# Performance Evaluation Of Flexible Machine Controller For Electrical Discharge Machine

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***Abstract*— The experimentation carried out with newly developed Flexible Machine Controller for die sinking Electrical Discharge Machine (EDM) on six different work piece materials with copper tool electrode. The Flexible Machine Controller was developed on Programmable Logical Controller. To communicate with die sinking EDM, a user interface has been developed on the basis of Supervisory Control and Data Acquisition system along with database program that assist the user in selection of EDM process parameters. Pilot experiments were conducted to create an experimental database. The experimental results of Flexible Machine Controller was compared with original machine controller has been carried out for six different work piece materials. It was observed that the material removal rate and surface quality of EDM machined component improved in Flexible Machine Controller as compared to Original Machine Controlled.**

*Keywords*— **Electrical Discharge Machining (EDM), Flexible Machine Controller (FMC), Original Machine Controller (OMC), Programmable Logical Controller (PLC)**

## I. Introduction

Die sinking Electrical Discharge Machining is a non-conventional material removal process. It is predominately used for the manufacturing of 3-D complex geometry and hard material parts that are extremely difficult-to-machine by conventional machining processes. In past decades, EDM researchers have explored a number of ways to enhance the machining characteristics such as surface roughness, material removal rate and electrode wear rate. The focus of most researchers was on development of models for the optimization of EDM process parameters. Kesheng Wang et al. [1] developed a hybrid model to optimize the EDM process. This hybrid model is the combination of hybrid ANN and GA. The inputs to hybrid model are pulse-on time, pulse-off time, discharge current, voltage between gap just before spark, discharge gap, servo sensitivity to changes in spark gap and out of the model is SR (Ra) and MRR. Experimental results shows the model optimized error for MRR was 5.60%, while the error of surface roughness was 4.98%. To enhance the EDM machining characters authors [2,3] divide the tool electrode into multiple electrtodes to get multiple discharge points for each pulse. Experimentally it was analyzed that in single pulse, conventional EDM gives one spark, whereas multi spark EDM gives multiple sparks. In PMEDM [4,5,6] the powder of various grain size of aluminium, chromium, graphite, copper and silicon were mixed with dielectric media and experimentations were performed. It was reported that the MRR and surface quality of the work-piece improved. Also it was observed that hardness, abrasion and corrosion resistance of the machined surface improved significantly. Ho and Newman [7] have reported the review of research work carried out die sinking EDM within the past decade. EDM research relating to improving performance measures, optimising the process variables, monitoring and control of the sparking process. Oguzhan Yilmaz et al. [8] reported a user-friendly intelligent system for parameter selection of EDM. This system was developed in fuzzy set theory of expert rules based on experimental results and knowledge of skilled operators. Rajurkar and Wang [9] has analyzed the research and development of advanced monitoring and control systems for die-sinking EDM and WEDM. They emphasized on future developments of EDM, in the integration of EDM into future agile manufacturing systems. Which requires the EDM control system to have capabilities of high level automatic and remote operation strong network access capability, standard software interface and ability to share CAD/CAM resources with remote EDM system and other remote manufacturing facilities.Hence, it was decided to develop a flexible machine controller that have all these capabilities, stable and easy to handle by a machine operator.

## II. METHODOLOGY

The Flexible Machine Controller has three major components namely Programmable Logical Controller as a hardware, Supervisory Control and Data Acquisition based user interface and a database. FMC was developed, interfaced with EDM and tested as mentioned in author's paper [10]. The PLC was programmed in such way that it controls the most influencing process parameters (discharge current, pulse-on time and pulse-off time) of EDM process [11-13]. Along with this PLC was also programmed to carry out three machining operations (rough, semi-finish and finish) successively to perform a machining operation on workpiece material. PLC was switching the machining operation from one to another automatically depending upon the tool penetration in workpiece.

A user interfacing screen was developed on Supervisory Control and Data Acquisition system for the interaction of EDM through PLC. Through this user screen user can control the EDM and fed the process parameters remotely from the personal computer. A database program was developed in Visual Basic and interfaced with user interface screen. This database helps the user for the selection of EDM process parameters. This FMC was interface with die sinking EDM with the help of relays and contactors [10]. The functionality of FMC was tested and result was published [10]. Further study was extended for the performance evaluation of FMC. For this first of pilot experiments were conducted on over all range of EDM. These pilot experiments was conducted on OMCed EDM and bypassing the FMC. This experimental data used for database. Then the evaluation experiments were conducted on OMC and FMC with the same process parameters

## III. PILOT EXPERIMENTS

The pilot experiments were conducted to create an experimental database on commonly used mould and tool die steel materials were selected for experimental investigation as work piece material. The work piece materials used during experimentation were AISI 1040, AISI 52100, AISI M2, AISI D2, AISI P20 and AISI A2. These materials have wide range of industrial applications: plastic injection moulding dies, forging dies, Zn/Al casting dies, automobiles, defense, pharmaceutical, aerospace, ship building industries etc. Copper of rectangular cross section (20 x10 mm) has been used as the tool electrode.

There are so many EDM process parameters that affect the EDM process, the most influencing process parameters like discharge current, pulse-on time and pulse-off time were selected for this study purpose based on earlier work of researchers [11-13].

The pilot experiments were carried out on TOOLCRAFT G30 (I) die-sinking EDM machine of TOOLCRAFT India Ltd. Bangalore, installed at Machine Tool Laboratory of Mechanical Engineering Department, N.I.T.T.T.R. Chandigarh, India.

Machine has the range of discharge current from 1.56 to 25 Amps and pulse-on time, pulse-off time from 2 to 2000 µs. In the EDM machine, discharge current splits in 6 switches, pulse-on and pulse-off splits in 10 parts each. To find out the best combination of these three factors for machining characteristics (e.g. surface roughness and material removal rate), One Variable At a Time (OVAT) approach takes 600 experiments for one work piece material and tool electrode. To over come from this Center Composite Design (CCD) methodology of Design of Experiment (DoE) was used to investigate the optimal values for machining characteristics. Two level and three factorial (23) design was considered because in the present research work, three process parameters and two machining characteristics have been used.

Based on CCD, 20 experiments were carried out to study the entire range process parameter combinations. The factorial design matrix obtained for 20 experiments with different values of input process parameters are shown in Table I.

TABLE I
FACTORIAL DESIGN MATRIX FOR EXPERIMENTATION

| **Experiment No.** | **Machine setting** | | |
|---|---|---|---|
| | **Discharge current, I (A)** | **Pulse-on time, Ton (µs)** | **Pulse-off time, Toff (µs)** |
| 1 | 12.50 | 500 | 500 |
| 2 | 21.87 | 1000 | 1000 |
| 3 | 12.50 | 500 | 500 |
| 4 | 3.12 | 10 | 10 |
| 5 | 12.50 | 500 | 500 |
| 6 | 3.12 | 10 | 1000 |
| 7 | 12.50 | 500 | 10 |
| 8 | 12.50 | 500 | 500 |
| 9 | 21.87 | 10 | 1000 |
| 10 | 12.50 | 500 | 500 |
| 11 | 21.87 | 500 | 500 |
| 12 | 12.50 | 500 | 500 |
| 13 | 12.50 | 1000 | 500 |
| 14 | 3.12 | 1000 | 10 |
| 15 | 3.12 | 500 | 500 |
| 16 | 3.12 | 1000 | 1000 |
| 17 | 12.50 | 10 | 500 |
| 18 | 12.50 | 500 | 1000 |
| 19 | 21.87 | 10 | 10 |
| 20 | 21.87 | 1000 | 10 |

Pilot experimentations were conducted by following the standard machining procedure with negative polarity for electrode, positive polarity for work piece material, submerged flushing type, 0.5 mm machining depth and Grade 30 EDM oil.

The pilot experimental results of all six workpiece material for 20 sets of experiments are illustrated in Table II with resulting machining characteristics

The minimum surface roughness obtained for six different workpiece materials are shown in Figure1. For the workpiece material AISI 1040, AISI 52100, AISI M2, AISI D2, AISI P20 and AISI A2, it was noticed that the minimum surface roughness value 2.42 Ra, 2.84 Ra, 2.26 Ra, 3 Ra, 1.78 Ra and 2.39 Ra are obtained. It was found that the process parameters, discharge current, I =3.12 A, pulse-on time, Ton= 1000 µs, and pulse-off time, Toff= 1000 µs gives least surface roughness values for all type of workpiece materials except for the material AISI A2. For AISI A2 material, least value of surface roughness has been reported for I = 3.12A, Ton = 1000 µs and Toff = 10 µs. These optimum parametric values are shown in the table 4.2 by highlighting them.

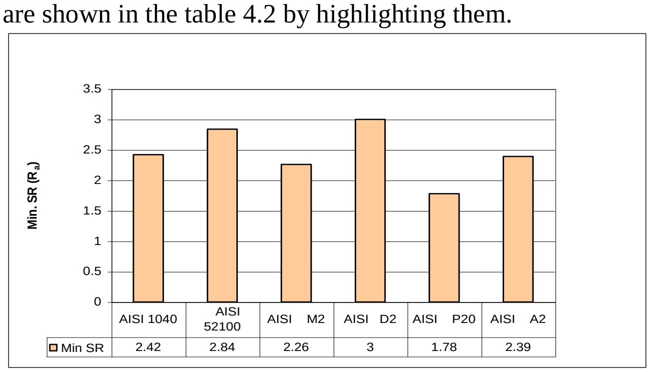


FIGURE 1 : VARIATION OF SURFACE ROUGHNESS FOR SIX DIFFERENT WORKPIECE MATERIAL WITH COPPER TOOL ELECTRODE

Figure 2 illustrate the variation of maximum material removal rate for six different workpiece material with copper tool electrode. It has been found that the maximum MRR of 44.5 mm³/min, 55.7261 mm³/min, 50.5 mm³/min, 52.057 mm³/min, 78.7982 mm³/min and 56.3607 mm³/min are obtained for workpiece material AISI 1040, AISI 52100, AISI M2, AISI D2, AISI P20 and AISI A2 respectively. It has been noticed that the process parameters, discharge current = 21.87 A, pulse-on time = 10 µs and pulse-on time = 10 µs gives maximum MRR for all workpiece materials.

The validation of FMC was reported in [14].

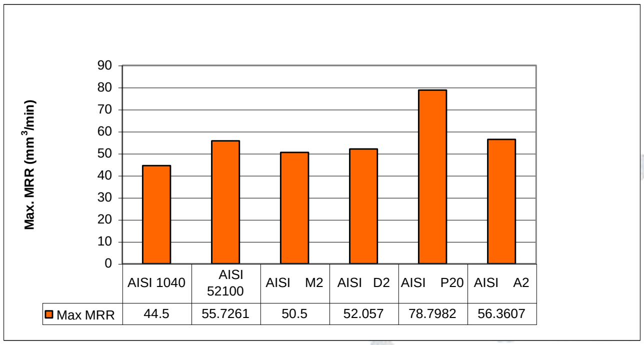


FIGURE 2 : VARIATION OF MAXIMUM MATERIAL REMOVAL RATE FOR SIX DIFFERENT WORKPIECE MATERIALS WITH COPPER TOOL ELECTRODE

## IV. EVALUATION

Performance evaluation of the developed Flexible Machine Controller was carried out with the Original Machine Controller by using same input process parameters. All the six workpiece materials (AISI 1040, AISI 52100, AISI M2, AISI D2, AISI P20 and AISI A2) were selected for experimentations along with the copper tool electrode material. The performance parameters used for evaluation were material removal rate and surface roughness. Two sets of experimentations were carried out on Flexible Machine Controlled die sinking EDM machine (developed FMC) and Original Machine Controlled die sinking EDM machine (OMC) independently. Same process parameters were used to conduct experimentation on both type of controlled die sinking EDM machine.

### *A. Evaluation On The Basis Of MRR*

The MRR values obtained from the experimentation with copper tool electrode are shown in Table III. Each experiment was repeated two times for averaging the MRR value obtained for a given tool electrode and workpiece material combination

TABLE II
MACHINING CHARACTERISTICS OF SIX MOULD AND DIE STEEL MATERIALS USING COPPER ELECTRODE

| Set of Expt. | I (A) | Ton (µs) | Toff (µs) | SR (Ra) | | | | | | MRR ($mm^3/min$) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | AISI 1040 | AISI 52100 | AISI M2 | AISI D2 | AISI P20 | AISI A2 | AISI 1040 | AISI 52100 | AISI M2 | AISI D2 | AISI P20 | AISI A2 |
| 1 | 12.50 | 500 | 500 | 15.13 | 17.61 | 13.63 | 15.35 | 13.90 | 11.968 | 15.4761 | 16.5578 | 14.5500 | 15.47 | 16.3704 | 15.2789 |
| 2 | 21.87 | 1000 | 1000 | 23.99 | 22.87 | 20.38 | 24.62 | 20.58 | 17.416 | 37.1400 | 35.6852 | 30.5800 | 33.61 | 39.6985 | 32.1848 |
| 3 | 12.50 | 500 | 500 | 16.13 | 17.08 | 13.69 | 15.47 | 13.80 | 12.21 | 13.4369 | 13.2669 | 15.2140 | 14.96 | 16.4231 | 17.2165 |
| 4 | 3.12 | 10 | 10 | 3.54 | 3.41 | 3.06 | 3.87 | 3.52 | 3.084 | 0.6641 | 0.6332 | 0.4460 | 0.6145 | 0.6415 | 0.7505 |
| 5 | 12.50 | 500 | 500 | 15.03 | 16.85 | 13.11 | 16.42 | 13.55 | 12.192 | 14.2588 | 15.3283 | 14.0400 | 15.14 | 16.23214 | 16.2682 |
| 6 | 3.12 | 10 | 1000 | 3.92 | 4.03 | 4.16 | 4.13 | 3.95 | 3.972 | 0.1089 | 0.1136 | 0.1288 | 0.1266 | 0.1387 | 0.1992 |
| 7 | 12.50 | 500 | 10 | 18.2 | 16.50 | 13.38 | 16.22 | 12.91 | 9.862 | 25.500 | 24.4328 | 20.2200 | 23.6354 | 33.77 | 21.2525 |
| 8 | 12.50 | 500 | 500 | 16.21 | 16.17 | 14.35 | 16.42 | 13.60 | 12.008 | 13.5500 | 14.4741 | 15.4375 | 15.15 | 16.8021 | 16.2910 |
| 9 | 21.87 | 10 | 1000 | 8.24 | 8.58 | 8.75 | 10.11 | 9.27 | 9.006 | 6.5530 | 6.7862 | 5.1254 | 5.8542 | 2.2839 | 2.4245 |
| 10 | 12.50 | 500 | 500 | 15.15 | 16.89 | 14.53 | 16.66 | 13.70 | 11.606 | 13.2250 | 16.5984 | 13.9600 | 16.31 | 16.55 | 15.6250 |
| 11 | 21.87 | 500 | 500 | 22.91 | 22.53 | 21.24 | 21.81 | 20.94 | 18.636 | 38.5200 | 40.1857 | 35.7855 | 39.5368 | 43.3842 | 34.8189 |
| 12 | 12.50 | 500 | 500 | 15.2 | 17.18 | 13.87 | 16.66 | 13.50 | 12.676 | 14.5540 | 16.8630 | 14.9825 | 15.1786 | 17.032 | 17.8465 |
| 13 | 12.50 | 1000 | 500 | 10.29 | 12.55 | 8.72 | 9.80 | 9.28 | 6.184 | 8.4353 | 10.1199 | 7.1971 | 8.6863 | 9.719 | 7.5705 |
| 14 | 3.12 | 1000 | 10 | 2.62 | 3.07 | 3.08 | 3.56 | 1.84 | **2.39** | 0.2688 | 0.2467 | 0.3538 | 0.4235 | 0.3011 | 0.3207 |
| 15 | 3.12 | 500 | 500 | 3.68 | 3.53 | 3.85 | 4.55 | 3.99 | 3.672 | 0.3595 | 0.3822 | 0.5468 | 0.5035 | 0.6791 | 0.6854 |
| 16 | **3.12** | **1000** | **1000** | **2.42** | **2.84** | **2.26** | **3.00** | **1.78** | 3.17 | 0.2180 | 0.2153 | 0.1712 | 0.1927 | 0.1783 | 0.2168 |
| 17 | 12.50 | 10 | 500 | 7.55 | 7.83 | 7.63 | 8.03 | 7.46 | 7.312 | 5.7580 | 5.5947 | 4.8500 | 5.1226 | 1.3834 | 2.0168 |
| 18 | 12.50 | 500 | 1000 | 16.22 | 17.04 | 14.73 | 15.51 | 14.25 | 11.862 | 10.8058 | 11.8182 | 10.7800 | 11.2442 | 14.6006 | 10.2368 |
| 19 | **21.87** | **10** | **10** | 6.64 | 8.55 | 7.65 | 9.24 | 7.71 | 9.418 | **44.5000** | **55.7261** | **50.5000** | **52.057** | **78.7982** | **56.3607** |
| 20 | 21.87 | 1000 | 10 | 22.28 | 21.00 | 17.99 | 19.77 | 16.09 | 17.164 | 42.5000 | 45.3393 | 42.1600 | 42.976 | 70.064 | 52.3584 |

TABLE III
VARIATION OF MRR FOR DIFFERENT WORKPIECE MATERIALS USING COPPER ELECTRODE

| Controller Type | Experiment No. | MRR (mm3/min) for Workpiece Material | | | | | |
|---|---|---|---|---|---|---|---|
| | | AISI 1040 | AISI 52100 | AISI M2 | AISI D2 | AISI P20 | AISI A2 |
| Original Machine Controller | 1 | 1.033 | 1.444 | 1.607 | 1.507 | 1.494 | 1.852 |
| | 2 | 1.055 | 1.389 | 1.551 | 1.572 | 1.534 | 1.829 |
| **Average MRR** | | **1.044** | **1.417** | **1.579** | **1.540** | **1.514** | **1.840** |
| Flexible Machine Controller | 1 | 1.114 | 1.511 | 1.780 | 1.633 | 1.714 | 1.876 |
| | 2 | 1.121 | 1.516 | 1.740 | 1.650 | 1.729 | 1.854 |
| **Average MRR** | | **1.118** | **1.514** | **1.760** | **1.641** | **1.722** | **1.865** |
| **Variation of MRR (%)** | | **7.07** | **6.83** | **11.50** | **6.59** | **13.69** | **1.35** |

Figure 3 depicts the variation in average MRR values for six different workpiece materials with copper tool electrode. It was observed that maximum average MRR=1.8656 mm3/min was obtained for the material AISI A2 and minimum average MRR=1.1184 mm3/min was obtained for the material AISI 1040 among the other workpiece materials types with the developed FMC. Results show that for all workpiece material, MRR values with developed FMC die sinking EDM are higher than that obtained with OMC die sinking EDM. This is mainly due to the fact that all the three machining operations (viz. rough, semi finish and finish) are performed simultaneously in case of developed FMC whereas in case of OMC, the workpiece material cools down slightly while changing the input process parameters for semi finish and finish machining. It was also noticed that developed FMC die sinking EDM gives 13.69 % higher MRR value for AISI P20 material and for AISI A2 material gives 1.35 % higher MRR value as compared to OMC die sinking EDM machining.

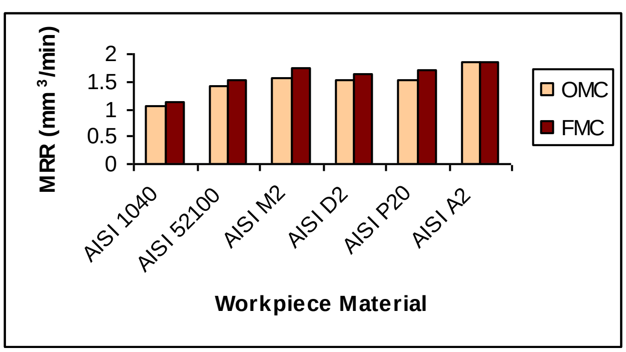


FIGURE 3: COMPARISON OF AVERAGE MRR BETWEEN DEVELOPED FMC AND OMC MACHINING USING COPPER ELECTRODE

*B. Evaluation On The Basis Of SR*

The performances of two controllers (OMC and developed FMC) were also evaluated on the basis of surface roughness values obtained during experimentation. The experimental results obtained with copper tool electrode for six workpiece material are shown in Table IV. Two sets of experiments were conducted for each of developed FMC and OMC die sinking EDM. Average of SR (Ra) was calculated for each material type with separate controllers on the die sinking EDM machine.

TABLE IV
VARIATION OF RA FOR DIFFERENT WORKPIECE MATERIAL USING COPPER ELECTRODE

| Controller Type | Experiment No. | A. MRR (mm3/min) for Workpiece Material | | | | | |
|---|---|---|---|---|---|---|---|
| | | AISI 1040 | AISI 52100 | AISI M2 | AISI D2 | AISI P20 | AISI A2 |
| Original Machine Controller | 1 | 4.162 | 4.696 | 3.64 | 4.55 | 2.626 | 3.32 |
| | 2 | 4.006 | 4.608 | 3.24 | 4.664 | 2.756 | 3.124 |
| **Average MRR** | | **4.084** | **4.652** | **3.44** | **4.607** | **2.691** | **3.222** |
| Flexible Machine Controller | 1 | 3.86 | 4.502 | 3.174 | 4.414 | 2.4 | 2.71 |
| | 2 | 3.986 | 4.446 | 3.064 | 4.318 | 2.518 | 2.764 |
| **Average MRR** | | **3.923** | **4.474** | **3.119** | **4.366** | **2.459** | **2.737** |
| **Variation of MRR (%)** | | **3.94** | **3.83** | **9.33** | **5.23** | **8.62** | **15.05** |

Figure 4 illustrates the average SR(Ra) values obtained for six different workpiece material with developed FMC die sinking EDM and OMC die sinking EDM. For developed FMC, maximum average SR(Ra) was obtained for the material AISI 52100 (Ra=4.474 µm) and minimum average SR(Ra) was obtained for the material AISI P20 (Ra=2.459 µm). Whereas with OMC, maximum average SR (Ra=4.652 µm) was obtained for AISI 52100 material and minimum average SR (Ra=2.691 µm) was obtained for AISI P20 material. The comparative analysis of SR(Ra) with developed FMC and OMC shows that the maximum SR (Ra) difference of 15.05 % (0.485 µm) was observed for AISI A2 workpiece material and minimum SR(Ra) difference of 3.83 % (0.161 µm) was observed for AISI 52100 workpiece material. It has been observed that for all workpiece materials better surface finish were obtained with the developed FMC as compared to the OMC of die sinking EDM. The surface finish improvement with the developed FMC ranges between 3.83 % to 15.05 % depending on the workpiece material.

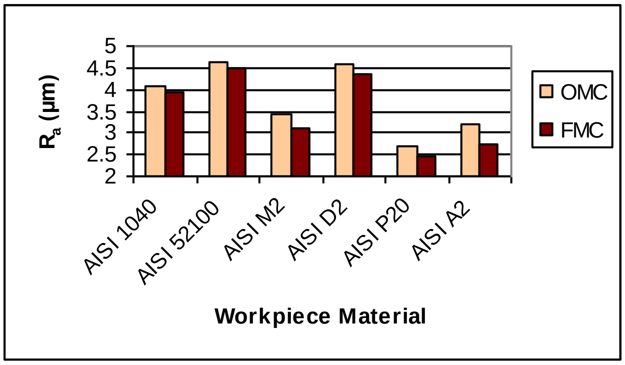


FIGURE 4: COMPARISON OF AVERAGE RA BETWEEN DEVELOPED FMC AND OMC MACHINING FOR DIFFERENT WORKPIECE MATERIAL USING COPPER ELECTRODE.

## V. CONCLUSIONS

After validating the results with the developed Flexible Machine Controlled die sinking EDM machine, the performance characteristics were analysed and the conclusions drawn from the said results are outlined as:

- A total of 120 records of experimental data were generated from the pilot experimentation for the experimental database.
- The minimum surface roughness was observed for all the workpiece material with copper tool electrode for the combination of input process parameter discharge current = 3.12A, pulse-on time = 1000 µs and pulse-off time = 1000 µs except for the material AISI A2.
- The experimental record shows that I = 3.12A, $T_{on}$ = 1000 µs and $T_{off}$ = 10 µs combination of input process parameters gives minimum surface roughness for material AISI A2 with copper tool electrode.
- The input process parameter combination giving maximum material removal rate for all six type of workpiece material and copper tool electrode were i.e. discharge current = 21.87 A, pulse-on time = 10 µs and pulse-on time = 10 µs.
- It has been observed that the developed Flexible Machine Control EDM machine gives 13.69 % higher MRR value for AISI P20 material and for AISI A2 material gives 1.35 % higher MRR value as compared to OMC die sinking EDM machine.
- It has been noticed from the experimentation results that for all workpiece material, MRR values with developed Flexible Machine Control EDM machine are higher than that obtained with OMC die sinking EDM machine.
- The comparative analysis of surface roughness values ($R_a$) with developed Flexible Machine Controller and OMC shows that the maximum SR value ($R_a$) difference of 15.05 % (0.485 µm) was observed for AISI A2 workpiece material and minimum SR value ($R_a$) difference of 3.83 % (0.161 µm) was observed for AISI 52100 workpiece material.
- The experimental investigations reveals that for all workpiece material better surface finish were obtained with the developed Flexible Machine Controller as compared to the OMC of die sinking EDM machine.

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