Experimental Investigation of Wire-EDM Process Parameters for Surface Roughness in the Machining of Carbon Steel 1017 and Aluminum Alloy 6060

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Received October 12, 2018; Revised November 17, 2018; Accepted November 28, 2018

Abstract

Electrical discharge machining is an old technology that has been used for old manufacturing processes. Nowadays, the modernized version of the machine is used to manufacture different objects using a wire feed. The parameters in which the machine operates have diverse effects on product quality and surface finish. This paper investigates the performance of a wire electrical discharge machining process for different wire feed rates. The process is a non-traditional machining method. Several tests have been performed considering a carbon steel 1017 and aluminum alloy 6060 machined via Wire-EDM. By using different wire feed rates (3 mm/min, 5 mm/min and 7 mm/min), the average surface roughness, $R_a$, has been investigated in this study. Results show that the wire feed rate is a significant variable to the surface quality finish. The surface roughness of the test target materials increased as this variable increased. The present study recommends setting the wire feed rate as low as possible with the aim of improving results in the surface quality finish. The obtained results and some of the most necessary parameters affecting the manufacturing process of wire-EDM are briefly defined and are then discussed in detail in this study.

Keywords: Wire-EDM, Surface Roughness, wire feed rate, carbon steel 1017, aluminum alloy 6060

Cite This Article: Mohammad S. Alsoufi, and Dhia K. Suker, “Experimental Investigation of Wire-EDM Process Parameters for Surface Roughness in the Machining of Carbon Steel 1017 and Aluminum Alloy 6060.” American Journal of Mechanical Engineering, vol. 6, no. 3 (2018): 132-147. doi: 10.12691/ajme-6-3-6.

1. Introduction

Historically, the first electrical discharge machining (EDM) application was based on old technology that utilized controlled electrical discharges to remove broken taps and drills metal. The machine was originally developed by Russian scientists during WWII in the Technical Institute of Moscow [1,2]. The essentials of EDM application can be traced back as far as 1770 when the English chemist Joseph Priestly discovered the erosive effect of electrical discharges or sparks. Nevertheless, it was not until 1943 at Moscow University when scientists exploited the destructive properties of electrical discharges in the manufacturing process [3,4]. Since that initial introduction to the manufacturing industry in the late 1940s, the EDM technique (an unconventional process) has become one of the preferred manufacturing methods used in machining materials as it does not require tools and there is no direct contact with the sample being manufactured [5].

Currently, in modern manufacturing industries, wire-EDM is defined as a technique of manufacturing involving 1D, 2D and 3D physical objects by a thin wire (0.1 to 0.3 mm diameter) eroding the material from a material which is a good conductor or semiconductor of electricity [6], for instance metals, metallic alloys, graphite, or even some ceramic materials [7,8]. The material removal during thin wire-EDM process takes place using the etching process, which removes materials form the workpiece, and flushing the debris using saline liquid [9,10,11]. The etching process occurs when the discharge current passes through the narrow gap between the electrode and the workpiece [12]. Generally, the conductor or semiconductor material is mounted on a computer numerical controlled (CNC) worktable. The gap between the target workpiece and the thin wire is around 0.025 to 0.05 mm and is maintained constant by a computer-controlled positioning system during the operation. The thin wire is continuously fed through the target workpiece by a microprocessor, which enables the machining of complex physical shapes [6,13].

Wire-EDM is an essential non-conventional machining process (thermo-electrical process), which is widely used in the aerospace [14,15], ordnance [16], automobile [17] and general engineering industries [13], because of a series of merits, such as workpieces with a wide range of hardness, the fact that there is no macro-mechanical force during the process, its high degree of precision, and so on [18,19]. The most significant benefit of the wire-EDM is its independence of the machined material’s mechanical properties and its independence from the cutting force. So, conductive materials that are characterized by brittleness, high hardness, and strength that are “difficult-to-cut” can
be machined easily to the desired shape [20]. The quality and cutting efficiency in wire-EDM depends on the material to be used, and the process parameters used [13].

2. Experimental Details

2.1. Workpiece Design and Materials

Carbon steel 1017 and aluminum alloy 6060 have been used as a workpiece material in this research work, and it has application in a great many modern manufacturing industries. The shape of the workpiece materials of carbon steel 1017 and aluminum alloy 6060 is a rectangular block which has been cut into a total of four small pieces of 20 mm thickness each. The specification of each piece is 60 mm × 25 mm × 30 mm (length, width, and height, respectively) in the rectangular shape as illustrated in Figure 1. The chemical composition of carbon steel 1017 and aluminum alloy 6060 were analyzed using PMI-MASTER Pro2 and are provided in Table 1 and Table 2, respectively. All workpieces are initially cleaned before experimenting.

It is of the utmost significance before starting the experiments to clean the specimens of any surface contaminants, such as dust, grease, or any other soluble organic particles so that there will be no adverse effect on the results. To achieve this, all specimens were ultrasonically cleaned with organic solvents (ethyl alcohol) for 15 minutes followed by warm drying air. After cleaning, the specimens were stored for 24 hours until testing to allow the sample surface condition to equilibrate with the environment. This procedure is considered adequate at this stage.

![Figure 1. Photo of the (a) aluminum alloy 6060, (b) carbon steel 1017 and (c) 3D schematic object](image)

Table 1. Chemical composition of carbon steel 1017

| Elements | Fe | C   | Si  | Mn  | Cr  | Mo  | Ni  | Al  | Co  | Cu  | Nb | Ti  | V   | W   | Pb  | Zr  |
|----------|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|----|-----|-----|-----|-----|-----|
| Composition (%) | 98.4 | 0.181 | 0.196 | 0.565 | 0.126 | 0.0263 | 0.0980 | 0.0084 | 0.0066 | 0.213 | 0.0096 | 0.0043 | 0.0058 | 0.0650 | 0.0750 | 0.0096 |

Table 2. Chemical composition of aluminum alloy 6060

| Elements | Al | Si | Fe | Cu | Mn | Mg | Zn | Cr | Ni | Ti | Be | Ca | Pb | Sn |
|----------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Composition (%) | 98.5 | 0.35 | 0.183 | 0.0094 | 0.0256 | 0.616 | 0.0788 | 0.0026 | 0.0198 | 0.0120 | 0.0010 | 0.0026 | 0.0067 | 0.0141 |

| Elements | Sr | V  | Bi | Zr | B  | Ga | Cd | Co | Ag | In | Ce | Hg | La |
|----------|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Composition (%) | 0.0010 | 0.0033 | 0.0401 | 0.0024 | 0.0078 | 0.151 | 0.0030 | 0.0058 | 0.0073 | 0.151 | 0.0050 | 0.0061 |

Table 3. Main properties of the thin brass electrode

| Electrode Material | Thermal Conductivity (W/m*K) | Melting Point (K) | Electrical Resistivity (Ω cm) | Specific Heat Capacity (J/g °C) |
|--------------------|-------------------------------|------------------|-------------------------------|-------------------------------|
| Brass              | 159                           | 990              | 4.7                           | 0.38                           |
2.3. Machining Method and Procedure

A commercial precision AgieCharmilles wire electrical discharge machine wire-EDM (purchased from GF Machining Solutions, USA) has been used to conduct the experiments. This consists of a machine tool, a power supply unit and a flushing unit. In the wire-EDM cutting machine, all three axes with a repeatable positioning accuracy of 1 μm and 0.1 μm resolution, are a closed-loop servo-controlled testing machine and can be programmed to follow computer numerical control (CNC) G-code routines which are fed by the control board. AC brass (CuZn37), 500 thin wire electrode of 0.25 mm diameter, has been used (costing about ~20 $/kg) with a total resistance of 500 N/mm², 20% elongation, 25% IACS conductivity and taking deionized water (costing about ~200 $ for 45 litter/machine and ~500 hours lifetime) as the dielectric fluid (electrically non-conducting), which also acts as a coolant and flushes the debris away. AC brass 500 thin wire electrode is made from a very pure alloy in order to guarantee consistent quality and performance for conic machining. Diamond guides are usually expensive to replace but last a long time. The thin brass wire was selected due to its properties that are suitable for high sparking energy machining. The thin brass wire travels through the target workpiece material from upper and lower thin wire guides. Once the brass wire is wound onto the wire drum, that amount of wire is used for all the experiments of each material and is replaced once the target material is changed in order to avoid wear phenomenon. Work material is tightly clamped onto the worktable to avoid any relative motion between the wire and the material. Constant dielectric flow is ensured during the experimentation. The main properties of the electrode characteristics used in in this experiment are listed in Table 3.

Typically, the cutting procedure occurs while the target workpiece material is submerged in deionized fluid, which aids in cooling down the procedure and flushing away the cut target material. It therefore leaves the target material with a smooth surface profile that often requires no further polishing or even finishing. It is worth mentioning that the thin cutting wire should not touch the conductive or semi-conductive material and that the cutting itself is due to the erosion that occurs when a spark forms between the thin cutting wire and the raw material.

The fundamental principle behind the wire-EDM process is a sequence of electric sparks created due to passing high current between the material and the thin wire electrode. The electrical discharging process generates dramatic heat causing melting and evaporation in the local surface layers on both target material sides and the electrode. In addition, the heat causes vaporization of the dielectric fluid and generates high-pressure waves, which wash out the molten and vaporized metal into small pieces from the target material. The fluid then carries the droplets of metal away.

2.4. Determination of Machining Parameters

The machining process parameters have a significant influence on the wire-EDM performance. According to the operating experience, machine limits and some preliminary tests, the basic machine setting parameters are shown in Table 4, in which there was no breakage of wire electrode throughout the process due to dynamic spark energy in the wire-EDM.

There have been a great many publications regarding the quality of the surface finish achieved by wire-EDM. The influences of some machining process parameters such as pulsed current [2,21-28], pulse-on time [21-25,27,28], pulse-off time [21,24,28], gap voltage [23,24,28], dielectric liquid pressure [23,25,27,29] and electrode material [30] have been thoroughly investigated. However, when seeking information about the effect of the wire feed rate on the surface roughness using wire-EDM, we found no authoritative public data available. Therefore, the influence of the wire feed rate was investigated and required close attention in this research with three different levels of each parameter while other parameters kept constant.

Table 4. Process parameters with their values at three levels

| Parameters                      | Symbol | Unit         | Level 1 | Level 2 | Level 2 |
|---------------------------------|--------|--------------|---------|---------|---------|
| Gap Voltage                     | V      | Volt         | 10      | 40      | 70      |
| Peak Current                    | PC     | A            | 10      |         |         |
| Pulse-on Time                   | T_on   | μm           | 6       |         |         |
| Pulse-off Time                  | T_off  | μm           | 12      |         |         |
| Wire Feed Rate                  | WFR    | mm/min       | 3       | 5       | 7       |
| Wire Tension                    | WT     | N            | 11      |         |         |
| Wire Size                       | WS     | Mm           | 0.25    |         |         |
| Wire Material                   | WM     |              | Brass   |         |         |
| Dielectric                      |        |              | Deionized Water |         |
| Polarity                        |        |              |         |         |         |
| Environment Temperature         | ET     | °C           | 20±1    |         |         |
| Environment Humidity            | EH     | %            | 40±5    |         |         |

Some of the most necessary parameters affecting the manufacturing process of wire-EDM are briefly defined as follows [1,8,23,31,32]:

- **Discharge Current**: this is the value of the current applied to the electrode during the pulse-on time in the wire-EDM. The discharge current is one of the critical input process parameters of the wire-EDM together with discharge duration and relatively constant voltage for a given tool and target workpiece materials.
- **Peak Current**: this is the amount of power used in discharge machining. During each pulse-on time, the current increases until it reaches a preset level, which is expressed as the peak current. In wire-EDM processes, the peak current is the surface area of the cut which governs the maximum amount of amperage. Higher current is used in roughing operations and in creating cavities or details with large surface areas. Higher currents will improve the material removal rate (MRR) but then again reduce the surface roughness, Rₚ.
- **Servo Voltage**: this acts as the reference voltage to control the wire advances and retractions. It is also
called a spark gap set voltage which refers to the actual gap between the workpiece and the wire electrode used for cutting. When the mean applied voltage is higher than the set servo voltage level, the thin wire advances. In contrast, if the mean applied voltage is lower than the set servo voltage level, then, the thin wire retracts. When a smaller value of servo voltage is set, the mean gap becomes thinner, which leads to a rise in some electric sparks, resulting in a higher machining rate. Nevertheless, the state of machining at the gap might become unstable, causing thin wire breakage.

- **Gap Voltage:** this is voltage applied between the electrode and the target workpiece during the wire-EDM. The greater the gap voltage, the more significant will be the electric discharge. If the gap voltage rises, the peak current will also rise. The open gap voltage is the voltage read across the electrode and workpiece space before the spark. In some wire-EDM machines, each of these factors shows machining voltage.

- **Pulse-on Time:** this is the time in microseconds (μs) for which the current is applied to the electrode during each wire-EDM cycle. The conductive material removed is directly proportional to the quantity of energy applied during the pulse-on time. The current and the pulse-on time control this energy. The higher the pulse-on time, the higher will be the energy applied, thereby generating a greater amount of heat energy during this period. MRR depends upon the total amount of energy applied during the pulse-on time. MRR depends on a longer or shorter pulse period. Longer pulse duration improves the MRR of debris from the machined area.

- **Pulse-off Time:** this represents the duration of time between the two simultaneous sparks, and is also expressed in microseconds (μs), which is the time between discharges. Pulse-off time does not affect discharge energy. Pulse-off time is the pause between discharges that allows the debris to solidify and be flushed away by the dielectric before the next discharge. With a lower value of pulse-off time, there are some discharges in a given time, increasing the efficiency of the sparking. Consequently, the cutting rate also rises. However, reducing pulse-off time can overload the thin wire, causing thin wire breakage and instability of the cut by not permitting sufficient time to evacuate the debris before the next discharge.

- **Wire Feed Rate:** this is the feed rate at which the wire electrode travels along the thin wire guide path and is fed continuously for sparking. In wire-EDM, wire electrode occupies almost 70% of the machining cost. Therefore, it is required to set a low wire feed rate where stable machining with no wire breakage occurs. As the wire feed rate rises, the consumption of thin wire along with the cost of machining will increase. Low wire speed will cause thin wire breakage at high cutting speed.

- **Wire Tension:** it is important to keep the wire tension high enough such that the wire stays straight otherwise the wire will be drawn behind. Within the range under consideration, an increase in wire tension significantly raises both the accuracy and the cutting speed. The higher tension reduces the wire vibration amplitude and hence decreases the cut width with the purpose of the speed increasing for the same discharge energy. Nevertheless, if the applied wire tension exceeds the tensile strength of the thin wire, it leads to thin wire breakage.

- **Dielectric Flow Rate:** this is the rate at which the dielectric fluid is circulated. Flushing is significant for effective machining. Flushing pressure is produced from the top and bottom nozzles. The high flow rate of the dielectric fluid is necessary for machining with high pulse power and also applies to cutting a thicker workpiece. Low input pressure is used for the thin workpiece dielectric fluid flow rate.

- **Duty Cycle:** this is a percentage of the pulse-on time relative to the total cycle time.

### 2.5. Measuring Method

There are various surface roughness amplitude parameters used in industry, such as average roughness, \( R_a \), root mean square, \( R_q \), ten-point height, \( R_s \), total profile depth, \( R_t \), skewness, \( R_{sk} \), kurtosis, \( R_{ku} \), and so on. The most frequently-used surface roughness amplitude parameter applied to the evaluation of machined surface materials is the amplitude parameter, \( R_a \), and it is becoming the universally recognized one. In this research paper, the average roughness, \( R_a \), is considered here and is defined as the area between the average surface roughness profile and its mean line or the integral with the real absolute distribution of the profile curve (peak-to-valley).

The average roughness, \( R_a \), was selected according to the recommendations in the literature review and with consideration of the data processing facilities available with differing levels of information [33-37].

There are several ways of measuring average surface roughness, \( R_a \), such as image processing, microscopes, contact and non-contact stylus type instruments, a profile tracing instrument, and so on. A conventional contact-type Taly-Surf® profilometer from Taylor Hobson Precision, Inc. was used with a contact force of 0.7 mN, displacement sensitivity of 50 nm and tip radius of a 2 µm. The experiments were performed under wear-free and high-precision position measurement, which can offer a high degree of precision of up to 0.8 nm, a measuring range (x-axis) of 12.5 mm, and linear speed up to 0.5 mm/s. The traces were auto-leveled, set up to a linear least-squares (LLS) straight line and then filtered with a standard low-pass of 0.8 mm cut-off wavelength and filter CR ISO. Details of the average surface roughness measurements procedure and calibration trials have been reported.
In general, the calibration results showed that the cantilever beam system (stylus with beam) at only one end was a linear mass-spring system ($R^2 > 0.999$) under operational and environmental conditions, generally at $20^\circ C \pm 1^\circ C$ temperature and $40\% \pm 5\%$ relative humidity, with an absolute uncertainties value of $< 1\%$ and measurement resolution down to at worst 50 nm. The obtained results were revised and analyzed qualitatively with Origin Lab® 2018 software. Figure 2 shows the measuring technique of the carbon steel 1017 (Fe = 98.4%) and aluminum alloy 6060 (Al = 98.5%).

3. Experimental Results and Discussion

According to the experimental set-up and process parameters setting shown in Figure 2 and Table 3, the average surface roughness, $R_a$, was measured and plotted using OriginLab® 2018 software. Bear in mind that only wire feed rate was set as a variable process parameter (3 mm/min, 5 mm/min and 7 mm/min) while other parameters were kept constant (gap voltage, pulse-on time, pulse-off time, wire tension, wire size, wire material and dielectric). The first part of the experimental study was conducted for machined workpiece surface roughness profile performance of the carbon steel 1017 (Fe = 98.4%) and aluminum alloy 6060 (Al = 98.5%) (see subsection 3.1), the second part of the experimental study was carried out for machined workpiece surface roughness finish quality performance of the carbon steel 1017 (see subsection 3.2) and the third part of the experimental study was carried out for machined workpiece surface roughness finish quality performance of the aluminum alloy 6060 (see subsection 3.3).

3.1. Surface Roughness Profile Performance

Figure 3 and Figure 4 show the significantly different conditions in the surface roughness behavior profiles of machined materials over a 10 mm measuring distance. Both Figure 3(a) and Figure 4(a) show the frequent peaks-to-valleys distribution with narrower and smaller wider peaks-to-valleys indicating that the wire-EDM process parameters controlled the cut face and mirror cut face. The machined cut face follows a new pattern regardless of the value of $R_a$ indicating that wire-EDM procedure plays a significant role in changing the overall peaks-to-valleys profiles. The data generated from Figure 3(a) reveal that the surface behavior distribution region of the carbon steel 1017 is smooth, $-7.711 \mu m < \text{surface profile} < +6.174 \mu m$, whereas, the data generated from Figure 4(a) reveal that the surface behavior distribution region of the aluminum alloy 6060 is rough, $-13.741 \mu m < \text{surface profile} < +11.862 \mu m$. The data generated from Figure 3(b) and Figure 4(b) show the histograms of the distribution of vertices and upgrades located on the machined samples. The distribution profile of both samples (carbon steel 1017 and aluminum alloy 6060) is characterized by a significant natural fluctuation of changes in the value of $R_a$-family parameters and more significantly changed the values of these parameters. Surprisingly, the $R_a$ of aluminum alloy 6060 (Al = 98.5%) was almost three times rougher than that of carbon steel 1017 (Fe = 98.4%), which is more consistent with the mechanical properties of both target materials. Notice that all three levels of process parameters show uniform profile distribution for both carbon steel 1017 and aluminum alloy 6060.
The profile roughness parameter ratio $R_q/R_a$ performance (root means square, $R_q$, to average surface roughness, $R_a$) tends to follow the similar periodic trend of about $\sim 1.2 \pm 0.03$ with only less than $\sim 2\%$ difference.

Figure 3(b) and Figure 4(b) provide the general trend of the third-order and fourth-order central moments of skewness, $R_{sk}$, (3rd moment) and kurtosis, $R_{ku}$, (4th moment). Skewness, $R_{sk}$ (3rd moment) is defined by ISO 4287 (1997) [52] as it evaluates the degree of asymmetry distribution and is categorized as positive skewness (surfaces are ‘full’ of material) or negative skewness (surfaces are ‘empty’ of material). This is a significant process parameter for tribological applications, such as friction, wear and lubrication. A Gaussian distribution presents $R_{sk} = 0$ whereas kurtosis, $R_{ku}$, (4th moment) is defined by ISO 4287 (1997) [52] as it evaluates the distribution sharpness with $R_{ku} = 3$ for the normal distribution. The surface profile is dominated by sharp peaks (spiky wave) when $R_{ku} > 3$, whereas the surface is dominated by bumpy peaks when $R_{ku} < 3$. It can be concluded that the general trend is a negatively skewed distribution for skewness, $R_{sk}$, (3rd moment) for both machined samples (carbon steel 1017 and aluminum alloy 6060). However, it shows 100% leptokurtic, homogeneous and narrow scatter with a high degree of peakedness for the kurtosis, $R_{ku}$, (4th moment) for carbon steel 1017 (Fe = 98.4%), while it shows 100% platykurtic distribution, heterogeneous, little wider scatter and peaks are bumpy with a low degree of peakedness for the kurtosis, $R_{ku}$, (4th moment) for aluminum alloy 6060 (Al = 98.5%).

3.2. Carbon Steel 1017 Performance

Figure 5(a), Figure 5(b) and Figure 5(c) show unpredicted behavior of the surface roughness performance of carbon steel 1017 cut by thin brass wire-EDM at level 1 process parameters (WFR = 3 mm/min) and measured at three different zones (A, B and C) and four different sub-zones (A1, A2, A3 and A4), (B1, B2, B3 and B4) and (C1, C2, C3 and C4) for both cut face and mirror cut face.

At level 1 (3 mm/min wire feed rate) and zone A, as shown in Figure 5(a), the surface roughness values of the cut face were increased from 1.87 µm (at the top area, sub-zone A1) until it reached 2.25 µm (at the bottom area, sub-zone A4), where the cutting has been done by a lateral cross-section of the target material whereas, the surface roughness values of the mirror cut face were increased from 1.95 µm (at the top area, sub-zone A1) until it reached 2.36 µm (at the middle-down area, sub-zone A3) and then decreased to 2.15 µm. This behavior indicates that there are some differences between the cut face and the mirror cut face by almost $-0.04$ µm implying smoother surface roughness in the former, although the same brass wire-EDM cutting method was used. This fluctuated in $R_a$ due to wear phenomenon during the process cutting in contact between the thin wire brass and target material.

At level 1 (3 mm/min wire feed rate) and zone B, as shown in Figure 5(b), the surface roughness values of the cut face were increased from 1.97 µm (at the top area, sub-zone A1) until they reached 2.33 µm (at the middle-up and middle-down areas, sub-zones B2 and B3), where the cutting has been done by a lateral cross-section of the target material. After that, the $R_a$ starts to improve by almost $-2.07$ µm (at the bottom are, sub-zone B4) whereas, the surface roughness values of the mirror cut face were increased from 1.63 µm (at the top area, sub-zone B1) until they reached 2.22 µm (at the middle-up area, sub-zone B2) and then decreased to 2.1 µm. This behavior indicates that there are some differences between the cut face and mirror cut face by almost $-0.14$ µm implying smoother surface roughness in the latter, although the same brass wire-EDM cutting method was used. It is also worth mentioning that the cut face and mirror cut face follow the same behavior and same trend of peaks and valleys unlike zone A performance.

At level 1 (3 mm/min wire feed rate) and zone C, as shown in Figure 5(c), the surface roughness values of the cut face were increased from 1.79 µm (at the top area, sub-zone C1) until it reached 2.11 µm (at the bottom area, sub-zone C4), where the cutting has been done by a lateral cross-section of the target material whereas, the surface roughness values of the mirror cut face started at 2.03 µm (at the top area, sub-zone C1) until it reached 2.3 µm (at the middle-up area, sub-zone C2) and then decreased to 1.94 µm. This behavior indicates that there are some differences between the cut face and mirror cut face by almost $-0.17$ µm implying smoother surface roughness in the former, although the same brass wire-EDM cutting method was used. Also, it is worth mentioning that the cut face and mirror cut face follow the same behavior and same trend of peaks and valleys unlike zone A performance.
face and mirror cut face show some irregularity of distribution between peaks and valleys unlike zone B performance. During machining of carbon steel 1017 using a brass electrode the factors result in the maximum wear ratio causing irregularity surface roughness distribution, but the wear cannot be avoided entirely. Nevertheless, to achieve the high surface finish quality, the wear has to be compensated for by the electrode’s renewal. This phenomenon governs tool wear characteristics either by erosion of electrode material and/or by deposition of workpiece material on the tool electrode. Besides, the surface roughness behavior at sub-zone C2 (for mirror cut face) shows very rough area \( R_a \approx 2.3 \mu m \) due to penetrating micro-cracks or scratches in the sub-surface.

Figure 5(d) shows the mean and standard deviation (mean±SD) values of the carbon steel 1017 cut by wire-EDM including the cut face and mirror cut face at level 1 of the process parameters (WFR = 3 mm/min). As can be seen, the mean±SD values at level 1 (zone A) were 2.09±0.17 \( \mu m \) (for cut face) and 2.13±0.17 \( \mu m \) (for mirror cut face) indicating that 2% increased for the mirror cut face compared to cut face at the same spot of measurement with the same standard deviation. The mean±SD values at level 1 (zone B) were 2.18±0.18 \( \mu m \) (for cut face) and 2.04±0.27 \( \mu m \) (for mirror cut face) indicating that 6% decreased for the mirror cut face compared to cut face at the same spot of measurement with 33% differences in the standard deviation. The mean±SD values at level 1 (zone C) were 1.9±0.14 \( \mu m \) (for cut face) and 2.07±0.15 \( \mu m \) (for mirror cut face) indicating that 8% increased for the mirror cut face compared to cut face at the same spot of measurement with 6% differences in the standard deviation. Roughly speaking, zone C (ending point) regardless of which subzones represents the smoothest average surface roughness compared with zone A (starting point) and zone B (middle point) due to stability of wire tension compared with the first impact at zone A.

Figure 6(a), Figure 6(b) and Figure 6(c) show unpredicted behavior of the surface roughness performance of carbon steel 1017 (Fe = 98.4%) cut by thin brass wire-EDM at level 2 process parameters (WFR = 5 mm/min) and measured at three different zones (A, B and C) and four different sub-zones (A1, A2, A3 and A4), (B1, B2, B3 and B4) and (C1, C2, C3 and C4) for both cut face and mirror cut face.

Figure 5. Surface roughness of carbon steel 1017 at level 1 parameters with different zones (a) zone A, (b) zone B, (c) zone C and (d) average surface roughness with a standard deviation
At level 2 (5 mm/min wire feed rate) and zone A, as shown in Figure 6(a), the surface roughness values of the cut face were increased from 1.98 µm (at the top area, sub-zone A1) until they reached 2.47 µm (at the middle-up area, sub-zone A2), where the cutting has been done by a lateral cross-section of the target material whereas, the surface roughness values of the mirror cut face were increased from 1.98 µm (at the top area, sub-zone A1) until they reached 2.54 µm (at the middle-up area, sub-zone A2) and then decreased to 2.34 µm. This behavior indicates that there are some differences between the cut face and mirror cut face by almost ~0.09 µm implying smoother surface roughness in the former, although the same brass wire-EDM cutting method was used.

At level 2 (5 mm/min wire feed rate) and zone B, as shown in Figure 6(b), the surface roughness values of the cut face were increased from 2.14 µm (at the top area, sub-zone B1) until it reached 2.54 µm (at the middle-down area, sub-zone B2) and then decreased to 2.34 µm. After that, the $R_a$ starts to improve by almost ~2.05 µm (at the bottom area, sub-zone B4) whereas, the surface roughness values of the mirror cut face were increased from 2.2 µm (at the top area, sub-zone B1) until they reached 2.4 µm (at the middle-down area, sub-zone B3) and then decreased to 2.22 µm. This behavior indicates that there are some differences between the cut face and mirror cut face by almost ~0.12 µm implying smoother surface roughness in the former as it is in zone A with rougher surface roughness by 25%, although the same brass wire-EDM cutting method was used. It is worth mentioning, in particular, that the cut face and mirror cut face follow the same behavior and same trend of peaks and valleys unlike zone A performance at subzone A4 where mirror cut face shows a slight improvement in $R_a$ compared with a cut face.

At level 2 (5 mm/min wire feed rate) and zone C, as shown in Figure 6(c), the surface roughness values of the cut face were increased from 2.17 µm (at the top area, sub-zone C1) until it reached 2.31 µm (at the middle-down areas, sub-zones B3), where the cutting has been done by a lateral cross-section of the target material. After that, the $R_a$ starts to improve by almost ~2.05 µm (at the bottom area, sub-zone B4) whereas, the surface roughness values of the mirror cut face were increased from 2.2 µm (at the top area, sub-zone B1) until they reached 2.4 µm (at the middle-down area, sub-zone C3) and then decreased to 1.91 µm. This behavior indicates that there are some differences between the cut face and mirror cut face by almost ~0.0015 µm implying smoother surface roughness in the latter, although the same brass wire-EDM cutting method was used.
cutting method was used. It is worth mentioning, in particular, the cut face and mirror cut face show some irregularity of distribution between peaks and valleys unlike zone B performance where no correlation between the two faces was observed. Besides, the surface roughness behavior at sub-zone C3 (for mirror cut face) shows a very rough area \( (R_a \approx 2.4 \, \mu m) \) due to penetrating micro-cracks or scratches in the sub-surface.

Figure 6(d) shows the mean and standard deviation (mean±SD) values of the carbon steel 1017 cut by wire-EDM including the cut face and mirror cut face at level 2 of the process parameters. As can be seen, the mean±SD values at level 2 (zone A) were 2.22±0.25 \( \mu m \) (for the cut face) and 2.31±0.23 \( \mu m \) (for the mirror cut face) indicating a 3\% increased for the mirror cut face compared to cut face at the same spot of measurement with the same standard deviation. The mean±SD values at level 2 (zone B) were 2.16±0.1 \( \mu m \) (for cut face) and 2.29±0.09 \( \mu m \) (for mirror cut face) indicating that 6\% increased for the mirror cut face compared to cut face at the same spot of measurement with the 10\% differences in the standard deviation. The mean±SD values at level 2 (zone C) were 2.17±0.08 \( \mu m \) (for cut face) and 2.16±0.21 \( \mu m \) (for mirror cut face) indicate a 0.4\% decrease for the mirror cut face compared to cut face at the same spot of measurement with the 61\% differences in the standard deviation. Roughly speaking, zones B and C (middle point and ending point) represent the smoothest average surface roughness compared with zone A (starting point). Indeed, in wire-EDM, due to the instability of wire tension at the impact point (starting point), the \( R_a \) always represents high values compared to other zones and sub-zones.

Figure 7(a), Figure 7(b) and Figure 7(c) show unpredicted behavior of the surface roughness performance of carbon steel 1017 cut by thin brass wire-EDM at level 3 process parameters (WFR = 7 mm/min) and measured at three different zones (A, B and C) and four different sub-zones (A1, A2, A3 and A4), (B1, B2, B3 and B4) and (C1, C2, C3 and C4) for both cut face and mirror cut face.

At level 3 (7 mm/min wire feed rate) and zone A, as shown in Figure 7(a), the surface roughness values of the cut face were increased from 2.14 \( \mu m \) (at the top area, sub-zone A1) until they reached 2.41 \( \mu m \) (at the middle-down area, sub-zone A3), where the cutting has been done by a lateral cross-section of the target material whereas, the surface roughness values of the mirror cut face were increased from 1.84 \( \mu m \) (at the top area, sub-zone A1) until they reached 2.55 \( \mu m \) (at the middle-up area, sub-zone A2) and then decreased to 2.28 \( \mu m \). This behavior indicates that there are some differences between the cut face and mirror cut face by almost ~0.03 \( \mu m \) implying smoother surface roughness in the former, although the same brass wire-EDM cutting method was used.

![Figure 7](image-url)
At level 3 (7 mm/min wire feed rate) and zone B, as shown in Figure 7(b), the surface roughness values of the cut face fluctuated all over zone B from 2.3 µm to 2.4 µm, where the cutting has been done by a lateral cross-section of the target material whereas, the surface roughness values of the mirror cut face were increased from 2 µm (at the top area, sub-zone B1) until they reached 2.8 µm (at the middle-up area, sub-zone B2) and then decreased to 2.24 µm. This behavior indicates that there are some differences between the cut face and mirror cut face by almost ~0.005 µm implying smoother surface roughness in the latter with rougher surface roughness by 83%, although the same brass wire-EDM cutting method was used. It is vital to mention that the cut face and mirror cut face follow the same behavior and same trend of peaks and valleys unlike their zone A performance. Besides, the surface roughness behavior at sub-zone B2 (for mirror cut face) shows very rough area ($R_a \approx 2.85$ µm) due to penetrating micro-cracks, spherical debris, recast layer, micro-voids or scratches in the sub-surface.

At level 3 (7 mm/min wire feed rate) and zone C, as shown in Figure 7(c), the surface roughness values of the cut face were increased from 2.15 µm (at the top area, sub-zone C1) until they reached 2.38 µm (at the middle-up area, sub-zone C2), where the cutting has been done by a lateral cross-section of the target material whereas, the surface roughness values of the mirror cut face started at 2.06 µm (at the top area, sub-zone C1) until they reached 2.65 µm (at the middle-up area, sub-zone C2) and then decreased to 2.08 µm. This behavior indicates that there are some differences between the cut face and mirror cut face by almost ~0.0017 µm implying smoother surface roughness in the former, although the same brass wire-EDM cutting method was used. It is vital to mention that the cut face and mirror cut face show some irregularity of distribution between peaks and valleys unlike zone A performance. Besides, the surface roughness behavior at sub-zone C3 (for mirror cut face) shows very rough area ($R_a \approx 2.65$ µm) due to penetrating micro-cracks or scratches in the sub-surface.

Figure 7(d) shows the mean and standard deviation (mean±SD) values of the carbon steel 1017 cut by wire-EDM including the cut face and mirror cut face at level 3 of the process parameters. As can be seen, the mean±SD values at level 3 (zone A) were 2.31±0.11 µm (for cut face) and 2.28±0.31 µm (for mirror cut face) indicating that 1% decreased for the mirror cut face compared to cut face at the same spot of measurement with the same standard deviation. The mean±SD values at level 3 (zone B) were 2.37±0.11 µm (for cut face) and 2.36±0.34 µm (for mirror cut face) indicating a 0.4% decrease for the mirror cut face compared to cut face at the same spot of measurement with the 67% differences in the standard deviation. The mean±SD values at level 3 (zone C) were 2.25±0.09 µm (for cut face) and 2.27±0.27 µm (for mirror cut face) indicating a 0.8% decrease for the mirror cut face compared to cut face at the same spot of measurement with 66% differences in the standard deviation. Roughly speaking, zone C (ending point) represents the smoothest average surface roughness compared with zones A and B (starting point and middle point).

In general, $R_a$ decreased with a decrease in the wire feed rate and the best-achieved surface roughness was $R_a = 1.63$ µm at 3 mm/min wire feed rate. Another exciting observation in the data analysis is that there are no striations all over the carbon steel 1017 samples and smooth cutting behavior appears at the top spot area and then the $R_a$ starts to fluctuate in the irregularity pattern. A possible reason for this feature would account for the flow of molten material during the discharge that significantly formed and recast on the cut surface. Such recast formation of the molten layer can subsequently fulfill some spark-induced cavities and other uneven features, thus decreasing the overall surface roughness. This explanation is also noted by Wang et al. [53] and Punturat et al. [54]. During Wire-EDM, high temperature of the parking zone (A, B, C) and sub-zones (A1, A2, A3, A4), (B1, B2, B3, B4) and (C1, C2, C3, C4) causes the target materials (carbon steel 1017, Fe = 98.4%) to melt during pulse-on time. During pulse-off time, part of the molten metal became solidified and quenched due to rapid cooling. Thermal residual stress produced due to such a rapid heating and cooling cycle results in the formation of surface cracks in the recast layer leading to high surface roughness finish.

3.3. Aluminum Alloy 6060 Performance

Generally, similar surface roughness finish quality results were noticed for aluminum alloy 6060 (Al = 98.5%) compared to carbon steel 1017 (Fe = 98.5%) when using thin brass wire-EDM. However, the surface finish quality of carbon steel 1017 was better when applying similar process parameter conditions.

Figure 8(a), Figure 8(b) and Figure 8(c) show unpredicted behavior of the surface roughness performance of aluminum alloy 6060 cut by brass wire-EDM at level 1 process parameters (WFR = 3 mm/min) and measured at three different zones (A, B and C) and four different subzones (A1, A2, A3 and A4), (B1, B2, B3 and B4) and (C1, C2, C3 and C4) for both cut face and mirror cut face.

At level 1 (3 mm/mm wire feed rate) and zone A, as shown in Figure 8(a), the surface roughness values of the cut face were increased from 3.15 µm (at the top area, sub-zone A1) until they reached 3.81 µm (at the bottom area, sub-zone A4), where the cutting has been done by a lateral cross-section of the target material whereas, the surface roughness values of the mirror cut face were increased from 3.53 µm (at the top area, sub-zone A2) until it reached 4 µm (at the bottom area, sub-zone A4). This behavior indicates that there are some differences between the cut face and mirror cut face by almost ~0.44 µm implying smoother surface roughness in the former by 11.3%, although the same brass wire-EDM cutting method was used.

At level 1 (3 mm/mm wire feed rate) and zone B, as shown in Figure 8(b), the surface roughness values of the cut face were increased from 3.28 µm (at the top area, sub-zone A1) until it reached 3.9 µm (at the middle-down area, sub-zone B3), where the cutting has been done by a lateral cross-section of the target material. After that, the $R_a$ starts to improve by almost ~3.5 µm (at the bottom area, sub-zone B4) whereas, the surface roughness values of the mirror cut face were increased from 3.53 µm (at the top area, sub-zone B1) until they reached 4 µm (at the middle-down area, sub-zone B3) and then decreased to 3.59 µm.
This behavior indicates that there are some differences between the cut face and mirror cut face by almost ~0.13 µm implying smoother surface roughness in the former by 3.5%, although the same brass wire-EDM cutting method was used. It is worth mentioning here that the cut face and mirror cut face follow the same behavior and same trend of peaks and valleys unlike their zone A performance. Besides, the surface roughness behavior at sub-zone B3 (for both cut face and mirror cut face) shows a very rough area ($R_a \approx 3.9$ µm and 4.0 µm, respectively) due to penetrating micro-cracks or scratches in the sub-surface.

At level 1 (3 mm/min wire feed rate) and zone C, as shown in Figure 8(c), the surface roughness values of the cut face were increased from 3.28 µm (at the top area, sub-zone C1) until they reached 3.44 µm (at the middle-down area, sub-zone C3), where the cutting has been done by a lateral cross-section of the target material. In contrast, the surface roughness values of the mirror cut face started at 3.29 µm (at the top area, sub-zone C1) until they reached 4.26 µm (at the middle-down area, sub-zone C3) and then decreased to 3.6 µm. This behavior indicates that there are some differences between the cut face and mirror cut face by almost ~0.42 µm implying smoother surface roughness in the former by 11.3%, although the same brass wire-EDM cutting method was used. It is worth mentioning here that the cut face and mirror cut face show some irregularity of distribution between peaks and valleys unlike their zone A performance. During machining of aluminum alloy 6060 using thin brass electrodes the highest material removal rate was witnessed. Wire brass as an electrode material does not allow the absorption of much heat energy because it has comparatively low thermal conductivity and most of the heat is consumed in the removal of material from a workpiece of the aluminum alloy 6060 at a small melting point.

Figure 8(d) shows the mean and standard deviation (mean±SD) values of the aluminum alloy 6060 cuts by wire-EDM including the cut face and mirror cut face at level 1 of the process parameters. As can be seen, the mean±SD values at level 1 (zone A) were 3.47±0.3 µm (for cut face) and 3.91±0.17 µm (for mirror cut face) indicating an 11.3% increase for the mirror cut face compared to cut face at the same spot of measurement with the same standard deviation. The mean±SD values at level 1 (zone B) were 3.56±0.25 µm (for cut face) and 3.69±0.21 µm (for mirror cut face) indicating a 3.5% increase for the mirror cut face compared to cut face at the same spot of measurement with 16% differences in the standard deviation. The mean±SD values at level 1 (zone C) were 3.29±0.11 µm (for cut face) and 3.71±0.41 µm (for mirror cut face) indicating a 11.3% increase for the mirror cut face compared to cut face at the same spot of measurement with 73% differences in the standard deviation. Roughly speaking, zone C (ending point) represents the smoothest average surface roughness compared with zone A (starting point) and zone B (middle point).

Figure 8. Surface roughness of aluminum alloy 6060 at level 1 parameters with different zones (a) zone A, (b) zone B, (c) zone C and (d) average surface roughness with a standard deviation.
Figure 9(a), Figure 9(b) and Figure 9(c) show unexpected behavior of the surface roughness performance of aluminum alloy 6060 (Al = 98.5%) cut by brass wire-EDM at level 2 process parameters (WFR = 5 mm/min) and measured at three different zones (A, B and C) and four different sub-zones (A1, A2, A3 and A4), (B1, B2, B3 and B4) and (C1, C2, C3 and C4) for both cut face and mirror cut face.

At level 2 (5 mm/min wire feed rate) and zone A, as shown in Figure 9(a), the surface roughness values of the cut face were increased from 3.71 µm (at the top area, sub-zone A1) until it reached 3.87 µm (at the bottom area, sub-zone A4), where the cutting has been done by a lateral cross-section of the target material whereas, the surface roughness values of the mirror cut face were dropped dramatically from 4 µm (at the top area, sub-zone A1) until it reached 3.8 µm (at the bottom area, sub-zone A4). This behavior indicates that there are some differences between the cut face and mirror cut face by almost ~0.13 µm implying smoother surface roughness in the former by almost 3.3%, although the same brass wire-EDM cutting method was used.

At level 2 (5 mm/min wire feed rate) and zone B, as shown in Figure 9(b), the surface roughness values of the cut face were increased from 3.94 µm (at the top area, sub-zone A1) until it reached 4.01 µm (at the bottom area, sub-zone B4), where the cutting has been done by a lateral cross-section of the target material whereas, the surface roughness values of the mirror cut face fluctuated between 3.65 µm to 3.93 µm all over subzones. This behavior indicates that there are some differences between the cut face and mirror cut face by almost ~0.02 µm implying smoother surface roughness in the former with rougher surface roughness by 0.5%, although the same brass wire-EDM cutting method was used. Another point worth mentioning is that the cut face and mirror cut face do not follow the same behavior and same trend of peaks and valleys as in their zone B performance.

At level 2 (5 mm/min wire feed rate) and zone C, as shown in Figure 9(c), the surface roughness values of the cut face were increased from 2.98 µm (at the top area, sub-zone C1) until they reached 4.05 µm (at the middle-up area, sub-zone C2) and then dropped to 3.38 µm where the cutting has been done by a lateral cross-section of the target material. In contrast, the surface roughness values of the mirror cut face fluctuated between 3.33 µm to 3.92 µm. This behavior indicates that there are some differences between the cut face and mirror cut face by almost ~0.46 µm implying smoother surface roughness in the former, although the same brass wire-EDM cutting method was used. Another point worth mentioning is that the cut face and mirror cut face show some irregularity of distribution between peaks and valleys unlike their zone A performance.

Figure 9. Surface roughness of aluminum alloy 6060 at level 2 parameters with different zones (a) zone A, (b) zone B, (c) zone C and (d) average surface roughness with a standard deviation
Figure 9(d) shows the mean and standard deviation (mean±SD) values of the carbon steel 1017 cut by wire-EDM including the cut face and mirror cut face at level 2 of the process parameters. As can be seen, the mean±SD values at level 2 (zone A) were 3.76±0.07 μm (for cut face) and 3.89±0.11 μm (for mirror cut face) indicating a 3.3% increase for the mirror cut face compared to cut face at the same spot of measurement with the same standard deviation. The mean±SD values at level 2 (zone B) were 3.79±0.36 μm (for cut face) and 3.81±0.12 μm (for mirror cut face) indicating a 0.5% increase for the mirror cut face compared to cut face at the same spot of measurement with 66% differences in the standard deviation. The mean±SD values at level 2 (zone C) were 3.28±0.58 μm (for cut face) and 3.74±0.29μm (for mirror cut face) indicating a 12.3% increase for the mirror cut face compared to cut face at the same spot of measurement with the 50% differences in the standard deviation. Overall, zone C (ending point) represents the smoothest average surface roughness compared with zone A (starting point) and zone B (middle point).

Figure 10(a), Figure 10(b) and Figure 10(c) show unpredictable behavior of the surface roughness performance of aluminum alloy 6060 (Al = 98.5%) cut by brass wire-EDM at level 3 process parameters (WFR = 7 mm/min) and measured at three different zones (A, B and C) and four different sub-zones (A1, A2, A3 and A4), (B1, B2, B3 and B4) and (C1, C2, C3 and C4) for both cut face and mirror cut face.

At level 3 (7 mm/min wire feed rate) and zone A, as shown in Figure 10(a), the surface roughness values of the cut face and mirror cut face follow the same patterns, that is, were increased from 3.62 μm and 3.42 μm (at the top area, sub-zone C1), respectively, until they reached 4.17 μm and 4.05 μm (at the middle-down area, sub-zone C3), respectively, and then dropped to 3.64 μm and 3.53 μm, respectively, where the cutting has been done by a lateral cross-section of the target material. This behavior indicates that there are some differences between the cut face and mirror cut face by almost ~0.12 μm implying smoother surface roughness in the later, although the same brass wire-EDM cutting method was used. It is absolutely worth mentioning here that the cut face and mirror cut face follow the same behavior and same trend of peaks and valleys unlike their zone A performance.
At level 3 (7 mm/min wire feed rate) and zone C, as shown in Figure 10(c), the surface roughness values of the cut face were almost constant at sub-zones C1, C2 and C3 by 3.9 µm and then dropped to 3.95 µm, where the cutting has been done by a lateral cross-section of the target material whereas, the surface roughness values of the mirror cut face play entirely different roles compared with the cut face. This behavior indicates that there are some differences between the cut face and mirror cut face by almost ~0.44 µm implying smoother surface roughness in the latter, although the same brass wire-EDM cutting method was used. It is absolutely worth mentioning that the cut face and mirror cut face show some irregularity distribution between peaks and valleys unlike their zone B performance.

Figure 10(d) shows the mean and standard deviation (mean±SD) values of the aluminum alloy 6060 cuts by wire-EDM including the cut face and mirror cut face at level 3 of the process parameters. As can be seen, the mean±SD values at level 3 (zone A) were 3.68±0.09 µm (for cut face) and 3.72±0.26 µm (for mirror cut face) indicating a 1.1% increase for the mirror cut face compared to cut face at the same spot of measurement with the 65% differences in the standard deviation. The mean±SD values at level 3 (zone B) were 3.82±0.25 µm (for cut face) and 3.7±0.27 µm (for mirror cut face) indicating a 3.1% decrease for the mirror cut face compared to cut face at the same spot of measurement with the 7% differences in the standard deviation. The mean±SD values at level 3 (zone C) were 3.81±0.14 µm (for cut face) and 3.73±0.62 µm (for mirror cut face) indicating a 11.6% decrease for the mirror cut face compared to cut face at the same spot of measurement with the 77% differences in the standard deviation. Roughly speaking, zone C (ending point) represents the smoothest average surface roughness compared with zones A and B (starting point and middle point).

In contrast with carbon steel 1017 (Fe = 98.4%), \( R_a \) decreased in aluminum alloy 6060 (Al = 98.5%) samples with increased wire feed rate and the best-achieved surface roughness was \( R_a = 2.44 \) µm (a better surface quality than carbon steel 1017) at a 7 mm/min wire feed rate (level 3) and with no striations all over the aluminum alloy 6060 samples. The surface roughness of aluminum alloy 6060 was increased compared to carbon steel 1017 samples due to the fact that the porosity found in aluminum alloy 6060 samples results in deeper cracks all over the profile. Hence, to obtain a good surface quality finish of a wire-EDM conductor material, it is desirable to set a low wire feed rate where stable machining without wire breakage becomes possible. As the wire feed rate increases, the consumption of wire will increase which consequently increases the machining cost. Low wire speed will cause wire breakage in high cutting speed. Along with the wire feed rate, pulse-on time and peak current should be set as low as possible (or pulse-off time should be set as high as possible). However, machining a material at low levels of these process parameters causes a lengthy machining time. More importantly, the surface roughness is directly dependent on the amount the target material solidifies on the machined surface.

4. Conclusions

In this paper, experimental investigation of the wire-EDM on both carbon steel 1017 (Fe = 98.4%) and aluminum alloy 6060 (Al = 98.5%) has been completed, and the following conclusions are drawn, based on the relationship between wire-EDM parameters and surface roughness, \( R_a \):

- No striation pattern was observed from the top of the cut to the bottom of the cut for both target materials and both cut face and mirror cut face.
- Penetrating micro-cracks in the sub-surface and localized smooth area were observed over a few regions.
- The surface roughness behavior of the carbon steel 1017 (Fe = 98.4%) is better than that of aluminum alloy 6060 (Al = 98.5%) as it is an excellent conductor material.
- Aluminum alloy 6060 (Al = 98.5%) has higher thermal conductivity and low melting point causing substantial creator formation resulting in increases in the average surface roughness, \( R_a \).
- The general trend observed indicates that the \( R_a \) quality improved and gives an excellent smooth surface with a reduction in the wire feed rate from 7 mm/min to 3 mm/min.
- Surface roughness was increased when the wire feed rate increased for both materials (carbon steel 1017 and aluminum alloy 6060). This indicates that the \( R_a \) of the wire-EDM workpiece is determined by the same machining variables, regardless of the material type being machined.
- Wire feed rate (WFR) is observed to have a significant role in the machining while considering the surface finish.
- Higher surface roughness is obtained for microscale surfaces mainly due to higher wear of the tool electrode and this may be one of the factors influencing irregular roughness.
- The cut face has always represented smooth surface roughness whereas the mirror cut face represents rough surface roughness for both machines’ target materials.
- Zone C (ending point) represents the lowest \( R_a \) for carbon steel 1017 (Fe = 98.4%) for all three different levels of process parameters.
- Zone B (middle point) represents the lowest \( R_a \) for aluminum alloy 6060 (Al = 98.5%) for only level 1 process parameter (WFR = 3 mm/min) while level 2 and level 3 process parameters (WFR = 5 mm/min and 7 mm/min) go to zone C like carbon steel 1017.
- Overall, there is a bias between the cut face and mirror cut face for both target materials and different process parameter levels, although the same thin brass wire-EDM cutting method was used and the same cutting direction was carried out by a lateral cross-section of the target materials.

Conflicts of Interest

The authors have no conflicts of interest.
Funding Source
The authors received no financial support for the research and/or for the publication of this article.

Availability of Data and Materials
The data analyzed for this manuscript is the part of our research work and is available for public users.

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