an electrode. One side of an electrical charge is carried by the wire, while the further side is carried by the work piece in WEDM process. The attraction of electrical charges produces a regulated spark as the wire gets close to the element, melting and igniting it and vaporizing small substance particles. The spark takes out a small portion of the wire, but after the wire is removed, since it passes through the work piece once, the system automatically throws out the used wire and advances fresh wire [44]. Thousands of sparks per second are produced in the process, but then the wire never comes into contact with the work piece. De-ionized water, which is a dielectric solution, is used to cool and flush the machining area. During the cutting process, high-pressure higher and lower flushing nozzles clean away microscopic particles from the adjacent region of the wire, in many cases, submerging the entire component in the dielectric fluid. In the machining area, the fluid also acts as a non-conductive barrier to stop the growth of channels that conduct electricity. As the wire gets nearby to the material, the electric field's force disables the barrier, causing current to pass amongst the wire and the work piece and ensuing in an electrical spark [45]. The material removal is started with an electric spark. A 0.25 mm diameter brass wire is a tool that acts as an electrode for directing the experiments. Figure 3 shows machined composites.

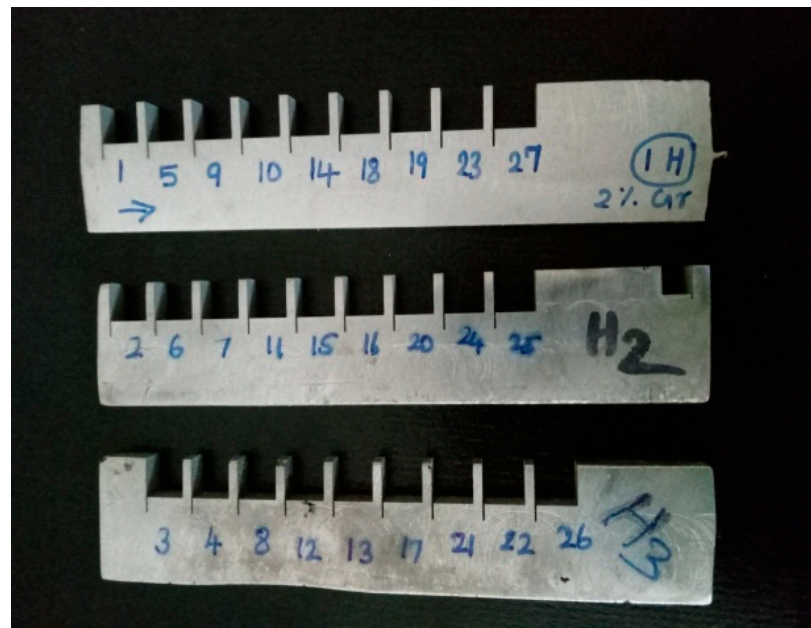


Figure 3. Photograph of Machined Hybrid Composites.

3.5. Design of Experiments

Using the Taguchi design of experiments approach, studies on wire EDM were conducted to test the significance of machining input variables on performance indicators and were analysed using grey relational analysis. The process parameters were chosen based on the literature review and their levels were chosen based on the pilot experiments conducted using the range for various parameters.

Analysis of variance (ANOVA) is a method of partitioning total variance into accountable sources of variation in an experiment. It is a statistical method used to interpret experimented data and make decisions about the parameters under study. ANOVA allows for performing hypotheses tests of significance to determine which factors influence the outcome of the experiment [46].

The basic equation of ANOVA is given by:

$$SS_{\text{Total}} = SS_{\text{Factors}} + SS_{\text{Error}} \quad (1)$$

The methodology was originally developed by Sir Ronald A. Fisher, the pioneer and innovator in the use and applications of statistical methods in experimental design who coined the name “ANOVA”. Table 2 displays the process parameters and levels for conducting experiments.

Table 2. Input Parameters and their levels.

Level	Pulse on Time T_{on} (μs)	Pulse off Time T_{off} (μs)	Gap Voltage GV (V)	Wire Feed WF (m/min)	Reinforcement % R %
1	110	30	20	3	6% ZrO ₂ + 2%Gr
2	115	40	30	6	6% ZrO ₂ + 3%Gr
3	120	50	40	9	6% ZrO ₂ + 4%Gr

3.6. Grey Relational Analysis

Multi-performance qualities can be challenging to optimize in complicated processes; as a result, GRA is frequently used to tackle this challenging issue. Grey system theory benefits have been empirically confirmed to be effective in overcoming the difficulties presented by imperfect, partial, and ambiguous data. In GRA, the terms black, white, and

grey have several definitions. Grey indicates the data that lie among black and white, while black and white signify systems with precise data. This method aims to enhance the reaction capabilities of contemporary manufacturing machines [47].

In grey relational analysis, data pre-processing the experimental information of the MRR, SR, and kerf are first normalized to be in the range of zero to one. Pre-processing data is typically necessary since the range and unit of one data collection may differ from others. Converting a sequence from one that is comparable to the original is known as data pre-processing. Different ways to perform data pre-processing for grey relational analysis are available based on a data series' characteristics. The original sequence has the "higher-the-better" feature if its target value is unlimited. Equation (2) below demonstrates how to normalize the original sequence:

$$x_i^*(k) = \frac{x_i^{(0)}(k) - \min x_i^{(0)}(k)}{\max x_i^{(0)}(k) - \min x_i^{(0)}(k)} \quad (2)$$

where $x_i^*(k)$ represents the normalized value, $x_i^{(0)}(k)$ represents the intended sequence, $\min x_i^{(0)}(k)$ represents the sequence's minimum value, and $\max x_i^{(0)}(k)$ represents the sequence's maximum value (k), and (k) , $i = 1, 2, \dots, m$ and $k = 1, 2, \dots, n$, respectively, represent the original reference sequence and pre-processed data. The number of experiments is m , while the total number of observations is n . The grey relational coefficient is a metric used in grey relational analysis to assess the relevance of two systems or sequences. The grey relational coefficient is used in grey relational analysis to show the degree of relationship between the sequences of $x_0(k)$, and $x_i(k)$ is shown in Equation (3).

$$\gamma x_0(k), x_i^* = \frac{\Delta_{\min} + \zeta \Delta_{\max}}{\Delta_{0i}(k) + \zeta \Delta_{\max}} \quad (3)$$

where $\Delta_{0i}(k)$ is also known as the deviation sequence and reflects the absolute value of the difference between $x_0(k)$ and $x_i^*(k)$.

$\Delta_{0i}(k) = x_0(k) - x_i^*(k)$;

$\Delta_{\min}$ —smallest value of $\Delta_{0i}(k)$;

$\Delta_{\max}$ —largest value of $\Delta_{0i}(k)$;

ζ is the distinguishing coefficient.

In most cases, if the value of the ζ is smaller and the distinct ability is larger, $\zeta = 0.5$ is employed. After calculating the grey relational coefficient, the grey relational grade is usually calculated using the average value of the grey relational coefficient. The grey relational grade is used to evaluate multi response characteristics. The following Equation (4) shows how it is expressed.

$$\tau_i = \frac{1}{n} \sum_{k=1}^n (\gamma(x_0(k), x_i^*(k))) \quad (4)$$

where n is the number of process responses, and τ_i is the grey relation grade. The greater grey relation grade shows that the associated experimental result is closer to ideal normalized value.

The final step in the Taguchi design of experiments is to predict the best answers using the best levels of each element and then perform confirmation trials. The optimum condition is chosen based on the experiment's goal, which is either minimization or maximization of the response. If there are three components A, B, and C, as well as three levels 1, 2, and 3, with the first levels being the best conditions, the projected optimum response is given with Equation (5).

$$\mu_{pred} = (\bar{A}_1 + \bar{B}_1 + \bar{C}_1) - 2\bar{Y} \quad (5)$$

where $\bar{Y}$ = overall mean response, and $\bar{A}_1, \bar{B}_1, \bar{C}_1$ = average response at level 1 of these factors.

4. Results and Discussions

4.1. Experimental Results

The experimental results on the wire EDM of LM5/ZrO₂/Gr hybrid composites are shown in Table 3. The analysis and discussions were focused on the GRG. GRA was used to figure out the best process parameters, and confirmation experiments were carried out. The GRC of the MRR, SR, and k_w are tabulated in Table 3 along with their grey relational grades and ranks.

Table 3. Experimental Results of GRG.

Ex. No	Pulse on Time (μs)	Pulse off Time (μs)	Gap Voltage (V)	Wire Feed (m/min)	Reinforcement wt %	GRC of MRR	GRC of SR	GRC of kerf	GRG	Rank
1	110	30	20	3	2	0.418	0.767	0.491	0.559	10
2	110	30	30	6	3	0.386	0.763	0.373	0.507	18
3	110	30	40	9	4	0.354	0.387	0.412	0.384	27
4	110	40	20	6	3	0.417	0.694	0.7	0.604	9
5	110	40	30	9	4	0.369	1	0.509	0.626	5
6	110	40	40	3	2	0.343	0.921	0.583	0.616	7
7	110	50	20	9	4	0.394	0.755	0.7	0.616	8
8	110	50	30	3	2	0.38	0.506	1	0.629	3
9	110	50	40	6	3	0.333	0.916	0.718	0.656	2
10	115	30	20	3	2	0.544	0.603	0.491	0.546	11
11	115	30	30	6	3	0.462	0.678	0.424	0.521	15
12	115	30	40	9	4	0.426	0.357	0.5	0.428	26
13	115	40	20	6	3	0.597	0.59	0.424	0.537	12
14	115	40	30	9	4	0.445	0.614	0.424	0.494	20
15	115	40	40	3	2	0.396	0.726	0.424	0.515	17
16	115	50	20	9	4	0.535	0.605	0.412	0.517	16
17	115	50	30	3	2	0.47	0.503	0.437	0.47	23
18	115	50	40	6	3	0.386	0.758	0.424	0.523	14
19	120	30	20	3	2	0.804	0.541	0.509	0.618	6
20	120	30	30	6	3	0.622	0.473	0.364	0.486	21
21	120	30	40	9	4	0.496	0.42	0.389	0.435	24
22	120	40	20	6	3	1	0.637	0.4	0.679	1
23	120	40	30	9	4	0.578	0.496	0.373	0.482	22
24	120	40	40	3	2	0.458	0.701	0.424	0.528	13
25	120	50	20	9	4	0.814	0.66	0.412	0.629	4
26	120	50	30	3	2	0.639	0.333	0.333	0.435	25
27	120	50	40	6	3	0.447	0.625	0.412	0.495	19

4.2. Analysis and Discussion

Utilizing the experimental data, the GRGs of the response traits for all variables at various levels were calculated. The main results of the GRG data processing factors were shown. A higher value of GRG is more helpful for improving product quality. At the level where each variable has the highest mean of means, the wire EDM settings for the responses are discovered. The GRG increases with a decreasing T_{on}, GV, and R% and raises

by increasing the T_{off} and wire feed, as shown in Figure 4. This happens as an outcome of the ejected energy rising with an increasing T_{on} , which causes a higher rate in material removal. As the pulse off time lowers, more discharges occur in an entire period, which leads to a higher MRR. The least SR and largest GRG values are caused by an average discharge gap, which expands as the GV increases [48].

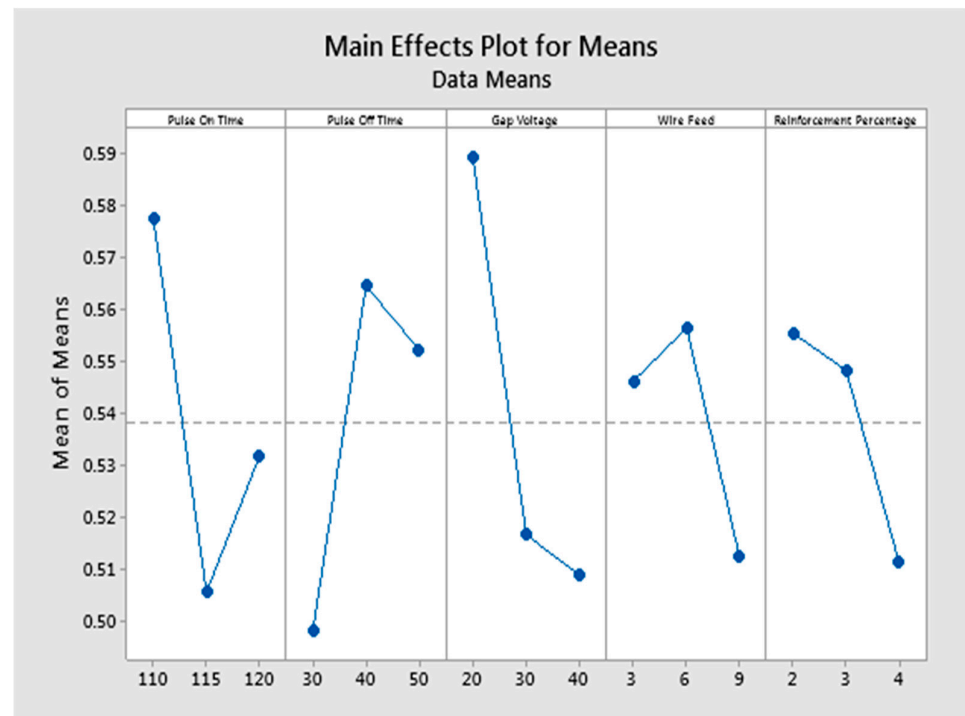


Figure 4. Response Graphs for GRG.

4.3. Optimal Levels for GRG

Table 4 displays the mean response trait (GRG data) for each of the levels of each factor and rank based on the delta value, which relate the degree of special effects compared to the other factors. The perceived consequence of each and every factor to the response is showed by the ranks. The ranks and delta values reveal that the utmost significant factor in accomplishing the maximum GRG is the T_{on} , which is followed by the GV, WF, T_{off} , and R %. The very first level of T_{on} , second level of T_{off} , first level of GV, second level of WF, and first level of R % produce the best results, as shown in Figure 4.

Table 4. Response Table for GRG.

Level	Pulse on Time	Pulse off Time	Gap Voltage	Wire Feed	Reinforcement %
1	0.5774	0.4982	0.5894	0.5462	0.5554
2	0.5057	0.5646	0.5167	0.5564	0.5483
3	0.5319	0.5522	0.5089	0.5123	0.5112
Delta	0.0718	0.0663	0.0806	0.0441	0.0442
Rank	2	3	1	5	4

ANOVA determined the significance of the process factors in relation to the GRG. At a 5% significance level, the F-values from the table are $F_{(0.05, 2, 8)} = 4.459$ and $F_{(0.05, 4, 8)} = 3.838$. So, according to Table 5, the F-values for T_{on} , T_{off} , GV, WF, the interaction of T_{on} with T_{off} , and the interaction of T_{on} with GV are also greater than the table value, and they are significant. The p value is also less than 0.05 for all above the mentioned parameters, so

the significance is confirmed. The error term was created by combining the interaction parameters of T_{on} with WF and T_{on} with reinforcement % [49].

Table 5. ANOVA for GRG.

Source of Variation	DF	SS	MS	F	<i>p</i>	C %
Pulse on Time	2	0.0237	0.0119	18.61	0.001	15.28
Pulse off Time	2	0.0224	0.0112	17.56	0.001	14.42
Gap Voltage	2	0.0355	0.0178	27.85	0	22.87
Wire Feed	2	0.0096	0.0048	7.52	0.015	6.18
Reinforcement %	2	0.0102	0.0051	7.96	0.013	6.53
$T_{on} * T_{off}$	4	0.0228	0.0057	8.95	0.005	14.70
$T_{on} * GV$	4	0.0260	0.0065	10.19	0.003	16.73
Pooled Error	8	0.0051	0.0006			3.29
Total	26	0.1554				100.00

4.4. Confirmation Experiments

The optimal parameters were utilized in the confirmation tests as well as in estimating the GRG. The factors at level A_1 , B_2 , C_1 , D_2 , E_1 , which are T_{on} 110 μs , T_{off} 40 μs , GV 20 V, WF 6 m/min, and R % 6% ZrO₂ with 2 percentage graphite, are the best settings for obtaining the maximum GRG. The experimental value of the GRG is 0.672, while the predicted value of the GRG is 0.679. A strong agreement is found amongst the predicted and the experimental GRG values, and the error is 3.61%.

4.5. Effect of Process Parameters on GRG

4.5.1. Effect of Pulse on Time on GRG

With a longer T_{on} , high discharge energy is released, ensuing in a more powerful explosion and deep craters in the work piece's surface. Deep craters imply a significant MRR and a poor surface quality. To achieve a better GRG, smaller values of T_{on} should be used, as is shown in Figure 5 [50]. The optimal pulse on time for achieving a higher GRG is 110 μs . The results suggest that increasing the T_{on} leads to an upsurge in cutting velocity due to increased thermal energy transfer from the wire to work piece. Due to the discharge energy, the MRR is greater, whereas the SR and kerf lowers, which in turn increases the GRG. The reason behind this is that the liberated energy surges with the T_{on} , and higher discharge energy creates a bigger crater, increasing the GRG [51].

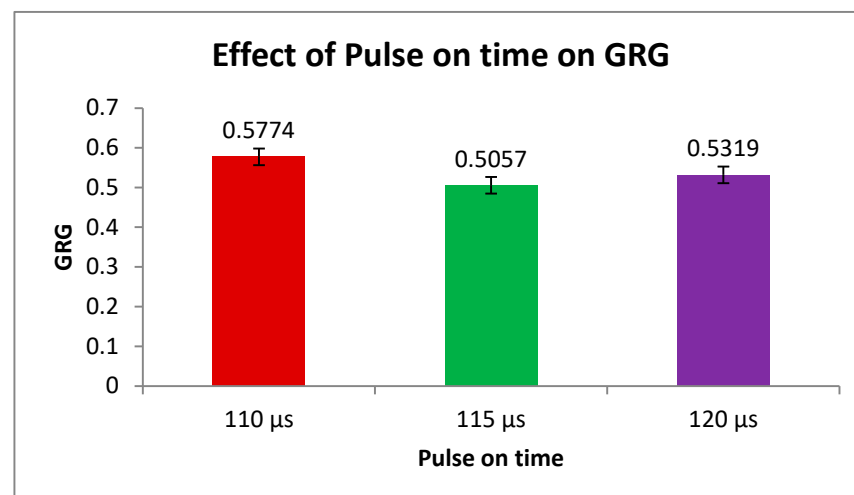


Figure 5. Effect of Pulse on Time on GRG.

4.5.2. Effect of Pulse off Time on GRG

The findings of the experiment show that the GRG value increases until 40 μ s and then decreases. An increased T_{off} results in a decreased cutting velocity due to prolonged non-cutting time. A longer pulse off time results in a narrower gap, but it also provides a longer flushing time to clear the debris in the gap. An optimal pulse off time is always used to prevent wire rupture or to eliminate the aberrant process [52].

With a shorter pulse off time and more discharges in a given period during machining, the cutting rate increased, resulting in huge craters and micro-damage on the surface. The optimal pulse off time for achieving a higher GRG is 40 μ s, as is shown in Figure 6. The craters on the machined surface are also caused by sparks that develop at the conducting phase, causing melting or potential evaporation. It goes without saying that high crater sizes result in a rough surface [53].

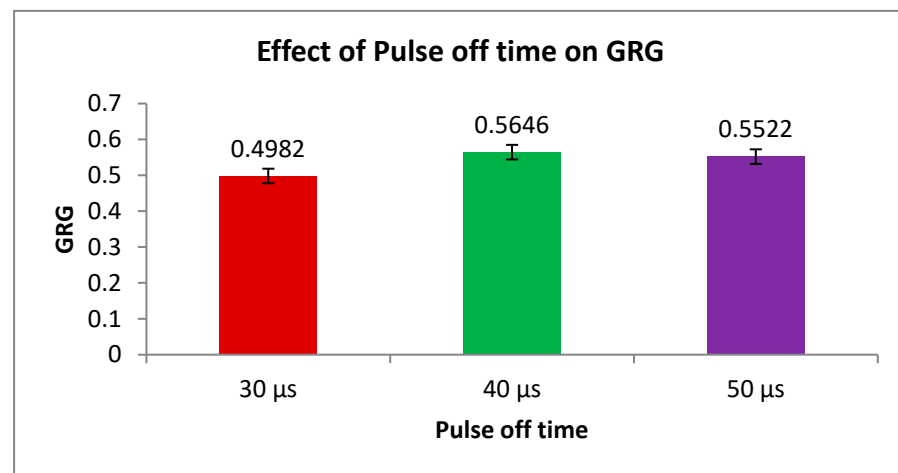


Figure 6. Effect of Pulse off Time on GRG.

4.5.3. Effect of Gap Voltage on GRG

The results show that the GRG increases as the gap voltage decreases. The optimal gap voltage for achieving a higher GRG is 20 V, as is shown in Figure 7. Actually, when the voltage rises, the electric field strengthens, and the spark discharge occurs more easily under the same gap. A lower voltage can provide enough energy to melt the dielectric particles around it [54]. The GRG immediately decreases as the gap voltage is increased.

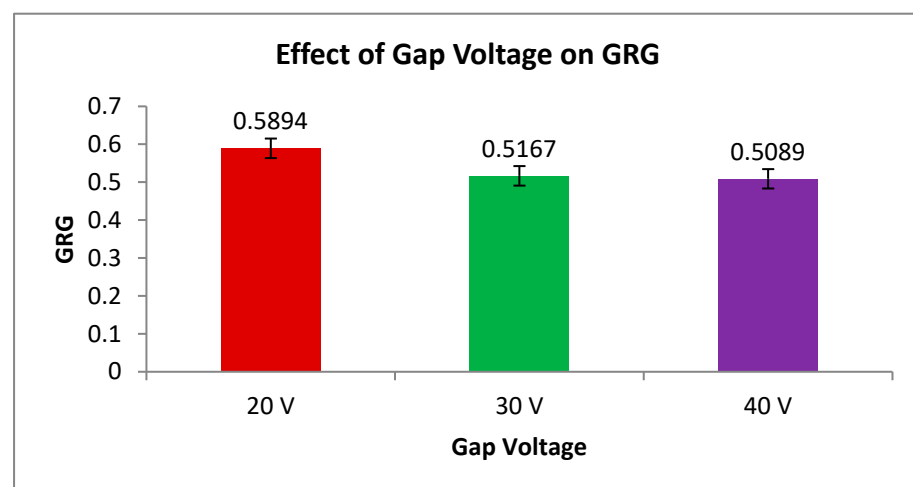


Figure 7. Effect of Gap Voltage on GRG.

4.5.4. Effect of Wire Feed on GRG

The wire feed is a neutral input parameter. The wire feed should be chosen in such a way that the wire does not break. The GRG rises as the wire speed increases, as shown in Figure 8. The optimal setting of the wire feed is 6 m/min for achieving a maximum GRG and also to prevent wire breakage [55]. In a nutshell, the results of this investigation agreed with those found in the literature. Despite the fact that this research was conducted on diverse materials, the results were consistent.

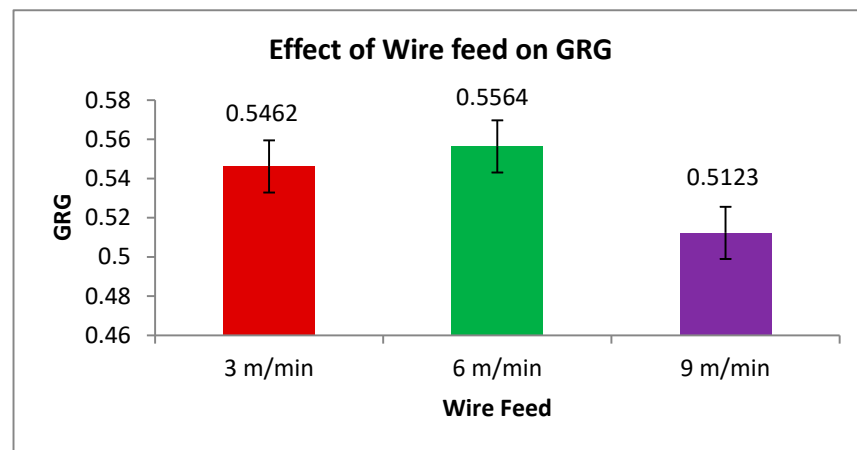


Figure 8. Effect of Wire Feed on GRG.

4.5.5. Effect of Reinforcement Percentage on GRG

The reinforcing percentage is a neutral input parameter. From the Figure 9, it was observed that the GRG is maximum at 6% ZrO₂ and 2% graphite. In a nutshell, the results of this investigation agreed with those found in the literature [56]. Despite the fact that this research was conducted on diverse materials, the results were consistent.

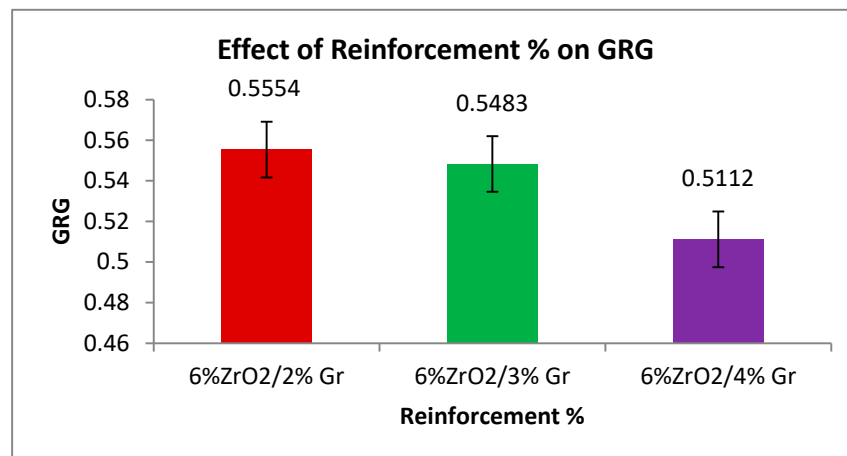


Figure 9. Effect of Reinforcement Percentage on GRG.

4.6. Mathematical Models

Mathematical models for the MRR, SR and kerf for LM5/ZrO₂/Gr hybrid composites were developed using linear regression and are shown in Equations (6)–(8).

$$\text{MRR} = -32.04 + 0.3599 T_{\text{on}} - 0.01489 T_{\text{off}} - 0.12646 \text{GV} - 0.0048 \text{WF} + 0.0912 \text{R} \% \quad (6)$$

$$\text{SR} = -6.15 + 0.0793 T_{\text{on}} - 0.0182 T_{\text{off}} + 0.0151 \text{GV} + 0.0373 \text{WF} + 0.1814 \text{R} \% \quad (7)$$

$$\text{Kerf} = 0.0834 + 0.0021 T_{\text{on}} - 0.0003 T_{\text{off}} + 0.000156 \text{GV} + 0.0008 \text{WF} + 0.00019 \text{R} \% \quad (8)$$

5. Conclusions

LM5/ZrO₂/Gr hybrid composites were made from stir casting with 6-weight percentage ZrO₂ as the reinforcement and varying graphite percentages of 2, 3, and 4%; the microstructure shows the uniform distribution of the reinforcement particles.

- i. Wire EDM was carried out using L₂₇ OA to trace out the paramount parameters for machining by adjusting the input parameters.
- ii. The findings were analysed using GRA to govern the maximum MRR, minimum SR, and K_w.
- iii. ANOVA was used to determine the significance of the machining variables on the standard characteristics and to assess the influence of the machining parameters.
- iv. A confirmation experiment was performed to acquire the best findings. The experimental findings and GRA show that the optimum process parameters for achieving the highest GRG are 6% ZrO₂ with 2% graphite reinforcement, a wire feed of 6 m/min, a T_{on} of 110 µs, a T_{off} of 40 µs, and a GV of 20 V.
- v. Gap voltage (22.87%) has the greatest impact on the GRG according to ANOVA, subsequent to the interaction between the pulse on time and gap voltage (16.73%), pulse on time (15.28%), and pulse off time (14.42%).
- vi. The predicted value of the GRG is 0.679; however, the experimental GRG value is 0.672. The values are well-aligned between the expected and the experimental results. The error is only 3.29%, which is acceptable.
- vii. Mathematical models were created for each response using linear regression.

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